MAINTAINING IN SITU NATURAL TURFGRASS

IN THE

UNITED KINGDOM

IN A

MULTI-USE COMPACT STADIUM

WITH A

RETRACTABLE ROOF

A THESIS SUBMITTED

TO THE

UNIVERSITY OF WALES.

BY

JOHN JAMES PHILLIPS.

FOR THE

DEGREE OF PHILOSOPHIAE DOCTOR.

The Welsh School of Architecture.

University of Wales College Cardiff. U.K.

MARCH 2005

This dissertation is dedicated to my late father who over sixty years ago took me to the home of Cardiff City, AFC, Ninian Park, Cardiff, UK. There my interest was kindled in the many facets of Association Football.

But it was sixty years from that point before I became interested in the use of in situ natural turfgrass as a playing surface.

DECLARATION

This work has not been previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

Signed

--CANDIDATE

Date 31st March 2005.

STATEMENT 1

This dissertation is being submitted in the fulfilment of the requirements for the degree of

PHILOSOPHIAE DOCTOR

Signed

--CANDIDATE

Date 31st March 2005

STATEMENT 2

This dissertation is the result of my own independent work/investigation, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

Signed

--CANDIDATE

Date 31st March 2005

STATEMENT 3

I hereby give consent for my dissertation, if accepted, to be available for photocopying, Inter-library loans and for the title and abstract to be made available to outside organisations.

Signed

-- CANDIDATE

Date 31st March 2005

ABSTRACT.
The preface and introduction of this thesis sets the background to the topic which explores in some depth the probability of maintaining in situ turfgrass in a multi-use compact stadium with a retractable roof in the United Kingdom. The research methods used are based on the measurement of three dimensional models, literature reviews and visits to stadia.

The study begins with a broad historic review of Greek athletic stadia and that of the Roman Amphitheatre and explains their modern legacies. The review then traces UK stadia development in outline between 1863 and 1965 and from then to 2000. It links that development to the expansion of various ball games and contemporary social conditions.

A definition of a compact stadium is established and the history of the retractable roof is traced. The impact these features have on stadia use, turfgrass cultivation and wear is considered, as is the impact on spectators.

Sufficient turfgrass science is provided to appreciate the problems of growing cool season turfgrasses in shaded conditions. It links these conditions with those similarly found in nature. This comparison confirms the view that where the supply of heat, light and wind are too little or too much, failure will follow. The study also traces other influences on turfgrass development which improve the efficiency of the photosynthetic processes; they include drainage, rootzone composition, turfgrass culture and horticultural practices.

Some developers have abandoned the use of traditional in situ rootzone in stadia but still use natural turfgrass. The study examines these non traditional methods, pointing out their problems and benefits.

The result of the research is produced in tables, charts, graphs and photographs; this data defines areas of shadow, light levels and air movement for each of the differing roofs. The superstructure is standard to each and allows air to pass beneath it. The research equipment is described in detail.

Part eight evaluates the problems of in situ turfgrass maintenance in multi-use stadia with retractable roofs. It considers the factors that bring about these problems and examines and comments on suggestions for countering or avoiding them. These suggestions are of two kinds, measures currently adopted and suggestions made by this work.

The importance of maintaining turfgrass in prime condition is considered. The question is asked whether such a condition can be achieved in multi-use stadia without reducing their commercial potential. From this follows a discussion on turfgrass wear and how that issue may relate to the seating capacity of a stadium.

The future of natural in situ turfgrass in stadia is considered and whether there is an inevitability that it will be replaced by artificial turfgrass.

In the UK. judicial enquiries inevitably follow football disasters. The appendices include the recommendations of the last three major enquiries of the 20th Century. These are included because taken together they form the basis of an historical survey indicating inadequacy of UK stadia, These recommendations are not usually found in a single document.

The development of a playing surface is traced through the history of Ninian Park, the ground of Cardiff City AFC, Wales UK. This ground is not untypical of grounds developed at the beginning of the 20th Century.

A section on artificial turfgrass is included its advantages and disadvantages are discussed.

The Case Studies provide an important historical contribution to the development of complex stadia from 1965 onwards. They record successes and failures of both playing surfaces and of retractable roof mechanisms. Stadia are included which do not have retractable roofs. Their inclusion is warranted because of the contribution they made to stadia development or to turfgrass preservation in hostile stadia environments.

The study concludes that the centrally located retractable roof provides the least environmentally favourable solution for the maintenance of turfgrass but its form is nevertheless convenient. The balanced view is that the most advantageous way to maintain turfgrass in the climate of a large compact stadium is to remove the turfgrass from a stadium when it is not required to be there. Turfgrass is not a satisfactory surface for multi-use activities but an artificial surface is.

ACKNOWLEDGEMENTS.

The laboratory research for this thesis could not have been conducted without a Wind Tunnel or an Artificial Sky. I am therefore grateful for the unlimited use of both these facilities located in The Centre for Research in the Built Environment (CRiBE) which is a Department of the Welsh School of Architecture. A most sincere thank you to Professor Philip Jones and Mr Don Alexander of (CRiBE) for bringing forward their plans to modify the wind tunnel. This gesture ensured that the research facilities would be available to measure the air movements over the playing surface of the model of the generic stadium used in this study.

I am greatly indebted to Mr Alexander for being my supervisor on those aspects of the dissertation related to the Wind Tunnel and the Artificial Sky. My research has gained significantly from his experience and watchful guidance.

I am also most grateful to Mr Huw Jenkins for his unstinting help with the processes of testing in the Wind Tunnel and in the Artificial Sky. I am also grateful to Mr Rob Arthur and my son, Gareth Phillips. Without their help it would have been difficult for me to have coped physically with moving the large models in and out of the Wind Tunnel.

I am also indebted to members of the Department for their general interest in my topic.

My thanks to Professor Malcolm Parry, the immediate past Head of the School of Architecture for both his cheerful friendship and constant encouragement during the preparation of this work.

I should also like to thank Ms Sylvia Harris, the Librarian W.S.A. and her staff, always pleasant and most helpful.

I am also grateful to a number of the staff at The Institute of Grassland & Environmental Research (IGER). Aberystwyth.Wales. Thanks are also due to Dr Brian Clifford, Dr James M^cduff and Dr Danny Thorogood, who during the course of the work became both critics and friends.

Then there are those various football groundsmen in England, Wales, Scotland and Italy, who all "looked at me vaguely, as drinking cattle do"[1] wondering what an architect could possibly

[1] Snake. Lawrence .DH (Modern Verse in English.1900-1950. Cecil & Tate Eyre & Spottiswoode London, 1958 (page 244).

know about grass or whether one could even care about it. Gentlemen, my thanks are to you. I did listen!

Numerous people have helped, too many to mention, but I must single out Beryl Phillips for her translations from the French and Italian into English and vice versa and also for her invaluable proof reading of the text.

Of signal importance is my general supervisor, Dr Mike Fedeski who had the courage to accept, some years ago a geriatric student into his M.Sc.Course. He then found even more courage to take me on for this study. Dr Fedeski is that rare person who has time for people and the challenges they present. He asks no more from a student than to extend the argument. I believe our long discussions on occasions left us both tired, but our time together was always to my considerable benefit. If there is merit in this work it is because of his pushing me further and further into probing my reasoning.

I shall always be grateful to Dr Fedeski also for his considerate and caring attitude. I thank him above all for making it possible for me to bring the summer back into the autumn of my life. I now believe through our association that it is not impossible to teach an old dog new tricks!

CONTENTS

TITLE.
DEDICATION.
DECLARATION.
ABSTRACT.
ACKNOWLEDGEMENTS.
CONTENTS.
LIST OF FIGURES.
PREFACE.
INTRODUCTION TO THESIS.

PART ONE.
AIMS AND METHODOLOGY.

PART TWO.
SURVEY OF STADIA DEVELOPMENT.

PART THREE.
TUFGRASS CULTURE

PART FOUR.
GROWTH & MAINTENANCE OF IN SITU TURFGRASS IN STADIA CONDITIONS.

PART FIVE.
DRAINAGE AND ROOTZONE COMPOSITION.

PART SIX.
OTHER METHODS OF SUSTAINING TURFGRASS IN STADIA..

PART SEVEN.
SHADE, LIGHT & WIND RESEARCH.

PART EIGHT.
DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS.

PART NINE.
APPENDICES.

PART TEN.
REFERRENCES.

LIST OF FIGURES AND TABLES
PART TWO

Fig 2.1.1.1.	Olympia 7th C. BC. Plan of Stadium.
Fig 2.1.1.2.	Olympia 7th C. BC. Archaeological Remains.
Fig 2.1.1.3.	The Stadium for the Inaugural Olympic Games of the Modern Era Greece 1896.
Fig 2.1.2.1.	The Flavian (Colosseum)Amphitheatre Rome 69-81.
Fig 2.1.2.2.	Cross section through a part of the superstructure of the Colosseum.
Fig 2.2.1.	An Illustration of Street Football in Medieval England.
Fig 2.3.1.	Crystal Palace London UK 1905.
Fig 2.3.1.1.	Points of Vantage, Crystal Palace, London UK 1914.
Fig 2.3.1.2.	Points of Vantage , Stamford Bridge, London UK 1946.
Fig 2.3.1.3.	Points of Vantage , Cardiff, UK 1921.
Fig 2.3.1.4.	Internal & External Views of Olympic Stadium, Stockholm 1912.
Fig 2.3.1.5.	Amsterdam Olympic Stadium, 1928.
Fig 2.3.1.6.	Ayresome Park Middlesborough . Master Plan 1903.
Fig 2.3.1.7.	St Andrew's Birmingham. 1906.
Fig 2.3.1.8.	Brighton and Hove Albion, the South Stand, 1910.
Fig 2.3.1.9.	Aston Villa Birmingham, 1914.
Fig 2.3.1.10.	Manchester United, Old Trafford,1920s.
Fig 2.3.1.11.	Arsenal Highbury circa 1925.
Fig 2.3.1.12.	Bristol City Aston Gate circa 1950.
Fig 2.3.2.1.	Condition of Typical Playing Surface, circa 1950.
Fig 2.3.2.2.	Surface Flooding, circa 1950.
Fig 2.3.2.3.	Fatal Consequences of Caging. Hillsborough, Sheffield, April 1989.
Fig 2.3.4.1.	Aftermath of the Heysel Stadium Riot Brussels May 1985.
Fig 2.3.8.1.	Aston Villa AFC Birmingham, Villa Park circa 1990s.
Fig 2.3.8.2.	The Arsenal AFC, London, Highbury Stadium circa 1990s
Fig 2.3.8.3.	Middlesborough AFC Cellnet Riverside Stadium. (A New Build Stadium)
Fig 2.3.8.4.	Manchester City AFC. Prior to relocation circa 1990s.
Fig 2.3.8.5.	Wembley Stadium London , Final Refurbishment Prior to Demolition.
Fig 2.3.8.6.	Manchester United AFC, Old Trafford AFC, circa 1995.
Fig 2.3.8.7.	Huddersfield AFC Huddersfield. The first stadium which cams as a direct response from Taylor.
Fig 2.4.5.	Illustration of comparative proportions of pitches for the various games of football.
Fig 2.5.3.	Illustrations of basic wear patterns imposed by the various games of football.

PART THREE

Table 3.1.6.	Approximate Number of Seeds Per Pound and Normal Seeding Rates for Selected Species.
Fig 3.2.5.	The Electromagnetic Spectrum.
Table 3.2.5.	Environmental Requisites for the Maximum Floral Induction of Fifteen Turfgrasses.
Table 3.2.6.	The Effects of 8 and 16 hour Day Lengths on the Growth Characteristics of Merion Kentucky Bluegrass

PART FOUR

Table 4.2.1.	Elements obtained from air & water and from soil.
Table 4.2.1.3.	Minor Nutrients or Micronutrients.

PART FIVE

Fig. 5.2.0.1. All Sand Drainage Systems.

Table 5.2.0.2.1. Particle size grade categories for sport turf soils.
Table 5.2.0.2.2. Typical commercial grades for particles larger than 2mm in diameter.

Fig 5.3.0.1.1. Stoke City Football Club UK. 1938. Staff attempt to thaw ground.
Fig 5.3.0.1.2. White Hart Lane UK. 1925. 3000 straw bales laid to protect pitch.

PART SEVEN

Fig 7.2.1. View into the Artificial Sky through the open overhead hinged door.
Fig 7.2.2. The Wind Tunnel and its Bellmouth.
Fig 7.2.3. Illustrates the Fans and Control Console.

Fig 7.3.1.1. Diagrammatically illustrates the 'Slice' arrangement.
Fig 7.3.1.2. The cross section through the model shows opposite grandstands separated by the arena.
Fig 7.3.1.3. Illustrates the plan of the model.
Fig 7.3.1.3.1. Shows the wind tunnel set up for the model representing the condition of a centrally located retractable roof.

Table 7.3.5.1. Values for Hourly Irradiation. Roof No. 1. For, January to June and December.
Table 7.3.5.2. Values for Hourly Irradiation. Roof No. 2. For, January to June and December.
Table 7.3.5.3. Values for Hourly Irradiation. Roof No. 3. For, January to June and December.
Table 7.3.5.4. Values for Hourly Irradiation. Roof No. 4. For, January to June and December.
Table 7.3.5.5. Values for Hourly Irradiation. Roof No. 5. For, January to June and December.

Fig 7.3.5.1. (R1). Base Model – No roof.
Fig 7.3.5.2. (R2). Longitudinal Bi-parting roof.
Fig 7.3.5.3. (R3). Asymmetrical Retractable roof. [Deep Structure]
Fig 7.3.5.4. (R4). Centrally located Bi-parting roof. [Deep Structure]
Fig 7.3.5.5. (R5). Centrally located Bi-parting roof. [Shallow Structure]
Fig 7.3.5.6. (R6). Centrally located Bi-parting roof. Exposed lattice construction, retractable roof open.
Fig 7.3.5.7. (R7). Centrally located Bi-parting roof. Exposed lattice construction, retractable roof closed.
Fig 7.3.5.8. (R8). Centrally located Bi-parting roof. Exposed lattice construction, retractable roof removed.
Fig 7.3.5.9. (R8). Roof with central lattice structure and retractable roof removed.
Fig 7.3.5.10. A section of the longitudinal Beam set over the San Siro Stadium, Milan, Italy.

Fig 7.4.1.1. No Roof 21st December 12:00 hrs.
Fig 7.4.1.2. No Roof 21st June 12:00 hrs.
Fig 7.4.1.3. Longitudinal Bi-parting Roof. 21st December 12:00 hrs.
Fig 7.4.1.4. Longitudinal Bi-parting Roof. 21st June12:00 hrs.
Fig 7.4.1.5. Centrally Located Retractable Roof. 21st December 12:00 hrs.
Fig 7.4.1.6. Centrally Located Retractable Roof. 21st June 12:00 hrs.
Fig 7.4.1.7. Centrally Located Retractable Roof. Lattice Construction. 21st December 12:00 hrs.
Fig 7.4.1.8. Centrally Located Retractable Roof. Lattice Construction. 21st June 12:00 hrs.
Fig 7.4.1.9. Asymmetrical Retractable Roof. (North West.) 21st December 12:00 hrs.
Fig 7.4.1.10. Asymmetrical Retractable Roof. (North West.) 21st June 12:00 hrs.
Fig 7.4.1.11. Asymmetrical Retractable Roof. (North East.) 21st December 12:00 hrs.
Fig 7.4.1.12. Asymmetrical Retractable Roof. (North East.) 21st June 12:00 hrs.

Chart 7.4.2 The Chart used to determine direct light areas and their locations.

Table 7.4.1.1. Percentage of Shadow Free Areas and their Locations. All Roof Types. JANUARY
Table 7.4.1.2. Percentage of Shadow Free Areas and their Locations. All Roof Types. FEBRUARY
Table 7.4.1.3. Percentage of Shadow Free Areas and their Locations. All Roof Types. MARCH
Table 7.4.1.4. Percentage of Shadow Free Areas and their Locations. All Roof Types. APRIL
Table 7.4.1.5. Percentage of Shadow Free Areas and their Locations. All Roof Types. MAY
Table 7.4.1.6. Percentage of Shadow Free Areas and their Locations. All Roof Types. JUNE
Table 7.4.1.7. Percentage of Shadow Free Areas and their Locations. All Roof Types. DECEMBER

Fig 7.4.1.13. Illustrates graphically the shadow free area on the turfgrass playing surface. January
Fig 7.4.1.14. Illustrates graphically the shadow free area on the turfgrass playing surface. February
Fig 7.4.1.15. Illustrates graphically the shadow free area on the turfgrass playing surface. March
Fig 7.4.1.16. Illustrates graphically the shadow free area on the turfgrass playing surface. April
Fig 7.4.1.17. Illustrates graphically the shadow free area on the turfgrass playing surface. May
Fig 7.4.1.18. Illustrates graphically the shadow free area on the turfgrass playing surface. June
Fig 7.4.1.19. Illustrates graphically the shadow free area on the turfgrass playing surface. December

Table 7.5.0.1. Illustrates the comparison between the diffuse and beam values for various sky conditions.

Chart 7.5.0.1. Lux and percentage conversion values. Roof No. 1
Chart 7.5.0.2. Lux and percentage conversion values. Roof No. 2
Chart 7.5.0.3. Lux and percentage conversion values. Roof No. 3
Chart 7.5.0.4. Lux and percentage conversion values. Roof No. 4
Chart 7.5.0.5. Lux and percentage conversion values. Roof No. 5
Chart 7.5.0.6. Lux and percentage conversion values. Roof No. 6
Chart 7.5.0.7. Lux and percentage conversion values. Roof No. 7
Chart 7.5.0.8. Lux and percentage conversion values. Roof No. 8
Chart 7.5.0.9. Lux and percentage conversion values. Roof No. 9

Chart 7.5.2.1. The Direct and Diffuse Light Location Diagram

Fig. 7.6.0.1. The Wind Tunnel Model Set to Measure the Influences of Centrally Located Retractable Roof.
Fig. 7.6.0.2. The Wind Tunnel Model Set to Measure the Influences of Asymmetrical Retractable Roof.
Fig. 7.6.0.3. The Power Law Formula.

Fig 7.6.0.4. Asymmetrical Retractable Roof. Extract Closed. (A.R.E.C.)
Fig 7.6.0.5. Asymmetrical Retractable Roof. Intake & Extract Open. (A.R.I.E.O.)
Fig 7.6.0.6. Asymmetrical Retractable Roof. Intake & Extract Closed. (A.R.I.E.C.)
Fig. 7.6.0.7. Asymmetrical Retractable Roof. Extract Open. (A.R.E.O.)

Fig 7.6.0.8. Bi-Parting Retractable Roof. Intake & Extract Open. (B.P.R.I.E.O)
Fig 7.6.0.9. Bi-Parting Retractable Roof. Intake Closed. (B.P.R.I.C.)
Fig 7.6.0.10. Bi-Parting Retractable Roof. Extract Closed. (B.P.R.E.C.)
Fig 7.6.0.11. Bi-Parting Retractable Roof. Intake Extract Closed. (B.P.R.E.C.)

Fig 7.6.0.12. Centrally Located Retractable Roof. Extract Closed. (C.L.R.E.C.)
Fig 7.6.0.13. Centrally Located Retractable Roof. Intake Closed. (C.L.R.I.C.)
Fig 7.6.0.14. Centrally Located Retractable Roof. Intake Extract Closed. (C.L.R.I.C.)
Fig 7.6.0.15. Centrally Located Retractable Roof. Intake Extract Open. (C.L.R.I.E.O.)

Fig. 7.6.0.16. Asymmetric Retractable Roof. Airflow Rates.
Fig. 7.6.0.17. Bi-Parting Retractable Roof. Airflow Rates.
Fig. 7.6.0.18. Centrally Located Bi-Parting Roof. Airflow Rates.

PART NINE

Fig 9.3.1.2.1. Ninian Park circa 1910.
Fig 9.3.1.2.1. Ninian Park circa 1922.

Fig 9.4.1.1. Internal view of Astrodome.
Fig 9.4.1.2. Birds eye view of Astrodome.

Fig 9.4.2.1. The relationship between the Tower and the Stadium.
Fig 9.4.2.2. Aerial view of the stadium.

Fig 9.4.3.1. The opening in the tower.
Fig 9.4.3.2. The process of withdrawing the fabric into the tower.
Fig 9.4.3.1. The interior of the Pontiac Silverdome Stadium.

Fig 9.4.4.1. The SkyDome in Baseball configuration.
Fig 9.4.4.2. The roof in the closed position.
Fig 9.4.3.3. The SkyDome in Cross Section
Fig 9.4.4.3. The SkyDome in Football configuration.

Fig 9.4.5.1. SkyDome: view of arena
Fig 9.4.5.1.2. Area A: the playing surface, August 1996.
Fig 9.4.5.1.3. Area A: the playing surface.
Fig 9.4.5.1.4. The supporting steelwork for the roof.

Fig 9.4.6.1. The Wales National Stadium (Arms Park).
Fig 9.4.6.2. The Millennium Stadium, 1998.
Fig 9.4.6.2.2. The Millennium Stadium – cross section.
Fig 9.4.6.2.3. The Old Stadium seen from the River Taff.

Fig 9.4.7.1. The Gelredome Stadium Arnhem.
Fig 9.4.7.2. Internal view of Stadium during construction.

Fig 9.4.8.1. The Sapporo Dome, Hokkaido, Japan.
Fig 9.4.8.1.2. The playing field passing through the 'letterbox'.
Fig 9.4.8.1.3. The Stands being moved.
Fig 9.4.8.1.4. Installing the artificial surface.
Fig 9.4.8.1.5. Preparing to swivel the playing surface through 90°

Fig 9.5.0.1. The equation summarising the photosynthesis process within the context of a leaf.

Fig 9.5.0.2. The cross section of a leaf showing the panels making up its structure and naming its parts.

Fig 9.6.1. Shadow Photosynthesis in the Artificial Sky (January).
Fig 9.6.2. Shadow Photosynthesis in the Artificial Sky (February).
Fig 9.6.3. Shadow Photosynthesis in the Artificial Sky (March).
Fig 9.6.4. Shadow Photosynthesis in the Artificial Sky (April).
Fig 9.6.5. Shadow Photosynthesis in the Artificial Sky (May).
Fig 9.6.6. Shadow Photosynthesis in the Artificial Sky (June).
Fig 9.6.7. Shadow Photosynthesis in the Artificial Sky (December).

PREFACE.

Elias Canetti, novelist and playwright, winner of the 1981 Nobel Prize for Literature, explores in his works the emotions of the crowd, the psychopathology of power and the positions of individuals at odds with the society around them. In one of his books, Crowds and Power published in 1962, he states under the section the "Crowd as a Ring" the relationship of the spectator with the stadium and the stadium with the city. These three paragraphs set out below were written circa 1960. They accurately describe the emotions and feelings engendered by a stadium more common on the continent of Europe and in North America than in the UK prior to 1990.

> Outside facing the city, the arena displays a lifeless wall; inside is a wall of people. The spectators turn their backs to the city. They have been lifted out of the structure of walls and streets and for the duration of their time in the arena, they do not care about anything which happens there; they have left behind all their associations, rules and habits.
>
> An arena is well demarcated from the outside world. It is usually visible from far off and its situation in the city-the space which it occupies-is well known. People always feel where it is, even if they are not thinking of it. Shouts from the arena carry far and, when it is open at the top, something of the life which goes on inside communicates itself to the surrounding city.
>
> But however exciting these communications may be, an uninhibited flow into the area is not possible. The number of seats it contains is limited; its maximum density is fixed in advance. The seats are arranged so that people are not too closely crushed. The occupants are meant to be comfortable in them and to be able to watch each from his own seat, without disturbing others[2]

The Canetti paragraphs forecast after 1990 the provisions in modern UK stadia in terms of planning, comfort and safety. These feelings and emotions should be compared with the impressions taken from experiences of Ninian Park Football Ground UK between 1938 and 1955. This ground was not that different from many others around that time. These impressions perhaps indicate why so many of the Official Reports on accidents in football grounds were not fully acted upon until the Popplewell Report of 1985. Even after that Report

[2] Crowds and Power, Canetti Elias Reprinted Penguin Books 1992. (pages 30-31)

more disasters were to follow. It appeared that however great was the discomfiture and risk, working class spectators were not put off attending a match. The Hillsborough disaster (1989) was to change that significantly and also the stadium environment for the foreseeable future in the UK.

"Ninian Park was never a stadium! It was at that time, referred to by the locals as the 'Ground'. In winter it was a cold, open and draughty place. Amid the excitement it offered, lurked the unrecognised potential for imposing injury to the person.

The majority of the spectators stood on the uncovered 'Bob Bank', so called because it cost a shilling to stand there. When crowded, the bank offered limited views over the playing area because of its configuration and shallow formation. The adventurous sought points of vantage on adjacent walls, poles or roofs. The memory is vivid on one occasion of two adventurers seeking a better view falling through the asbestos roof of an adjacent covered terrace. The game went on!

On the Bank, crowd support barriers were limited in number and laid out without an apparent strategy. When the bank was full, the crowd swayed forwards and backwards in response to the excitement of a game. The pressure imposed by these movements was both frightening and uncomfortable. It was not uncommon to see injured spectators being handed over the heads of the crowd to receive first aid treatment at the edge of the pitch, which was also the exciting but dangerous refuge for some children. The danger came from the exposure to contact with players.

When the weather conditions were bad, they were even worse for the players. They slid uncontrollably over water-logged ground, which rapidly turned into mud around each goal area and at the centre circle. The crowd felt at one with the players and shared in their discomfiture, and were emotionally participating in the game. When it rained they got wet, very wet! Water penetrated the shoulders of topcoats and also ran down the neck. But the weather was never a deterrent. Then there was often a four-mile walk home.

The excitement was to arrive at the ground early especially to see the first match of the season. The whole playing surface was visible because the ground was practically empty. The turf was now restored to being completely green but as the ground filled the extent of the green grass visually diminished. But it was a new season, a new beginning and a new hope!

For many in those days the first stadium they visited which could be now recognised as a stadium was Wembley, London. The pitch would have been a perfect green. But for many spectators there could be no visual intimacy with the players.

Years later, those who visited the Astrodome, Houston, Texas, USA, found the structure impressive. The stadium could be easily reconfigured. It was safe. The comfort conditions excellent. The food had been changed from the cold, greasy pies of old into a five-course meal in luxury surroundings. But some spectators found the magic had gone! It was not just the passage of time. The experience had been sanitised away and with it the ability to grow and maintain natural turfgrass in that stadium as in most other large stadia.

INTRODUCTION TO THESIS.

The New Oxford Dictionary defines a stadium as an "athletic or sports ground with tiers of seats for spectators". [3] These elements are consistent in any modern stadium: an arena to display events and an inclined space surrounding it, from which spectators view them.

Both of these elements were present in early Greek stadia and Roman Amphitheatres, but it was only the physical characteristics of the Amphitheatres that were transferable to modern stadia. These transferable features included the segregation of the arena from the viewing area and the amphitheatre from its surroundings. Segregation coupled with the introduction of vomitoria in the viewing galleries made it possible, for example the Colosseum, Rome, Italy, (AD 70-82) to demonstrate an organised and efficient management structure capable of controlling a complex building accommodating at least 50,000 spectators, most of whom were seated.

These features have now become essential elements in the design of stadia providing spectator safety and comfort as well as players' safety. To these features within a stadium must be added safety and comfort for spectators in the immediate vicinity of a stadium.

Therefore, the compilers of the New Oxford Dictionary would more accurately define a contemporary stadium by examining the virtues of both enclosing a stadium and separating it from immediate surroundings.

On doing so they may decide to add the word 'enclosed' to its current definition of a stadium, to allow it to read "an enclosed athletic or sports ground with tiers of seats for spectators".

Roof protection now plays an important part in the development of stadia. The technical expertise and the materials are now available to develop a range of options to protect spectators from the climatic conditions. These options are as follows:

- enclosing a stadium with a roof. Such a stadium may have a capacity of between 80,000 and 100,000 spectators all of whom may be seated.
- enclosing a stadium with a roof but allowing it to open or close. The capacity of such a stadium may extend from 30,000 to 80,000 spectators.

---

[3] The New Oxford Dictionary of English. Edited by Judy Pearsall, Clarendon Press, Oxford 1998.Page 1808.

- providing continuous cantilevered roofs over spectators. The degree of the protection is dependent on the length of the cantilever.

A stadium may be built without a roof of any kind and the cavea will therefore be completely open to the elements. This is currently not a fashionable option for newly built large stadia in the Northern Hemisphere. Nevertheless, it is the configuration which is most favourable for the growth and maintenance of turfgrass. The other options provide an environment which makes the growth of turfgrass either impossible in the case of the closed roof, or problematic in the other roofing options.

It is essential to understand that where Association Football is played at the highest level the playing surface currently must be natural turfgrass. This creates a conflict between the desire to provide high standards of spectator weather protection and the needs of turfgrass. A fixed roof provides the highest standard of spectator protection but also produces conditions totally alien to the needs of turfgrass.

There is no evidence to link the introduction of the retractable roof to aid the needs of turfgrass. Chronologically, the first major retractable roof (1961) came before the turfgrass failure under a fixed roof (1965). The second retractable roof (1976) like the first retractable roof was introduced simply to allow a building to be used in either the open or closed position. It was not until 1989 that a designer introduced a retractable roof and in his design acknowledged that turfgrass in stadia with high standards of weather protection was accompanied by turfgrass problems. That designer provided options to include hard surfaces and a removable turfgrass surface in a single pallet. These early retractable roofs were all built in North America where at that time Association Football was rarely played.
The introduction of a retractable roof significantly increases stadium building costs, thereby necessitating the need to intensify the use of a stadium in an effort to recoup its capital and running costs. This strategy is, for a number of reasons, rarely successful.

The need to increase stadia activities has brought about the introduction of multi-use activities often in conditions that are inappropriate. What history reveals is that all successful multi-use venues have had floor surfaces, the maintenance of which is not dependent on the environment in which they are used.

When in the early 1990s developers in Europe began to consider the inclusion of the retractable roof in stadia where playing surfaces had to be natural turfgrass, they looked to simplify the method of retraction. There was concern at the capital involved in the successful 1989 Canadian solution: this was prohibitive. The solution they favoured was the centrally located bi-parting retractable system. It was, in principle, the most economic and straightforward mechanical solution to moving the roof.

However, the centrally located bi-parting roof arrangement system, in principle, decreases the amount of light entering a stadium compared with a continuously cantilevered roof offering the same size free opening to the sky. With a moving roof of this type it is necessary to remove the turfgrass by some means away from the stadium to maintain it. Alternatively, another way must be found of maintaining the playing surface such as re-turfing.

It has already been recorded that a moving roof inflates stadium capital and running costs. These costs are further inflated by measures needed to maintain the turfgrass. The extent of these costs reinforces the need to increase the use of the stadium as much as possible.

It is clear that where multi-uses are involved artificial surfaces are superior to in situ natural turfgrass because of their facility to increase the rate of event turnover in a stadium. This conclusion is drawn from USA evidence. But artificial surfaces are not acceptable for any of the games of European football played at the highest level. This stipulation has the potential to create problems in maximising the use of a stadium over a wide range of events. These problems are later considered in some detail in the body of the text.

Traditionally stadia displayed only one sport, occasionally two. Because of this they lay idle often for two weeks between events and for months between seasons. The aim of owners has been to expand stadium use, thereby spreading the costs of overheads. It is commercially impractical to apply this idea to every stadium. There must be selective criteria for establishing a programme of between 250 and 300 multi-use events annually in stadia. The floor of a stadium must be artificial or have a simple option of being made so. There must be an infrastructure, which makes available direct and economic access for a regionally based public to a stadium. There must also be a broad range of appealing events available and the economy of a region must be able to sustain that level of commercial activity. Where the range and number of events are limited, the competition to display them must also be limited.

Where turfgrass cannot economically be removed from a stadium and be reinstated on that same basis and where an anchor tenant requires the use of an in situ natural turfgrass-playing surface between 26 and 35 times a season, achieving the multi-use events target of 250 to 300 is an impossibility. It can be argued that not all events are displayed to their best advantage in a large cavea intended to display a fast moving game occupying the whole of its playing area for a relatively short period of time.

Where turfgrass cannot be removed and the intention is to maximise the use of a stadium, areas of the surface will need surface protection when uses are introduced which are inappropriate to turfgrass. This will inevitably further reduce light reaching the grass. Turfgrass relies on light energy to activate the essential photosynthetic process. This interference is more detrimental during the cold seasons than in warm periods. The tendency to use a stadium over the whole year makes matters more difficult because the turfgrass does not have adequate time to build its energy for the more dormant periods.

The growth and maintenance of turfgrass in stadia are complex issues. The more comfortable a stadium becomes, the greater are the capital and running costs. The greater these costs are, the greater is the need to use a stadium.

Unless a strategy setting out the way a stadium will be used, prior to the initial planning stage, is drawn up, difficulties may well occur in maintaining the playing surface. This is especially so in a multi-use stadium.

These difficulties have been demonstrated at both ArenA Amsterdam, Netherlands and the Millennium Stadium, Cardiff.UK, where measures have had to be put into place to replace the turfgrass, a requirement not anticipated during the planning stages.

This thesis principally examines how stadia might be developed in a way that would allow more light and air on to the turfgrass. The absence of these two factors along with the overuse of the playing surface are amongst the principal reasons for inhibition turfgrass maintenance in large compact stadia.

INDEX PART ONE.

CHAPTER ONE.

1.1.0 AIMS.
1.1.0.1 Introduction.
1.1.0.2 The Research Questions.
1.1.0.3 The Research Objectives.

CHAPTER TWO.

1.2.0. METHODOLOGY.
1.2.0.1. Introduction
1.2.0.2. Data Collecting form models in an Artificial Sky and a Wind Tunnel.
1.2.0.3. Literature Review.
1.2.0.4. Stadia Visits.
1.2.0.5. Schedule of Stadia Visits.
1.2.0.6. Data Collection by Architectural Modelling.

PART ONE.

CHAPTER ONE.

1.1.0 AIMS.

1.1.0.1 Introduction.

The aims of this Thesis are embodied in the Research Questions and Objectives. These questions and objectives stem from anecdotal evidence that difficulties occur in growing and maintaining grass in large compact stadia with or without retractable roofs. The broad question is: why is this so? An answer to overcome these difficulties is sought in respect of multi-use stadia with retractable roofs.

Currently there are only two European examples matching the criteria of multi-use stadia with retractable roofs and in situ turfgrass playing surfaces. These are the Millennium Stadium, Cardiff, Wales UK (spectator capacity 72.500) and the Amsterdam ArenA, Amsterdam, Netherlands. (spectator capacity 52.500) Despite the fact that they share a concept, the fundamental elements of their design vary. Therefore making direct comparisons between them is not possible. They exhibit compelling evidence of their inability to provide satisfactory in situ turfgrass playing surfaces. To overcome their problems in the short term, their playing surfaces have to be renewed on a number of occasions annually.

The limitation of examples of stadia with retractable roofs and the inability to make direct comparisons between the two known stadia made it necessary to inspect the condition of in situ turfgrass in other large stadia, without retractable roofs. It has also been necessary to carry out desk studies on a number of other stadia with retractable roofs, principally in North America. The North American stadia had different forms of playing surfaces. The extension of the retractable roof study was carried out to provide a more consolidated view of the influence of stadia with retractable roofs. Some of these stadia form a number of the Case Studies, which appear in the appendices.

The stadia considered without retractable roofs were the San Siro, Milan, Italy, Nue Camp, Barcelona, Spain, Stade de France, Paris, France, St James' Park, Newcastle, UK, Old Trafford, Manchester, UK and Ibrox Park, Glasgow, Scotland, UK. Two of these stadia, the San Siro and Nue Camp have capacities exceeding 80,000. None of them had a capacity of less than 50,000. All these stadia have recorded in situ turfgrass failures to varying degrees; all demonstrate differing conditions of use, climate and environmental standards. These studies led to the theory that the retractable roof was not necessarily the factor which led to failure. However, the degree of failure in the principal two stadia with retractable roofs was greater than in those stadia, which could be principally defined as open. This observation led to the consideration of a number possibilities for the turfgrass failures in the stadia :

(1) Were their playing surfaces subjected to more and varied use than those of the open stadia?
(2) Did the retractable roof induce lower environmental standards than those produced by an open stadium?
(3) Did the form of a stadium superstructure influence in anyway the environmental standards, making them less suitable for turfgrass maintenance?

From the evidence of observation, growth processes of turfgrass are influenced primarily through the levels of heat, light and air falling on the turfgrass leaves. This is confirmed by the indisputable visual evidence from nature that shade or over intensity of light, the reduction or excess of air movement can affect both growth and maintenance of turfgrass plants. What also is clear is that other factors contribute towards turfgrass failures, the most notable being turfgrass wear. The impact of wear is practically and visually significant in stadia because wear can affect the appearance and playing qualities of a turfgrass surface. In nature wear has traditionally been accepted as a consequence of use. The source of the wear can be moved from time to time to alleviate a problem. Nevertheless, wear is clearly the product of overuse, irrespective of its location. But all things being equal some locations will influence wear more than others.

The suggestion is that without the imposition of wear the separate but interwoven contributory factors of heat, light and air provide healthy turfgrass. The dosage of these factors above or below limiting levels provides unhealthy turfgrass and unhealthy turfgrass will more rapidly show the influence of wear.

The requirements of heat, light and air in this thesis are termed the primary requirements. There are also residual requirements needed to ensure healthy turfgrass growth. Within this category there are also primary and secondary requirements. With the exception of heat, light and wear, these requirements are horticulturally based and consist of turfgrass nutrition, rootzone composition, drainage, aeration, defoliation, appropriate turfgrass species, disease treatment regimes, the controlled use of the turfgrass and ordered turfgrass maintenance regimes.

1.1.0. 2. The Research Questions

- **Can a retractable roof irrespective of its planning configuration help to provide in a compact stadium, environmental conditions suitable for the growth and maintenance of an in situ turfgrass playing surface.**
- **If the answer is no! Would it be possible to modify the superstructure in order to improve the environmental conditions within the stadium.**
- **Would such changes, to the superstructure inhibit the function of a stadium.**
- **Are there other methods which could be adopted which would reduce the dependency on environmental factors for the maintenance of in situ turfgrass within a compact stadium**

1.1.0. 3. The Research Objectives.

- **To research through established literature biological and horticultural practices sufficient to determine how these factors contribute towards the growth and maintenance of healthy in situ turfgrass in a compact stadium.**
- **To measure the environmental conditions in a generic model and translate that data to determine if the standards produced can provide the biological conditions necessary to allow turfgrass to be grown and maintained in a compact stadium.**
- **To consider from observation the influence of turfgrass wear on its growth and maintenance.**

CHAPTER TWO.

1.2.0. METHODOLOGY.

1.2.0.1 Introduction.

Answers are sought to the aims of this thesis through the following methodologies.

(1) Data collecting from models in an artificial sky and a wind tunnel.

(2) Literature Reviews.

(3) Visiting Stadia.

1.2.0.2. Data collecting from models in an artificial sky and a wind tunnel.

Two different forms of the same design of a generic stadium were used for the collection of data. The data collection was of three different strands. The first of these related to the extent of the shadowing generated by different roof configurations. The second related to the lighting levels falling on a grid formation set on the modelled playing surface. The third related to air movement over the narrow width of the playing surface. The air movement measurements also are picked up vertically at fixed points as far as the underside of the retractable roof levels. The details of the models and the methodologies used for carrying out the data gathering are set out in **Part Seven.**

1.2.0.3. Literature Review.

As yet there is no in depth critical review of either the Millennium Stadium or the Amsterdam ArenA. Articles are available from newspapers and magazines but in most cases provide inadequate, over simplified or biased reviews. Both buildings in many aspects represent features which exceeded the state of the art of stadia design at the time of their construction: but both record failures in respect of fulfilling the original concepts for their turfgrass playing surfaces. The available literature fails to assemble a body of evidence based on the in depth views of all the parties involved in their development. The anticipation is that if the evidence was analysed and presented by an independent researcher the result would help designers and developers to establish the lessons beneficial to future projects with similar objectives.

Other sources of literature include promotional articles and conference lectures: in the case of ArenA a magazine entitled 'Dream Arena' or in the case of the Arnhem Stadium 'I have seen the future', a critical appraisal of the stadia to which reference has been made at Amsterdam, Cardiff and Montreal was produced by Phillips. In a MSc Thesis, Welsh School of Architecture, Cardiff University, Cardiff, UK. 1997.

There is also a dearth of literature in the public domain concerning the development reasons for the commitment to the design concept of the Civic Centre Pittsburgh USA. What is available are semi-technical articles appearing in Civil Engineering 'Retractable Dome For the Pittsburgh Dome' pages 52-57, June 1961, and Architectural Record 1961 the latter are only visually informative. Makowski provides a reference on the Pittsburgh Dome, pages 137-138, Steel Space Structures, Michael Joseph. London. There are also three references in The Structural Design of Retractable Roof Structures, WIT press. These are lacking in depth and none record the mechanical failure of the roof.

The literature of the Montreal Olympic Games 1976 is voluminous. Within that body of work is the official history of the Olympic Stadium, (1976-1988). The extent of the literature is recorded *(et al)* in the biographical essay by Bruce Kidd in the Historical Dictionary of the Modern Olympic Movement, Edited by Findling and Pelle, Greenwood Press 1996, page 159-160. The detail contained in these references in recording the failure of the roof of the stadium is beyond the scope of the investigation required for this thesis. The Case Study is therefore based on the **'Study of a Masterpiece of Textile Architecture'** written and published in French by Professor Taillibert, the Stadium Architect, from site visits and correspondence with an American Engineer who worked on a subsequent roof restoration. The consequence of studying the Architect's own literature is that the result is descriptive and fails to provide a reasoned analysis of the failed technical system and of the failure of material used to cover the roof.

Textbooks based on the generality of stadia design provided few references to turfgrass except to indicate that difficulties in maintaining it can occur in stadia. These draw attention to the need to seek specialist guidance in respect of using turfgrass in stadia. Expert guidance is needed in specification of turfgrass in any category of stadium.

There is little published information on the performance of turfgrass in stadia except for Baker (STRI) Bingley, Yorkshire, UK and Rogers *et al* Michigan State University USA. The application of the latter work is best demonstrated in the studies carried out for the closed environment of the Pontiac Silverdome, Pontiac, Michigan USA. The studies presented an optional solution to the problem of providing turfgrass playing surfaces set in removable pallets for use in closed environments. Case study **9.4.3**, provides the detail of this influential experiment.

Dr M^{c} duff of IGER confirms the results of this search "that effects of shading have received little attention in the last twenty years, as research has moved on." A view can be taken however, that what work has been conducted relates to the influence of shade on turfgrass imposed by trees, (Dudeck and Peacock 1992)and is based on American Research.

It was against this background that this study began with the objectives set out in **(1.1.0.3)**. These objectives are repeated here for convenience:

- **To research through the literature, biological and horticultural practices sufficient to determine how these factors combine with the environmental conditions to provide for the healthy growth and maintenance of turfgrass in a stadium.**
- **To determine through the measurement levels the of shading, light and air movement in stadia with differing roof configurations.**
- **To consider other ways of providing natural turfgrass other than by the established method of a rootzone in a permanent location.**

The background studies for this thesis have been wide sweeping and extensive. These studies have covered not only Turfgrass Science but also those areas dealing with the historical detail of stadia and also the historical social need for them. In that respect the studies began with the ancient stadia of Greece and the Roman Amphitheatre.

The sources of the ancient Greek periods of stadia building are distilled from the work of scholars who derived their interpretations from the contemporary literature and later from archaeological excavations, primarily those of the 18th and 19th Centuries AD, directed principally by German Archaeologists.

The main source of literature used for the background for this part of the study is that of Norman E Gardiner's. **Greek Athletic Sports and Festivals,** 1910, revised and abridged and re-titled **Athletics of the Ancient World,** 1930. This latter book has been superseded by a reprinted American edition 1978. The preface to that edition by Professor Murray picks up references that Gardiner could not have known. The preface renews in some respects the authority of the 1910 edition. The 1978 edition and the 1910 edition should be jointly consulted.

The writing of H A Harris, 1967 and 1972 also makes a contribution to the level of study sufficient for this broad analysis. Gardiner's contribution remains significant even if parts of his analysis should be considered in the light of Murray's preface. Harris points out that "Anyone who works in a field like this must owe a great debt to his predecessors...... Dr E.N. Gardiner towers above all others". But Harris himself highlights the narrow and limited arrangement of Ancient Greek stadia, ensuring the impossibility of transferring the model of early stadia to the modern era. The other titles used in the Ancient Greek study are listed in the Bibliography in **Part Ten.**

Literature confirms that there was nothing spatially transferable to modern stadia, but revealed the significant influence the ethos engendered by the Games had on those seeking to re-establish the Modern Olympic Games in 1896.

Professor Murray in his preface page XII, to the American edition of Gardiner, published 1978, presents a less utopian view than that imparted by the Ancient Games on the founders of the Modern Olympic Movement, a view shared by many other present day commentators. The introduction and prologue of the **Historical Dictionary of the Modern Olympic Movement.** edited by Findling, Kimberly and Pelle, should also be consulted for an alternative view on the ethics and the interpretation adopted by those who established the new Olympic Movement.

Murray suggests "that the reader with a natural idealistic tendency may be reluctant to accept such a verdict, but it seems to be correct and we must realise that amateurism is a modern concept." However, it must not be forgotten the influence the Modern Olympic Movement has on Stadia Development.

The Roman period of stadia building was limited to an examination of the Flavian Amphitheatre, Rome. **(72-80, AD),** which after the 11th Century became known as the Colosseum. The issue that concerns this thesis is the controversial one of whether or not the Colosseum was covered by a retractable roof. The anecdotal view must be that the need for shade at the Colosseum was essential. The Romans were so adept at solving engineering problems that it seems inconceivable that they did not provide a solution to that problem. The following extract is taken from the introduction to Retractable Roof Structures -

> "Retractable roofs have been used since ancient times: it is known that the audience part of the roof of the Roman Colosseum could be opened and closed and the remains of the columns of the retractable roof can be seen amongst the ruins".

There is no direct archaeological evidence that retractable roofs were used over any of the Roman amphitheatres. There is, however, the literary evidence of Vitruvius, Lucretius and Pliny who record their experiences of seeing awnings in use, not necessarily associated with the Colosseum. Vitruvius records "how before a performance could begin" 'the audience had to be seated, the awnings spread out and the machinery put in place'. But such references may be linked to other public buildings.

Some literature suggests that the corbel stones set below the fourth storey at the Colosseum had the purpose of bearing structural masts used to support the roof structure. Other authorities suggest the corbels were there to support flagpoles. There may also be evidence for the support of poles on the amphitheatre at Nîmes, France. The Colosseum probably had guy rope supports set into the ground, having the purpose of stabilising the vertical roof supports. There are stone slabs which represent what may have been such supports, but these posts according to Connolly have no structural foundations.

The quotation from the **Structural Design of Retractable Roof Structures** is from a Japanese source and maybe the quotation suffers in its translation. Whatever the reason, the quotation provides an inaccurate picture. Wider reading suggests the roof may not be retractable within the modern definition. If it existed, the roof took the form of an awning which was taken down when not required or when wind affected its stability. The suggestion is also that the fabric used for the roof was that used for sails on the Roman Cargo Ships. Therefore the movement of the retractable roof was best managed by sailors who had experience of sails. There is archaeological evidence of a sailors' quarters near the Colosseum. There may be one of two reasons for this find:

a) sailors were required for the display of naval battles it is suggested were staged in the early days of the Colosseum;

b) sailors were used to manipulate the sail-like temporary roof awning which may have formed the roof.

Mario Salvardori also assumes that a roof spanned the Colosseum. "The August Sun in Rome can be quite hot and the 50,000 Romans enjoying the bloody spectacle of the gladiators in the Coliseum (*sic)* were sheltered from it by a retractable canvass tent, supported by ropes spanning as much as 512 feet, shortest distance between opposite points at the top of the amphitheatre's exterior walls". Illustrations of a canvas roofs spanning the Colossuem with an oculus in the centre are familiar in some established volumes of the History of Architecture volumes. Such a roof would require an outer compression ring and an inner tension ring. The former could be provided on the Colosseum fourth storey and the tension ring by the oculus.

For this type of roof to work the roof fabric and the supporting ropes had to be in tension.

In ancient times neither the ropes nor the roof fabric may not have had the inherent strength necessary to withstand stresses imposed by spans necessary to cover the Colossuem. It is more likely that the retractable roof over the Colosseum was limited to a simply supported awning. Tented roof techniques were first established in the middle of the 20th Century but the theoretical technology was known before that date

.

The Colosseum literature reveals the Roman appreciation for planning and providing a contextual setting and organisation for a building required to accommodate 50,000 people on a daily basis for week after week, this truly was the first multi-use stadium and it lasted for hundreds of years serving its original function a function which was eventually abandoned through the imposition of different moral code.

The results of a survey of stadia development in the UK up to 1983 are best seen from Simon Inglis' book, Football Grounds of Britain. "This work is the result of visiting 132 clubs and countless more grounds, former grounds and future grounds of Britain." It is also the result of distilling the histories of the league clubs of England, Wales and Scotland. The titles of these histories are recorded in the book's bibliography together with a list of other relevant reading.

The record of the failures to develop stadia in a coherent and safe manner is best seen by the number of stadium disasters which have occurred in the UK since the turn of the 20th Century. The consequence of these failures has normally resulted in a Report from Judicial Enquiries held after each major tragedy.

The most influential Reports are those of Wheatley, Popplewell and Taylor. The recommendations of these reports provide an historic understanding of the extent of the failure to provide for spectator safety and comfort. Guidance on these matters, and those of fire precautions and evacuation from grounds stemmed from Wheatley in 1972. These matters formed in 1973 the first Edition of the Guide to Safety at Sports Grounds. The third edition published in 1990 incorporated the recommendations of the Taylor Report, published 1989. The fourth edition published in 1997 appeared at a time of rapid advance in the development of new grounds and brought facilities of a higher standard.

It should be noted that the **Guide Safety at Sports Grounds** has no statutory force and only receives its powers through safety certificates issued under the **Safety of Sports Grounds Act,** 1975 or the **Fire Safety and Safety of Places of Sport Act**,1987.

The Day of the Hillsborough Disaster (A Narrative Account) describes the day of the Hillsborough Disaster, which led to the Taylor Report. This account is not substitute reading for the Report, although passages from the report are interwoven with personal accounts of those who were present on the 15th of April, 1989.

This book provides the account of those who had eventually to come to terms with the deaths of 96 football fans on that day. These were deaths not brought about through violence but through inadequate facilities and poor crowd control management. These were factors which were to lead to fundamental changes in the design of Football stadia which were soon to follow.

The Stadium and the City, Edited John Bale and Olof Moen consists of a compilation of essays presented to the conference The Stadium and the City held in Gothenburg, Sweden October 1993. The following two essays are interesting reading relevant to the background of stadia development:

- Growth Politics, Urban Development, and Sports Stadium Construction in the United States; A Case Study Kimberley S, Schimmel.
- Toronto's SkyDome : The World's Greatest Entertainment Centre. A study by Bruce Kidd.

Both essays provide essential background reading to the involvement of excessive costs in stadia development and how those costs necessitate the overuse of a stadium which begins a financial spiral which can rarely be contained. This emphasis on use makes in situ turfgrass an unsatisfactory playing surface.

The essay in the same volume by John Williams provides a background to the post Taylor stadia building in UK. The essay also sets some history of ground development pre-Taylor and is usefully read in tandem with the Simon Inglis Histories of Football Grounds of Britain.

The Geraint John and Rod Sheard, **Stadia A Design and Development Guide** provides a practical guide to stadia development. It remains, however, necessary to cross-reference this work with the raft of changing legislation. The book is the design source from which to develop, expand and test ideas over the complex range of stadia development.

References also need to be made to the publication of the **Football Advisory Design Council.** This is only one of two official publications indicating Football should be played on Grass; the other is the **Premier League Handbook Season 2003-2004.** The Football Advisory Design Council Handbook should be treated with a degree of circumspection in considering its recommendations for avoiding turfgrass wear.

The literature essential to the study of turfgrass science and the growth of grasses in this study involved the following:

R.H.M.Langer's, **'How Grasses Grow'**. His piece extends to 62 pages and deals in particular with pasture grasses. The work begins with a description of the parts of the turfgrass plant and goes on to explain the morphological and biological events of germination, through to the processes of seed production and adaptation.

Biology: Concepts and Connections by Campbell, Mitchell and Reece has been used to illustrate the photosynthetic processes. The study of that process appears in the appendices **9.5.0.**

The major recognised references for Turfgrass Science are: **Turfgrass Science and Culture** by Beard. **Turfgrass,** Edt Waddington, Carrow & Shearman Agronomy 32. Both books are comprehensive in their coverage, extensively cross-referenced with the research of others: in the case of Beard papers up to 1973 and in the case of Agronomy 32 up to 1990. Beard is accepted despite its publication date as a major reference textbook. Agronomy 32 is composed of 22 sections each written by an expert in his topic; Beard is a contributor. The book provides an interesting overview of the Turfgrass Industry, Artificial Turfgrass and the Effects of Traffic on Turfgrass. All the sections are comprehensively referenced, many of which refer back to Beard. These major sources are best used in tandem.

Turfgrass Science and Management by Emmons is also an American Publication. This work covers much of the same ground as Beard and Agronomy 32 but not in the same depth. The approach is a practical one, this is confirmed by the style and extent of its illustrations. Each chapter begins with a list of objectives. These provide valuable points of reference but it should not be assumed that each list is comprehensive for that particular topic. This book can be an initial point of reference before moving towards other textbooks to establish the background of a topic.

International Turf Management Handbook Edt by Aldous is an Australian Publication. This publication is on similar lines to that of Emmons. The layout and content takes a more academic approach. This book whilst not as comprehensive in its content as Beard or Agronomy 32 provides references up to 1998. The work also contains a Chapter on The playing quality of turfgrass sports surfaces, by S.W. Baker from STRI of England. UK.

Natural Turf for Sport and Amenity: Science and Practice by Adams and Gibbs provides the same scientific approach as those textbooks which are American based. But in addition this work is thoroughly practical. It provides an excellent insight into soils, turfgrass drainage and weed identification. If soils are to be considered in more detail then the **Introduction to Soils by Wilde** should be considered. The advantage Adams & Gibbs has over other literature discussed is that it represents a UK perspective and is the result of much research, some of which is in collaboration with STRI. Sections of this work deal with topics that are not relevant to this study such as Golf Greens, Racecourse and Amenity Grasses for Non-Sporting Uses.

Two other books Drainage for Sportsturf and Horticulture and Growing Media for Ornamental Plants and Turf both offer science and practice. The former should be considered with the corresponding chapters in Adams and Gibbs publication for a complete practical picture.

Horticulture and Growing Media for Ornamental Plants and Turf presents a thorough study, but much of it not relevant to turfgrass, but those sections dealing with the rootzones for turfgrass are of great practical importance. This book should be considered in tandem with **Drainage for Sportsturf and Horticulture.**

1.2.0.4. Stadia Visits.

One essential part of the methodology involved visiting a number of stadia both in the UK and in Europe. They were chosen because viewing them would make a constructive contribution to the anecdotal evidence that large compact stadia provided difficulties in growing and maintaining insitu turfgrass in large compact stadia.

The first and most important of the visits was in August 1996 to the ArenA Amsterdam, Netherlands, Europe. It was visited to confirm the reports in the 'Dutch Press' that the turfgrass playing surface had failed to be maintained in good playing condition. The visit was used to collect data for another degree. There were subsequent visits to compare the similarity of that stadium with the proposed Millennium Stadium Cardiff Wales UK. The visits raised the fundamental question if the turfgrass failed at Amsterdam why would it not fail in Cardiff, when the conditions in and aims of both stadia were similar. The several subsequent visits confirmed continuing turfgrass problems. The evidence of the use of mechanical fans around the perimeter of the playing surface indicated there was a lack of air movement over it. The cavea natural lighting levels were low. The use of the turfgrass surface was extensive.

The timing of the initial visit followed closely on the opening of the stadium. Prior to the first visit the surface had been returfed which seemed to indicate that the turfgrass problems might not have been associated with use.

ArenA had a centrally located retractable roof and a complex drainage system. These aids were included to provide a satisfactory environment for the growth and maintenance of the in situ turfgrass-playing surface. These aids appear to have failed in their purpose.

What was important about the initial visit was the extent of the misinformation it provided to the candidate. The extent of this was established after further research. The reasons for the misinformation subsequently became clear; arbitration between the parties involved in the contract were looming.

Further meetings were conducted in the UK and Da Hag in the Netherlands which enabled a Case Study could be written with authority.

Visits to Stadia in Milan and Barcelona also indicated that they encountered turfgrass problems. Both these stadia had capacities marginally in excess of 80.000. These stadia were different from each other in form and character, the outside walls of the cavea of both presented considerable points of intervention for the suns rays. The failures here in all probability were related to these interventions. In the case of Barcelona the evidence was that the stadium was not over used. Unlike in Milan where there was no ground sharing. Adjacent to the Nue Camp there was a small stadium with a 20,000 capacity used by the lower team of the Barcelona Club.

It shared the same external environment with the Nue Camp and displayed no evidence of turfgrass failure.

There was however, little willingness to discuss the methods adopted to counter the turfgrass problems in either Milan or Barcelona. Management of both stadia were concerned with the need to keep commercial confidentiality. This was not an uncommon practice when visiting a number of stadia.

Amsterdam ArenA was the first European stadium with a retractable roof, **(Case study 9.4.5).** ArenA incorporated in most respects the features and aims of the theoretical stadium used in this study, except it has a smaller capacity. The candidate made the first of several visits to ArenA in 1996. The initial visit confirmed Dutch newspaper reports traced through reports in English newspapers that the in situ turfgrass had failed to maintain a satisfactory playing surface even during its opening month.

From interviews [before this study began] with the stadium Management and the main contractor the cause of the turfgrass failure in their view was clearly lodged with the horticultural subcontractor: the horticultural contractor considered the cause of the problem lay with his subcontractor.

A number of points emerged retrospectively from this meeting. These were as follows:

- The extent of the failure had taken all the parties by surprise but the conviction was that it could be put right within the existing format.
- All parties were guarded in their comments, which in some cases could be legally sensitive.
- Consequently it would have been more productive to interview each party individually rather than collectively.
- Despite the fact that the nature of the interview had previously been defined, neither the main contractor nor the horticultural contractor fielded the appropriate technical representative.

The significance of the initial ArenA interview was that it established a base for more meaningful contacts, at later dates, in Amsterdam, De Hag and the UK. These contacts included meetings with the stadium management staff and the groundsman. Meetings were also held with the main contractor, the horticultural contractor, his subcontractor, and an independent consultant, Dr Jeroen Van Arendonk.

From this second group of meetings came the beginnings of an understanding that turfgrass failure was brought about by a range of issues, not just the single issue of a failure in turfgrass biology. Biological failure was the primary cause brought about by the absence of light and air; the rate of failure could be reduced by the influence of a range of horticultural actions. But the rate of failure could be accelerated by the overuse of the turfgrass.

In nature turfgrass failures were primarily associated solely with three issues related to the reduction in levels of light and air movement caused by tree shading, hedgerow shelter- belts and by overuse. Turfgrass failure in stadia was the product of these same circumstances. In the case of ArenA the overuse was intense. It also quickly emerged that the running of the stadium was a commercial issue; in that context turfgrass was but a secondary factor. Leading from this early experience came the appreciation that historically any successful multi-use stadium had an arena surface which was biologically independent for its maintenance and flexibility in use.

To understand this complex and interwoven problem it was clear for the need to bring together a number of disciplines. The problems involved in doing so lay in the fact that when stadia are commercially procured there is no time for the necessary research to solve the individual problem which each site presents. If the research is done there is little time in commercial contracts to analyse the data and apply it.

The ArenA horticultural contractor confirmed that he had collected environmental data pertaining to the turfgrass failure. But for reasons of commercial confidentiality he would not allow the candidate access to the data. This unwillingness was also related to the fact that litigation against the horticultural contractor was about to proceed.

The speculation was however, that the data would have concentrated on the levels of light and air falling on the turfgrass, the effectiveness or failure of the drainage system and importantly the contractual log books relating to the top rootzone and seeding application. This data would have perhaps only confirmed the reasons for the problem, nevertheless it would been useful in seeking ways of solving the complex problems.

This initial visit to the ArenA was the most influential of all visits to the many stadia made during the study. It was the springboard for many ideas. The visit reinforced the concept that a stadium should be considered differently from some other buildings, in this sense that it was composed of two distinctly differing parts: the cavea, the building's dominant feature and the ancillary accommodation. The cavea was used for limited periods; the ancillary accommodation could be used for 15 hours for most days.

If this was so, the cavea superstructure could incorporate adjustable openings at low levels to promote the passage of air through the superstructure and over the turfgrass which might be beneficial to it. The openings could be closed when the cavea was in public use and opened when it was not. The other pertinent issue in respect of air movement in relation to the turfgrass playing area was the juxtaposition of a stadium's ancillary accommodation to the cavea. An important example of the design of a stadium with limited ancillary accommodation surrounding its perimeter as can be seen at Bari, Southern Italy, Europe.

A visit of major importance was to the Gelredome Stadium, Arnhem, Netherlands, Europe. **(Case Study 9.4.7.).** The visit signalled the significant development of a solution to the problems of turfgrass maintenance in a multi-use compact stadium with a retractable roof. It did this by removing turfgrass in a single pallet from the stadium when not required. Although the solution was successful, it raised a number of issues which required further study in relation to the transfer of the single pallet. These issues related to larger stadia set in an urban context and also the way in which the pallet was transferred to and from the stadium.

The contacts made during this visit were technically at the right level. These most useful contacts were then transferred to management when the stadium opened.

Visits to other stadia without retractable roofs were made. Most reported turfgrass failures. The core of their problems was clearly related to environmental conditions, stadium capacity, the degree of weather protection and the plan configuration. In most of these cases persistent overuse of turfgrass appeared not to be the prime contributor to unsatisfactory turfgrass surfaces. Where inappropriate overuse was a factor the commercial benefits outweighed the disadvantage to the turfgrass.

The writer was not given access to the Millennium Stadium, Cardiff until the Thesis was almost complete. The information relating to this stadium has therefore been gleaned from visiting events and from a period of time engaged with others in advising the contractor on the anticipated problems relating to the turfgrass.

It also became clear from visits that the detailed conditions in each stadium were fundamentally different from each other, because of the extent of the variables; data collected at one stadium was not readily cross-referenced to another stadium. However, the scientific principles of turfgrass maintenance could be transferable.

It has not been possible to discuss turfgrass issues in stadia in the U.K. except with groundsmen and academics, none of whom had commercial interests to protect. These discussions have been helpful in determining the practical issues involved in cutting, feeding, aerating, scarifying and patching playing surfaces and the advantages of ground analysis and the detection of plant disease.

In large clubs groundsmen usually have the guidance of turfgrass consultants and the candidate was shown the data presented by these consultants. These consultants are of two categories. The first are commercial companies providing in house science and contracting expertise. They will respond to costing the implementation of the specifications prepared by groundsmen or their own specifications. The second category of consultants is the academic who provides horticultural specifications, then seeks competitive prices from a range of specialist contractors to implement their proposals. Both types of specialist provide an after care service. During the after care period core samples are taken to confirm the correct levels of compaction, and that nutrient and pH levels are being maintained. Levels of grass cover are estimated and means of disease control are specified.

It has been interesting to note that no successful attempt had been made, except at Arnhem, Glesenkerchen, Germany and the Sapporo Dome, Japan, to address the fundamental issues required to maintain in situ turfgrass in stadia. Removing the turfgrass was also the preferred method at the Millennium Stadium but that was an afterthought and has proved impractical and uneconomic to manage.

No one in Europe has addressed the issue of adjusting the superstructure to allow light and air into a stadium. The visit to San Nicoló Stadium, Bari, Italy, did indicate the means of providing both light and air to the stadium. That innovation was arrived at not as a means to satisfy the requirements of the turfgrass but rather to satisfy the primary structural objective. The visit was helpful in creating a method in which air could be passively moved over a playing field surface in a compact stadium.

At the stadia visited without retractable roofs, a solution to wear was sought through turf patching during the season. The groundsman at Arsenal Association Football Club described the process of end of season scarification which produces one of the best playing surfaces in the UK, but it is also an open ground with a capacity of only 38,000. Other clubs rely on end of season partial, reseeding with improved cultivars in lieu of returfing sections of the surface. To alleviate wear in some stadia, plastic grass reinforcement strips had been added to the upper part of rootzone material.

It is perhaps because of the reliance on these methods that commercial specialists wish to safeguard their techniques. What was clear in most locations was that the environmental fundamentals involved in maintenance of turfgrass had not been considered in the development stages of new stadia or stadia which were being redeveloped. This was the impression whether or not a stadium had a retractable roof.

Visits to all types of stadia reinforced the message signalled almost 2000 years ago at the Colosseum, Rome, that in stadia displaying multi-uses with the aim of using the stadium intensively, the composition of the arena surface is of prime importance. If this is so, in situ turfgrass is not the material to use for this purpose.

Visits provided the evidence that in stadia which had the pretension of staging multi-use events, the most economic way of doing so was to employ hard surfaces and not in situ natural turfgrass. This is best demonstrated by the example of the arena sometime known as the Astrodome Houston, Texas. Alternatively a similar result, but with more flexibility can be achieved by employing turfgrass surfaces that can be rapidly substituted for hard surfaces as that developed at the Arnhem Stadium, Netherlands.

Despite the availability of the evidence from this successful stadium, few developers took note of it. They chose rather to pursue the hope that next time a stadium was developed the outcome would be different. The outcome can be different but it will not be so unless the scientific needs of in situ turfgrass are managed at both the design stage and when the stadium is in use.

The contribution made to this thesis by the many visits, discussions with academics and groundsmen, helped considerably in understanding the horticultural aspects of this work. These visits also alerted the candidate to the fragility of the turfgrass plant, a point forcibly demonstrated by walking over the playing surface after a major game. That clearly indicated that sports turfgrasses are vulnerable to unsympathetic use and after those uses, they require immediate restoration by replacing divots, levelling of the surface and rest.

1.2.0.5. Schedule of Stadia Visits.
The following stadia have been visited during the course of the study or prior to it.

Alfred Mc Alpine Stadium, Huddersfield, England, UK. Europe

Amsterdam ArenA, Amsterdam, Netherlands, Europe.

Arena Amphitheatre, Verona, Italy, Europe.

Arena Amphitheatre, Arles, France.

Arena Amphitheatre, Nîmes, France.

Colosseum Amphitheatre, Rome, Italy. Europe.

Gelredome Stadium, Arnhem, Netherlands, Europe.

Harris County Dome, Houston, Texas, USA.

Ibrox Park, Glasgow, Scotland, UK. Europe.

Nue Camp, Barcelona, Spain, Europe.

Millennium Stadium, Cardiff, Wales UK. Europe.

Montreal Olympic Stadium, Montreal, Quebec. Canada, North America.

Murrayfield Stadium, Edinburgh, Scotland, UK. Europe.

Old Trafford Stadium, Manchester, England, UK. Europe.

Olympic Stadium, Barcelona, Spain, Europe.

Olympic Stadium., Rome, Italy, Europe.

Raebock Stadium, Bolton, UK. Europe.

San Siro, Milan, Italy, Europe.

San Nicolò, Bari, Italy, Europe.

Stade de France, St. Denis, Paris, France, Europe.

Stadium of the Alps, Turin, Italy, Europe.

Stamford Bridge, Chelsea, London, UK Europe.

St James' Park, Newcastle on Tyne, England, UK. Europe.

1.2.0. 6. Data Collection by Architectural Modelling.

Visits to stadia for the purposes of this work confirm the instinctive understanding that no two stadia can be identical: they could not be so, even if they were to be built from the same plans incorporating identical structural techniques. Factors also involving the seasonal influences of latitude, the uncontrollable consequences of siting and the use of stadia reinforce the view that absolute uniformity is not possible. The method therefore adopted in this thesis for collecting data is from a generic stadium model, thus allowing the sieving out of the factors of variability.

The use of architectural modelling also allows for experimental variations in the superstructure, and materials used to cover the roofs: how these variations affect the lighting levels, air movement and shading factors in the model stadium.

FACTORS WHICH CAN BE MEASURED BY THE MODELS USED IN THIS WORK.

- Latitude.
- Site contexts.
- Planning configurations.
- Superstructure sizes.
- Superstructure modifications.
- Siting of ancillary accommodation within the stadium site.
- Lighting levels falling on the playing surface..
- Air movement over the playing surface.
- Shadow formations over the playing surface.
- Influences of orientation.
- Influences of roofing materials.

FACTORS WHICH CANNOT BE MEASURED BY THE MODELS USED IN THIS WORK.

- Climatic conditions such as precipitation.

- Temperature.
- Duration of turfgrass use.
- Horticultural regimes.
- Rootzone depth and composition.
- Influence of drainage techniques.
- The effect of polystand or monostand turfgrass cultures.

The measurements recorded over the playing surface are therefore as follows:

- Masking of sunlight by shading.
- Lighting levels falling on the turfgrass.
- The movement of air over the turfgrass.

The description of the base models; the methodologies used in recording the measurements and the evaluation of the results is set out in **Part Seven.**

INDEX PART TWO.

CHAPTER ONE.

2.I. 0. OVERVIEW OF ANCIENT PRECEDENTS.
2.1.1. The Greek Stadium.
2.1.2. The Roman Amphitheatre.

CHAPTER TWO.

2.2.0. EARLY INFLUENCES ON THE DEMAND FOR STADIA.
2.2.1. Introduction.
2.2.2. Implications of Unified Rules.
2.2.3. Consequences of Changing the Rules.
2.2.4. Extending the Administration of the Game.
2.2.5. Further Divisions within the Games of Football.

CHAPTER THREE.

2.3.0. DEVELOPMENT OF STADIA IN THE UK.
2.3.1. Stadia Development before 1965.
2.3.2. Stadia Development after 1965.
2.3.2.1. Introduction.
2.3.2.2. Safety and Violence in Grounds.
2.3.3. Changes in Stadia Development towards the end of the 20th Century.
2.3.4. Disasters Influence Stadia Development.
2.3.5. The Lord Justice Wheatley Report.
2.3.6. Mr Justice Popplewell Report.
2.3.7. Lord Justice Taylor Report.
2.3.8. Grounds became Stadia.

CHAPTER FOUR.

2.4.0. COMPACT STADIA AND THEIR PLANNING AIMS.
2.4.0.1. Introduction.
2.4.1. Definition of a Compact Stadium.
2.4.2. Stadia Planning.
2.4.3. Comments on Published Data on Stadium Planning.
2.4.4. The Influence of the Superstructure.
2.4.5. Factors Influencing Arena Size.
2.4.6. The Relationship between Arena Size and Spectator Capacity.

CHAPTER FIVE

2.5.0 TURFGRASS MAINTENANCE IN STADIA.
2.5.1 Introduction.
2.5.2 Overuse of Turfgrass.
2.5.2.1 Measures Against Turfgrass Wear.
2.5.3 Patterns of Play.
2.5.4 Footballers' Footwear.
2.5.5 Duration and Times of Play.
2.5.6 Warm up Periods.

2.5.7 **Compaction.**

CHAPTER SIX.

2.6.0. THE PLAYING AREA REQUIREMENTS FOR MULTI-USE STADIA.

CHAPTER SEVEN.

2.7.0 THE ELEMENTS OF A STADIUM.
2.7.0.1. **The Cavea.**
2.7.0.2. **The Amenity and Management Areas.**

CHAPTER EIGHT.

2.8.0. THE EMERGENCE OF MULTI-USE STADIA.
2.8.1. **Introduction.**
2.8.2. **The Aim of Introducing Multi-Use Activities.**
2.8.3. **Are Multi-Use Stadia Appropriate for the Events they Display?**
2.8.4. **The Character of an Event.**
2.8.5. **The Viability of Reconfiguration.**
2.8.6. **The Suitability of Large Stadia for Some Events.**
2.8.7. **The Demand for Pop Concerts.**

CHAPTER NINE.

2.9.0. THE ADVENT OF THE RETRACTABLE ROOF.
2.9.1. **The Historical Background of the Retractable Roof.**
2.9.2. **Retractable Roofs built between 1961-2000.**
2.9.3. **Retractable Roofs Relevant to this Study.**

CHAPTER TEN.

2.10.0. NON-SPORTING USES.
2.10.1. **Introduction.**
2.10.2. **Suitability of Multi-Use Stadia to Display Non-Sporting Events.**

PART TWO
SURVEY OF STADIA DEVELOPMENT.

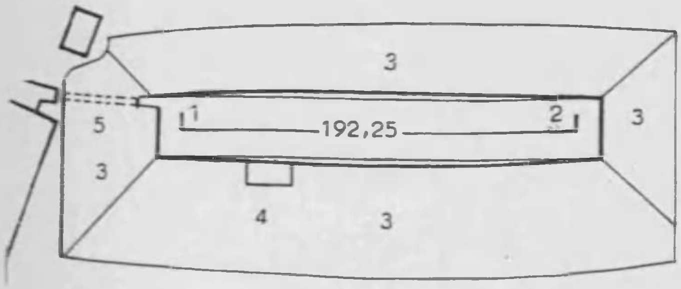
CHAPTER ONE
2.1.0. OVERVIEW OF ANCIENT PRECEDENTS.

2.1.1. THE GREEK STADIUM.

This chapter considers if Ancient Greek stadia exerted an influence on stadia of any other era. The evidence is that they did not have a physical influence. But the events they staged produced at the end of the 19th Century an ideological impact, on those who founded the Modern Olympic Movement. This led to an impetus in modern stadia development. However, the current opinion amongst scholars is that, the adopted vision portrayed a myopic view of the ancient ideals presented by the Games.

The keynote of Greek stadia is a stifling simplicity befitting a sporting culture that evolved just seven events in a thousand years.[1]

Stadia consisted of rectangular flat areas with spectator banking. The arena was of inconsistent length but in broad terms they were between 220 and 230 metres long and between 30 and 35 metres wide. Sometimes there was a sphendone at one end, either end or none at all as at Olympia



Fig, 2.1..1.1. Olympia 7thC, BC.

1&2, Start & Finish Lines.
3, Earth Embankments for 40,000.
4, Grandstand for 160 VIPs
5, Crypt Entrance.

Fig. 2,1.1.2. Olympia 7thC, BC.

Archaeological Remains, 20th C.

[1] Harris H.A Sport in Greece and Rome. Thames &Hudson. London ,1972. Page 20

This narrowness was to forbid its influence on future stadia. Confirmation of this statement can be found by examining the Stadium used for the inaugural games of the Modern Olympic Games held in Greece in 1896.

Fig 2.1.1.3. The Stadium for the inaugural Olympic Games of the Modern Era, Greece, 1896.

A stadium was first built on this site in B.C. 331 by Lycurgus.

This was reconstructed in white marble by Herodes Atticus, A.D. 160.

And remodelled for the 1896 Games by Metaxas.Completed Spring 1905.

2.1.2. THE ROMAN AMPHITHEATRE.

If there is no evidence that Greek stadia produced a physical legacy there is strong evidence that in the Roman Amphitheatron Form there were the well-developed roots of modern stadia design. The Flavian Amphitheatre, Rome, Italy, (72-80,AD), after the 11th Century became commonly known as the Colosseum.[2]

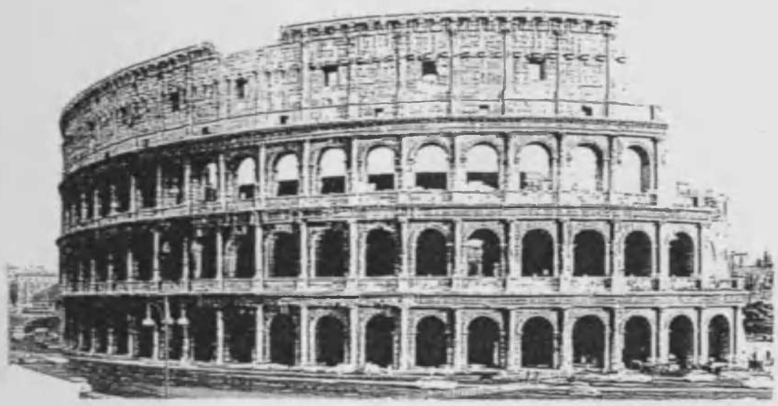


Fig. 2.1.2.1. The Flavian (Colosseum) Amphitheatre Rome. 69-81 to 96 A.D. View of External Ring.

Vespasian 69-79A.D . Planned & began the construction. Titus 79-81AD.Completed the buildings began by his Father. Domitian 81-96A.D. Completed the subterranean structures.

---

[2] "The name Amphitheatrum-Colyseus appeared for the first time in the 11th Century as a designation of a building which had previously been called Amphitheatrum Caesareum and was later extended regio Colisei to the entire valley. It derives from the colossal bronze statue of Nero which stood in the immediate vicinity", Cappelli, R, Edt, The Valley of the Colosseum, Electra Milan, 1997. Page 8

The Romans understood that their complex displays required a complex building, one with no historic precedents except perhaps that of the form of two Greek Theatres placed back to back. The Colosseum was the most developed building of this genre. It could accommodate at least 50,000 seated spectators, sometimes for eight hours in a day.

That building provided the following features:

- The physical control and isolation of the amphitheatre from its surroundings.
- The creation of safe, adequate and separate circulation patterns within the building.
- The introduction of vomitories linking terraces with the multi-storey circulation patterns.
- The understanding of the ingress and egress problems posed by 50,000 spectators.
- The introduction of numbered seats thereby assisting crowd control.
- The inclusion of banked seating with good sight lines, which also assisted crowd control.
- The introduction of complex design features, thereby allowing a facility for multi-uses.
- The possible inclusion of a retractable roof over sections of the terraces.
- The attempt to reduce odours by spraying scented water in the arena.
- Separation of combatants, allowing them to arrive separately in an arena.
- Disposal of bodies and carcasses and the continuous cleansing of the arena.
- Isolating the cavea from the arena ensuring audience safety and line of sight.
- Providing Spectator comfort with uninterrupted views.

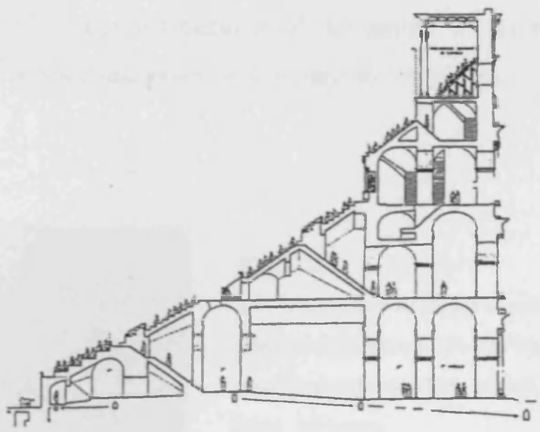


Fig 2.1.2.2. Cross section through a part of the superstructure of the Colosseum.
The section indicates both the way the cavea was divided and the vomitories linking with the circulation routes.

Some of these features anticipate by almost 2000 years many of the recommendations laid down in Judicial Enquiries in the UK held as a response to 20th Century stadia disasters. What is clear is that a study based on an awareness of the methods of crowd control built into the Colosseum would have obviated some of the difficulties that have occurred in the stadia design of the late 19th and early 20th Centuries. The Colosseum was the most developed building of this genre.

CHAPTER TWO

2.2.0 EARLY INFLUENCES ON THE DEMAND FOR STADIA.

2.2.1. Introduction.

Prior to 1863, there was little demand for grounds (stadia) for the display of sports. The demand was mostly confined was mostly confined to Cricket and Horse Racing. After 1863, there was a surge in the display of Football and in particular, Association Football. The significance of 1863 was that the English Football Association was founded. That year was also significant because the Rules of Football were drawn up. These however were not finally agreed until1867.

The historical claims for the origins of football are obscure. It may have been played in some form in Ancient Egypt, China or Mexico. Also the Romans may have brought a version of the game to Britain between B.C.54 and 55.

Once established in Britain, its popularity spread in the 11th and 12th Centuries. Football became the game of the mob; it was officially opposed because of the uproar it caused and because it reduced the interest in archery, a sporting practice relevant to the defence of the country.

Fig. 2.2.1.
An Illustration of street football in Medieval England. Games were unorganised and often ended in gang violence.

The Universities of "Oxford and Cambridge accepted football as a competitive sport, as early as the seventeenth century." Thus began the transformation of football from the game of the mob into one also played by the upper classes. Nevertheless football remained predominantly the game of the working classes; they continued to play it, without unified rules and without fixed venues.

The late 18th and the early 19th Centuries saw the patronage of the major public schools accelerate the development of football. Teams were formed of unspecified numbers. The object of the game was to force a ball over the opponent's goal line or between posts placed on that line. Usually the ball was kicked or sometimes players ran with it. This game was a mixture of modern Association Football and Rugby Union. The playing area was of undefined length, demarcated by the goal lines. The grass playing surface was either grazed, scythed or after 1830 perhaps mown. [3]

Public Schools could not often play football against each other because of the variations in the rules and in the mode of play. These differences accompanied players when they went up to the university. Attempts were made at Cambridge University between 1843 and 1850 to codify the rules. Between 1850 and 1863 most Public Schools adopted the so-called Cambridge rules. There are no records of these rules.

Around this time outside the influence of the Public Schools other clubs were being formed. This expansion made it essential to formalise the rules. A natural progression from this expansion was to form an umbrella organisation. This occurred on October 26, 1863, when some interested individuals and eleven clubs founded the English Football Association.
During October 1863 the new rules were printed but two controversial issues remained unresolved: the banning of hacking and the strict offside rule. It took until 1867 before the rules were accepted. There are records of these rules.

2.2.2. Implications of Unified Rules.

The unification of the rules eventually had a number of implications,

- Expansion in the formation of clubs brought with it spectator loyalties and rivalries.
- By 1870, the membership of the Football Association had increased to thirty.

[3] The patent for a lawn mower was obtained in the name of Edwin Budding in 1830. The Grass is Greener, Our love Affair with the Lawn, Harper Collins Publishers, London. 2000. (Pages 107-111).

- By 1885 professionalism increased playing standards and the Game's popularity.

Improved playing standards in turn stimulated larger attendances made possible by the introduction in "1850 of The Fixed Hours Act which allowed the closing of all factories at 2 pm on Saturdays"[4].

This sanction allowed the game to expand significantly in the Industrial areas of the North of England and the Midlands. The combination of the freedom to spectate, the unification of the rules and the introduction of professionalism were the triggers which allowed the game to expand. Expansion strengthened the interest of the working classes; they developed loyalties and rivalries between teams. These factors created the demand for new grounds or larger grounds.

These grounds were nothing more than crude places of unspecified capacities and remained so in most cases for almost a hundred years. Many spectators were unable to see the whole playing area during a match. They were often in physical danger through overcrowding or some form of secondary structural collapse.

2.2.3. Consequences of Changing the Rules.

It had taken 20 years to print a set of unified rules, a step ironically not achieved without division. The Game had been a combination of kicking and handling and hacking; these issues were the source of the division[5].

One of the eleven founder members, the Blackheath Club withdrew "from the FA, because it resented the rule which banned hacking". Their withdrawal in December,1863 was important, in that it established the separation between Rugby and Association Football. From this separation the English Rugby Union was formed in 1871.

2.2.4. Extending the Administration of the Game.

---

[4] Lewis, K and Branton, N, The Rise of British Commerce The Bedrock Series, Pitman, Bath, Melbourne and Toronto, 1930 Page 93

[5] The kicking of an opponent's legs in an attempt to gain possession of the ball, behaviour unacceptable in the modern game. The Blackheath Club described hacking as essential to the manliness of football. The president of the F.A.- suggested such dangerous behaviour was "likely to prevent a man who had due regard for his wife and family from following the game." Pickering, D Soccer companion, Cassell, London, 1998, (page 138).

With the formation of the Football Association, the Game began a power shift to a broader support base. The popular literature suggests the working classes took back control of the game at this time. This is not so, the game at club level was often run and financed by wealthy middle class businessmen: the working classes were the essential patrons of the game.

Below a line South of Birmingham the game remained essentially amateur. Above that line the game was moving towards professionalism. Irrespective of these divisions Association Football was expanding more rapidly than Rugby in all regions. This expansion increased with the important formation in 1888 of the Football League, which brought to the game a threefold impact.

1. Discipline was introduced into the management of clubs and their players.
2. Teams were divided into competitive leagues; with time these increased in number.
3. Promotion and relegation between leagues was introduced.

2.2.5. Further Divisions Take Place within the Games of Football.

Rugby Union Football itself was divided in 1895 by the breakaway of "22 clubs from Yorkshire, Lancashire and Cheshire to form the Northern Rugby Football Union, later renamed the Rugby Football League. It spread to Australia, New Zealand, France, and other countries".[6] The rift came about over the question of compensation for loss of wages whilst playing the game.

Therefore, by 1895 there were three different versions of football each requiring the use of grounds. Initially there was some limited ground sharing. As the individual codes became stronger and the Rugby Union became more rigid in their stance towards the conflicts between amateurism and professionalism, the idea of sharing grounds became more remote. This position was to remain until the 1990s when the Rugby Union embraced professional and ground sharing became not unusual. This thesis comments on the consequences of ground sharing in the modern stadium in a subsequent chapter.

CHAPTER THREE.

2.3.0. DEVELOPMENT OF STADIA IN THE UK.

[6] Copyright 1994-1999 Encyclopædia Britannica

2.3.1. Stadia Development before 1965.

The character of the early grounds was one of openness. Spectators viewed games by surrounding touchlines and byelines and some viewed them from points of vantage surrounding grounds.

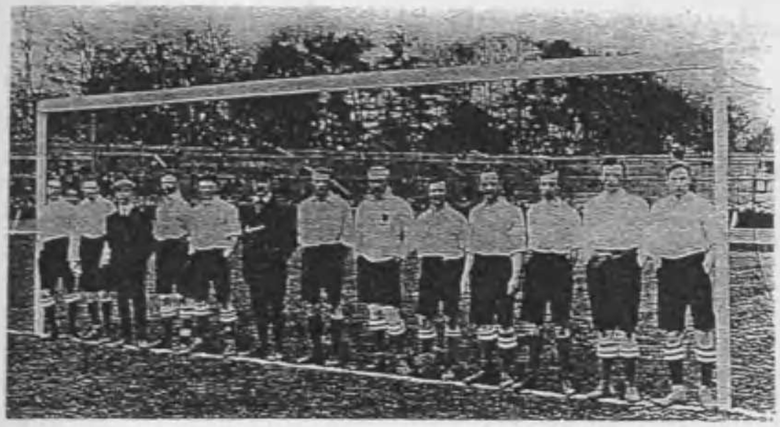


Fig.2.3.1. Grounds were open in character. Crystal Palace. London 1905.

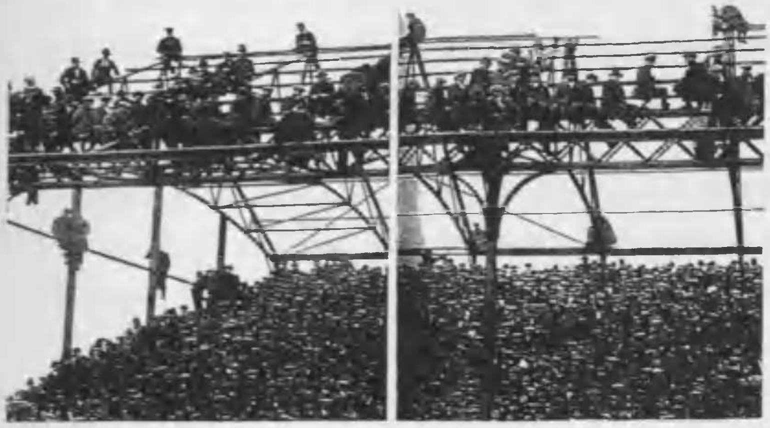


Fig. 2.3.1.1. (top left) Points of Vantage. Crystal Palace, London. UK, 1914.
Fig. 2.3.1.2. (top right) Points of Vantage. Stamford Bridge, London. UK 1946.
Fig. 2.3.1.3. Points of Vantage. Ninian Park, Cardiff . UK, 1921.

With the advent of professionalism, it became necessary to enclose grounds and to include viewing banks; these were rudimentary. Gradually limited covered accommodation was added; as time passed the extent of this increased. Viewing from covered positions was often disrupted by vertical supports for roofs. Not all could follow a game as spectator numbers exceeded the ability of the accommodation to provide appropriate standards for viewing, comfort or safety.

Football grounds during a playing season were used bi-weekly as matches were played on a home and away basis. Between home fixtures and between playing seasons grounds lay dormant. There were seasonal exceptions to this when F.A Cup games were played. The frequency of these depended on the success of a team. A successful club might also have had a second team, who might have used the same ground.

During the earlier period of this review there is some limited evidence of ground sharing between the various games of football. In most cases this stopped when the sharp divide emerged between the ethics of professionalism and amateurism.

Finance was made available to develop grounds through self-generated revenue of 'gate' money or through the injection of capital from club directors who were wealthy industrialists. Banks were prepared to allow overdraft facilities, the extent of which was dependent not a Club, irrespective of its status, but on the financial probity of a Club Chairman.

Besides a limitation in capital for ground development, it is suggested, that chairmen of some clubs would not develop grounds when spectator numbers were high, because development would disrupt cash flow; when spectator numbers were low, they would not develop grounds because of a lack of cash flow.

The financial culture in which clubs were developed in the UK, was opposite to the way they were developed in France or Germany, where the playing of Games was considered to be advantageous to the development of the morale of the State.

The German observer of British sport, Rudolf Kircher, has noted:

"It has never occurred to the English mind that the state, town council, or anyone else could provide them with a sports ground offering them everything their hearts desired from a swimming bath to a football ground."[7]

And following from this observation Bale has pointed out the problem with UK grounds:

> In contrast to the *ad hoc* and idiosyncratic unitary development of local private stadiums in Britain to house largely working class audiences, by the mid 1930s many cities in continental Europe possessed their own classically designed publicly funded 'sports parks' aimed at a rather wider class base.[8]

This attitude put the continental developers ahead of their UK counterparts even though they started developing sports buildings about one or two generations earlier than the continentals. The consequence of this was that some continental stadia were developed with more consideration for both spectator and player.

However, in 1908 plans for a UK stadium were published which predated continental examples by almost twenty years. This stadium was to be the home of Manchester United Football Club.

> The plan was to develop a stadium capable of holding 100,000 spectators with 12,000 of those seated. More than 30,000 would be under cover with facilities such as tea rooms, a gymnasium, a billiard room and laundry. It would be the most magnificent ground in the country. The plans were drawn up by Archibald Leitch, a young Scottish architect *(sic)* who over the years would become well known for the many soccer stadiums he designed. The cost of constructing the ground itself was reckoned to be £30,000 but for United and their rich benefactor, money was at first no object. The stadium was finally opened on the 19th of February, 1910...... but although Leitch's original design promised a capacity of 100,000, plans had to be scaled down as costs began to rise.....Today, virtually no trace of the original design stands although Old Trafford remains one of the most exciting and dramatic stadiums in the land.[9]

[7]Williams J, English Football Stadiums after Hillsborough. The Stadium and the City, Edt Bale & Moen, Keele University Press, Keele, Staffordshire, UK. 1995.page 222.
[8] Ibid page 222
[9] Athletic News 8th March 1908. Publisher not Recorded.

What is known is that Archibald Leitch was not an architect, as stated in the article: he was an engineer. It could be argued that few contemporary architects could have expressed so clearly and logically the function of the stadium both in terms of crowd control and the visual expression of the façade. It was not perhaps until the Stockholm Olympic Stadium (1912) that an architect made a significant visual contribution to stadium architecture.

Fig. 2.3.1.4. Internal & External of Views of Olympic Stadium 1912, An architects contribution.

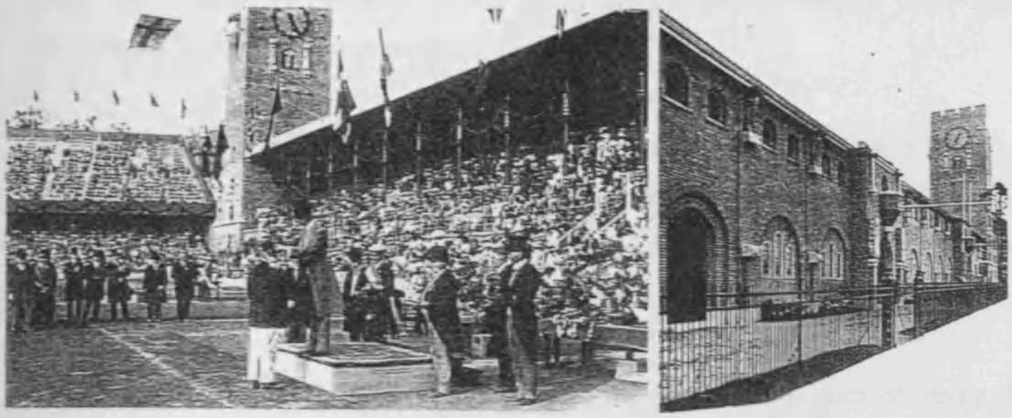


Fig. 2.3.1.5. Amsterdam Olympic Stadium. 1928. After the manner of Leitch (circa 1910)

Simon Inglis emphasises the importance of Archibald Leitch as a designer of early stadia. He suggests that the shape and form of many British grounds were dictated by the Scottish Engineer, Archibald Leitch. From 1900-39, Leitch's firm was involved with no fewer than 27 grounds, a number no modern design company is ever likely to approach. Inglis also records that Archibald Leitch was involved or became involved in developments between

1905and 1912: Fulham, Chelsea Tottenham Hotspur, Manchester United, Millwall and Huddersfield. Then he was appointed to work on Arsenal's Highbury Stadium after that period.

Arsenal was considered the doyen of UK football clubs during the mid-period of this review. Simon Inglis has covered the essential development of the club with thoroughness and sensitivity[10]. During interviews held at the Highbury Club for this work it was confirmed that there were no records of the horticultural details in their files concerning the development of the playing surface.

This work does describe a more modest development: Ninian Park, Cardiff, Wales, UK. This description serves as a not untypical example of how some football grounds were developed during this period. The history provides some indication of playing surface development in general. These details are set out in **Appendix 9.3.0.1.**

Safety in UK football grounds had been neglected from the start of stadia development. Many grounds offered inadequate, inconsistent and often treacherous viewing conditions for the standing spectator. This inadequacy and inconsistency led to increasing spectator densities in those more favourable viewing areas, with the consequence that injuries were caused through crushing or by secondary structural collapse of a grandstand. Disasters even when accompanied by death did not lower attendances.

Appendix 9.1.0. records the major disasters in Football Grounds in the UK and elsewhere in Football Grounds before and after 1965.

The more successful the club, the larger would be the number of spectators. Even so, clubs were often running at a financial deficit especially in times of economic depression between 1925 and 1935. In the larger centres of population they sought to find additional uses for their grounds: the popularity of greyhound racing was increasing and some grounds incorporated dog tracks. These could be used three times a week.
Whilst Greyhound tracks in football and rugby grounds were comparatively few in number, they had an impact on the way those grounds were managed. Sharing a ground with a dissimilar sport was to prove disruptive at a time when football fixtures were rapidly increasing at the end of this review period.

---

[10] See pages 17 to29, Inglis, Football Grounds of Britain, Collins Willow, 1996, together with the Arsenal Club Histories recorded on Page 477.

In 1946 "The Football League carried a resolution that no ground used by Football League Clubs could be used for Greyhound Racing"[11]. The exception to this rule was that such racing carried out before June 1946 should continue, but if this racing had ceased or if it discontinued in the future it must not be restarted. There were two reasons for this action: betting took place at the grounds, considered by the Football League as an inappropriate image for football; also sharing the grounds interfered with the development of fixture arrangements. The growth in football fixtures was made possible by the introduction into the UK of floodlights into football grounds. Flood lighting was first tried out in 1878 but "the first official League match under floodlights was not played until 1956,..... at Fratton Park, Portsmouth UK."[12] By the end of the review there were more games of football being played on pitches, which in some cases were beginning to improve in quality.

Stadium development was still piecemeal and the compact stadium had not yet arrived in the UK. Major changes in the design of grounds were to follow in the next period of the review. Changes which were eventually forced on the clubs by the consequences of three major tragedies at football ground causing the loss of many lives. These changes were aided by Government and by income received from 'televising' football.

Figs. 2.3.1.6. to 2.3.1.13. show the evolution in the range of configurations of some typical grounds up to 1965. From these illustrations it can be seen that the earlier grounds were open in character. When building development took place it was gradual and where it became more intensive the corner junctions between grandstands were typically left open. This avoided the complex planning and constructional involved in providing corner continuity between grandstands. These residual openings made it possible to provide ingress and egress at each corners of a ground.

Fig 2.3.1.6. Ayresome Park Middlesborough Master Plan. 1903.

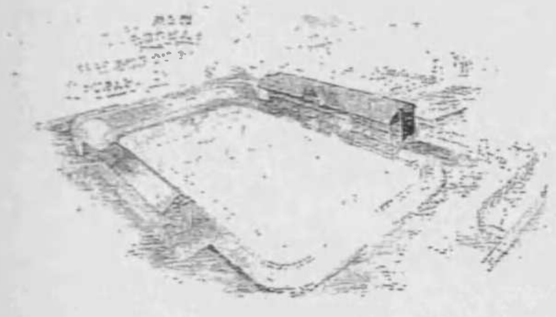
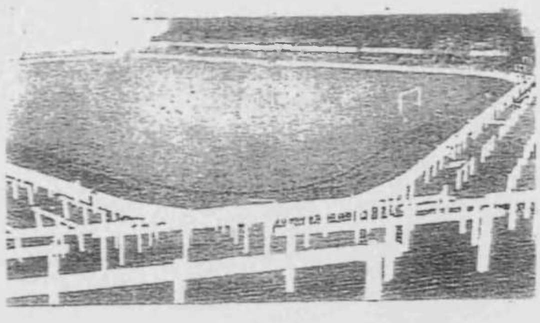


Fig ,2.3.1.7. St Andrew's Birmingham 1906.



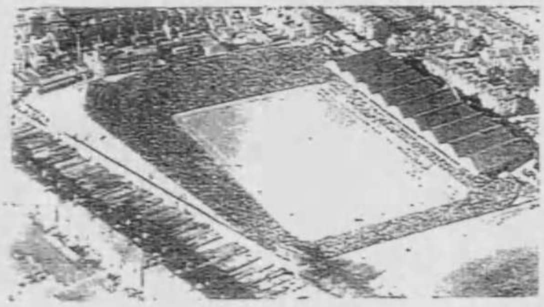
[11] Golesworthy, M, The Encyclopaedia of Association Football, Robert Hale Ltd, 1956. Page 83
[12] Pickering, D, The Cassell Soccer Companion, London, 1998. pages 112-113

Fig, 2.3.1.8. Brighton & Hove Albion.
The South Stand, 1910.

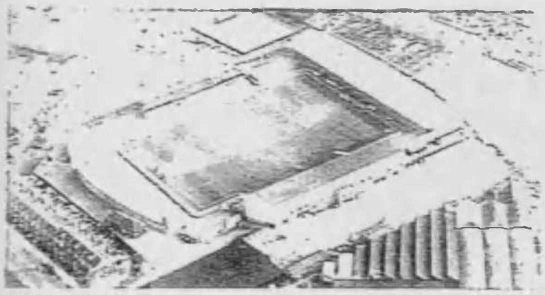
Fig, 2.3.1.9. Aston Villa, Birmingham 1914.

Fig. 2.3.1.10. Manchester United.
Old Trafford, 1920's.

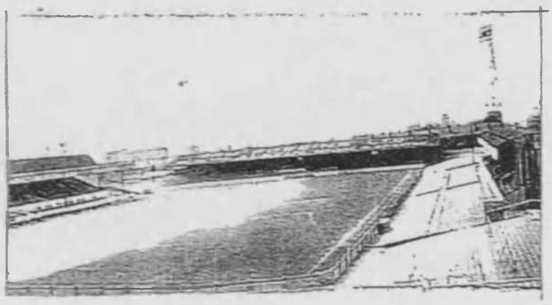
Fig, 2.3.1.11. Arsenal, Highbury, circa 1925.
Showing a Multi span roof over the grandstand.



Fig, 2.3.1.12. Bristol City.
Ashton Gate. 1950's.



Fig, 2.3.1.13. Coventry City.
Highfield Road. 1961.



The character of early UK grounds was the consequence of a number of issues:

- UK grounds were developed from first principles, which were slow to develop.
- They were the first football venues to be developed anywhere, one or two generations earlier than on the continent.
- They were built from private capital and were not financially risk free enterprises. There was no strong case made by football fans for grounds to be comfortable and safe with the consequence that advances were slow in implementation.

2.3.2. Stadia Development after 1965.

2.3.2.1. Introduction

1965 is not an arbitrary point of division between the review periods; it was selected because that point represented a sea change in stadia development. This change occurred with the opening of the Harris County Dome Stadium, Houston, Texas, USA. The stadium was enclosed. Its purpose was to display football and baseball under cover and also to display and extend that range of events traditionally displayed in multi-use stadia.

The Harris County Dome provided uninterrupted views over the arena, in an air-conditioned environment. The stadium was comfortable and safe. It had shops, cafés and restaurants, ideals not incorporated in any stadia in the UK until towards the end of the 20th Century.

The inheritance of UK grounds from the previous review period was one of shabbiness and dilapidation. The grounds were also generally unsafe and lacking in both comfort and amenity. Most spectators stood to view a game in open conditions.

The ad hoc attitude towards development, the continuing lack of finance, the indifference of the majority of spectators towards conditions within grounds and the limitation of both legislative control and enforcement resulted in these conditions. Ingress and egress positions were usually concentrated at the corners of a ground as corners were uneconomic to develop. It was therefore opportune to leave the corners open as circulation routes.
This position prevailed for the greater part of this review until legislation forced a change towards the latter part of the 20th Century.

In principle, open conditions in stadia will aid the biological development of turfgrass. Nevertheless, during the earlier period of this review turfgrass playing surfaces remained of poor quality.

Fig 2.3.2.1.

Illustrates a typical surface condition of a mid-winter playing surface of a professional club around the late 1950's and the early 1960's. The area shown will be that of the zone of intensive play. The ground is not named by the picture source.

But from a study of the complete picture the probability is that the location is the ground of Aston Villa.

The advantages gained from openness were probably counterbalanced by unsuitable rootzone composition, inadequate or ineffective drainage or none at all, a lack of understanding of the needs of maintenance and of the selection of unsuitable turfgrass species.

Fig. 2.3.2.2.

Illustrates a not uncommon condition of surface flooding. This example is from the mid 1950's. The problem continued in many grounds into the 1960's. The location is White Hart Lane,
The location is White Hart Lane, **London.**

The playing surfaces of some grounds remained unsatisfactory beyond the middle period of this review. The reasons for this were the same reasons for the turfgrass failures prior to 1965 but now, in addition, fixture lists were being extended which increased the wear factor.

However, other issues began to preoccupy clubs other than the condition of playing surfaces which began to improve after the middle of this review period. These other issues concerned poor ground safety and growing crowd violence. Solutions to overcome these problems were implemented towards the end of the 20th Century. These solutions would have positive implications on both spectator safety and violence, with the consequence that UK stadia development would begin the process of catching up with the sea change started in 1965 with the opening of the Harris County Dome. The implementation of these solutions may have adversely influenced the growth and maintenance of in situ turfgrass in stadia.

The adopted solutions came about only after the failure of the initial ill thought low cost expedient measures to overcome safety and violence in grounds. These measures would eventually lead to further football tragedies, tragedies they were meant to prevent.

2.3.2.2. Safety and Violence in Grounds.

Safety in UK football stadia continued to be an issue after 1965. Prior to 1965, 62 deaths and 995 injuries were recorded in the five most notable football disasters of that period. After 1965 deaths increased to 221 but injuries fell to 474 in five more incidents. It appeared that irrespective of the directives of the many official reports, which invariably followed accidents, no effective official action was taken to resolve safety issues. That position began to change in 1973, when the Wheatley Report initiated the Safety of Sports Grounds Act of 1973. That report followed the fourth accident in ten years on Stairway 13 at Ibrox Park, Glasgow, Scotland.

With limited exceptions the dilapidated condition of grounds remained much as they were before 1965. Some individual stands were built in some of the wealthier clubs. But the fans displayed a general complacency about the ground accommodation. Inglis puts it succinctly, commenting on those who died during the Hillsborough disaster in 1989.

> With them died a set of assumptions, a whole way of life, and a stinking, rotten system of ground control and crowd management which had evolved over the years with the complicity of all parties: the Government, football authorities, clubs, police, local authorities, and yes, the fans too.[13]

The problems were appearing because there had rarely been in any part of this review period coherent individual planning strategies for ground development. Grounds neither provided high safety standards for spectators nor solved the problems posed by violence.

John Williams suggests that many of these difficulties were rooted in tribal displays of physical violence both in the ground and in its environs. The inference of this is that football became the vehicle for the enactment of violence and not necessarily the cause of it.

The measures taken to counter violence were

- to heavily reinforce the police presence inside and outside grounds.
- to employ more stewards and introduce crowd surveillance techniques.

Two additional ways of crowd control were introduced. These eventually had major repercussions on the attitude of management towards stadia design. These additional ways were

- the segregation of home and away supporters by 'penning'.
- the isolation of the playing area from the terraces.

[13] Inglis, Simon, Football Grounds of Britain, Collins Willow, 1996 page 329

Segregation was achieved by the employment of high, steel see-through fences which were used to form large pens to isolate some spectators and also as a separation between the spectators and the playing area. Therefore there could be no interaction between rival fans inside grounds.

Fig, 2.3.2.2.

Illustrates the fatal consequences for some spectators of penning. as seen at the Hillsborough disaster.

Hillsborough Stadium,Sheffield, April 1989.

Grounds had with passing of time become more and more dilapidated. A survey conducted in 1993 compared the average age of the building stock of top division grounds in the UK with those of Germany and Italy and then with stadia used in the USA for the 1994 FIFA World Cup. The results are set out below;

Table 2.3.2.2. AVERAGE AGE OF TOP DIVISION SOCCER STADIUMS. [14]

COUNTRIES.	AVERAGE AGE.
England	88 years.
Germany	48 years.
USA	43 years.
Italy.	37 years.

2.3.3. Changes in Stadia Development Towards the End of the 20th Century.

The violence in some football grounds during the 1970s and 1980s is well documented. This was however not new to football. Incidents of violence occurred in the latter part of the 19th Century and at the turn of the 20th Century, in both England and Scotland

Football is a game that has always created high passion with both its players and spectators. However, there appeared now to be a difference between the type of violence engendered by

[14] Source: Adapted from the Economist,18th April, 1993.

that passion: the early patterns related to the actions from the game, but now it extended beyond that, to a gratuitous violence often predetermined, motivated by tribal instincts.

English soccer crowds continued to grow in numbers, with the absence of or a minimal framework of formal regulation or control. As a consequence, injuries as a result of crushing were not uncommon and went unrecorded except locally. But in the main,

> English soccer crowds of this time seem to have been well behaved and by modern standards, they were unusually alert to the dangers posed to themselves and to their fellow supporters by their sheer weight of numbers, shoehorned as they were into poorly-appointed and poorly regulated spectator facilities.[15]

A change from the indifferent attitude shown by stadia developers to matters relating to safety and comfort was inevitable. Change may have been brought about by both rising social standards and comparisons made between UK and foreign stadia. But this was not the case. Change enforced on clubs through legislation was brought in after a series of disasters in football grounds.

2.3.4. Disasters influence Stadia Development.

Four disasters were eventually to have a direct influence on stadia development in the UK: Three of these were in the UK; the fourth disaster occurred in Belgium. The latter disaster was influential because it involved the fans of the Liverpool Football Club, UK. and also because it demonstrated that dilapidated grounds were unable to meet the 20thCentury problems presented by Association Football.

Fig. 2.3.4.1.

The scene at the aftermath of the riot at the Heysel Stadium, Brussels, 29th May 1985. The riot involved the fans of Liverpool Football Club.
The British Government asked that the circumstances leading to the riot were included within the findings of the Popplewell Report.

The Heysel Stadium proved to be dilapidated and unable to provide conditions of safety necessary to cope with crowd control.

---

[15] Williams J, English Football Stadiums after Hillsborough. The Stadium and the City, Edt Bale & Moen, Keele University Press, Keele, Staffordshire, UK. 1995.page 222.

The historic sequel of football disasters was an enquiry: there have been ten between 1924 and 1989. However, of these enquiries three were of significance. In chronological order these were the reports of Wheatley, Popplewell and Taylor. Of these three, the Taylor Report, the last report of the 20th Century, brought about the most fundamental changes. That report resulted from the Hillsborough disaster.

The conclusions or recommendations of each of the three reports are included in Appendices **9.2.1 to 9.2.3.**

The tragic event of the 15th April, 1989, forced the dramatic change on stadia development. That change was not the direct consequence of violence but came from the failure to control the numbers of spectators entering a penned section of the Hillsborough Stadium, Sheffield. The idea of penning had been introduced to effect the control of crowd violence by separating the spectators of opposing teams.

The fundamental change initially brought about by the Taylor Report was to ban all standing accommodation in stadia. The implication of this was to reduce the spectator capacity of stadia. This was of no matter for many clubs, as they were not filling their stadia. But for those clubs who were, it was a matter of moving to a new site or redeveloping within existing sites to regain some of their lost capacity. The requirement for redevelopment on existing sites emphasised the need for master planning. Developments on new sites resulted in a master plan even if that plan was carried out in a piecemeal manner. Stadia became in principle more compact the consequences of which in some cases was that they were developed to a greater height. Additionally in most cases improved weather standards were included in the developments. It was this strategy of more compact stadia built to a greater height and with the incorporation of increased weather protection, which led in some cases to turfgrass difficulties.

A short review setting out why the Reports were commissioned and the impact they produced is recorded below.

2.3.5. The Lord Justice Wheatley Report. (1972)

This report stemmed from an accident on infamous Stairway 13 at Ibrox Park Glasgow, Scotland, on the 2nd of January, 1971. There had been three previous accidents on the same Stairway in 1961, 1967, and 1969. As a result of the latest accident 66 spectators were killed, mostly from asphyxiation, some victims dying standing upright. The Government commissioned Lord Justice Wheatley to report his findings and recommendations.

The Wheatley report gave guidance on the safety of spectators: the recommendations in the report were extended to include fire precautions and emergency evacuation. They formed the basis of the first Guide to Safety at Sports Grounds Act published in 1975. That Act in its latest 1997edition continues to be the base from which safety in sports grounds is assessed.

2.3.6. Mr Justice Popplewell Report, (1985).

This report stemmed from the fire that occurred on the 11th of May, 1985 at the Bradford City, Valley Parade Ground, Bradford, Yorkshire, UK. The fire started beneath a wooden grandstand because a lighted match or cigarette was dropped between the open spaces between the seating tiers of the all timber grandstand, igniting on the floor beneath extensive tinder dry debris. The resulting fire engulfed the stand in minutes, causing 55 deaths and 200 injuries through burns and the inhalation of smoke.[16] Simon Inglis points out "the stand was due to be replaced during the closed season"[17].

On the same day as the Bradford fire the Leeds United and Birmingham City disaster occurred. Popplewell was commissioned to extend his enquiry. His remit was further extended to report on the riot that accounted for 39 deaths and 100 injuries, on the 29th of May,1985 at the Heysel Stadium, Brussels, Belgium.

The Birmingham disaster was the result of a riot between the fans of Leeds United and Birmingham City at the St.Andrew's Ground, Birmingham. The riot resulted in one death and injuries to 96 policemen. Inglis records one innocent spectator was also injured.

The Popplewell remit was extended to cover the Heysel Stadium disaster because fans of Liverpool Football Club, UK and Juventus Football Club, Turin, Italy were involved in a riot at the stadium. The Heysel Stadium was yet another antiquated stadium unable to cope with the tribal tendencies of some football supporters.

The report highlighted the fact that ground safety was seriously in need of a thorough overhaul. Regular inspections of grounds were to be established and smoking banned from

---

[16] The Building Research Station, Video Library Album, The Fire Valley Parade Bradford, UK.

[17] Inglis, Simon, Football Grounds of Britain, Collins Willow, 1996 page 66.

wooden stands. There had been 86 fires at UK grounds between 1977 and 1983. A controversial national scheme of identity cards was recommended but not implemented. The report served as a focus to highlight the lack of safety in football grounds. It took another major disaster and a different financial structure for football to influence the need to bring structural change to Association Football.

2.3.7. Lord Justice Taylor Report, (1989)

The Report stemmed from the Hillsborough disaster which occurred on the 15th April, 1989, at the ground of Sheffield Wednesday Football Club, Hillsborough, Sheffield. The disaster was in no way linked with violence; it was responsible for 95 deaths on the day and one death occurring later. The youngest victim was 10 years old and the oldest victim was 67.

In simplistic terms the disaster arose from severe overcrowding at the stadium's Leppings Lane end. Inglis suggests three sides of the Hillsborough ground always suffered from circulation problems.

The involvement of some Liverpool supporters in the Belgian riot led to some inaccurate reporting of the cause of the disaster. The tragic events had no association whatsoever with the violence of Liverpool fans. It was a matter of crowd control failure.

The Interim and Final Reports are the authoritative sources of information setting out the reasons for the disaster. There is another account of the day's events. It does not disagree with the report but is complementary to it. It provides a human perspective in an account both vivid and moving, told in narrative form in the book 'The Day of the Hillsborough Disaster'[18]. This book portrays the emotional impact on those involved directly or indirectly in the tragedy; their accounts are anecdotal and are interwoven with relevant inter-linking passages of both the Interim and Final Reports of Taylor.

The Taylor Report has changed the image of British football grounds and in doing so has changed the relationship between the fans and their clubs. The most transparent impact of the Report was the notion of the all-seating stadium.

---

[18] Taylor R, etal The Day of the Hillsborough Disaster, A Narrative Account, Liverpool University Press, Liverpool. England, 1995, Page X11.

The consequences which followed the Hillsborough tragedy were to change what were characterised as grounds, into stadia, making them safer, more comfortable places, providing in some clubs a recognition of the needs for some social amenities for the complete cross section of football spectators.

A new addition of the Safety at Sports Grounds Act, 1990 was published; additional tightening of ground certification followed under the Football Licensing Authority. Football Administrators also reacted by setting up the Football Stadia Advisory Design Council.

Not all of the seventy-nine recommendations resulting from the Taylor Report were implemented: those that were, had a profound impact on the development of football.

The significant consequence of the Taylor Report was the reduction in spectator capacity, which was accompanied by spectator comfort and safety. The implementation of the ensuing legislation was forced upon clubs and was backed by public, private and commercial partnerships which allowed the finance to be available to allow fundamental structural changes to be made in the organisation of Association Football in particular and also in the other games of football.

2.3.8. Grounds became Stadia.

The signal event in the design of new stadia in the UK was the opening on the 20th of August, 1994 of the Alfred McAlpine Stadium, Huddersfield, Yorkshire, UK. The story of the procurement and description of the stadium is told by Simon Inglis.[19]

Suffice it to say for the purposes of this work that the significance was that it was a purpose-designed dual use stadium for Huddersfield Association Football Club and Huddersfield Rugby League Club.

Consequently, there are two distinctly different playing patterns imposed on the in situ playing surface. The stadium is also used from time to time for other events. It is understandable that the playing surface became quickly affected by these added wear patterns, a situation not helped by the Rugby League Club using the turf in summer when grasses should be recovering from winter wear.

---

[19] Inglis, S, Football Grounds of Britain, Collins Willow, 1996 Pages 184-191.

Though only desk research studies has been undertaken on this stadium as a part of this thesis, the supposition is based also on visits is that it is unlikely that the grandstands pose extensive problems of intervention between the sunlight and the playing surface. The shape of the roof trusses are of assistance in reducing intervention and the lightweight nature of the trusses allowed by their shape produces a reduction in the filigree on the turfgrass.

The stadium appears to be generated by four issues: its capacity, concentrating as much of that capacity along the centre of the touch-lines; the provision of unrestricted viewing and producing structural economy. The overall capacity of the stadium is no more than 25,000 to 26,000 spectators; that capacity is fixed by the master plan. This fixture may be its limiting feature, but the concept reflects the current needs of the clubs. Any forward thinking may have weakened the notable coherence scheme.

It is this confidence in the design brief that has allowed the designers to produce a landmark stadium. The lightweight roof construction has made a significant contribution to the low cost. However, in general terms this structural solution does produce uneconomic corners in terms of generating spectator capacity. The other factor is that there is little spectator weather protection afforded by the roofs.

The topography of the site may influence to advantage air movement over the turfgrass. That may also be enhanced by the shape of the roof and the four partly open corners of the stadium. The corner spaces house the means of restraint for the so-called 'Banana' trusses and also provide space for the supports of the floodlight towers. The shape of the roof prohibits the attachment of floodlighting to it, necessitating the use of lighting pylons.

The playing area was re-laid with Desso Turfgrass reinforcement in 1997 in an attempt to reduce the wear on the playing surface. The Desso plastic insert 400 mm long is equally folded to a length of 200 mm and inserted into the playing surface, leaving approximately 30 mm free standing. The technique is similar to weaving carpets. The sewing of the strands is carried out with a roller powered by a machine. The aim of the process is to stabilise the natural roots of the turfgrass by encouraging them to intertwine with the plastic strands.

The supposition proposed from experience of site visits is that the turfgrass failure in this stadium is due almost certainly to its mixed use and not to the absence of light and air movement.

The Huddersfield Stadium was a response to the Taylor Report and could only have been built on a new site. Other such stadia have since been built or planned. Some of these may have retractable roofs and removable turfgrass playing surfaces.

Not all the responses to the Taylor Report resulted in new developments; as previously indicated some clubs redeveloped existing grounds with the aim of making up spectator density lost through the all-seating provision. This approach had an adverse effect on the turfgrass: it necessitated building higher and in a compact manner. Where maintaining capacity was not an issue many clubs accepted the reduction in capacity that all-seating stadia imply. The Government also subsequently allowed clubs of the lower divisions of the Football League to wave the all-seating requirement of the Taylor Report. **Figs 2.3.8.1. to 2.3.8.7.** indicates a range of development in football grounds after 1965.

Fig 2.3.8.1. Aston Villa AFC Birmingham, Villa Park, circa 1990s.

Fig2.3.8.2. The Arsenal AFC, London, Highbury Stadium, circa 1990s

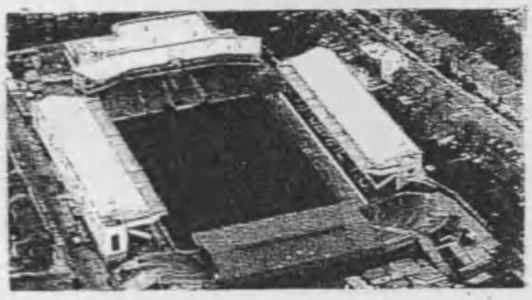


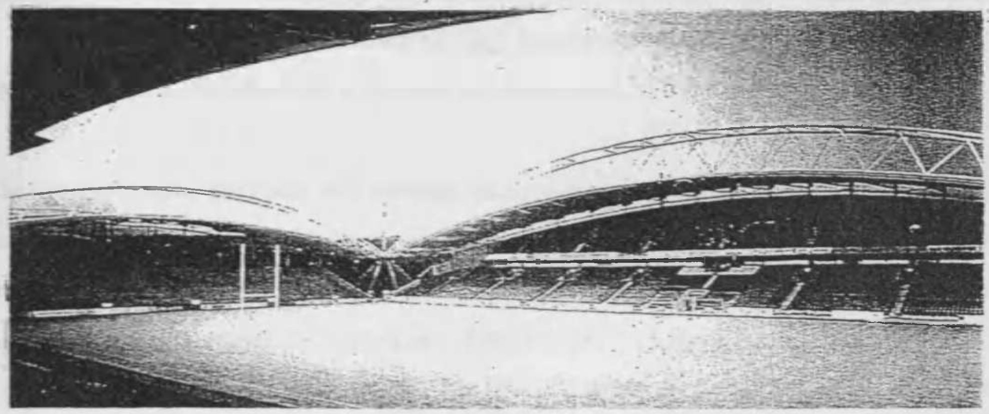
Fig.2.3.8.3. Middlesborough AFC, Cellnett Riverside Stadium. A new build stadium.

Fig.2.3.8.4. Manchester City AFC. Prior to relocation circa 1990s

Fig.2.3.8.5. Wembley Stadium. London.
Final refurbishment prior to demolition.

Fig.2.3.8.6. Manchester United, AFC.
Old Trafford, circa 1995.

Fig. 2.3.8.7. Huddersfield AFC. Huddersfield.
The first stadium which came as a direct response to the Taylor Report.



CHAPTER FOUR

2.4.0. COMPACT STADIA AND THEIR PLANNING AIMS

2.4.0.1 Introduction

This chapter defines a compact stadium, discusses some of its planning requirements not covered in published technical works and considers the advantages and disadvantages of the compact stadium.

The salient recommendation of the Taylor Report ensured that within the upper leagues of football, all-seating stadia would become obligatory. This would ensure a reduction in spectator capacity and density. Thus spectators would become spatially more comfortable and consequently safer than they were traditionally. With the advent of the Taylor Report stadia spectators were also to become better protected from the weather.

The reaction to the Taylor Report by some of those who manage or develop stadia was to accept the inevitable loss of spectator capacity. Where necessary they found ways and means within existing sites of maximising seating capacity. They did this by utilising the corner junctions between terraces and grandstands and also by building higher. The other response to Taylor was to develop stadia on new sites. This approach provided opportunities to produce safe and efficient spatial densities and to develop an infrastructure capable of managing large crowds both inside and outside stadia. These latter developments were usually but not always in the form of compact stadia.

2.4.1. Definition of a Compact Stadium

This thesis suggests the definition of a compact stadium as one where spectator seating commences at the outer edge of an arena and in principle continues uninterrupted around that perimeter and then in increasing linear dimensions forms an angled bank of terraced seating. A limited number of banked terraces may be set one above the other. The capacity of a terrace will be determined by a number of constraints, which will be discussed elsewhere.

The compact configuration will perhaps be a normal response to a stadium development on a green field location. It is a form which is almost certainly prescribed where some form of retractable roof is incorporated. Alternatively, asymmetrical planning arrangements can maximise seating capacity commonly without the inclusion of a retractable roof. Where developments take place on existing sites they are often on an ad hoc basis and do not always use the available space efficiently.

2.4.2. Stadia Planning

This thesis does not repeat the criteria for stadia planning set out in the following works:

- Stadia. A Design and Development Guide.[20]
- Safety in Sports Grounds Act latest edition.[21]
- Building Regulations.[22]
- Technical Recommendations and Requirements for the Construction or Modernisation of Football Stadia.[23]
- The publications of the Football Stadia Advisory Design Council. The Council was discontinued in 1993.[24]

---

[20] John, G, Sheard,R, STADIA. A Design and Development Guide, First Edition Butterworth, London, 1994. Second Edition Architectural Press, Woburn 1997.
[21] Safety in Sports Grounds,4th Edition The Stationary Office,London, 1997
[22] The Building Regulations and Scottish Regulations.
[23] FIFA. Technical Recommendations and Requirements for the Construction or Modernisation of Football Stadia. FIFA House Hitzigweg 11 CH-8030, Zurich 1995

The practical interpretation of design standards provided by Stadia. A Design and Development Guide and the standards laid down in the three other publications currently provide a basis for UK stadia standards, for those who design and develop stadia. There are limited references in the first and last of the listed works to the problems raised by the use of in situ turfgrass in stadia.

Page 60 volumes 1&2 of Stadia. A Design and Development Guide presents the following in the form of guidance in respect of growing grass in various types of stadia:

- Completely open stadia "will accept any playing surface".
- Partly roofed stadia require expert guidance to counter the effects of a "combination of shading from sunlight and reduced airflow at pitch level."
- Totally permanently enclosed stadia at present "cannot have natural turfgrass pitches".

The Technical Recommendations and Requirements for the Construction or Modernisation of Football Stadia comments on turfgrass for football as follows:

- In cold climates, the playing field should be equipped with an undersoil heating system to prevent it from freezing in extreme winter conditions.
- Whilst the laws of the Game stipulate the maximum and minimum dimensions for playing fields, it has to be appreciated that a stadium arena should provide a larger grass area than is required to display the game, or in the case of a multi-use stadium the various games of football.

2.4.3. Comments on Published Data on Playing Areas

Completely open stadia "will accept any playing surface". The certainty of the statement in respect of the turfgrass surface depends, on the size and configuration of a stadium superstructure and latitude. Even when there is no roof, experiments have shown in large compact stadia that moving air will reach only certain areas of the playing surface. The requirement for air in relation to turfgrass is not only an aid to photosynthesis it also assists turfgrass drying out processes. In addition the consequence of high superstructures even without spectator weather protection will increase the extent of shadowing.

---

[24] Football Stadia Advisory Design Council. London. *See Bibliography for list of Publications.*

The management of stadia with retractable roofs requires guidance to counter the effects of both shading and reduced airflow at pitch level; these adverse influences damage the grass. The evidence is clear that both the nature and timing of that guidance is critical. In the case of stadia with retractable roofs the configuration of a roof is a significant consideration as is the need to devise the means of providing air movement over a turfgrass playing surface at speeds which are beneficial to turfgrass. But many advantages gained from early investigations into design aspects will be negated if the playing surface is over-used or abused by inappropriate uses. **(2.6.4)**

It is consistently clear from all the evidence that permanently enclosed stadia at present cannot sustain natural in situ turfgrass playing surfaces. It would appear from laboratory testing that artificial lighting of prescribed wavelengths can sustain turfgrass in enclosed environments. Those experiments have not as yet been transferred to stadia conditions. However sections **(3.2.1-3.2.8) (8.0.2.) (8.0.3.) (8.0.7.) and (8.0.8.).** consider ways other than biological ways of sustaining turfgrass in enclosed stadia.

Section four of the FIFA publication-Technical Recommendations and Requirements for the Construction or Modernisation of Football Stadia sets out the requirements for a playing field for Association Football. The section suggests that turfgrass is a required surface for Association Football. "In cold climates, the playing field should be equipped with an undersoil heating system to prevent it from freezing in extreme winter conditions."[25]
This topic is analysed in some depth in paragraph **(4.8.0.).**

The section also stipulates that "Whilst the laws of the Game stipulate the maximum and minimum dimensions for playing fields, it has to be appreciated that a stadium should provide a larger grass area than is actually required for the playing field, in order to allow for the possibility that the playing field may be shifted from time to time, by a few metres, in any direction

This suggestion raises two issues:
Changing the position of the location of the playing area would affect spectators' sight lines, which are calculated under strict criteria to ensure spectators can see the action of play on the touchline nearest to their viewing position. If the playing pitch were to be moved from time to time, the problem raised by that movement would become an issue at the design stage.

Moving touchlines and byelines by a few metres would not avoid wear patterns showing unless the playing area was moved before wear became apparent. Wear along touchlines is usually severe. Moving a pitch would bring a strong linear pattern of wear within one side of the playing area. For practical reasons moving a pitch is most unlikely. But in that event it is necessary to be aware of the shape of the wear patterns imposed on a playing surface by the various games of football and to judge how these patterns reflect on the playing surface as a whole where multi-use stadia are concerned. Wear patterns caused by the various games of football are considered in **2.4.0.6.**

The intensity and the frequency of use cause wear patterns. The impact of these can be reduced by allowing turfgrass to recover in an appropriate environment, assisted by horticultural treatment. The problems of wear on turfgrass will be more intense in a multi-use stadium with or without a retractable roof.

2.4.4. The Influence of the Superstructure.

Another biological influence on the growth and maintenance of turfgrass is the flow of air over its leaves. Research carried out for this dissertation suggests that the most effective location for an air inlet is at the base of a stadium superstructure. The inlets should theoretically be located continuously around the superstructure base, the lower level of the inlets should be as near as possible to the level of the playing surface. Continuity of openings is obviously not possible because of the need for structural columns and vertical access to upper levels of a stadium. However, it would appear that it may be possible to include in the region of 55% to 60% of the outer perimeter of a superstructure to provide equally distributed free space. The shape and form of that free space is discussed in **(9.2.0.2.).**

Buildings or topographical features adjacent to a stadium may affect the efficiency of free to air openings at the base of the superstructure. Veiling features are not taken into account in this work. Where they exist, the influence that they exert must be noted. The veiling influences can be modelled by wind tunnel testing a stadium model set in its surrounding context. The visual modelling will suggest whether or not a passive strategy for moving air over the turfgrass surface can be applied.

Because of the lack of air movement at pitch level in the Amsterdam ArenA, mobile fans were introduced along each touchline. The flow of air from these fans ceased to be

---

[25] Recommendations &Requirements for the Construction or Modernisation of Football Stadia. FIFA 1995 .PAGE 7

measurable between 19-21 metres beyond the fan position. The airflow over the initial 5 metres exceeded the recommended air flow speeds for healthy turfgrass. The implication was that only three-quarters of the playing surface received a useful dosage of air.

Further research is required to establish whether it is practical to distribute mechanically air over a playing surface in a controlled and measured manner. It might be possible to lay below the rootzone a network of air supply ducts into which fans could be linked when the playing surface is not in use. Access to the ducts could be provided through removable turfgrass pallets. The movement of air over the turfgrass has two purposes it controls the opening and closing of stomata and also aids the process of drying turfgrass leaves.

2.4.5. Factors Influencing the Arena Size.

This section examines the theoretical criteria for determining the size of an arena for a multi-use stadium with or without a retractable roof. The section also comments on the general guidance given on some of the issues related to turfgrass in stadia in the publications: Stadia. A Design and Development Guide and The Technical Recommendations and Requirements for the Construction or Modernisation of Football Stadia.

The theoretical criteria used to determine the size of the playing arena for a multi-use stadium in the UK will be based on accommodating the playing space standards laid down by the organising Bodies of Association Football, Rugby Union, and Rugby League Football. The space requirements for American Football will fit easily into the playing requirements of the other three codes.

These standards include turfgrass safety margins required for players' protection. Beyond that is a requirement for a hard surface maintenance track, 3 to 4 metres wide, providing access for emergency vehicles, horticultural machinery, mobile TV cameras and advertisement boards. The maintenance track requires direct access to the hard outer surroundings of a stadium. The suggestion of some published literature is that one access is required. It would appear prudent to provide at least two points of access, located diagonally opposite each other. Thus allowing a more rapid response in situations of emergency and also a choice of access for stadium reconfiguration, thereby relieving pressure on the in situ turfgrass.

The outer edge of the maintenance track will define the limits of an arena. An arena is defined "as a level area surrounded by seating in which sports, entertainments, and other public events are held".[26] The distinction between the playing area and the arena is that the playing area is contained within the arena.

2.4.6. The Relationship between Arena Size and Spectator Capacity.

The perimeter of the arena generates the setting out of the stadium seating. Therefore, the greater the girth of the perimeter, the greater is the capacity potential. Other physical factors influencing capacity are the rake of the seating, the distance between the rows of seats and their size. There is however, a theoretical limitation on the capacity determined by the maximum distance a spectator with 20-20 eyesight can clearly follow a moving ball. This distance will vary depending on the size of the ball and the speed at which it travels. If a decision is taken that spectator capacity should not be curtailed by these restrictions then capacities of 200,000 are theoretically possible. Such capacities would have at least two implications: the need to develop appropriate infrastructures; the superstructure would be considerably bigger and as a consequence of its size impede even more light and air over a playing surface. Studies carried out for this work suggest that a capacity of 80,000 would be the upper limit for an acceptable standard of visual acuity for the games of football.

There is a fundamental spectator preference between the arena configuration of UK stadia and those of some European stadia. The strong preference in Europe is to include a running track surrounding the football area. The implication of this is that spectators' sightlines are extended. Most UK spectators wish to be as near as possible to the action of the players. However, inserting a running track does increase the multi-use potential of a stadium.

CHAPTER FIVE

2.5.0. THE NEED FOR TURFGRASS MAINTENANCE IN STADIA

2.5.1. Introduction

Irrespective of their use and location turfgrass plants considered in this Thesis require maintenance. This may in agricultural or amenity turfgrasses take the form of defoliating, in the first case by grazing or cutting or in the second case by cutting alone. One of the purposes for cutting is to suppress invasive competition from other aggressive plants associated with turfgrasses: these otherwise would take over the space occupied by turfgrass plants by ensuring that light and air did not reach the crown and tillers of turfgrass plants. In both categories of turfgrasses it will almost certainly be necessary to supplement growth by feeding to ensure healthy and vibrant turfgrass

[26] The New Oxford Dictionary of English, Clarendon Press, Oxford , 1998, Page 87.

Those same principles of defoliation and nutrient supplementation are used in treating the in situ turfgrasses in stadia playing surfaces. In these locations the likelihood is the turfgrass playing surfaces will receive almost continuous treatment. Turfgrass difficulties in stadia are more likely to be caused by reduced levels of light and air, conditions made worse by misuse and in certain areas of the playing surface, over-use. Such abuse can destroy turfgrass roots.

These studies have demonstrated how critically interwoven are the factors of light, temperature, shade, air movement, feeding, defoliation, pest control and aeration in turfgrass growth. However, irrespective of the availability of these factors at optimum levels their value will be negated by persistent misuse and overuse of turfgrass and wear will result.

This section looks at the contribution made by some of the other additional factors, that contribute to turfgrass wear in stadia.

2.5.2. Over-use of Turfgrass

As stated in **2.5.1,** despite the availability of all or most of the horticultural and environmental requirements essential for turfgrass growth and maintenance, turfgrass can fail. This failure will occur through its persistent over-use. Under the conditions of over-use, failure can show itself in both open and restricted environmental conditions. The effects of failure will appear, all other factors being equal, more quickly in a restricted environment than in an open one. Most large stadia present restricted environments, these studies have also shown that stadia with centrally located roofs provide, for most periods of a year, severely restricted environments.

Turfgrass failure in open conditions can be seen, for example, in fields around cattle drinking troughs. These locations suffer from continuous use, spillage of water, surface compaction and poor drainage. These factors present prime conditions for the destruction of the roots of turfgrass plants. The conditions in some stadia can mimic those conditions found in an open environment.

2.5.2.1. Measures Against Turfgrass Wear.

Periods of rest after turfgrass is used will aid turfgrass recovery. The length of the recovery will depend on the turfgrass species, the environmental conditions and the stress to which the turfgrass was subjected. The difficulty in applying periods of rest may be dependent on the commitment to keep to a contractual programme of events for a stadium.

If use continues when turfgrass is distressed, the plant leaves will be eradicated. This will cause a loss in ground cover and increase both surface wear and compaction, which in turn will reduce standards of efficiency of rootzone drainage and aeration, eventually leading to the loss of the plant roots. Under these circumstances the only course of action to restore a surface is to re-seed which in the situation of a tight use schedule is impractical. An alternative is to returf the affected areas, see **6.4.1.**

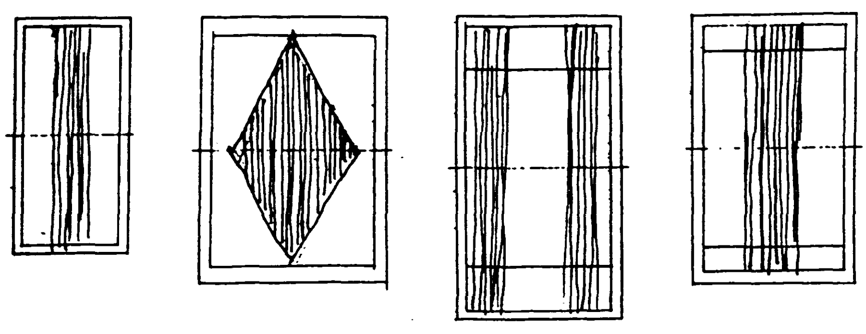
2.5.3. Patterns of Play.

In UK stadia where ground sharing for the games of football occurs it will usually be restricted to Association Football, Rugby Union Football or Rugby League Football. Currently the demand for American Football in the UK is limited.

On a line North of Birmingham the pattern of sharing is likely to be between Association Football and Rugby League. Below that line, Rugby Union will replace Rugby League.

Each game demonstrates differing playing characteristics and they impose different patterns of wear. These are broadly predictable in position and shape. The degree of compaction and surface tearing differs with each game. Rugby Union is likely to cause the most surface damage. Where dual uses occur of different games their wear patterns become superimposed, making turfgrass reinstatement more difficult. These problems are more acute when different wear patterns are fused together on a regular basis and when these uses extend into the summer season. Traditionally during this period stadia turfgrass was the subject of extensive recovery programmes.

Fig 2.5.3.
Illustrates the basic wear pattern imposed by the Games of Football



A, American Football. B, Association Football. C, Rugby Union. D Rugby League.

2.5.4. Footballers' Footwear.

Players' footwear is an important influence on turfgrass wear. Playing boots have become lighter and more supple, as the game has become faster. Professional grade boots have flexible soles on the line of the instep, contributing to a firmer grip between players' feet and the playing surface.

Association football boots have truncated cone studs set into each sole, four 15mm studs in the instep and two 18mm in the heel. The studs are made of plastic or metal and can be replaced to suit different ground conditions. There is a trend to replace studs by metal or plastic fixed cleats set into the sole. The suggestion of the Ipswich Football Club Groundsman through uncontrolled photographic evidence is that cleats cause more damage to turfgrass surfaces than studs. This is confirmed by the anecdotal evidence of a number of other groundsmen.

Rugby boots are similar to football boots except that they have six studs on the sole and two studs on the heel and are usually metal.

2.5.5. Duration and Times of Play.

In this section the question of the time a multi-use stadium playing area is in use for a single event, relates to the display of the various games of football. Uses outside those spheres are considered in **2.8.6**

The rules of these games as currently formulated limit their duration of play to 80 minutes for Rugby Football and 90 minutes for Association Football. However, in the latter case some special fixtures, where a winning result cannot be obtained in normal time, an extra 30 minutes of time is added to the format of play. Alternatively, a re-match is made at another time and place. In either case, a way may be sought to obtain an immediate result if a stalemate exists at the end of either form of fixture. These interventions limit the overall use of a turfgrass playing surface to no more than 120 minutes of continuous competitive play at any one stadium. These extensions in time relate to a limited number of events.

The game of American Football will extend over a much longer time period. This is because more periods make up the length of play, each of these periods being of shorter duration but intervals between them are longer.

Not only has there been an increase in the number of fixtures played by the successful clubs but the times when matches are played are now linked with the viewing schedules of worldwide television. The implication of this is that games may be played at the time of day when weather conditions may be less environmentally advantageous to turfgrass, for example, during late evening in some parts of a season when there may be frost or dew present.

Another adverse influence on wear occurs when two clubs share the use of a stadium's playing surface. This influence is increased when teams play games from differing codes of Football. Games can occur on consecutive days; at certain times of the year fixtures of one club can extend beyond the fixture period of the other club. The consequence is turfgrass use extends into a period when the grass would be resting and recovering from use. This may not theoretically affect turfgrasses if such extension of use takes place when the plant sugar reserves are at a high level.

The visual evidence is that irrespective of the time of year there is clearly a change of colour and visual evidence of the playing patterns. Those grounds that have reasonable playing surfaces restrict the use of their surfaces. When such grounds are shared, it is on limited occasions and then there is an immediate input of thorough surface restoration.

The anecdotal evidence of some Association Football groundsmen is that it is not only playing patterns and frequency of use that affects wear: the less skilful player can sometimes cause severe damage to the playing surface. The implication is that the less skilful player more frequently misses a tackle than does the more skilful player. Missing a tackle altogether can cause turfgrass surface tearing. There is no research to support anecdotal assumption.
The visual evidence is that the playing surfaces of most of the smaller grounds are of poor quality. This is so even when they are more open to the receipt of light energy and air movement. These advantages may be negated, by lower standards of play and by inadequate investment in the structure and maintenance of their playing surfaces. This is the result of poor rootzone and drainage systems. The consequences of this low investment can be seen by standing water on a turfgrass surface after heavy but not abnormal rainfall. Smaller Clubs are also more likely to share their playing facilities because it is often an economic necessity.

Lessons of turfgrass failures through over-use in the smaller clubs are available for observation by the larger club but they still seek to ground share. The management of these clubs hold back from sharing not on the basis of turfgrass science but on the tribal instincts of their fans.

2.5.6. Warming up Periods

Where Games of football are organised by FIFA or UEFA, away teams are allowed limited practice on an opponent's arena. Where this right is exercised play is usually concentrated on one half of the playing surface. "Sixteen players can cause as much turfgrass damage as footballers can cause in an actual match."[27]

2.5.7. Compaction.

Table 2.4.9.1. PARTICIPATING PLAYERS AND OFFICIALS IN THE VARIOUS GAMES OF FOOTBALL AT ANY ONE TIME.

Games	Players in playing area.	Officials in playing area.	Officials outside playing area.
Association Football	22	1	2
Rugby Union Football	30	1	2
Rugby League Football	26	1	2
American Football.	22	5*	

*This figure increases to 7 in the National Football League. (NFL)

Table 2.4.9.2. Maximum and Minimum Playing Areas for Each Game and Area taken up by each Player and Official within the Playing Area in square metres.

	American Football.	Association Football	Rugby Union Football	Rugby League Football
Max Area.	5,353 [198]	8,625 [375]	6,900 [223]	6,800 [252]
Min Area.	4,460 [165]	7,480 [325]	**********	4,840 [179]

Playing area [ ] surface area per player.

Playing areas for Rugby Union and Rugby League exclude the dead ball zones.

CHAPTER SIX

2.6.0. THE DISPLAY AREA REQUIREMENTS FOR MULTI-USE STADI

2.6.1 Assessing the Display Area for a Multi-use Stadium.

Assessing the space for the playing area for a multi-purpose requirements has been considered in outline in **2.4.5-2.4.6. Fig 2.4.5.&Table 2.4.5,** defines in some detail the consideration of the spatial requirements for the Games of football. The purpose of this chapter is to comment on the difficulties that can occur if the display objectives of a stadium are not clearly defined by those who write the brief. The question of the size of the display area is linked with the range of events to be displayed and it can also determine the potential capacity of a stadium. The ways to maintain turfgrass in a stadium are separate from this question and are considered in **6.3.0&6.4.0.**

The question needing consideration is can the anticipated multi-use programme of display events be fitted within the area required to accommodate the Games of Football. If they can be there will be little difficulty, because the spectator sight lines will be set for those games. Where difficulties can occur is by the introduction of an athletic arena within a multi-use stadium. These is no physical problem with this concept. But the barrier to their introduction in the UK is the desire of most spectators to be as close as possible to the action of the Games of Football. In principle an athletic track pushes the spectator away from the action. This is arrangement is acceptable on the continent of Europe with the consequence that some of their stadia provide more flexibility than UK stadia.

It should be noted that there are no European stadia with retractable roof's and running tracks. The structural problems are greater with these combined facilities. There will also be difficulties with providing optimum eye-line sighting for spectators.

In a Multi-use stadium the most favourable option would be to limit the scope of the uses to be displayed to within that which can be accommodated within the areas needed for the Games of Football as these uses are most likely to provide the most consistent display use.

Other factors that can be taken positively into account are considered and assessed in **2.4.5-2.4.6**.

The maximum and minimum playing sizes for the four games considered are set out in **Fig. 7.5.2.2.**

CHAPTER SEVEN

2.7.0 THE TWO ELEMENTS OF A STADIUM.

2.7.0.1 **The Cavea**

[27] Manchester United Head Groundsman. Conversation March 2003.

With or without a retractable roof any major stadium consists of two elements: the cavea and the combined amenity and managerial areas. The volume of a cavea may range from 500,000, to 1,750,000, cubic metres; it is the larger of the two elements. When seated spectators occupy it the period of its use may be limited to 3 to 6 hours at any one time. But the playing area is used, for example, for exhibitions the cavea may be occupied for a period of days

The use of a cavea will depend upon a number of factors which may limit the frequency of its use. The factors are these: the absence of an anchor tenant; commercial competition; the lack of suitability of an event for the background setting of a large stadium; the time scale involved in arena configuration and reconfiguration; the influence the events of an anchor tenant or tenants have on other events in arena programming. As has been emphasised in this thesis, the make-up of the arena surface can also be a major consideration in determining arena programming and the suitability of an event for that surface. Where an arena surface is made up of in situ turfgrass, the growth and maintenance of that surface will be influenced by how that surface is used and by the frequency of those uses.

Because of the uncertainty of the continuity of events which may be brought about by the restrictive factors listed above, the use of a cavea could perhaps be classified as that part of a stadium which is in use spasmodically.

In contrast the managerial section can be occupied 8 hours or more a day and for 7 days a week. The amenity areas when used by the public may extend that time period by 5-6 hours on as many days as is commercially possible.

The distinction is drawn between the length of the occupancy of the two sections, because that admits the possibility that these elements can be managed and controlled on a differing basis, and they may, if so required, be physically separated from each other.

Separating the elements has the advantage of allowing the cavea to be considered as simply the bowl containing the seats, with some amenities included. By not maximising the use of all the space formed between the soffit of the seating terraces and the outer perimeter of the superstructure, this allows the profile of the superstructure to be shaped to facilitate the passage of air through to the openings at the base of the superstructure. The residual ancillary and managerial accommodation can be included in separate blocks of accommodation. These issues will be discussed in **Part Eight.**

The cavea contains two elements: seating and in the UK a natural turfgrass playing surface. In contrast the amenity and managerial areas have diverse uses and are composed of a series of comparatively small volumes requiring different environmental standards.

Natural turfgrass requires light and air for growth and maintenance at levels found in open conditions. These conditions are not found in large stadia. Stadium designers should seek therefore to maximise these values by considering how the superstructure intervenes to reduce the availability of heat, light and air. The important issues are in this respect, the shape, form and size of the superstructure and how it might admit air over the turfgrass. Consideration should be given to the configuration of a retractable roof and how that configuration also may assist light and air. Research indicates that a centrally located retractable roof is not the best option for turfgrass growth and maintenance.

Concern may be expressed by management that patterns of opening roofs that differ from the centrally located models will increase costs in keeping seats clean and dry. Observation informs that in properly managed stadia seats are clean before use, irrespective of the form a roof takes. What is essential is that a roof is open to its maximum potential for maximum periods, thereby providing conditions advantageous to turfgrass. The discussion in **Part Eight** will centre around the issue of whether any form of roof can provide the environmental conditions suitable for large stadia.

2.7.0.2. The Amenity and Management Areas

It is not the purpose of this work to design a stadium. Nevertheless, a cavea had to be designed and built in model form to allow analytical measurement to be considered.

That design fulfils the viewing requirements of a stadium capable of accommodating 60,000 spectators, together with the playing space required to satisfy the needs of the various games of football.

Besides providing the cavea spatial factors only two other factors were of significance in developing external profile of the stadium model.

1) How to effect the entry of air across the playing surface.
2) To influence the external profile of the stadium superstructure to facilitate that process.

These factors are considered and recorded in **Part Seven.**

Thus far in stadium design passive air movement across a playing surface appears not to have been considered. The concept of the San Nicola Stadium Bari, Italy may be considered as the exception to this statement. If air movement across the playing surface occurs there, no measurements have been taken for this work to verify that it does. But the evidence provided by examination of the building and the drawings is that the stadium's easily recognisable structural clarity and its simplicity of construction together with the consideration of personal security may have accidentally allowed the conditions to facilitate air movement to occur.

The outcome of the San Nicola Stadium design strategy results in the separation of the Amenity and Managerial accommodation from within the upper volume of the cavea.

It was observed during earlier studies and in the preliminary wind tunnel experiments for this degree, that shaping the outside face of a superstructure to reduce its base width, air travelled through the space between the ground level and the superstructure soffit more efficiently.

The consequence of reforming the profile of the superstructure in this way results in the reduction of the potential area available for development within the girth of the super structure. The result of this abstraction in development area moves some way towards the spirit of the Bari design.

Air movement, at optimum levels, over turfgrass leaves is one of those necessary factors required for its satisfactory development: the question is how best to provide it?

In this work the principal aim to achieve this objective was, 1) to free the base of the superstructure to allow air to flow beneath it, and 2) shaping the superstructure profile. Both strategies involve a range of practical difficulties. These difficulties are considered in **Part Eight.**

A comparison between the cross section of the Colossuem Fig 2.1.2.2. with that of the cross section of the Millennium Stadium **Fig 9.4.6.2.2.** indicates the difference in the approach of using space beneath the cavea. The spaces beneath the cavea in the Colossuem were used for circulation and ablutions. The spaces beneath the cavea of the Millennium Stadium are developed for those same functions as the Colossuem but in addition the space is developed to satisfy the amenity requirements. Maximising development below the cavea and not providing extensive open spaces at the base of a cavea, as experienced at the Millennium

Stadium and the Amsterdam ArenA appears to provide little air movement across their playing surfaces. The form of both these stadia appear to be more suited to a playing surface of artificial turfgrass.

The Roman Colosseum is an example of a stadium that limits within its superstructure the spectator circulation and ablutions areas. The complex arrangements for the administration of events are located beneath the arena area. This arrangement is both efficient and flexible.

Developing below the playing surface provides an option for designers to consider. The issues to be considered in this approach are whether the approach is economic and are there other ways of providing a means of allowing air to move over the playing surface in ways that are not passive. These issues are also discussed in **Part Eight**.

CHAPTER EIGHT

2.8.0. THE EMERGENCE OF MULTI-USE STADIA

2.8.1. Introduction.

An assumption commonly made is that the Harris County Dome, 1965 **(Appendix 9.4.1.)** was the first building to display multi-use activities; this is not so. The Colosseum Amphitheatre, Rome AD 80, probably was. The organisation of the multi-use events displayed and its spectator capacity remained unequalled until the emergence of the Harris County Dome almost two thousand years later.

After the Roman period there was a hiatus in the development of any form of building to display sport until the early 18th Century in the UK.

In London, James Figg (*circa.*1695-1734) in 1720 opened an academy of arms, which also included boxing. His amphitheatre could be considered to be a multi-use building. Prior to this, boxing had taken place in a theatre in London in the late 17th Century.

Henning Eichberg reports:

In 1724 John Wood presented his plans for the completion and new construction of the English town of Bath. In this town there already existed some places 'for taking the Air and Exercise, in Coaches or on Horseback' and a course for horse-racing. But the new project included a 'Grand Circus' for the exhibition of Sports. When developing a new social leisure culture, England's imperial gentry and bourgeoisie tried to relate themselves to their Roman heritage.[28]

The Royal Albert Hall, London, UK (1868) was an early example of a building which displayed multi-use activities and has retained that status. The building is based on the Amphitheatrum form, with an audience capacity of 8,000.

In the USA a notable example of a multi-use building was the Madison Square Garden, New York City, New York, USA. Between 1879 and 1968 four versions of 'The Gardens' were developed on three different sites. With each new building came an increase in size with a spectator capacity rising from 5,000 to 20,000. The latest of these developments is still in use.

In the USA before 1965, the term ' multi-use building was not in common usage' despite the fact that there were venues displaying multi-use events, which were similar in character and with similar space requirements, therefore requiring little reconfiguration. These displays were comparatively small in scale when compared with American Football and Baseball, which games were traditionally played in separate stadia.

In the UK at the turn of the 19th Century a number of Rugby Union or Rugby League Clubs shared playing facilities with Association Football Clubs. This practice was abandoned only to return in the last decade of the 20th Century.

During the latter part of the first half of the 20th Century some Football grounds incorporated Greyhound or Speedway racing tracks within their arenas. Neither event required significant reconfiguration as their tracks were permanent features. These grounds could be classified as dual use stadia but not multi-use in the sense now understood by that term.

When the Harris County Dome opened in 1965 it produced a sea change in the way stadia in general and the multi-use concept in particular was to be perceived. It might be said with authority that with the opening of the Dome a stadium began to be thought of as a multi-use building.

[28] Eichberg H. Essay:- Stadium, Pyramid, Labyrinth: Eye and Body on the Move, The Stadium and the City Edt., Bale & Moen, Keele University Press, Keele, Staffordshire, UK. 1995. Page,326

The Harris Dome was to influence standards in comfort and safety and arena flexibility; but this flexibility was achieved through the failure of the initial playing surface of the arena. **(Appendix 9.4.1.).**

The failure necessitated the substitution of the in situ turfgrass by an artificial surface.

This substitution allowed the display of events similar to those displayed at 'The Gardens' but on a larger scale and in addition events which could not be displayed there, such as American Football and Baseball. This was made possible by the physical size of the building.

"The Dome rests on a circular substructure with a diameter of almost 216 metres"[29]. It could be configured to provide capacities of 57,000 for Baseball and 66,000 for Football. Either capacity allowed the Dome to claim to be the first multi-use stadium to provide an all seating capacity greater than that of the Colosseum, Rome, Italy, 80 AD.

Historically, the few known buildings used for multi-use purposes reveal the important part the floor plays in these enclosed buildings. They had solid floors, which provided support for the displays without constraints and allowed easy reconfiguration.

By staging events such as football and baseball the Dome set itself apart from other multi-use venues through its size and spectator capacity. These games necessitated an in situ turfgrass- playing surface, opposed to the traditional multi-use floor surfaces such as wood, concrete or sawdust on an earth base. The turfgrass floor had the disadvantage of being biologically dependent for its survival. It is now a historical fact that the turfgrass surface failed and was replaced by an artificial surface. With this change the Dome came into line with other multi-use buildings by having a floor finish with limited environmental dependency. With this change from natural to artificial began the discussion relating to the conflicting requirements of the surface finish in multi-use stadia.

Materials, not adversely affected by environmental conditions provide the most satisfactory surfaces for multi-use stadia provided they

- allow players to exhibit their skills to their best advantage.

---

[29] The STADIUM, The Architecture of Mass Sport, Edited by Michelle Provoost, NAI Publishers Rotterdam, Netherlands, 2000. Page 148.

- provide reasonable protection to players.
- can absorb heavy weights imposed by some of the multi-uses.
- facilitate the processes of reconfiguration.

The last two of these factors cannot easily be accommodated with the use of in situ turfgrass. **(6.1.1.to 6.1.3.)**, suggests ways of overcoming these problems.

2.8.2. The Aim of Introducing Multi-Use Activities into Stadia.

The introduction of multi-use activities in stadia with or without a retractable roof has the aim of extending their range of activities and periods of use.

A retractable roof allows a stadium to be used irrespective of climatic conditions. Whether commercial viability is achievable in such stadia depends on a broad range of factors; an analytical discussion on these factors is not an objective of this dissertation. But it has become clear from the study of the Millennium Stadium, Cardiff, UK, and others, that stadia of this type in allowing these games to be played may not be financially viable. The North American evidence confirms this, at least where the first generation of stadia with or without retractable roofs is concerned.

2.8.3. Are Multi-Use Stadia Suitable for the Events they Display?

The question applies equally to large stadia with or without retractable roofs. Arguments defining their suitability for multi-uses are based on three levels, which are discussed in the following sections.

2.8.4. The character of an event

The cavea of a multi-use stadium may generate volumes of between 500.000 to1,750,000 cubic metres; they may also have an arena, the area of which may be in excess of a hectare. From the magnitude of these sizes the background in which events may be displayed can be envisaged. Such stadia are principally designed to display the games of football. These games when played at a high level can attract audiences up to 80,000; their modes of play are appropriate for the size of such stadia. The character of these games is such that their action continually moves over the whole playing surface, following a ball, which is sufficiently large that when projected at speed it can be seen by most spectators in such a stadium.

The viewing distances stemming from such large volumes determine whether a stadium can provide an atmosphere appropriate to the character of the event being displayed. Clearly the character of games of football can be appropriate for that range of volumes, but the game of Lawn Tennis is inappropriate. A stadium suitable for Lawn tennis should be limited in size, to allow a high percentage of spectators to satisfactorily follow a comparatively small ball, used by between two and four players on a court of limited size. The accepted understanding based on actual examples is that the maximum stadium capacity providing a high percentage of viewing conditions should not exceed 18,000.

The character of Pop concerts is appropriate for large stadia. Compared with ball games the actions involved in their display are almost static. The demand made on a stadium by a pop concert is size: the use of the arena partly for spectators and partly for location of an acoustical backdrop. Enclosing the câvêa by retracting the roof can aid the acoustical standards and also help to attenuate sound break out. The demand for such large stadia for pop is less than is commonly supposed.

A stadium capable of seating up to 80,000 may not provide a sensitive ambience for an event where an audience may not exceed 30% of that capacity. The now imploded Kingdome, Seattle, USA which had a capacity of 88,000, provides a practical example of a stadium where a poor atmosphere resulted from a regular but limited audience of 30,000 for basketball games. Basketball eventually ceased at the Kingdome, one reason being the poor ambience produced by the never to be filled 58,000 seats.

This problem was recognised at the Toronto Skydome, Canada where a smaller prefabricated stadium is erected from time to time within the volume of the stadium, to house events requiring a more appropriate atmosphere for an audience of 30,000 or fewer.

There is a tradition for displaying opera in the Roman Amphitheatre in Verona, Italy, Europe. The spectator capacity of the cavea, with space deductions made for the stage, is reduced to approximately 15.000. In contrast the character of an opera house is traditionally intimate, with seating capacity of between 1,800 and 3,000. This intimacy contrasts with the atmosphere produced by a modern stadium. Even so, popular classical concerts have been held at the Millennium Stadium, Cardiff. where audiences of around 63,000 have been claimed.

2.8.5. The viability of re-configuration

In situ turfgrass in multi-use stadia will restrict the range and frequency of events. In situ turfgrass will also cause difficulties in reconfiguring an arena. It is for these reasons that there is recognition that turfgrass is an inappropriate surface for multi-use stadia, unless the turfgrass can be removed where its use is not essential to the display of an event.

In addition to those events included for display discussed in **2.5.3.1,** the following events are sometimes considered for inclusion in multi-use stadia: Championship Hard-court Tennis, World Championship Boxing, Unconventional cricket, Equestrian Events, Speedway Racing, Stock Car Racing, National and Regional Festivals, Religious Conventions, Exhibitions and Three-Ring Circuses and there may under certain circumstances be wind surfing on water. Athletics is a more common event in European stadia where athletic tracks are often automatically set around a football pitch. But that would not be the case in a UK stadium. However, in a stadium with a retractable roof and an athletic track it would be possible to display athletics on an all year basis providing the opportunity to supplement the separate sport of indoor athletics which is based on different track configurations.

The following events in a multi-use stadium impose degrees of severity of impact on the in situ playing surface.
In the display of **Unconventional Cricket,** the playing area (the wicket) is 'dropped in' into the rootzone area. At the Millennium Stadium the rootzone can be removed in individual pallets; the task therefore of inserting the pitch is straight-forward, as would be changing back to the original surface. Where the rootzone is fixed this task could be complicated by the potential disturbance of the drainage system. Under those circumstances other ways should be sought to provide the playing surface, such as stretched plastic matting set on a rolled built-up area after thinly removing the turfgrass surface to provide the area required. Reconfiguring the playing area would imply turfing the area. There is little else to configure for this event, other than to ensure that the artificial lighting levels are appropriate for playing at night.

In the display of **Speedway and Stock Car Racing** the measure of reconfiguration is considerable. Unless the turfgrass can be removed in whole or in part from the arena these events should perhaps not be considered in a multi-use stadium. There is not only the requirement for a special track which will imply the importation of many tonnes of hardcore into the area and its subsequent removal there is also the need to safeguard spectators by protective fencing. These events are best suited to a dedicated stadium or one where the facilities can be built into a stadium as a part of the original planning concept if they occur on a regular basis.

The display of **Equestrian Events** requires more than the availability of an arena. They also require a considerable area of land adjacent to the stadium, to stable and exercise the horses between events. If such space is not available, the practicality of holding such events is very limited. But if the additional facilities are available, the problem then centres on the maintenance of the turfgrass. If that is removable from the arena then material has to be imported into the arena and consolidated to provide a surface suitable for jumping. If the turfgrass stays in position, the turfgrass will have to be replaced and the upper surface of the rootzone treated to reduce compaction.

Artificial surfaces simplify the reconfiguration processes: in situ natural turfgrass surfaces complicate those processes, even if the turfgrass can be removed from a stadium. The degree of the complexity is dependent on the method of turfgrass removal. Part Six describes the available methods of turfgrass removal from stadia and also the problems encountered when natural turfgrass is in situ.

2.8.6. The Suitability of a Large Stadium for Particular Events

The White City Stadium used for the Olympic Games (London 1908) could be classified as a multi-use stadium. Besides the athletic track, (its inner field was used for field athletics and football) it also had a banked concrete cycling track and a 100 metre swimming pool contained in a tank.

But after the Games of 1928 the use of the main stadium was limited to track and field athletics, and where played, the Final of the Association Football Competition.

One reason for changing the policy was that a large stadium provides an inappropriate setting for the display of events, such as weight lifting, boxing and judo etc. Another reason was that a wide range of events had to be programmed within a very short time scale. Both these problems could be accommodated by having available a range of venues appropriate to meet both the demand and function. The diversity of appropriate stadia also provided for the possibility of continuity in the development of those sports, which could not be developed in a multi-use stadium.

That is an argument different from that generally used for the procurement of multi-use stadia or any other stadium outside the Olympic Movement. Commercial criteria for size will be determined by the catchment area and by the anticipated popularity of the principal sport or sports to be displayed. Other events to be displayed will have to fit into a space designed principally to meet the needs of the core user, irrespective of how unsuitable that environment may be for the display of those other events.

2.8.7. The Demand for Space for Pop Concerts

During the course of this study, audience figures for 1082 pop concerts for 1996 were analysed to test demand against capacity in the USA. The data examined was abstracted from the weekly editions of the magazine Amusement Business[30]. The audience capacities were divided into multiples of 2500 up to 10,000 and multiples of 5,000 from 10,000 to 105,000; above that figure capacities were expressed separately.

The figures recorded 'top concert grosses' in America, but also included a limited number of audience figures from the UK, Netherlands, Europe and Mexico, South America. These references were so few in number their presence did not contaminate the overall USA figures. None of the figures quoted relate to stadia with retractable roofs.

The data highlighted only a limited demand for large stadia, that is over 60,000.in capacity. The study indicated one demand for an audience of up to 174,000. Where ticket demand exceeded the capacity of a stadium irrespective of its size, repeat performances were planned to satisfy the need. **Table 2.5.0.4.1.** illustrates the data from which will be seen that there is no overwhelming demand for large stadia to house pop concerts.

CHAPTER NINE

2.9.0. THE ADVENT OF THE RETRACTABLE ROOF

2.9.0.1. Introduction.

"Retractable roofs have been used since ancient times; it is known that the audience part of the roof of the Roman Colosseum could be opened and closed, and the remains of the columns of the retractable roof can be seen amongst the ruins".[31] Research has suggested that the authority of this statement cannot be established beyond doubt.

The main amphitheatre in Rome and those of Nîmes and Arles may well have demonstrated the form of a cantilevered lightweight fabric roof, over at least some part of their seating

[30] Amusement Business is- The International Live Entertainment & Amusement Industry Newspaper, BPI Communications, Inc., 1515 Broadway, New York City, NY 10036, USA.

[31] Ishii, Kazuo. Editor. Structural Design of Retractable Roof Structures, WIT Press, Southampton, Boston, ISBN 1 853126195. Page 3.

galleries. Connolly draws attention to a wall painting from the amphitheatre at Pompeii. "The wall painting is unique in depicting an a amphitheatre with its awning extended."[32] If these roofs existed, when they were not required or when wind threatened their stability, they were removed. The probability is they did not greatly extend over the terracing **(2.1.0.3.).** The temptation is to infer that they were the first retractable roofs: they were not. At best they could be defined as awnings, which were manually removed and then reassembled.

These roofs do not fall within the acceptable definition of a retractable roof, which is "a type of structure in which a part of or the entire roof structure can be moved or retracted in a short period of time so that the building can be used in an open state or in a closed state of the roof ".[33]

The tenuous link between the amphitheatre's awnings and a modern retractable roof is that early experimental work on retractable roof systems utilised fabrics as roof coverings.

There may, however, be a factual link between the development of modern fabric retractable roofs and the tents of early travelling circuses.
The German Structural Engineer, Professor Fri Otto, in the early 1950s experimented with suspending and withdrawing fabric roofs over relatively small spaces. After the significant failure of the fabric retractable roof at the Montreal Olympic Stadium (1976-1988), the design methodology based on suspended tented fabrics has thus far not been taken any further in relation to large stadia projects **(8.0.2).** There are, however, examples of retractable roofs using fabric materials amongst which are the Gerry Weber Tennis Stadium, Halle/Westfalia, Germany and the Pusan Dome, Korea Asia

2.9.1. The Historical Background of the Retractable Roof

The first large and complex retractable roof was at the Civic Arena, Pittsburgh, USA, 1961. It was built in the shape of a dome 127 metres in diameter. The form of the Dome was defined as a "compound spheroid with a plan shape that was nearly circular".[34]

This multi-purpose building was used for concerts, boxing and hockey. The floor was solid, following the tradition of multi-use buildings. The spectator capacities were 9,200 permanent seats for concerts; 10,500 for hockey and 13,600 for boxing.

---

[32] Connolly P, Colosseum Rome's Arena of Death. BBC Books London 2003, page 63.
[33] Ibid, page 3.

The Dome consisted of eight almost equal segments, two of which were fixed by the focal central axis of the auditorium. The segments were centrally pivoted at the head by means of a large down-stand rack and pinion, supported from the outside by a cantilevered arched box beam. The base of the segments was supported on wheels running on rails fixed to a reinforced concrete ring beam set 10·5 metres above ground level. The upper face of the ring beam was angled 13·5° inwards. This facilitated the passage of the rotating stainless steel framed segments; these moved in two groups of three in opposite directions, finally nestling over each other behind their adjacent fixed segments. The final configuration produced a 270° opening, achieved in 2·5 minutes.

The developer's reason for including a retractable roof over the building is not recorded. The probability is that the roof was developed on the encouragement of the professional design team. The Architectural Forum, March 1961, reports the following:

> "But perhaps the most significant fact regarding the building and one which should be encouraging to anyone who laments the lagging state of building technology, comes from Structural Engineer, Edward Cohen, of Ammann & Whitney, who says that it was unnecessary to evolve any new structural principles in the auditorium's design.....His point is that recent advances in technology now make such fanciful structures technically feasible."[35]

In a relatively short period of time the roof mechanism failed owing to the structural deflections exceeded their anticipated values. The consequence of this was the roof had to remain closed.

What was known about retractable roofs before the Pittsburgh Dome was that in the 1930s work was being developed on small roofs based on the crane method of retraction. These were the same principles used in the development of the Pittsburgh Dome and in 1993 for the principles of overlapping rotary retraction used on the Fukuoka Dome, Fukuoka, Japan.

It is also known that rectangular horticultural greenhouses were being designed in two equally divided sections. Each section was mounted on wheels ran on 'U' shaped rails located on the long sides of the rectangle. When required to do so the sections of a

---

[34] Architectural Forum/March 1961. Page number not recorded.

[35] Ibid.

greenhouse parted, thereby opening its interior to the external environment. This work anticipated the now conventional centrally located bi-parting retractable roof.

The work of the German Structural Engineer Professor Fri Otto on roof retraction was based on small-scale roofs. This work involved suspending fabrics from a complex hollow concrete pole or poles of relatively substantial diameter. The aim was to suspend a fabric from a pole and retract it by furling it into or onto a pole systematically. This experimental work was further developed by Professor Taillibert, *et al* for the retractable fabric roof mounted over the Montreal Olympic Stadium. That roof eventually failed in respect of its method of retraction and also in the choice of its fabric cover. That failure amongst other factors demonstrates that, the method of retraction and the choice of a roof cover are interdependent. **(9.4.2.).**

The facts are that the first two major retractable roofs built failed to function in a relatively short time period after they were completed.

A hiatus then ensued before the Toronto Skydome demonstrated the first large-scale complex retractable roof in 1989: this complex technical success has been sustained. The steel-framed metal-skinned surfaced roof was formed in four separate parts, one of which was fixed. The roof shapes were based on the developed parts of a semi-sphere: the geometry of the roof was complex. The cost of the stadium rose 380% during its development. **(9.4.4.)**

The overburdening financial impact of both the Montreal Olympic Stadium and the Skydome, led John & Sheard to comment that "these designs may not be widely emulated".[36] That has so far been the case excepting that the design spirit of Fukuoka Dome, Japan owes something of the inspirational example provided by the Toronto Skydome.

The aim of this historic review limits itself in principle to stadia with retractable roofs and performing spaces large enough to display the games of football. If it also restricts itself to European stadia then that discipline provides only four examples eligible for review. As each of these stadia has a centrally located bi-parting retractable roof the variations in the development of the retractable roof will be inadequately demonstrated. Therefore, stadia in

---

[36] John, G & Sheard, R. Stadia A Design and Development Guide, Butterworth-Architecture, Oxford England.

North America and Asia are included in the review, provided they meet the criterion of size and were completed before the year 2000. The variations in the roof configurations are shown graphically.

The other objective of the review is to explore any historic reason why retractable roofs were initially developed. Dr Stefan J, Medwadowski, President IASS. Oakland, California in his foreword (written in1998) to the book Structural Design of Retractable Roof Structures, suggests the following as an explanation:

> In the last few decades, retractable structures, and particularly retractable roofs, have become relatively more common. The driving force behind the construction of such buildings was the desire for very large spaces for the provision of athletic and other events which would provide complete audience and player protection from inclement weather, but which could remain open if the weather was good...... It is very clear that very large spans have been achieved and that a number of structural materials and systems can be successfully used to realise retractable structures.

The pioneering work on retractable roofs was carried out on small-scale projects such as buildings for swimming and theatres. These venues have a tradition of open-air display. There can be no questioning the environmental advantages there may be to a user, if a building can be opened or closed in response to the climatic conditions.

There is one stadium, which seemingly plays no part in this review of stadia with retractable roofs. That stadium is the Harris County Dome, Houston Texas, USA. What seems to bar it is that it has a fixed roof, the justification for its inclusion lies in its prototype status as a stadium building. This thesis contains many references to it, recording its successes and failures in fostering trends in the development of modern stadia. **(9.4.1.).** The Harris County Dome came into being four years after the Pittsburgh Civic Dome.

The Civic Arena is included because it demonstrated the technical confidence in responding to the challenge of opening and closing the walls of a building in response to the climatic conditions. At that time, 1961, the technical will was not matched by the analytical techniques required to fully understand the dynamic problems in the mechanical movement of the Dome.

The importance of the Pittsburgh Civic Arena and the Harris County Dome buildings was not only their adventurous concept but also the lessons they provided in the form of technical their failures.

The next important retractable roof was the textile cover over the Montreal Olympic Stadium, 1976 to 1988. The significance of this roof was its expense, the complexity of its method of movement and its failure to function. **(9.4.1.).**

Initially the Montreal Stadium had an in situ natural turfgrass surface. There is, however, no evidence to indicate that the Harris Dome turfgrass failure influenced the introduction of the retractable roof at the Montreal Stadium to ease the problems of turfgrass maintenance. The closing of the fabric roof would have significantly reduced the natural lighting levels, which would have been adverse to turfgrass growth and maintenance.

The proposal of Roger Taillibert, the stadium architect, to provide a retractable roof appears to be based on technical self-gratification encouraged by the Mayor of Montreal. The evidence for this is set out in his publication, "A Masterpiece of Textile Architecture".[37]

Taillibert's previous experience was based on fabric roof structures in the South of France. However, the size of the roof and the temperatures encountered in Montreal are significantly different from the South of France. The harsh climate of Montreal records average temperatures of –7°C,-11°C,-9°C,-3°C, between December and March.

Any benefit to the environmental conditions afforded by a fabric roof in those extremes of temperature would require a roof formed of a double skin fabric, the constructional depth of which requires to be calculated. With this form of construction and the imposition of snow loads would have further increased the problems already existing in retracting the fabric. The argument that the roof would not have to be retracted in the winter months is not sustainable: if the roof remained closed the turfgrass beneath would have died, **(9.4.2.).**

The designer of the Skydome retractable roof not only provided a consistently dependent mechanical operating system. His method of retraction exposed 90% of the cavea to the elements, thereby theoretically acknowledging turfgrass dependency on the photosynthetic process.

Nevertheless, an artificial playing surface was installed as the primary surface in addition to a movable natural turfgrass surface. Installing an artificial surface displayed an awareness of the historical importance the hard floor has played in successful multi-use buildings.

Compared with the success of the Toronto roof the Montreal roof failed to meet any of its design criteria. Although the system at Montreal allowed 100% exposure of the playing surface its retracting system had the disadvantage of a large travel distance between the point of cover and the storage position. The large support tower also veiled the playing surface.

The failure of two large-scale retractable roofs made it imperative that the Skydome should succeed, thereby providing confidence in the mechanical techniques required to move a roof.

The suggestion is made that the political rivalry between the cities of Montreal and Toronto provided the assurance that the funds would be made available to ensure the success of the Skydome roof. One aspect of this rivalry is that Toronto failed in its 1976 bid for the Olympic Games. They were awarded to Montreal. Toronto had proposed a stadium with a fixed roof. Toronto also failed in its 1960 bid for the Olympic Games at which time it also proposed a fixed roof stadium. Had the bid succeeded, the resulting stadium would have predated the Harris County Dome by at least six years.

The Skydome success established a degree of confidence in the design of stadia with retractable roofs. This was especially so in Japan. But in Europe the conditions for the installation of retractable roofed stadia were economically more stringent and it was imperative that the playing surface beneath the roof had to be in situ natural turfgrass.

These conditions led European developers to move towards simpler methods of retraction such as the bi-parting centrally located system. This arrangement does not favour the introduction of light and air into the cavea. This fact has forced the developer to consider ways and means of removing turfgrass from the cavea when it is not required to be there.

It has become recognised that the centrally located roof does have disadvantages except that of comparative structural simplicity. Other forms of retraction are now being considered. A graphical survey of the various forms of retraction is set out below.

---

[37] As described in text.

2.9.2. Retractable Roofs Built Between 1961 and 2000

The majority of these buildings covered by retractable roofs between these dates are theatres, swimming pools, tennis courts, ice rinks and small arenas providing the traditional locations for multi-use facilities. There are now an increasing number of stadia with retractable roofs have been developed or being developed for the various games of football or baseball. These are sited or to be sited in North America, Australia, Asia and Europe. A list of all significant retractable roofs built between 1961 and 2000 are set out in the schedule **Appendix 9.6.1.**

Stadia with retractable roofs that have relevance to this study are set out under **Table 2.6.2.** that list is abstracted from **Appendix 9.5.0.1.** Those with relevance have natural turfgrass arenas and may also include the facility to interchange surfaces from natural turfgrass to artificial turfgrass. Those stadia less relevant to the study because their arena surfaces are artificial are also included, this has been done to highlight the development trends there may be in this respect.

2.9.3. Retractable Roofs Relevant to this Study

Montreal Olympic Stadium, Quebec Canada.	1976	Multi- purpose stadium.
Skydome Canada. Toronto, Canada.	1989	Multi -purpose arena.
Amsterdam Arena, Amsterdam ,Netherlands.	1996	Multi-purpose Stadium.
The Millennium stadium , Cardiff, Wales UK	1998	Multi-purpose stadium.
Bank One Ball Park, Phoenix, Arizona, USA.	1998	Baseball stadium.
Millar Park stadium Milwaukee, Wisconsin, USA	1998	
Enron Field, houston Texas.	1999	
New Pacific Northwest Ballpark, Seattle, Washington, USA.	1999	
Gelredome, Arnhem, Netherlands , Europe.	1997	Football & multi-use Stadium.
Schalke 04 stadium , Gelsenkirchen, Germany, Europe.	1999	Football & Multi-use Stadium.
Pusan Dome, Pusan, Korea, asia.	1998	

2.6.3. Retractable Roof openings and Support strategies.

Section **2.6.2.** lists and illustrates the form of retractable roof stadia relevant to this study. The illustrations depict some of the strategies so far deployed in forming openings within them. The disposition of an opening may depend on a number of factors; the principal one ought to maximise the advantage for which a retractable roof has been incorporated. These purposes may vary, in Europe for example, where large stadia display the games of football, a retractable roof will be obligatory to endeavour to maintain in-situ turfgrass in a healthy condition within a stadium. In North America the primary decision to use a retractable roof may be in order to provide the choice between displaying an event in open or closed conditions. The display surfaces in North American stadia may be artificial with an option to change to natural grass. Where only artificial surfaces are provided there is no requirement for a retractable roof in a closed stadium unless it is to provide a choice of display conditions. There is a preference amongst American players of both Baseball and Football to return to turfgrass as a playing surface. So the North American practice for the inclusion of a retractable roof may follow the European criteria by taking into account the biological needs of natural turfgrass.

The current trend in North America is to maximise the openings in retractable roofs. This continues the three early North American examples of retractable roof stadia. This continuation may be in recognition of player preference, or to maximise open conditions in advantageous climatic circumstances. Nevertheless when such openings are provided artificial surfaces are incorporated, suggesting that artificial surfaces are preferred for multi-use activities. The advantages and disadvantages of maximising the size of the openings are considered in **(8.1.1.)**.

Of the three early North American examples of retractable roof stadia only the opening mechanism of the Skydome remained successful. The mechanism of the bogie movement system and the geometric development of the Skydome proved uneconomic and over burdened the running costs of the stadium.

John and Sheard, referring in part to the Skydome suggest "these designs may not be widely emulated" Rod Robbie, the principal designer of the Skydome, suggests that European architects, by adopting the principle of the centrally located retractable roof "have got it wrong".

The John and Sheard argument centres on cost. The Robbie argument is based on the centrally located retractable roof not being the best roof configuration for allowing light and air into a stadium.

The work of this thesis indicates that the centrally located retractable configuration is marginally less efficient in providing light and air over the turfgrass than is the traditional continuously cantilevered roof surrounding an arena. This is so, providing the residual free area, location and orientation of the roof are the same in both cases. Any centrally related opening is in principle not the most beneficial way of satisfying the biological needs of in situ natural turfgrass even if that opening provides acceptable standards of weather protection. The Millennium Stadium, Cardiff and ArenA Amsterdam through their turfgrass failures confirm this evidence.

When configuring openings in retractable roofs, support and movement strategies are parallel considerations. The movement strategy for example at the Skydome reduces the shadow masking because the roof movement takes place on a flat plane and the sections of the dome settle behind each other, leaving a free opening of 90% of the original roof area. The moveable sections of a centrally located retractable roof settle over the fixed part of the roof which is in line with its moving parts. The consequence of this is that the height of the structure is increased at the overlap and this may increase the masking of the sun from the playing surface.

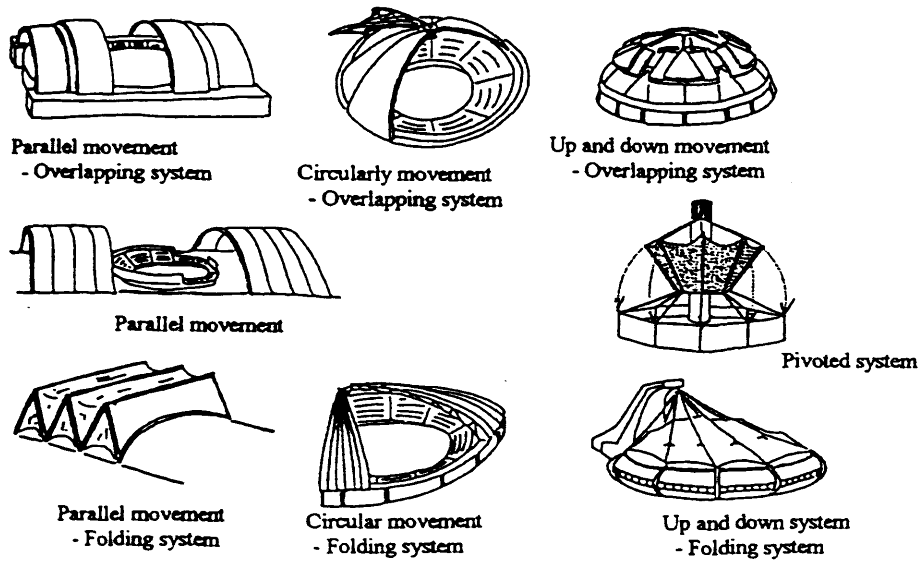
An arched roof structure will produce a shallower structural depth than flat beam construction over equal spans. Arched structures will however produce more shadowing on the playing surface because of the increased height they produce: this can be seen with the structural arrangement at ArenA Amsterdam.

The support for the centrally located retractable roof at the Millennium Stadium is provided on the long span by triangular beams; these in turn are supported on the short span by similar beams. At the junctions of these beams, their support is aided by three cable stays fixed to outwardly splayed steel columns set in each corner of the stadium. This arrangement produces a lighter roof structure, thereby reducing shadows.

A range of types of retractable roof openings is illustrated in **(Fig 2.6.3.).**

Fig 2.6.3.

Illustrates movement options available to effect roof retractions.[38]



The Movement strategies illustrated have in most cases been used in some form. The group does not show the centrally located Retractable Roof that form and variations of it based on material changes to areas surrounding the moving roof are illustrated in **Figs 7.3.5.4 - 7.3.5.7.**

CHAPTER TEN

2.10.0. NON-SPORTING USES.

2.10.1. Introduction.

Where European stadia, with or without a retractable roof, display games of Football they automatically will require the facility of a natural turfgrass playing surfaces. In some instances these surfaces may be removable; this facilitates multi-use activities. Turfgrass has a biological, environmental and horticultural dependency. Where these factors are not provided at optimum levels, turfgrass stress will be evident; this will be true of any location.

[38] Ishii, K, Edt. Structural Design of Retractable Roofs ,WIT Press, Boston, USA2000, page 5

between uses. If these requirements are ignored turfgrass wear will result. This will be true of any location not only that of a stadium.

The influence of the wear factor is made worse by the absence of controlled periods of rest. This chapter asks the fundamental question can natural turfgrass provide a suitable surface in stadia for non-sporting uses. The answer is they will not: but the experience is that commercial values usually take precedence over the needs of turfgrass maintenance.

2.10.2. Suitability of Football Stadia to display Non-Sporting Events.

With the exception of the Colosseum AD 80 and the Astrodome, (1965), the earlier generations of multi-use stadia or arenas bore little resemblance to the multi-use stadium being considered in this work. The spectator capacity of the original multi-use buildings did not exceed 20,000. They became part of the fabric of the downtown areas, as in the case of the Madison Square Gardens, New York, the Maple Leaf Gardens, Toronto, Canada and the Albert Hall, London.

Successful multi-use stadia demonstrated from the Colosseum onwards that their arena surfaces needed to be flexible in use, formed of materials that were not biologically dependent and easily re-configured. In contrast the central focus of football stadia will be their natural turfgrass arenas. So far these surfaces have not matched the needs of multi-use events in the critical sense. The problem with modern multi-use stadium does not only relate to the inappropriate turfgrass surface they can also fail to meet on the required quality of the ambience needed for some events.

Currently advantage is being taken of large stadia designed principally for football to display events, which is too large to display in the traditional multi-use buildings. In addition, they also display many events more suited to the smaller traditional multi-use buildings.

Despite the potential these venues have, at least two factors militate against the commercial potential:

- An arena surface is often inappropriate for an event being displayed.
- The cavea is often inappropriate for an event being displayed.

Non-sporting events differ in the demands they make on turfgrass. Many such events require the turfgrass to be covered to reduce compaction and wear. Covering turfgrass in the long term will destroy it. The contrasting requirements of most non-sporting events and the games of football do not easily fit together. Nevertheless, despite this, a multi-use stadium with in situ turfgrass endeavours to embrace both.

The list of multi-use events in stadia may include Pop and Classical Concerts, Conventions, Trade Displays, Speedway & Stock Car Racing, Informal Cricket, Tennis, Boxing etc and in some cases water sports. These events have to be programmed with the games of football the frequency of these games make event programming complex. Relief from these programming complexities can be provided by the rapid removal of turfgrass from a stadium or alternatively less advantageously frequently returfing the playing surface.

If turfgrass cannot be removed it may be protected with one of the several proprietary plastic covers these take the form of tiles or rolled sheets. The literature for some of these products claim they allow some light and ventilation to the turfgrass surface. However, there is no published research and their claims seem to lack a basic logic.

Nevertheless, covering grass allows safer access for spectator, circulation for light vehicles and distributes loads more evenly, thereby reducing surface compaction. For non-sporting uses, such as Pop Concerts, the turfgrass surface will be covered in part with a stage and audio towers weighing up to 100 tonnes spread over a small area. This equipment will be set up in front of between 8,000 and 10,000 spectators standing on the protected playing surface for perhaps up to 6 hours

Case Study 5.5.5 illustrates an example of a stadium where plastic covers are used for turfgrass protection during the display of some non-sporting uses.

The requirement to provide surface cover for trade shows, for example, will be longer. They may last for a number of days, excluding the time involved in setting them up and clearing the arena on completion. To these periods must be added the time to restore the playing surface.

The effective way to provide for non-sporting uses is to remove the turfgrass from a stadium in a single pallet because natural turfgrass is not an appropriate surface for multi-use activities.

INDEX PART THREE.

CHAPTER ONE.

3.1.0. INFLUENCES ON TURFGRASS DEVELOPMENT.

3.1.1. Turfgrass Growing Cycle.
3.1.2. Cool Season Grasses.
3.1.3. Establishing Cool Season Grasses.
3.1.4. Turfgrass Communities.
3.1.5. Relationship between Plants in Turfgrass Communities.
3.1.6. Seed Measures and Blends.

CHAPTER TWO.

3.2.0. IMPACT OF HEAT, LIGHT, AIR & CO_2 ON TURFGRASS GROWTH.

3.2.1. Influence of Temperature on Turfgrass Growth.
3.2.2. Temperature build-up and Heat Transfer.
3.2.3. Influence of the Microclimate.
3.2.4. Influence of Light Energy on Turfgrass Growth.
3.2.5. Spectral Influence on Turfgrass Growth.
3.2.6. Plant Physiological Responses to Light.
3.2.7. Influence of Wind on Turfgrass Growth.
3.2.8. Influence of Shading on Turfgrass Growth.

PART THREE.

CHAPTER ONE.

3.1.0. INFLUENCES ON TURFGRASS DEVELOPMENT.

This section examines the influences of temperature, light, air movement and carbon dioxide on the growth and maintenance of turfgrass communities. Additionally, it looks at the morphological and physiological responses of cool season turfgrass plants to these environmental influences.

> The turfgrass plant lives in a dynamic environment. Environment is the aggregate of all surrounding conditions influencing a grass plant or turfgrass community. The many atmospheric, soil, and biotic factors that combine to influence plant responses are known as the controls of turfgrass quality.[1]

The three botanical classifications for turfgrass plants: they are termed the C_3, C_4 and CAM plants. The broad differences between them are the ways they fix CO_2; these ways have evolved to suit the environments in which they have developed.

Turfgrass plants relevant to this study are the C_3 plants: these are classified as Cool Season Grasses. "In cool-season grasses, the photosynthetic process is in the Calvin or C_3 cycle under which initial products of C assimilation are 3-carbon acids, which are further used for the formation of carbohydrates (Cooper&Tainton1968)."[2] The photosynthetic processes are outlined in **appendix 9.4.1**. The C_4 plants are Warm Season Grasses; they will be referred to only where reference to them may be essential. In CAM category of plants "the mode of carbon fixation and water conservation has evolved in pineapples, many cacti and most succulent plants,"[3] and as such have no relevance at all to this study.

3.1.1. The Turfgrass Growing Cycle.

The biological growing cycle in grasses is completed.....

> when the fertilised flowers turn into fruits and the fruits germinate to begin the next generation. The fruits of grasses are usually called seeds or grains. The seeds are seldom scattered naked and are more usually what are known as false fruits, still with the florets attached to them, which is why grain seed needs to be winnowed. These

[1] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 179.
[2] Waddington, D, *et al* Ed, Turfgrass Agronomy 32, Madison, Wisconsin USA, 1992, page 269.
[3] Campbell,N,A, Mitchell, L,G, Reece,J,B, Biology Concepts and Connections. The Benjamin/Cummings, P.C. Inc 1994 Page120.

sections of the floret are often elaborate and are often referred to as dispersal mechanisms, but in fact they have more to do with the way in which the seeds come to rest on the ground preparatory to germination. The awns are conspicuous in this respect. In some grasses they form a long, feathery, flexible tail attached to the lemmas which clasp the seed. In this case the tail acts as a parachute, ensuring that the seed touches the ground first, and then revolves in the wind or squirms as dry and wet weather alternate, gradually driving the seed into the ground.[4]

3.1.2. Cool Season Grasses.

Cool season grasses have a temperature optimum of 15° to18° C. They are found in the cool temperate regions such as the British Isles, as well as in cool, humid, sub-humid climates and cool and semi-arid climates. C_4 grasses have a temperature optimum of 27° to 37°C.

Cool Season grasses can occur in temperatures set somewhere between the optimum requirements for both types of grass. The inference is that the success of both types of grass is dependent on the values of both the ground and air temperatures. However, besides these influences C_4 grasses are adapted to conserve water.

The influence of these values will differ within the species, cultivars and categories. How these and other factors affect growth and maintenance are considered for those turfgrass species used for sports grass in the UK.

Cool season grasses are propagated with seed: warm season grasses may alternatively be propagated vegetatively. Vegetative planting is reproduction by asexual means and is a response to high air and ground temperatures which would inflict high levels of mortality in planting with seed. In UK stadia vegetative planting is unlikely to be used except to establish ornamental and decorative grasses.

3.1.3. Establishing Cool Season Grasses.

Successful seed germination of cool season grasses is dependent on a range of factors including the composition and condition of the rootzone and the ground and air temperatures.

Adams and Gibbs put it simply

[4] Grounds, Roger, Ornamental Grasses, David and Charles, 1998, page15.

> Successful establishment from seed requires a moist but adequately aerated soil and a soil temperature above 10° C. Germination is slow at temperatures below 10° C and this slowness results in higher seedling mortality through attack by pathogenic fungi. ....Waterlogged anaerobic conditions can usually be avoided, but desiccation can occur on sandy soils. Rapid drying out of sand-dominant soils is a major hazard in the post winter recovery period. [5]

Other authorities agree but suggest that germination can take place at temperatures of 5°C or even lower, but the time taken to do so is considerably increased and so presumably is seed mortality.

Beard expands the discussion suggesting

> that the optimum temperature varies with seed age, seed source, cultivar, seed lot, and duration of the germination period. Fescue seed germinates over a wider temperature range as it ages. The optimum germination temperatures of certain species may not involve a specific temperature, but a rhythmic alternation of temperatures..... Germination of freshly harvested seed of certain species is stimulated by 8 weeks pre-chilling. The maximum and minimum temperatures are poorly defined because of the extreme slowness of germination, especially for the minimum.[6]

Langer reports that at a later stage in the development of grasses

> Even in perennial ryegrass *(Lolium perenne)* leaves do not appear appreciably faster at 25°C than at 18°C and indeed a range of 18°C to29° C has been found optimal in other experiments. Several other temperate grass species have similar temperature optima, but subtropical species respond to still warmer conditions. Thus paspalum *(Paspalum dilatatum)* produces leaves most rapidly between 29°C and 33°C but at low temperatures it is inferior to perennial ryegrass. We can use this kind of result to predict the climatic requirements of a species and where it is most likely to grow successfully. Another point which arises from these differences between species is the possibility that the plant breeder may be able to select grasses with rapid rates of leaf production."[7]

Cool season grass swards are usually established from more than one turfgrass species or cultivar. The mixes of the seeds representing the species are proportioned in measure with

---

[5] Adams,W&Gibbs R, Natural Turf for Sport &Amenity. Science and Practice, CAB International,1994 Page 45.

[6] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 225.

[7] Langer R.H.M. How Grasses Grow, 2nd Ed. Edward Arnold, London, 1979, Page 11.

the aim of meeting both the aesthetic and utilitarian requirements of a sward. The aim in choosing the mix would be to meet these standards by producing the best wear tolerance in a high tillering, dense, short, slow growing sward. Additionally, the aim would be to produce a turfgrass which would resist diseases like Helminthosporium and Fusarium. The probability is that such diseases may be encouraged in closed stadia. The desired qualities may not be unique to a single species or cultivar; this is why species are combined. But there are other reasons for establishing a combination of sward mixes, such as the influence of turfgrass communities. The interaction between turfgrass communities is explored later. Establishing turfgrasses is a complex issue: it begins with the choice of a seed mix but extends beyond it.

The proportional balance incorporated in a turfgrass mix will include dominant and sub-dominant species. The composition of a mix will be established through interpreting research data drawn from field trials of polystand communities and data drawn from trials of individual species and cultivars. Reports setting out the data are available from independent organisations such as the Sports Turf Research Institute. (S.T.R.I,) England, UK, Institute of Grassland and Environmental Research, (I.G.E.R,) Wales, UK, R.A.G.T, Semences, France, Europe and Zelder the Netherlands, Europe.

The aim of species selection is to choose species that will yield the required performance characteristics and standards of a turfgrass surface set in a specific environment. The species will be chosen from data collected at field trials. The information yielded from the trials will provide only an indication of the general behavioural pattern of the species under the use and environmental conditions set up in the trials. The conditions under which 'trials' are carried out will not generally be those encountered in a stadium with or without a retractable roof.

It is left to the horticulturist to make intuitive connections between the established data and the anticipated conditions within a stadium with a retractable roof. A more accurate assessment may be made by the construction of a one-quarter scale mock-up of a stadium to replicate an environment which would match as nearly as possible that of the full size stadium. It would also be possible to simulate to a degree the impact of wear on the turf.

3.1.4. Turfgrass Communities.

Beard defines a turfgrass community as "an aggregation of individual turfgrass plants that have mutual relationships with the environment as well as among the individual plants."[8] He further describes two broad classifications of turfgrass associations within communities: monostand, those composed of one cultivar and polystand communities composed of turfgrass plants of two or more cultivars and /or species. Polystand communities will be those encountered in the turfgrasses of stadia playing areas.

3.1.5. Relationship of Plants in Turfgrass Communities.

The individual turfgrass plant in polystand communities lives in close association with other plants that may or may not be of the same genus, species or cultivar. Each group of plants will have its own minimum horticultural, botanical and biological survival requirements. Competition is set up between the plants when there is a resource deficit; the degree of the competition depends on the extent of the deficit.

> Competition occurs between biotypes of similar genetic constitution or between different cultivars, species, or genera. Competition may involve the mechanical crowding out of a weaker cultivar or species by a stronger cultivar or species that is more vigorous in growth rate, particularly in the rate of vertical leaf extension. The germination rate and seedling vigour is a major factor influencing the competitive ability of a cultivar during turfgrass establishment. The quantity of carbohydrate reserves in the seed varies greatly among species and affects the seedling vigour.[9]

Examples of competition in turfgrass communities can clearly be seen in any uncontrolled area. In these areas species with deeper rooting systems may, for example, draw on a larger volume of what may be a limited supply of water or nutrients compared to neighbouring species. These advantages allow plants to become dominant. Once dominance is established, in an uncontrolled situation the condition will increase. The dominance will be increased by greater shoot and leaf growth, with the consequent increase in leaf light utilisation factor. The successful root system of the dominant plant also has the benefit of larger quantities of carbohydrates for continued root growth.

---

[8] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 166

[9] Ibid Page 165.

Polystands are selected for a number of reasons, principally to combine the individual genetic characteristics of species and cultivars. When mixed together a polystand may provide the qualities required in a playing surface set in a particular environment. Polystand selections should be made up of plants which form deep-rooting systems and are as near as possible equally vigorous to ensure, as far as it is possible, surface stability, which is an essential requirement for stadium turfgrass. There will be a tendency for a dominant species to emerge in a polystand but that dominance can be controlled by leaf defoliation. The success of defoliation depends on the length and the frequency of the cut.

Clearly, controlling turfgrass competition is a broader issue than just defoliating. Other essentials required are a balanced fertility regime, the control of rootzone water, awareness of pest infestation and a prescribed method of control treatment when infestation does occur. A polystand should also produce a consistent colour match, colour retention and a consistent turfgrass texture. To provide these qualities plants should produce similar " leaf textures, growth habit, colour, shoot density, and vertical growth rate." [10]

A stadium will produce significant patterns of light and shade, contributing to differing turfgrass microenvironments. Such areas may need different fertility regimes, pest control measures and changes in a seed mix composition. Therefore, a polystand specifier must understand the genetic structure of each species used in a mix to be aware of the contributory characteristics they bring to a sward and how environmental conditions impact on those characteristics.

3.1.6. Seed Measures and Blends.

A polystand provides a wide range of genetic characteristics, the extent and variation of which, as yet, are not available in a monostand. Data defining characteristics of species and cultivars seeds are available from a supplier's catalogues. The horticulturist will decide the proportion and composition of the polystand. Beard suggests that 'blending' is common in cool season grasses and consists of two or three grasses. But the evidence is that in the UK it is not uncommon for blends of stadium grasses to consist four species or cultivars.

The species within a polystand exert a competitive influence for available light and air. It is difficult to determine these interactions except by experiment. The degree of this influence may fluctuate during the life of a plant. If undesirable domination occurs, adjustments can

[10] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page171.

be made to the proportion or composition of a turfgrass mix; but the problem may be in maintaining the original polystand characteristics.

The surface cover rate at which a seed mix is sown and the methods of sowing are important influences on the establishment of a vigorous turfgrass sward.

Beard *et al* points out the proportional mix of a polystand is influenced by the size and weight of a seed and goes on to say

> The competitive ability of a single species in a mixture is best evaluated on the seed number rather than on a weight basis. Seed mixtures are usually prepared and sold on a weight basis. This may be misleading owing to the large variation in seed size and weight among the turfgrass species.[11]

Table 3.1.6.

Approximate Number of Seeds Per Pound and Normal Seeding Rates for Selected Species.

Turfgrass species.	*Approximate no of seeds per lb.*	*Normal Seeding Rates.*	
		lb per 1000 sq ft.	*no of seeds per sq in.*
Bentgrass:			
Creeping.	7, 890,000.	0.5-1	27-55.
Velvet.	11, 800,000.	0.5-1	41-81.
Fescue:			
chewing	546,000.	3.5-4.5.	13-17.
meadow.	227,000.	7-9	11-14.
red.	546,000.	3.5-4.5.	13-17.
sheep.	530,000.	3.5-4.5.	13-16.
Tall	227,000.	7-9	11-14.
Redtop.	4,990,000.	0.5-1.	17-34.
Ryegrass:			
italian.	227,000.	7-9.	11-14.
perennial.	227,000.	7-9.	11-14.
Timothy.	1,134,000.	1-2.	8-16.

CHAPTER TWO.

3.2.0. IMPACT OF HEAT, LIGHT, AIR MOVEMENT & CO_2 ON TURFGRASS.

Turfgrass leaf appearance and growth is influenced by a number of other factors besides temperature: light intensity, the length of the photoperiod ,the influence of air movement on

[11] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page170.

the opening and closing of the stoma and the consequences of the Carbon Dioxide (CO_2) exchange. These factors all play interwoven roles in turfgrass development. This section covers in outline the role heat, light, wind and carbon dioxide have on turfgrass development.

3.2.1. Influence of Temperature on Turfgrass Growth.

The contents of the following paragraph by Beard serves as a concise introduction to the influence temperature has on turfgrass growth and development.

> The germination, growth and development of turfgrasses are restricted to a specific temperature range. This range can vary considerably among turfgrass species, cultivars and individual plants. Turfgrass pests, including diseases, insects, nematodes and weeds have a temperature response range. As temperatures are increased or decreased from the optimum range, growth is proportionally reduced until it ceases. Death occurs due to the destruction of the protoplasm if the turfgrass plant is subjected to a further increase or decrease in temperature. There is relatively little biological activity above 125° F or below 32° F. Turfgrass growth is usually confined to a temperature range of 40°F to105°F. Temperature regimes within this range are a major factor influencing the adaptation of turfgrasses. This temperature effect is most obvious in the latitudinal distribution of turfgrass species.[12]

3.2.2. Temperature Build-up and Heat Transfer.

The temperature of a turfgrass plant is ultimately determined by the difference between the relative heat it gains and then loses. Heat is gained by the transfer of solar radiation and through the transfer of thermal radiation from the surrounding ground. Heat losses occur mainly through evapotranspiration, re-radiation, conduction and convection. Without these actions turfgrass plants would suffer lethal distress. The residual energy within the plant not only affects a plant's specific heat balance but also the turf temperature. Turfgrass temperatures are linked to climatic changes between the latitudes. Additionally, variations in altitude, time of the year, time of the day and the degree of the masking of solar radiation also make significant temperature differences.

[12] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 209.

In the case of a stadium, with a centrally located retractable roof, sited at European latitudes, the degree of solar radiation masking or its absence, will cause significant differences, at certain times of the day and of the year, in the levels of turfgrass temperatures. **Sections 4.7.0.1 to 4.7.0.9** set out the solar radiation masking patterns for a range of options for openings in retractable roofs. The masking patterns show clearly the possibility that temperature variation can exist across a playing surface through the intervention of a superstructure on incoming solar radiation. Such interventions can have a significant impact on limiting growth and increasing the need for maintenance of turfgrass, and reducing resistance to wear.

Air temperatures within stadia will be significantly increased by heat re-radiated from superstructures; most of that heat will be retained in the stadium, depending on the configuration of a retractable roof. An additional contributory factor to air temperature will be the heat transfer from spectators to the air volume of a stadium. There will, on occasions, be 60,000 and 70,000 spectators in the stadium, each of whom will in theory emit a third of a kilowatt of heat, totalling a transfer load of 20,000 to 23,333 kilowatts per hour. Raised air temperature will increase evapotranspiration rates.

In arriving at a temperature model for stadium turfgrass, factors other than those referred to have to be considered. They include site context and how that context might impose solar masking, increasing or overriding the masking imposed by a stadium superstructure.

Stadium temperatures have to be at levels appropriate to support turfgrass and spectator comfort. These needs may be best met by the introduction of forced ventilation and/or passive ventilation. Without such measures, when roofs are closed, air temperatures within stadia will significantly rise above outside temperatures. This will be so, irrespective of the roof configuration. The contributory factors to this increase will be the heat re-radiated from the superstructure, and significantly the transfer of body heat from spectators to the air volume of a stadium.

The higher the stadium temperature, the higher the rate of evapotranspiration and with that the need to compensate for vapour loss by adjusting the rootzone water balance through controlled irrigation. An increase in evapotranspiration together with perspiration emitted from spectators will increase humidity levels. With the roof closed the humidity levels can only be controlled by the introduction of adequate levels of tempered ventilation. The levels of ventilation can be determined by taking into account the total environmental conditions in a stadium.

3.2.3. Influence of the Microenvironment.

The turfgrass microenvironment is located within the rootzone; this is active within the depth formed between the root tips and the turfgrass surface. The involvement of the interchanges between energy, gas and water takes place within this depth. These factors have interdependent influences on each other to optimise their biological benefits.

The depth of the zone of activity will vary, depending on the intensity of the root activity and the vigour of a species. The microenvironmental zone in a community may therefore vary in depth.

A stadium polystand should provide, amongst other things, roots that are sufficiently deep to resist being 'kicked out' by users. Therefore the minimum physical function of a root system is to avoid this.

The literature suggests depths for the rootzone between 200mm and 400mm. However, when roofs are closed, the evidence is that the depth of the rootzone should be determined by the use of the sward and by the species incorporated in the sward. The rootzone should have sufficient depth to allow root development and migration, a soil sink of adequate capacity and additionally, space for a drainage zone providing falls. The lower figure of 200mm would be appropriate for decorative lawns but unsatisfactory for a stadium playing surface under a retractable roof because of the horticultural and playing requirements. It may, for example, be necessary to verti dig to a depth of 200mm to increase soil aeration. A rootzone of at least 400 mm provides a more flexible depth for a stadium playing surface. This depth was used at Ajax ArenA, Amsterdam.

The space between the turfgrass surface and an imaginary line set six feet above a turfgrass surface is termed the macroenvironment: this zone is set at five feet in North America. Most weather station temperature measurements are recorded at the edge of either of these two zones. "The macroenvironment is representative of the overall climate and has a considerable influence on the turfgrass microenvironment".[13]

---

[13] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page179.

Pronounced vertical temperature gradients occur within both the macroenvironmental and the microenvironmental zones. Beard indicates, for example, that in the macroenvironmental zone, a temperature of 125°F, recorded at turfgrass level will decrease to 95°F, five feet above that level. The decrease is due to a decline in effective heating by re-radiation and accumulated conduction as well as increased air turbulence.

Maximum diurnal temperatures usually occur just below the surface of dense, close cut turfs, because this is the region of radiation absorption that results in heat. The air and soil adjacent to the turf are warmed by conduction. The heat contained in the adjacent air layer is then transferred by convection to layers further above the turfgrass surface.

Heat energy is lost by long wave re-radiation from the turfgrass surface but between sunrise and mid-afternoon the loss is more than compensated for by incoming solar radiation. At night and in the late afternoon a major portion of the heat is lost through long wave re-radiation. The surface of the turf is cooled and the temperature of the adjacent air is lowered by conduction. An inversion results with the adjacent air layers being cooler than the upper and more distant layers.

Natural soil warming occurs by conduction that restricts the depth of heating and causes a substantial lag in temperatures. The rootzone soil temperature lag increases with depth. The vertical soil temperature gradient reverses and adjusts according to the seasons of the year.

Beard suggests- "the complex nature of the microenvironment is not fully understood" and continues as follows, "the environmental factors influencing turfgrass growth and development can be classified into three major groups: Climatic (light, temperature, water and air.) Edaphic (soil related) and Biotic (imposed Cultural practices)."[14]

These influences are considered in some detail in the following sections.

3.2.4. Influence of Light energy on Turfgrass Growth.

"Mowed turfs are capable of absorbing and converting to chemical energy only 1% to 2% of the total incident radiation"[15]. A major portion of the incident radiation is absorbed, then re-radiated at longer wavelengths. The release of this heat significantly affects turfgrass

[14] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page180.

[15] Beard, J, Ibid, Page181.

temperatures. The proper utilisation of light can only take place when the supply within the microenvironment of water, temperature, nutrients and carbon dioxide are not limiting.

Beard also suggests that

> Maximum light absorption by turfgrass leaves is vital since a majority of the photosynthetically active leaf area is removed by mowing. Incident radiation can be absorbed, reflected, or transmitted. Light transmission through turfgrass leaves varies from 15%to30%. The relative degree of light absorption and reflection is affected by the orientation of the leaf surface to incident radiation. On a diurnal basis, light penetration into a turfgrass canopy is highest on or at mid-day. The amount of light absorption decreases as the angle between the incident radiation and the leaf surface decreases.[16]

Cultural practices are designed to enhance dense, vertical leaf growth for high turfgrass quality. But upright leaf orientation is not particularly favourable for light absorption as only the uppermost leaves in a community are fully exposed to the incident solar radiation. But light absorption occurs on both sides of a leaf; a significant amount of reflected light is absorbed by the lower leaf surface with a vertical geometry.

Leaves with semi-vertical orientation are subjected to considerable light intensity variations along their length. Where leaves are glossy or young they reflect a higher percentage of incident radiation than old leaves. The amount of reflection is generally higher at low altitudes of the sun near sunrise and sunset. This point has significance in a stadium with a retractable roof.

Other factors involving light absorption include leaf surface geometry, shading due to interleaf orientation, pubescence, leaf thickness, the nature and distribution of leaf pigments and the number and orientation of the leaf chloroplasts.

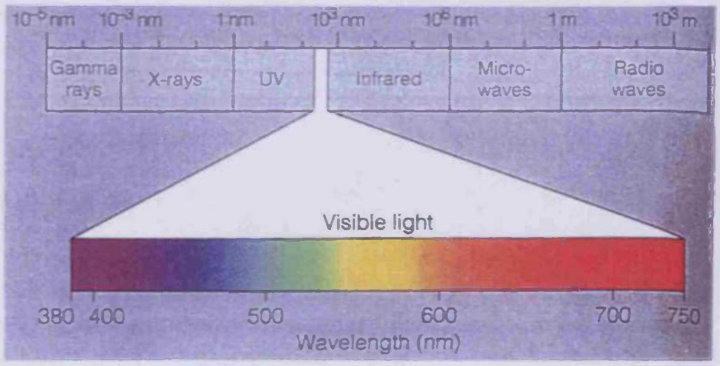
3.2.5. Spectral Influences on Turfgrass Growth.

The electromagnetic spectrum is represented by wavelengths ranging from 10^{-5}nm to 10^{3}m.. Visible light forms only a small fraction of the overall spectrum and falls

[16] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page182.

between the wavelengths of 380nm and 750 nm. Visible light is located at the lower end of the visible band, adjacent to ultra violet light (UV) and at the upper end, adjacent to infrared light. Colours within the visible band range from violet, blue and green at the lower end. Yellow is located approximately in its middle, with orange to red at the upper end of the band.

Fig 3.2.5. The Electromagnetic Spectrum.



The violet, blue, ultraviolet (UV) regions are the most important in influencing anthocyanin synthesis and phototropic responses. The violet and blue wavelengths produce a short, sturdy growth, whilst the yellow to red sections enhance shoot elongation and spindly growth. Wavelengths between "The 630 nm and 780 nm are important in promoting or inhibiting flowering, stem elongation, seed germination, leaf enlargement, rhizome development and other photomorphogenic plant responses. A photoreversible pigment called phytochrome is involved"[17].

The indications are that when turfgrasses are grown under the blue and green wavelengths their performance is more vigorous than when grown under the red end of the visible spectrum. Beard indicates the unfolding of grass leaves is promoted by red light of 660nm and inhibited by 710 nm. Mesocotyl elongation of tall fescue and sheep fescue is inhibited a thousand times more by red light (624nm) than by blue light (436nm). Light quality is also a factor in the sporulation of certain turfgrass diseases. For example, low intensity UV wavelengths of 265nm to 325 nm stimulate sporulation of Typhula blight.

It is important to note that there are diurnal and seasonal differences in light intensity. The angle of incidence of the sun's rays to the surface is less at dawn and dusk and consequently

[17] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Pages 182-183.

the proportion of orange and red wavelengths increases at dawn and dusk, while the violet and blue wavelengths decrease. The longer, infrared wavelengths are significant owing to their heating properties. The longer the wavelength, the greater the heating effect. The higher moisture content in the atmosphere will result in an increased absorption of the red and near infrared wavelengths.

Only 50% of the light falling on turfgrass is actively useful for the purposes of the photosynthetic process see section **7.5.0.1.**

Beard further indicates:

> The seasonal and diurnal variations in light quality do not cause any major changes in turfgrass growth when turfgrass is grown in full sunlight. One reason for this is that most plant responses have a degree of sensitivity to all visible wavelengths, to all wavelengths in the visible spectrum. Also, the wavelength variations are small in relation to the total daily radiation.[18]

The literature also indicates the influence of the light quality on turfs growing in full sunlight is not as significant as is the intensity or duration of the light. Turfgrass species should adapt and proliferate through natural selection in the day lengths of a region.

The composition of a polystand should consist of species or cultivars native to the region in which a sward is located. Many species exhibit sensitivity to day length that determines whether the plant continues vegetative growth or produces a flowering response. **(Table 3.2.5**

Vegetative growth is desired in normal turfgrass culture as seed head development disrupts turfgrass uniformity, increases the mowing difficulty and impairs the smoothness of turfgrass.

Flower induction of many cool season perennial turfgrasses occurs during the short, cool days of autumn. The general light and temperature requirements for maximum floral induction of eighteen turfgrasses are presented in **Table 3.2.6.**

---

[18] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 183.

Table 3.2.5.
Environmental Requisites for the Maximum Floral Induction of Fifteen Turfgrasses

Turfgrass	**Scientific Name**	**Photoperiod**	**Temp***
Annual bluegrass	**Poa annua**	Short**	Cool
Bulbous bluegrass	*Poa bulbosa*	Long	Cool
Canada bluegrass	*Poa compressa*	Long	Cool
Colonial bentgrass	*Agrostis tenuis*	Short	Cool
Creeping bentgrass	*Agrostis palustris*	Short	Cool
Fairway wheatgrass	*Agropyron cristatum*	Short	Cool
Kentucky bluegrass	*Poa pratensis*	Short	Cool
Meadow fescue	*Festuca elatior*	Short	Cool
Perennial ryegrass	*Lolium perenne*	Short	Cool
Red fescue	*Festuca rubra*	Short	Cool
Redtop	*Agrostis alba*	Short	Cool
Rough bluegrass	*Poa trivialis*	Short	Cool
Sheep fescue	*Festuca ovina*	Short	Cool
Tall fescue	*Festuca arundinacea*	Short	Cool
Velvet bentgrass	*Agrostis canina*	Short	Cool

* "Cool" temperatures are from 40 to 50° F.
** Species are capable of flowering over a wide range of photoperiods.

Table adjusted from Page 184 Turfgrass Science and Culture[19].

Table 3.2.6.
The Effects of 8 and 16 hour Day Lengths on the Growth Characteristics of Merion Kentucky Bluegrass (Expressed as the Average of 20 Plants per Light Treatment).

Plant Characteristic	Photoperiod, hr	
	8 hr	16hr
Leaf length, mm	86	220
Leaf width, mm	2.8	3.2
Number of shoots per plant	21	16
Total dry weight of shoots per plant, g	3.6	5.2
Number of rhizomes per plant	1.3	1.1
Total dry weight of roots and rhizomes per plant, g	1.7	1.9
Leaf growth habit, degrees to horizontal	47	75
Succulence % water	70	65

1.Increased shoot density (59, 60, 120, 152).
2.Increased tillering (87, 107, 114, 115, 128, 144, 149).
3.Increased leaf appearance rate (107, 128, 144).
4.Reduced leaf and shoot length (54, 60, 107, 114, 120, 128, 134, 139, 142, 144, 152, 164).

Table take from Page 185 Turfgrass Science and Culture[20].

[19] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 184.
[20] Ibid.

Short day plants require day lengths of 12hr or less, while long day plants require more than 12 hr. Some cool season, perennial turfgrasses remain vegetative owing to a short day requirement. But long day lengths favour floral development.

> Temperature interacts with the photoperiod in inducing flowering. Cool temperatures can greatly alter or even replace the photoperiod requirement of certain turfgrasses. Temperatures of 32° to 40°F can substitute for the short day photoperiod requirement of perennial ryegrass and tall fescue.[21]

The growth habit of turfgrasses is affected by day length. Beard *et al* reports some "typical responses of turfgrasses grown under short day lengths are 1) Increased shoot density. 2) Increased tillering. 3) Increased leaf appearance. 4) Reduced leaf and shoot length. 5) Reduced internode length. 6) A prostrate growth habit with individual plants frequently growing in a rosette shape".[22]

The night illumination of sports turf in stadia for the purpose of play prolongs the photoperiod. The illumination level set for the UK Premier Football League " is an average lux value of at least 800 with a minimum lux value of 500 at any location on the pitch"[23]. Turfgrass responses to night lighting are primarily developmental in nature rather than growth orientated.

> A longer day length results in more radiant energy available for absorption and utilisation in photosynthesis. Turfgrass plants grown under long days have a higher carbohydrate level and generally exhibit greater shoot growth than when grown under short days at the same temperature. Physiologically there is a shift to lower soluble nitrogen and amide contents under long day lengths.[24]

> The light intensity varies greatly depending on (a) the season of year, (b) latitude, (c) time of day, (d) degree of atmospheric screening, and (e) topography of a region. Light intensities are highest during the summer season and decrease with increasing latitude. The diurnal variation in light intensity is characterised by a broad curve with a minimum level at sunrise and sunset, increasing to a maximum at midday. Light intensities on a clear day in temperate regions are commonly around 1·5 cal per cm^2

[21] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page183.
[22] Ibid Page 186.
[23] The F.A. Premier Handbook, Section 1, Rule, 25,The FA Premier League Ltd, London, 2004, Page, 52.
[24] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page186.

per min (10,000 lumens). Maximum light intensities of 1·8 to 2·0 cal per cm^2 per min have been reported.[25]

"Atmospheric pollutants such as smoke and dust or smog will screen incoming solar radiation. Cloud cover will reduce incoming radiation by up to 96%. This degree of screening can significantly reduce the photosynthetic rate".[26]

Turfgrasses growing on locations positioned normal to the incident radiation receive the highest intensities. Stadia located in the higher regions of the UK are subject to higher light intensities since the intensity increases proportionally with altitude.

Beard also points out that a vertical light intensity gradient exists within the turfgrass canopy, which is affected by the cutting height and shoot density. The highest light intensity occurs at the top of a turfgrass stand. "A large decrease in light intensity occurs over a short vertical distance downward through the turfgrass canopy. A minimal amount of light actually reaches the soil surface in dense turfs. The percentage penetration of light into the turfgrass canopy is greater during periods of water stress when the upper leaves are rolled or folded."[27]

Photosynthesis exceeds respiration by a large margin under non-stressful growing conditions. Carbohydrate reserves are utilised for respiration in darkness and at light intensities below the compensation point.

Carbohydrate reserves of a turfgrass plant can become exhausted during extended periods of light intensities below the compensation point: for most turfgrasses that point is between 2% and 5% of full sunlight. "The consequences of exhaustion are decline in plant vigour, recuperative potential, and turfgrass quality..... Leaves continuously exposed to light intensities below the compensation point are likely to die or must obtain carbohydrates by translocation from other plant parts."[28]

Light intensities above the compensation point are required for growth to occur without utilisation of the carbohydrate reserves. The maximum photosynthetic rate of individual

---

[25] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973. Page 187.
[26] Ibid Page187.
[27] Ibid Page 187.
[28] Ibid Page 188.

turfgrass leaves occurs at light intensities about one-third of full sunlight. Most leaves within the turfgrass community are not orientated perpendicular to the incoming radiation. As a result, very high light intensities are required to reach light saturation. Light saturation of Bermuda grass turfs cut daily at 1" and 2" does not occur at intensities less than 1·0 cal per cm^2 per min. Light saturation occurred at 0·75 cal per cm^2 per min when turfgrass was cut daily at 8". Light saturation at the 8" cutting height resulted primarily from less interleaf interference to the incident radiation. There was no difference in the leaf area index at the 2" and 8" cutting heights. The 2" cut had vertically oriented leaves, while the 1" cut had many short, overlapping leaf stubs. Thus, a large increase in the incident light intensity is required for even a small increase in absorption by individual leaves. Light saturation of close cut turfs occurs infrequently, if at all, because of the leaf orientation and shading.

The light intensity impinging on a leaf is not necessarily constant. Large, rapid variations in light intensity may occur owing to the passing of clouds or the movement of tree leaves caused by wind. The photosynthetic process responds quite rapidly to such changes in light intensity.

Increased net assimilation at higher light intensities results in greater leaf, stem, rhizome, stolon and root growth. A higher root-shoot ratio indicates that the root system is more responsive to increased light intensities than the shoots. The shoots utilise the limited carbohydrate reserves at the expense of the root system at low light intensities. A positive factor affecting the carbohydrate reserves is the reduced respiration rate at low light intensities.[29]

3.2.6. Plant Physiological Responses to Light

Beard records that plants grown at long light intensities exhibit distinct physiological responses. In this discussion a light intensity of less than 0.4 cal per cm^2 per min is considered low. Typical physiological changes observed in plants grown under low light intensities are

1 Higher chlorophyll content.

2 Lower respiration rate.

3 Lower compensation point.

4 Lower carbohydrate reserve.

5 Lower carbohydrate-to-nitrogen ratio.

6 Reduced transpiration rate.

7 Higher tissue moisture content.
8 Lower osmotic pressure.

> Light is necessary for the production of chlorophyll. A relatively low light intensity is sufficient to stimulate chlorophyll synthesis. High light intensities increase the rate of chlorophyll breakdown and cause a decrease in the chlorophyll content of leaves. The chlorophyll content increases with decreasing light intensity. The maximum chlorophyll content occurs at a relatively low light intensity with any further decrease in intensity causing a reduction in chlorophyll content.[30]

"Light also stimulates the stomata guard cells to open. High light intensities are usually associated with high transpiration rates. Other plant water relations affected by low light intensities include increased succulence and a lower cellular osmotic pressure".[31]

> The lower carbohydrate-to-nitrogen ratio at reduced light intensities is attributable primarily to a decreased carbohydrate level. The total nitrogen level, especially the nitrate component, increases at low light intensities, while the protein content declines. High light intensities result in increased carbohydrate reserves, assuming other factors are not limiting. The respiration rate tends to decrease at lower light intensities.[32]

Heat and moisture stress are frequently associated with high light intensities. Beard suggests that it is difficult to determine whether the morphological responses are the direct result of a low light intensity or are due to a combination of light, heat, and moisture effects. Numerous morphological changes occur at reduced light intensities. He goes on to suggest the following responses are observed:

1. Thinner leaves with less weight per unit area.
2. Reduced leaf width.
3. Increased leaf length and plant height.
4. Reduced shoot density.
5. Longer internodes.
6. Reduced tillering.
7. Reduced stem diameter.

---

[29] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Pages188-189.
[30] Ibid Pages189-190
[31] Ibid Page 190.
[32] Ibid Page 190.

8. Reduced appearance rate of successive leaves on the stem.
9. More upright growth habit.

"The leaf structure is modified by the light intensity under which it is grown. Specific effects of a high light intensity include (a) thicker cell walls, (b) more fully developed supporting tissues and vascular system, (c) a thicker cutin layer".[33]

"The thinner, more delicate structure of leaves grown at low light intensities is advantageous since the light absorption capability is increased. However, the delicate, poorly developed structure and increased succulence also result in reduced wear, disease, heat, drought and cold tolerance."[34]

Increased shoot elongation, poorly differentiated tissues, widely spaced internodes and reduced leaf number occur in darkness or at minimal light intensities......The inhibition of tiller, shoot and rhizome development at low light intensities is related to the total quantity of light energy available for photosynthesis. The longer leaves internodes quantity of light energy and overall plant height are due to an increase in cell elongation that commonly occurs at low light intensities.

> It is hypothesised that light controls the direction of stem growth by increasing or decreasing the relative strength of the positive geotropic response. The light stimulus for controlling the positive geotropic response can be transmitted to stolons growing in the dark. The more upright growth of shaded turfgrasses results in a greater percentage of the plant being removed during mowing. The reduced leaf area results in weaker, more open turf having a slow establishment rate. Turfgrass development and form can show distinct changes within 4 to7 days after exposure to reduced light intensities.
>
> Leaf orientation and movement are due to the influence of light on auxin synthesis and degradation. Leaves tend to orient perpendicular to the incident light. The auxin level is greater on the shaded side when the stem of a leaf is exposed to light from only one side. The net result is stimulation of cell elongation on the shaded side that causes the

[33] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page190.
[34] Ibid Page 191.

stem or leaf to turn toward the light. Phototropic responses are limited under modern turfgrass culture.[35]

Turfs can be extensively damaged by total light exclusion for an extended period. Light exclusion can result from artefacts placed on the turfgrass, or by clippings not being removed after defoliation of turfgrass or by certain fungal organisms such as slime mould. "The accumulation of plasmodium on the leaf surface can become large enough to exclude light."[36]

Light exclusion from turfgrass causes it to turn from a yellowish colour and then to a whitish colour, as a result of a loss of chlorophyll. The shading of turfgrass plants causes their leaves and stems to become etiolated.

> The turf is capable of recovering quickly if the object or cover is removed soon enough. The above ground tissues are killed if light is excluded for a sufficient length of time. Rhizomatous turfgrasses whose shoots are killed by light exclusion are capable of recovery from the underground nodes, while bunch-type turfgrasses lack the recuperative capability.[37]

The duration of light exclusion that results in death of a plant will vary with temperature and the physiological state of the turfgrass plant. Succulent tissues are more quickly injured by light exclusion, especially at higher temperatures. Light exclusion may also enhance disease development.

Light competition is quite critical during turfgrass establishment. The rate of germination and vertical leaf extension are key factors affecting light competition during establishment. Also of importance is the inclination of the first leaf initials produced.

The order of the species competition is positively correlated with the germination rate. Seedling vigour of certain ryegrass cultivars results in excessive light competition and with subsequent failure of weaker species. The intensity of culture following establishment tends to mask the effects of light competition among turfgrass species. However, a degree of light competition always exists, even within a monostand. The growth habit and the ability to

---

[35] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973,. Page 191.
[36] Ibid Page 192.
[37] Ibid Page 192. .

compete are important factors in the succession of turfgrass communities. Certain prostrate growing perennials such as bentgrass and bermudagrass have a more favourable leaf orientation for light absorption. The ability of bentgrass and bermudagrass to invade other turfgrass species is due, in part, to a greater capability to compete for light. Many common weeds have a prostrate growth habit and leaf orientation that favours competitive light absorption within a turfgrass community. The very low light intensity at the soil surface of dense turfs may be inadequate for the growth of weed seedlings. A high leaf area index results in greater competition for the available light and is important in weed suppression within a turfgrass community.

Excessively high seeding rates result in weak, spindly growth of individual plants within the turfgrass community. Severe competition for light between individual plants is a key factor, causing the weak, immature growth habit. On the other hand sub-optimal seeding rates result in a high light intensity at the soil surface that encourages the germination and development of weedy species.

Shading is the result of interception of direct solar radiation. Such interventions, where drastic, involve the alteration of a number of environmental factors other than the reduction in lighting intensity. Some other relevant factors associated with large compact stadia, influenced by shading which promote difficulties in turfgrass culture are:

Moderation of Extremes in Diurnal and Seasonal Temperatures.
Restricted Wind Movement.
Increased Relative Humidity.
Increased Carbon Dioxide Level. [38]

A superstructure can screen out a significant portion of the incident radiation, resulting in reduced temperatures in and adjacent to the turf. Also, the superstructure restricts the nocturnal cooling process by inhibiting the loss of heat as outgoing long wave radiation. The net effect is a moderation of extremes in air and soil temperature. Water transpired from the turfgrass leaves increases the relative humidity in a stadium. Generally, the highest relative humidity levels occur during the night and gradually decline throughout the day.

[38] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973. Page 194

A lack of air movement results in temperature and relative humidity stratification with the highest levels occurring adjacent to the turfgrass. The mixing action of the wind is generally desirable and can be enhanced by allowing air to move through a superstructure.

The intensity and frequency of dew will be less in compact stadia but when it does occur it remains for a long duration. This will be so because there can be reduction in wind movement and light intensity in stadia and these factors decrease the rate at which dew evaporates.
The CO_2 content of air under a woodland canopy is generally higher than outside the canopy. Concentrations exceeding twice the normal atmospheric level have been measured. The rate of photosynthesis is a function of the light intensity and carbon dioxide concentration. A higher carbon dioxide level would increase the photosynthetic rate of shaded turfs.[39]

Subject to confirmation by research it may be assumed that the influence of shaded areas in stadia would have the same effect as the canopies of trees have on turfgrass in respect of CO_2 concentrations. The contributions of spectators could be added to those levels of concentration. The alterations in atmospheric gas concentrations may increase the net assimilation rate of turfgrasses and act as a positive factor in shade adaptation. However, the importance of such a response is minimal. The mixing action of wind can reduce the atmospheric carbon and the atmospheric dioxide content to more normal levels and negate any positive response to the higher carbon dioxide levels.

Soil moisture stress in turfgrass root zone is more severe in full sunlight than under shade during extended drought. The reduced evapotranspiration rate and higher atmospheric relative humidity are responsible for the increased efficiency of soil water utilisation. Turfs on the north east side of shelter are generally coolest and have the highest soil moisture level.

> The reduced light intensities under shade conditions limit the carbohydrate reserves and the growth of roots, shoots, rhizomes and stolons. Turfs shaded in the forenoon and then suddenly exposed to full sunlight wilt more quickly than turf growing in full sunlight throughout the day. The reduced root system, thin cuticle, and poorly developed vascular system of turfgrass growing in shade result in an increased wilting tendency.

[39] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973. Page 197

Morphological and physiological changes resulting from a shade environment cause an overall deterioration in plant vigour and hardiness. Shaded turfgrasses have a more delicate structure and are more succulent. The net result is reduced tolerance to heat, cold, drought, and wear stress as well as increased susceptibility to disease and insects. The rhizomes and stolons of shaded turfgrass tend to grow upright. The establishment rate under shaded conditions is seriously inhibited owing to the reduced rhizome number, more upright growth habit, decreased tillering, and limited carbohydrate reserves.[40]

Low light intensities serve to reduce carbohydrate reserves causing a decrease in shoot density. A complete loss of turf occurs if the light reduction is severe enough. However, if the light intensity is sufficiently above the compensation point in many shade situations this permits the maintenance of an acceptable turf. Several hours of full sunlight plus the diffuse light from leaf reflection transmissions are usually adequate for turfgrass growth.

The more favourable microclimate for disease development and the lack of disease resistant cultivars are key factors limiting the shade adaptation of certain cool season turfgrasses. Pathogen activity in the shade is enhanced by a longer dew period, higher atmospheric relative humidity, reduced wind movement, altered light quality, low evapotranspiration rate and more succulent plant tissue.

Adequate disease resistance is an important factor in the development of shade adapted cool season turfgrasses. Similar disease problems have been noted with certain warm season grasses grown under shade. However, the disease problem is not as critical as with cool season grasses.

The ability to overcome disease problems contributes significantly to shade adaptation. Other factors that may be involved in shade adaptation are

(a) a lower compensation point, respiration rate or carbohydrate requirement.
(b) lower nutrient and water requirements.
(c) greater competitive ability for light and nutrients.
(d) a lower light requirement.

> The relative importance of these four factors has not been determined.
>
> The survival of seedlings at low light intensities is greater in species ..... that have inherently slow rates of dry matter accumulation. The growth of red fescue is not influenced as much by reduced light intensities as some other turf grass species..... Plants grown at low light intensities have a lower compensation point and become light saturated at considerably lower intensities than when grown in full sunlight. Evidently the photosynthetic apparatus of certain shade tolerant turf grasses can adjust more readily to a low light intensity so that the available light is utilised more efficiently.[41]

Red fescue continues to be the preferred species for shaded environments in cool climates. The bent grasses are satisfactory where a preventative fungicide programme is followed and the soil is moist. Tall fescue and ryegrass are adapted to shade in the warmer parts of a cool, humid climate where winter-kill is not a problem.

Beard, *et al*, suggests that the underlying principles of improving turfgrass growth in a shaded environment is to modify that environment. The result of improving varying air movement over turfgrass will result in more beneficial levels in temperature and relative humidity. The consequences of these improvements will be less disease owing to lower relative humidity and the conditions for drying grass leaves. Cultural practices can also be modified to improve shoot density in the following ways:

- Raise the cutting height.
- Avoid excessive nitrogen.
- Irrigation should be deep but infrequent.
- Use fungicides when needed.

These points are considered below.

A higher height of cut increases the leaf area index, thus providing a greater capability to absorb light and synthesise carbohydrates. A cutting height of 2"-2·5" is beneficial for shaded lawn turfs.

---

[40] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 197.
[41] Ibid Page 198.

Carbohydrate depletion is moderated by using the minimum nitrogen fertilisation level that meets the requirements of the species. Excessive nitrogen fertilisation produces a succulent tissue that is more prone to injury from disease and wear.

Irrigation to a depth of 150mm ensures adequate moisture for turfgrass growth Water rates, however, should not exceed the infiltration rate. Excessive and improper timing of water dosing should be avoided to reduce pathogenic activity. The timing of irrigation should be so that water stays on leaves for a minimum period of time. This will help reduce infection by fungi.

Turfgrass disease occurs under shade conditions; control can be achieved by the application of appropriate fungicides.

Turfgrass in shaded positions should be protected as much as is practical because of its greater susceptibility to wear injury and reduced ability to recover. Early autumn establishment of cool season turfgrasses in shaded positions is preferred. The turfgrass should receive the maximum amount of light and air during the establishment period.

3.2.7. Influence of Wind on Turfgrass Growth.

Winds are composed of bodies of air, which have both velocity and direction. These forces are caused by differences in the density or pressure. Air moves relative to the Earth. Air is not a single gas. When it contains no vapour it is made up by volume of 78% nitrogen (N) and 21% oxygen (O), 0.93% argon (Ar) and 0.03% carbon dioxide (CO_2); a range of trace gases completes its composition see **Table 4.2.1.** Beard suggests that only CO_2 shows any variation that might be significant in plant growth. The influence CO_2 has on turfgrass development is considered in this section.

Many plants display an abnormal growth habit in response to strong directional winds that prevail. But low growing turfgrasses do not generally behave in this way.

> Atmospheric pressure and wind are not as important as temperature and precipitation in directly influencing turfgrass growth; but both exert a major indirect influence controlling temperature and precipitation. A diurnal variation in wind velocity is

frequently observed in temperate climates. The maximum velocity generally occurs around noon with the minimum around daybreak and noon.[42]

The horizontal wind velocity is zero at the top of a close cut turf. This will nearly always be the condition of a turfgrass playing surface in a stadium. Beard points out that the stronger the wind, the more rapid the rates of increase at vertical heights near the turf. The resistance due to surface roughness that a close cut turf exerts on wind may be called smooth.

> The mixing action of the wind is important in affecting CO_2,, temperature and water vapour microenvironment immediately above the turf. The turbulent transfer of air increases proportionally with the wind velocity. Turbulent transfer generated by wind tends to bring the CO_2 concentration adjacent to the leaves more nearly in equilibrium with the normal atmospheric level of 300ppm. The influence of turbulence on the CO_2 supply near the surface is demonstrated by the increase net assimilation that occurs with increasing turbulence.[43]

Air stratification increases temperatures immediately adjacent to the turf canopy, whereas the air mixing can effect cooling during heat stress. Cooling will increase with the speed of the wind. This results in reduced temperatures and increased rates of transpiration. Beard suggests that air movement is an important factor in reducing the adverse influence of the hottest parts of the day on turfgrass.

3.2.8. Influence of Shading on Turfgrass Growth

Reduced light intensities induced by shaded conditions limit carbohydrate reserves, root growth, shoots, rhizomes and stolons, causing an overall deterioration in plant renewal, vigour and hardiness. Shaded turfgrasses have a more delicate structure and are more succulent; growth tends to be upright, producing longer, thinner and lighter stems with a greater tendency to wilt. In these circumstances there is a diminishing vascular system, a lower tolerance to heat, cold and drought. Wear stress is increased and there is greater susceptibility to diseases and insect attack than found in turfgrasses set in shadow free positions.

---

[42] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973. Page 316
[43] Ibid. Page 316

Langer suggests that turfs shaded in the forenoon, suddenly exposed to full sunlight, wilt more quickly than turfs growing in sunlight throughout the day. Emmons suggests "It is difficult to grow turfgrass on heavily shaded sites where the grass receives less that four hours of full sunshine". [44] However, the extent of the minimum sunlight dosage required for healthy turfgrass needs to be more latitude related before the useful dosage can be expressed in those terms. In the temperate climates several fine-leafed species of the genus, *Agrostis*, *Festuca* and *Poa* are favoured for shaded positions.

The rate of photosynthesis of grasses, in common with all other green plants, depends on the level of light energy. From low intensities of about 0·5-1·0 Klux, photosynthetic rate rises rapidly in proportion to light energy received. But with higher intensities the rate of increase falls off, until light saturation is reached with no further improvement in the rate of photosynthesis. The saturation of light intensity for individual leaves of many temperate species has been found to be around 30 Klux, although there is considerable variation among genotypes, and shade-loving species tend to have lower values. This corresponds to a maximal net photosynthesis rate of 20-30 mg CO_2 dm-2h –1. However, within recent years attention has been drawn to the fact that in subtropical and tropical species….. light saturation of leaves is not reached until much higher light intensities exceeding 60 or even 100 Klux. Maximal assimilation rates are also higher, ranging from 50-70 mg CO_2 dm-2h –1. Response to temperature also differs between these climatic groups; about 35° C appears to be optimal for net photosynthesis in tropical grasses compared with about 20° C in those grasses of the temperate zone. This means that the higher maximum rates in the former are only attained when conditions are suitably warm, and that temperate species usually photosynthesise more rapidly at 20° C or less.

A further physiological difference is that respiration in perennial ryegrass, cocksfoot and other temperate grasses is stimulated by light, resulting in the release of CO_2, most of which is not recycled in photosynthesis. A more immediate objective is to use both types of plants to the best advantage in intermediate latitudes or altitudes where temperatures are neither too low for tropical nor too high for temperate grasses. Pastures composed of species with complementary growing seasons and growth potential might provide optimal use of environmental resources.

[44] Emmons R, Turfgrass Science and Management, 3rd Edition, Delmar 2000, page 370.

INDEX PART FOUR.

CHAPTER ONE.

4.1.0. GROWTH AND MAINTENANCE OF TURFGRASS IN STADIA.
4.1.0.1. **Introduction.**
4.1.1. **Impact of Defoliation on Turfgrasses.**
4.1.2. **Machinery used for Defoliation.**

CHAPTER TWO.

4.2.0. TURFGRASS NUTRITION.
4.2.0.1. **Essential Elements.**
4.2.1. **Primary and Secondary Nutrients Obtained from Soil.**
4.2.1.1. **Primary Nutrients.**
4.2.1.2. **Secondary Nutrients.**
4.2.1.3. **Minor Nutrients or Micronutrients.**

CHAPTER THREE.

4.3.0. WEED INFESTATION.
4.3.0.1. **Introduction.**
4.3.1. **Turfgrass Weeds.**
4.3.2. **Weed Control.**

CHAPTER FOUR.

4.4.0. COMPACTION AND THATCH.
4.4.0.1. **Introduction.**
4.4.1. **Compaction.**
4.4.2. **Irrigation.**
4.4.2.1. **Introduction.**
4.4.3. **The Influences of Irrigation.**

CHAPTER FIVE.

4.5.0. ROLE OF WATER IN TURFGRASS.
4.5.0.1. **Introduction.**
4.5.1. **Transpiration.**
4.5.2. **Evapotranspiration.**
4.5.3 **Water Use Rates.**
4.5.4. **Water Deficits.**
4.5.5. **Diurnal and Seasonal Variations.**
4.5.6. **Leaf Wilt.**
4.5.7. **Wilt Prevention.**

PART FOUR.

CHAPTER ONE.

4.1.0. GROWTH AND MAINTENANCE OF TURFGRASS IN STADIA.

4.1.0.1 Introduction.

In addition to light, heat, air movement and water essential to turfgrass photosynthesis, there is a second group of factors which help, hinder or negate that process. These factors can interact separately or collectively and include defoliation, nutrition, pest control, aeration, drainage and turfgrass wear. Two of this group, defoliation and wear can be outside the control of horticultural influence.

The evidence for this statement is that

- when commercial opportunities occur to maximise the use of turfgrass they consistently take precedence over the needs to maintain turfgrass.
- Defoliation influences turfgrass maintenance: a longer leaf length optimises the efficiency of the photosynthetic process by providing a bigger catchment area for light and wind. These factors, along with leaf orientation and angle, serve the needs of photosynthesis. Short leaves better serve the needs of the Games' of Football,

The contributory influence all these factors have on turfgrass growth will be discussed in the following sections.

4.1.1. Impact of Defoliation on Turfgrasses.

Adams and Gibbs state that

> a feature of turfgrasses is their ability to tolerate regular mowing, but the closeness of the mowing tolerated differs between species and between cultivars of the same species. Thus fine-leaved fescues and bent grasses can be mown at a height of 5mm whereas most cultivars of perennial ryegrass (*Lolium perenne)* and smooth-stalked meadow grass (*Poa pratensis)* become severely stressed if mown shorter than around 20mm. The stress is caused by close mowing and is primarily a result of removing a high proportion of the actively photosynthesising leaf tissue.[1]

Langer states that

> Grasses are well adapted to being grazed or cut because before the flowering stage is reached leaf formation continues during and after each defoliation. This is because

[1] Adams, W. A. & Gibbs, R. J. Natural Turf for Sport and Amenity: Science and Practice. Cab International.1994. Page 162.

during the vegetative phase the meristematic zones are located close to the soil surface, beyond the reach of animals and machines. Even if some meristems are removed by defoliation, they may readily be replaced by the appearance of new tillers. Few other plants have such an efficient mechanism of recovery growth, and thus it is no wonder that grasses have assumed such a pre-eminent position as forage plants"[2].

But the problem remains that

mowing removes the mature parts of the leaves which, through photosynthesis make the main part of the contribution to the energy balance of the plant. Severe mowing may not damage meristematic tissue but it removes much of the active photosynthetic tissues, leaving stem bases and immature leaves which may not be energy self-sufficient. Recovery requires the use of the plant's carbohydrate reserves which are small in rapidly growing turf. Mowing should be sufficiently frequent to minimise stress which is primarily determined by the proportion of the leaf tissue removed rather than the height of cut. Ideally the uncut height cut should not be more than 50% greater than the cut height. This demands a frequency of mowing which is not practicable in some situations. Nevertheless, uncut height should not be allowed to exceed double the cut height[3].

Recent history has seen the length of the grass cut reduced from 50 mm (2") for Rugby Football and from 38 mm (1·5") for Association Football to what is now a standard for both games of 20 mm.

4.1.2. Machinery used for Defoliation.

Prior to 1830, grass length was controlled by grazing or cutting with a scythe. The use of the scythe would have been the preferential means for preparing playing fields. Grazing disfigured the grass with animal droppings.

The scythe came into agricultural use during the 8th Century AD. [4] But by "1830 the scythe had a rival in the newly invented lawn mower".[5] The appearance of that mower is not markedly different in concept from the present day cylinder or reel mower.

The first Rotary mowers were developed in the1930s and became extremely popular because of their ability to cope with long rough grass and ground showing small stones.

---

[2] Langer R.H.M. How Grasses Grow, 2nd Ed Edward Arnold, London 1979,
[3] Adams, W&Gibbs R, Natural Turf for Sport and Amenity, Science and Practice, CAB International,1994, Page 48,
[4] Encyclopeadia Britannica 1994-1999. CD.
[5] Fort, T.The Grass is Greener, Our Love Affair With The Lawn. Harper Collins, 2000 page109.

In 1963 The Swedish designer, Karl Dahlman introduced the Flymo. It was a rotary mower in which the cutter revolved over a cushion of air." [6] However, only the cylinder mower is able to provide both close accurate cutting levels and the delivery of a cut, which is refined and aesthetically pleasing. But the cylinder mower can pull up very young grass; therefore the first few cuts of new turfgrass are best made with a rotary mower.

> Rotary mower technology is based on a horizontal cutting blade rotating at high speed. There is only one contact surface: the cutting blade. The impact of the cutting blade against the turfgrass leaf provides the cutting action. Dull blades and low rpm are the primary causes of undesirable quality of cut. Turfgrass species with tough vascular tissue in their leaves do not cut well when a rotary mower is used. Leaf blades tear rather than being cut cleanly. Ragged cut leaves form protective callus tissue slowly. Callus tissue once formed results in a brown discoloration to the surface of turf.[7]

The most appropriate arrangement for cutting established grass in a stadium is a lightweight tractor with cylinder mowers set in a configuration of head and side mowers. This arrangement allows for a maximum cutting area with the minimum tractor circulation, thereby reducing surface compaction.

CHAPTER TWO.

4.2.0. TURFGRASS NUTRITION.

4.2.0.1. Essential Elements.

There are four essential groups of elements: within the first group are Carbon, hydrogen and oxygen. These are obtained from the air and from water. Under satisfactory environmental conditions they are available to in situ turfgrass plants for the essential photosynthesis process. In addition there are another fourteen elements essential to turfgrass growth which are obtained normally from soil. These additional elements are classified in three groups termed primary, secondary and minor or micronutrients. The latter group are measured in parts per million. (PPM) The seventeen elements are listed in **Table 4.2.1.** Only Emmons includes Nickel in the list of required micronutrients but in doing so, suggests its absence from soil would not provide a problem to turfgrass balance.

The efficacy of turfgrass nutrition will be assisted by testing the chemical composition of the rootzone. This includes testing for pH values. These values indicate a logarithmic index for a

[6] Fort, T.The Grass is Greener, Our Love Affair With The Lawn. Harper Collins, page109.

hydrogen ion concentration in an aqueous solution. "Readings below seven indicate acidity; above seven indicates alkalinity, when tested at 25°C"[8]. The assessments determine if the range of nutrients is present at optimum levels and also determine if a soil has an acid /alkaline ratio that assists the uptake of the nutrients. If these elements are not available at ratios that produce optimum working levels, deficiencies should be rectified by feeding. Emmons, however, suggests, "that with the exception of iron, trace element deficiency is rare"[9]. This may be considered a sweeping scientific statement when reference is made to the Earth Heals Everything by Justine Glass published by Peter Owen, London 1964 pages 56-81. This chapter indicates that micronutrient deficiency is common in many locations. Any soil used for cultivation should be tested to establish such deficiencies.

The repeated application of primary and some secondary fertilisation elements are essential to provide a sports field turfgrass of a high playing and visual quality. But, "liberal fertilisation may be detrimental to turfgrasses grown under low light intensity. Reduction of non structural carbohydrates and growth, especially roots, have been reported for both bermudagrass and bentgrass grown under reduced light when heavily fertilised with N".[10]

However, any form of turfgrass maintenance will be opposed by the inappropriate and intensive overuse of turfgrass, the persistent practice of which causes both surface wear and compaction, eventually destroying the roots. **(4.6.0.4)**. Turfgrass problems in stadia are usually added to by the reduction in the levels of light and air at the playing surface. These topics are considered in **(3.2.0.)**.

4.2.1. Primary and Secondary Nutrients Obtained from Soil.

4.2.1.1. Primary Nutrients.

Nitrogen (N), phosphorus (P), and potassium (K) are the primary elements needed for turfgrass maintenance.

"**Nitrogen (N)** is a gaseous element, forming a diatomic, colourless, odourless gas. Determination of its ram [Relative Atomic Mass] led to the discovery of the inert gases in the

---

[7] Aldous, D,E Ed International Turf Management Handbook, Butterworth-Heinemann, 1999, Page 162.
[8] Walker,P,Ed, Dictionary of Science and Technology. LAROUSSE, Edinburgh & NewYork, 1995 page 815.
[9] Emmons, R, Turfgrass Science and Management, 3rd Ed, Delmar Thomson Learning.......UK, USA. Page 177.
[10] Waddington, d, et, al Etd Turfgrass Agronomy 32, Madison, Wisconsin USA,1992, refs (Burton& Davane,1952 Schmidt &Blaser1967,1969b), page152.

atmosphere e.g. argon. Approximately 80% of the normal atmosphere is nitrogen. It is also widely spread in minerals in the sea and in all living matter". [11]

"Nitrogen is a constituent of the chlorophyll molecule, amino acids, proteins, enzymes and vitamins (Epstein 1972). Nitrogen makes up 20 to 60 g kg^{-1} of the dry matter of turfgrass plants, (Butler & Hedges 1967) depending on the species. Nitrogen concentration has also been shown to be inversely proportional to the mowing height and directly proportional to N-fertilisation rate.[12]

There is more likelihood of a deficit in nitrogen in turfgrass than there is of any other of its essential elements. Losses of nitrogen occur by leaching and in gaseous exchanges to the atmosphere. The latter occurs more commonly on alkaline ground when nitrogen fertiliser is not watered in. Nitrogen losses are especially severe when the turfgrass is growing on sandy soils where irrigation occurs frequently. Beard suggests that "the extent of leaching depends on the amount of precipitation and irrigation, temperature and soil texture".[13] The removal of clippings from the turfgrass surface also contributes to nitrogen loss.

A deficiency in nitrogen can be visually detected by a change in colour from green to yellow/green. The determination of nitrogen deficiency should be obtained by either rootzone or foliar testing. A reduction in Nitrogen results in diminished vertical shoot growth indicated by longer intervals between cuts and a lower clippings yield. A return to Nitrogen balance reverses the defects listed.

> Nitrification requires molecular oxygen and therefore aerated soil conditions. In contrast denitrification, the non-assimilatory reduction of nitrate to nitrous oxide and nitrogen gases occurs in poorly aerated and waterlogged soils. The compacted, organic rich surfaces of many sports soils provide highly favourable conditions for denitrification for two reasons: firstly, through an increased tendency for excessive wetness and secondly, because denitrifying bacteria are most active when readily decomposing organic matter is present. Injudicious irrigation giving rise to alternating periods of good soil aeration and waterlogging results in substantial losses of nitrate through denitrification[14]

[11] Walker,P,Ed, Dictionary of Science and Technology. LAROUSSE, Edinburgh & NewYork, 1995 page 815.

[12] Waddington, d, et. al Etd Turfgrass Agronomy 32, Madison, Wisconsin USA,1992, refs (Turgeon et al., (1979)."page. 386.

[13] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 414.

[14] Adams, W. A. &Gibbs, R. J. Natural Turf for Sport and Amenity: Science and Practice. Cab International.1994. Page 37.

TABLE 4.2.1. ELEMENTS OBTAINED FROM AIR & WATER AND FROM SOIL.

FROM AIR AND WATER

Carbon

Hydrogen

Oxygen

FROM THE SOIL

	Element	Chemical Symbol	Available Form	Concentration in Dry Tissue	Deficiency Symptoms
Primary (fertiliser) nutrients	Nitrogen	N	NO_3-,NH_4+	2.5-6.0%	Older leaves yellow-green, reduced shoot growth.
	Phosphorus	P	H_2PO_4-,HPO_4--	0.2-0.6%	Older leaves dark green first, then appear purple or reddish.
	Potassium	K	K+	1.0-4.0%	Interveinal yellowing especially on older leaves, leaf tips and margins scorched.
Secondary nutrients	Calcium	Ca	Ca++	0.2-1.0%	Deficiency rare, new leaves reddish-brown and stunted.
	Magnesium	Mg	Mg++	0.1-0.5%	Interveinal chlorosis, a striped appearance, cherry-red margins.
	Sulphur	S	SO_4--	0.2-0.6%	Yellowing of older leaves.
Minor or micronutrients	Iron	Fe	Fe++,Fe+++	50-500 p.p.m.	Interveinal yellow of new leaves.
	Manganese	Mn	Mn++	Very small amounts	Rare, similar to iron deficiency.
	Copper	Cu	Cu++	Very small amounts	Never a problem.
	Boron	B	H_3BO_3-and others	Very small amounts	Rare, cholorotic, stunted growth.
	Zinc	Zn	Zn++	Very small amounts	Rare, growth stunted, thin and shrivelled leaves, appears desiccated.
	Chlorine	Cl	Cl-	Very small amounts	Never a problem.
	Molybdenum	Mo	MoO_4--	Very small amounts	Rare, older leaves pale green.
	Nickel	Ni	Ni++	Very small amounts	Never a problem.

Phosphorus (P) occurs widely and abundantly in minerals (as phosphates) and in all living matter.....but mainly the phosphate is *apatite,* a widespread accessory mineral of igneous rocks, which also occurs in sedimentary phosphate deposits, guano and bones. It is manufactured by heating calcium phosphate with sand and carbon in an electric furnace.

Phosphorus is taken up by young plants in relatively large quantities and is used in the making of proteins and assists in the transfer of energy within a plant. The efficiency of the absorption of phosphorus is greatest with soil pH levels between 6 and 7 and in periods of active growth.

> Phosphorus deficient turf appears stunted and shows a red purple colour beginning at the leaf tips. Test levels of 15to30 PPM. in soil and 0.3 to 0.6 per cent phosphorus in leaf tissues are sufficient. Even though phosphorus is relatively immobile in soils, it is seldom deficient in the plant under normal growing conditions because the extensive root system of actively growing grass does an excellent job of scavenging for phosphorus.[15]

Thinned out turfgrass can be quickly re-established by building up higher levels of phosphorus thus developing roots, rhizomes, stolons and tillers. Each develops a spreading habit, thereby quickly restoring turfgrass cover. Turfgrass treated in this way additionally must have suitable periods of turfgrass rest to allow the plant restorative processes to take place.

> Elevated levels of phosphorus may also benefit poorly rooted mature turf that is similarly affected in intense traffic areas..... On cool and warm season grasses phosphorus is applied at the rate of 20 to 40 kilograms per hectare. There is a good scientific basis for applying phosphorus once per year in conjunction with nitrogen and potassium to promote growth on sports fields.[16]

Potassium (K).

"Although not directly associated with the molecular structure of any plant constituents, K has been determined to be an essential element in the numerous plant functions, such as photosynthesis, carbohydrate formation, water relationships, and enzymatic activity"[17]. It is a very reactive alkali metal, and silvery white. In the form of the element, it has little practical

[15] Aldous, D,Ed, International Turf Management HANDBOOK. Inkata Press Australia. 1999, page 149.
[16] Aldous, D,Ed, International Turf Management HANDBOOK. Inkata Press Australia. 1999,(ref Adams & Gibbs) page 149.
[17] Waddington, d, et, al Etd Turfgrass Agronomy 32, Madison, Wisconsin USA,1992, pages, 405&406.

use, although its salts are used extensively. In combination with other elements it is found widely in nature. Potassium shows slight natural radioactivity due to ^{40}K.(half-life $1{\cdot}30\times10^{9}$.)[18] Potassium is involved in the plant metabolic processes, some of which are linked to the use of water. Potassium is highly soluble and as a consequence does not stay long in the rootzone. Therefore, rootzones based on sandy soils or those of pure sand which drain easily will also lose the effects of potassium more rapidly than traditional rootzone soils.
Shearman & Cartice *et al.* point out that turfgrass plants utilise **(K)** at about the same rate as it does **(N)**, thus necessitating the application of **(K)** as often as turfgrass needs the application of **(N)**.

4.2.1.2. Secondary Nutrients.

Calcium (Ca) is found in relatively large quantities in turfgrass tissues ranking third after nitrogen and potassium. "Calcium is the known component of one enzyme, amylase, and is a cofactor of several other enzymes. It is a major component in the middle lamella of cell walls and thus becomes important in the mechanical strength of tissues. Calcium plays a strong role in meristematic activity".[19]

"Non-limiting levels of calcium enhance root growth, particularly root hair development. Calcium ions also exert a strong influence on the absorption of other ions by the turfgrass plant. Specifically, the uptake of potassium and magnesium is modified by the concentration of calcium ions. A deficiency in calcium results in increased proneness to red thread and *Pythium* blight".[20]

Magnesium (Mg). Beard indicates that magnesium is essential for the maintenance of the green colour and growth in turfgrass because of its vital links with the chlorophyll molecule. Magnesium is also an actual constituent of living cells. Since it is also involved in phosphorus translocation within plants, it affects phosphorus utilisation.

Magnesium levels are normally highest in leaves although accumulations may also occur in the growing tips of stems and roots and seeds. High magnesium concentrations can be toxic to the turfgrass plant and decrease the degree of flocculation under certain conditions. This condition is most likely to occur in sodic soils.

---

[18] Walker,P,Ed, Dictionary of Science and Technology. LAROUSSE, Edinburgh & NewYork, 1995 page 815.
[19] Waddington, d, et, al Etd Turfgrass Agronomy 32, Madison, Wisconsin USA,1992, pages, 416
[20] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 416.

Magnesium does not exert a great influence on the physical or chemical properties of a soil, but its content is likely to be higher in fine textured soils than in coarse.

Sulphur (S) occurs in plants primarily in the form of proteins, sulphates, and certain volatile compounds and is fairly evenly distributed throughout the plant. Sulphur deficiency disrupts protein synthesis; consequently it stunts growth and in some turfgrass species brings on mildew disease.

Sulphur is taken up by turfgrass roots primarily in the SO—ion, although some is absorbed by the leaves as gaseous sulphur dioxide. A considerable portion of sulphur in soils is contained in organic matter and thus is concentrated in the surface horizons of the soil profile. The amount occurring in the sulphate form is quite small because of its high solubility. The sulphur content of soils is usually lower under conditions that accentuate organic matter decompositions and here leaching is more severe.[21]

Some other researchers have suggested that, since the acceptance by some 31 States in 1979 of the Treaty on Long Range Trans-boundary Air Pollution the result has been that "less sulphur dioxide is being emitted into the atmosphere with the result that less is deposited onto soil and crops"[22]. To counter this, sulphur can be added to the soil in the form of calcium sulphate (gypsum), ammonium sulphate, or as single super-phosphate when phosphate is also needed.

4.2.1.3. Minor Nutrients or Micronutrients.

Table **4.2.1.3.** has been compiled from a number of sources but Adams and Gibbs in their Table **4.2.1..4.**[23] have evaluated the dry tissue available in young leaves of turfgrasses of all the elements. Some other experts indicate seven of the elements as being available 'in very small amounts'. The Adams and Gibbs figures establish that the quantum of these seven are very small, but the extra refinement can be useful to the horticulturist.

TABLE 4.2.1.3.

Element		**% in dry tissue.**
Nitrogen	(N)	2.0 - 4.5.
Phosphorus	(P)	0.2 - 0.5.
Potassium	(K)	2.0 - 4.0.
Chlorine	(C)	0.5 - 2.0.
Magnesium	(Mg)	0.1 - 0.5.
Sulphur	(S)	0.2 - 1.0.

Element		**$\mu g\ g^{-1}$ in dry tissue.**
Iron	(Fe)	100-500

[21]Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 419-420.
[22]Smith and Warr, Global Environmental Issues. The Open University ,Milton Keynes, UK page 8.
[23]Adams, W&Gibbs R, Natural Turf for Sport and Amenity, Science and Practice, CAB International,1994, Page 31,

Manganese	(Mg)	30-100
Zinc	(Zn)	40-100
Copper	(Cu)	5-50
Boron	(B)	5-50
Molybdenum	(Mo)	1-4

The micronutrients are just as important to the plant as are the micronutrient elements but they are required in significantly smaller amounts. Certain organic soils, intensely leached sandy soils, those modified to a high sand content and soils used for growing turf may be deficient in one or more of the micronutrients. Deficiencies are prone to appear with intense irrigation and where soil is compacted. "Manganese, zinc, copper and boron are likely to produce toxic effects on turfgrasses at higher concentrations".[24]

Iron (Fe) is in practical terms probably the most important in the group of micronutrients, but Beard points out that it is the one most likely to be deficient in turf. An iron deficiency is usually the result of insolubility rather than the absence of the element in the soil. "Deficiencies of iron are most common in soils that are alkaline, high in phosphate, manganese, zinc, or arsenic, high in organic matter content, waterlogged or excessively thatched. Iron is physiologically active only in the ferrous state". [25]

Fe is "essential for chlorophyll synthesis as a constituent of several haem and nonhaem enzymes and carriers, and may play a role in nucleic acid synthesis, and therefore is important for turfgrass colour"[26]. Turfgrass with a deficiency in iron is chlorotic and does not respond to the presence of nitrogen. Also, when iron is present in the soil it has the tendency to form insoluble compounds.

Manganese The manganese content is normally highest in acidic, imperfectly drained, poorly aerated and /or compacted soils. Alkaline conditions or intense leaching frequently result in manganese deficiencies. Deficiencies usually occur because manganese is not available in a usable form rather than because of its absence. The utilisation of iron and manganese is closely linked; a high concentration of iron can induce a manganese deficiency, which will result in turf discoloration.

Zinc is essential to plants but only in minute quantities. Higher concentrations are very toxic to turfgrass plants, particularly rhizomes. The zinc level in soils is usually highest near the soil

[24] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 420.
[25] Ibid page 420
[26] Waddington, d, et. al Etd Turfgrass Agronomy 32, Madison, Wisconsin USA,1992, pages, 419-421

surface because it is immediately fixated by the soil when returned in plant residue. The actual role of zinc as an essential nutrient is not well documented.

Copper is highly toxic to plants except in very dilute concentrations. Deficiencies are most common in highly alkaline organic soils or intensely leached sandy soils. The copper content is usually highest in actively growing tissues. A copper deficiency that impairs plant growth hormone synthesis can cause the death of the axillary buds in the apical meristem of turfgrasses.

Molybdenum A deficiency results in nitrate accumulation and impaired protein synthesis. Molybdenum is usually absorbed as the molybdate ion. The molybdenum concentration is usually higher in the leaf blade and the other active parts of the plant; its level is also higher at the soil surface than the depth profile of the soil. A deficiency of Molybdenum results in nitrate accumulation and impaired protein function.

Boron. Beard *at el* points out that the exact function of Boron is not well understood; it is thought to function in calcium utilisation. Relatively low concentrations of Boron can be toxic to plants, under acid conditions. Turfgrass colour is sometimes poorer when there is a shortage of Boron.

Chlorine. Deficiencies in Chlorine are rare. It is one of the most abundant anions found in plants but the needs of the turfgrass plant for it are relatively small. "The role of chlorine is not well defined".[27] However, chlorine is thought to regulate osmotic pressure and cation balance within plant cells.

CHAPTER THREE.

4.3.0 WEED INFESTATION.

4.3.0.1. Introduction

A commonly accepted definition of a weed is any plant growing in an unintended location. Not only are weeds visually intrusive within a given context, they also compete with the selected species for the available heat and light, air, water and soil nutrients. The intervention of weeds in stadia turfgrasses, for example, may cause "interference to play, unacceptable differences in colour and growth and durability problems within the sward."[28].

---

[27] Waddington, d, et, al Etd Turfgrass Agronomy 32, Madison, Wisconsin USA,1992, page, 424.
[28] Aldous, D,Ed, International Turf Management HANDBOOK. Inkata Press Australia. 1999, page173.

4.3.1. Turfgrass Weeds

Adams &Gibbs illustrate and describe in outline forty-two "Weeds and Herbs in mown Turf".[29] Within this group of cool season weeds thirty-one are perennial and seven are annual species. Of the remaining four, three fall into the category of annual or biennial weeds and the last of the considered species, the Mouse-Ear Chickweeds *(Cerastium spp)* can be either annuals or perennials. Adams & Gibbs divide their examples into 14 generic categories, a significant number of which belong to the Daisy grouping, *(Compositae)*. In considering the methods of eradicating these plants it is essential to understand the life cycle and growing habits within their preferred environmental conditions.

The illustrations of the weeds concentrate on their plan form. The illustrations are of value in recognising the weeds in situ, but an attached scale would have been helpful in determining the degree of ground cover they each impose on a selected turfgrass species. These illustrations also confirm broadly that "turfgrass weeds can be classified as exotic narrow-leaf species and broad-leaf weed species".[30]

Within the classification of annuals, biennials and perennials, annual weeds are capable of being further subdivided into summer and winter annuals. Unlike annuals and biennials, perennials persist over periods longer than one or two years, but usually overwinter in a dormant state. Many perennials spread primarily by seed, others do so vegetatively.

Outside the common classification there is an additional group of annuals. These are "Indeterminate annual weeds: this category includes weeds such as chickweed (Stellaria media) and annual blue grass or winter grass *(Poa annua)*, that germinate and grow during most seasons and in certain regions". [31]Annual bluegrass or winter grass is known in the UK as Annual Meadow Grass.

Hubbard crystallises Annual Meadow Grass as "a rather variable and ubiquitous turfgrass plant"[32]. He then goes on to expand that description:

> Although not an ideal lawn grass, it is often abundant in shaded and closely mown turf, where it provides a fine green sward except under dry conditions. This is due to its seeding throughout the year and to the continuous replacement of dying plants by new

[29] Adams, W&Gibbs R, Natural Turf for Sport and Amenity, Science and Practice, CAB International,1994, Pages 192-207, ISBN 085198 720 6

[30] Aldous, D,Ed, International Turf Management HANDBOOK. Inkata Press Australia. 1999, page173.

[31] Ibid page 173

ones from seed. The short-lived perennials' races,(racemes) var, *reptans* and var. *aquatica* Aschers,. are found usually in loose sandy soils or under moist conditions respectively.[33]

It is its ability to continually replace dying plants by new that makes it difficult to control. Annual Meadow Grass is considered a weed despite the fact that it does provide in any sward valued for its appearance 'a fine green sward except under dry conditions. In stadia it does not provide an ideal surface for high performance football games. Evidence of its invasive qualities is provided by the Groundsman at Ninian Park, Cardiff, Wales. He reported that before the playing surface was re-seeded, it was estimated the original surface contained 80% Annual Meadow Grass. "Weed seed numbers of 45,000 to 200,000 seeds per square metre have been recorded in Poa Annua dominated turf."[34]

Factors that contribute towards weed invasion of turfgrass:

- Some annual weeds are prolific seed producers, ensuring continuity of growth.
- Seed transfer by the wind, animals, birds and humans.
- Inappropriate soil profiles which are poorly drained and subject to compaction and shade.
- Soil cultivation stimulates seed to germination and in addition activates underground vegetative growth.
- Timing and intensity of turfgrass mowing, verti-cutting and fertilisation.

Weed control has been defined as any practice designed to prevent weed emergence or cause a shift from an undesirable to a more desirable turfgrass situation. Successful weed control programmes begin with the use of strategic cultural practices that provide the desired species with a competitive advantage. Annuals reproduce only by seed. Control methods must therefore aim at preventing the setting of seed. With many biennials the first year of growth is purely vegetative with the flower and seed forming in the second year. Control methods should be aimed largely at the vegetative growth or seeding period. Perennials live for many years. Therefore control methods should aim at limiting seed production and then reducing the infestation.[35]

4.3.2. Weed Control

[32] Hubbard C, Revised Hubbard J, Grasses,3rd Edition, Penguin Books, England, UK.1984 pages,166-167.
[33] Ib id page 167.
[34] Aldous, D.Ed. International Turf Management HANDBOOK. Inkata Press Australia. 1999, page174.
[35] *Ib id* page 174.

Weed Control is primarily exercised by chemical and non-chemical means. The principal groups of chemicals used on weeds and insects are as follows:

Fumigants can be applied to soil to control weeds, seeds, nematodes and disease-causing micro organisms.

Fungicides are non-systemic and are contact applied to turf foliage to prevent pathogens from entering a plant. Complete spray cover is necessary over the whole surface area for it to be protected.

Herbicides control unwanted plants and can be selective or non-selective. They usually control either broad leaf or grassy plants; they are classified as pre-emergence and post-emergence chemicals.

Insecticides. These are chemicals that are used to control insects. They do so by disrupting the nervous system or act as a stomach poison. These chemicals can also be injurious to humans.

Under European Control of Pesticides and the Biocidal Products Directive, eighty of the above products used by amateurs and one hundred and thirty of those products used by professionals will not be supported in stages two and three of the European Commission. Review. They are therefore banned, the last day of sale being 24th July 2003. 31st December is the last day of use, the 31st of March 2004 is the last day of storage (for disposal purposes only)

The anticipation is that forms of these four treatments will remain available with permitted substances, although the evidence is that some Non-Governmental Organisations are pressing for extending the list of chemicals used in agricultural treatment products. The chemicals which remain available, presumably will remain, subjected to conditions for application.

The probability too will be that herbicides will remain divided into two categories of applications: pre and post-emergence herbicides. The pre-emergence types are "often best incorporated into the top 25 to 60 mm of soil by irrigation where the chemical is taken up by the roots and shoots of the emerging weeds"[36]. Post-emergence herbicides work through the vascular system and eventually interfere with a key plant process and ultimately kill the weed.

But the application of herbicides may be broadcast or spot applied. Broadcasting carries the largest potential risk to the macroenvironment and microenvironment. Most of the research in these matters has been conducted in the open field condition. What needs to be established is

---

[36] Aldous, D,Ed, International Turf Management HANDBOOK. Inkata Press Australia. 1999, page174.

how broadcast spraying would disperse in the comparatively static conditions of a compact stadium. Would all the material fall on the turfgrass or would it hang in the air and in doing so pose a greater hazard than if the surplus material was dispersed into the atmosphere? Until this assessment is made, even if chemicals used are on an approved list, it would be in accordance with the precautionary principle to treat weeds chemically in a stadium by the spot method.

Non-chemical means of weed control may include mechanical methods, the use of cultural processes, and biological control.

The only mechanical methods that are appropriate in controlling weeds during a season are hand pulling, or the use of weed free propagation materials. But at the end of a season scarifying can be an appropriate method of surface renewal.

Mechanical methods are particularly effective with annuals where the seed supply in the soil is limited and short-lived. Biennials and perennials are discouraged by close cutting, but many grow back from their roots.

> Cultural controls are based on the fact that plants differ in their ability to compete with one another; they may include a selection of a more suitable turf species, renovation to introduce resistant species and /or cultivars, competitive mowing heights and frequencies, changes in nitrogen amounts and source, improving the surface and sub- surface drainage, more favourable soil conditioners and pH, reducing compaction, and proper adjustments to equipment and machinery. [37]

On mature turfgrass surfaces weed problems are often the result of overwatering or underwatering, mowing too close or too high, low fertility, excessive wear, disease or insect damage, soil compaction and low light levels. Excessive fertiliser use or watering beyond the needs of a turfgrass can frequently be the cause of serious weed problems. Similarly, frequent mowing will prevent or reduce seed production in some weed species. Most erect growing weeds can be controlled by frequent mowing at the correct heights so that the seed heads can be removed before viable seed is produced. Persistent removal of top growth will eventually reduce biennial and perennial weed populations by depleting their reserves of carbohydrates.

Biological weed control is an approach that uses other living organisms to control or reduce the population of the undesirable weed species. Some examples of living organisms that have been

---

[37] Aldous, D,Ed, International Turf Management HANDBOOK. Inkata Press Australia. 1999, page174.

used in biological weed control programmes are insects, mites, fungi, nematodes and aquatic and terrestrial vertebrate herbivores. However, only limited success has been achieved.

"A disease is defined by Smiley {1983} as an abnormal alteration in the physiological processes or morphological development of a plant by a pathogenic organism or environmental factor." [38]

> Such agents of disease can either be biotic such as plant pathogenic species of bacteria, fungi, mycoplasmas, nematodes and viruses or abiotic agents which bring about physiological disorders by unfavourable environmental conditions or physical injury. Such injury can be induced by chemical agents (pesticides, animal urine or salts or chemical spills) physical agents (extremes of temperature, lightning and soil compaction) or mechanical agents (scalping with a mower or abrasion injuries).[39]

Pathogens are disease causing agents and most are also parasites. Parasites are organisms that obtain part or all of their nutrients from a living turfgrass host.

Disease organisms such as rust or powdery mildew or yellow tuft are obligate parasites as they depend on a living host for nutrients. Other organisms such as slime mould live on dead organic matter such as thatch and mat and are called saprophytes. Still other organisms can live as parasites but under certain conditions are capable of saprophytic growth; these are called facultative parasites.

As a result of different injuries, turf exhibits various symptoms, which show themselves as changes in leaf, leaf colour, stem and root rots and swellings. Symptoms are often unique to a particular pathogen and its interaction with a particular host plant assists in identification.

For any disease to become active, three interactive conditions are necessary:

- The existence of the pathogen.
- A susceptible host or grass.
- A favourable environment. [40]

For a disease to develop all three components must be present. Correct identification of the disease is best carried out under laboratory conditions, in doing so, providing strict records of the plant environment and horticultural procedures and use pattern imposed of the plants tested.

---

[38] *Ib id* page 178.
[39] Aldous, D,Ed, International Turf Management HANDBOOK. Inkata Press Australia. 1999, page174.
[40] *Ib id.* page 179

An analysis provides the important clues in identifying the probable cause of a disease. Samples of plants being tested should contain both healthy and unhealthy turfgrass.

Smiley proposed four important disease control strategies:

1. Prevent the pathogen from becoming established in a new turfgrass stand.
2. Change the genetic composition of the turfgrass plant so that it will resist the attack.
3. Change the surrounding environment so that the susceptible plants can overcome an attack.
4. Protect the plants from being infected. [41]

These control strategies translate into making better use of sanitation procedures, greater use of disease resistant plant cultivars and implementing operations leading to best practice in cultural management. Sanitary procedures include the careful inspection for and the removal of inoculum found in top dressing and contaminated vegetative material and the use of mowers with cutting blades that are both accurately set and sharp[42].

CHAPTER FOUR.

4.4.0. COMPACTION AND THATCH.

4.4.0.1. Introduction.

To ensure turfgrass derives the carbon, oxygen and hydrogen essential for its existence, it is necessary for those elements to be transferred to its roots via the rootzone through water and air. This transfer can be interrupted by surface compaction and thatching.

Compaction is caused by particles of soil being pushed together by pressure, thereby reducing the size of the pores between the soil particles. The effect of this is more severe in clays than in loam and some sands.

Thatch "is a tightly intermingled layer of dead and living stems and roots that develops between the zone of green vegetation and the soil surface"[43] Thatch also minimises the passage of air and water to the turfgrass roots. This fibrous mat can create a disease-forming turfgrass environment. Thatch will also cause the application of certain pesticides to become ineffective.

The mechanical method of alleviating these problems is as follows:

- in the case of compaction it is to aerate the soil with a solid or hollow corer.

---

[41] *ib id* page 179
[42] Aldous, D,Ed, International Turf Management HANDBOOK. Inkata Press Australia. 1999, page179-180.
[43] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 495.

- in the case of thatch it is to traverse the grassed area with "a powered drag mat after coring".

4.4.1. Compaction.

Compaction in relation to turfgrass is the result of persistent pressure caused by various forms of traffic on those surfaces. The visible consequences of compaction are reflected in surface wear. Beard, *et al*, points to the "hidden effect" of compaction, which is the "pressing together of the soil into a more dense soil mass." This causes a reduction in the free spaces (pores) in the rootzone material. Compaction usually takes place in the upper 2" to3" of the soil.

- Reducing the pore size restricts water movement through the soil.
- When water is retained or moves slowly through the soil, there is an accompanying reduction or exclusion of oxygen, essential for vigorous root growth.

"Soil compaction is influenced by (a) soil texture, (b) soil water content, (c) severity of the pressure applied, (d) frequency at which the force is applied and (e) the amount of vegetation."[44] Understanding the role such influences play in controlling or reducing compaction is important. The influence of compaction will be less in some sands and in loam and most severe in clays.

Beard provides a definition for thatch as a

> tightly intermingled layer of dead and living stems and roots that develops between the zone of green vegetation and soil surface. Physically, it is composed of sclerified vascular strands of stems and leaf sheaths plus the nodes of stems.
> Nodes of stems and crown tissues are the most resistant to decay, while stems and roots are intermediate and leaves the least resistant. Leaf remnants occur only in the upper surface layers as a pseudo thatch. [45]

Thatch develops when the accumulation rate of dead organic matter from the actively growing turf exceeds the rate of decomposition. Cultural or environmental factors can stimulate excessive shoot growth and can impair decomposition. Factors such as abundant vegetative growth, vigorous growing species, high rates of nitrogen fertilisation, infrequent mowing and excessive use of plant pesticides encourage the formation of matted thatch.

[44] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 372.
[45] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 459-496.

The chemical test on thatch reveals a high lignin content and leads Beard to suggest that thatch is generally an undesirable feature. But Waddington reports, after Beard (1973) that the detrimental effects of thatch are often emphasised. However, a thin layer of thatch may add resiliency to a playing surface, increase wear tolerance and insulate soil from temperature extremes.

Rogers & Waddington report that a thatch layer (no thickness recorded) could be of importance in providing greater impact absorption on turfgrass areas. Such an effect could be of importance in lowering the number of impact type injuries to players but it would adversely affect ball bounce. In this respect it would be appropriate to refer to Adams & Gibbs, pages 182 to 183 where they deal with the need to restore the level of playing surfaces made uneven by the consequences of the build up of organic matter on winter games pitches under UK conditions. Association Football relies on ball roll and certainty of bounce to develop football skills. These factors are provided only on flat and even surfaces. These surfaces not encouraged by allowing thatch to develop.

4.4.2. Irrigation.

4.4.2.1. Introduction.

Beard provides an outline of the strands which cover the topic of irrigation

> The total and seasonal distribution of precipitation is not usually adequate to maintain a dense green turf of acceptable quality. Irrigation practices are needed under these conditions if an adequate shoot density and colour are to be maintained. The microclimate of irrigated turfgrass areas is altered considerably. Both soil and air temperatures adjacent to an irrigated turf are cooler than un-irrigated areas. Irrigation is one of the most difficult aspects of turfgrass culture. Once irrigation is initiated during a drought, it should be continued for the duration of the drought. Sporadic irrigation is not effective and can actually be detrimental to the turf in terms of reduced carbohydrate reserves, vigour, and drought resistance. Consideration in developing an irrigation programme includes (a) irrigation frequency, (b) quantity of water supply, (c) certainty of water supply and (c) method of irrigation.[46]

4.4.3. The Influences of Irrigation.

The interpretation of Beard is that irrigated water is introduced into plant life as a supplement to or even as a replacement for precipitation: it does this with the purpose of maintaining or

[46] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 466.

adjusting the critical balance between the supply and demand for water in plant life. The volume of water required to meet this balance depends on the water already available to a rootzone. Water requirement will depend on the depth of the rootzone and its soil texture and structure. These factors influence available water infiltration and percolation rates.

The volume of the irrigation water should be such as to wet the rootzone to its full depth. This may be from 150 to 600 mm. A probe should be undertaken to assess the water need and then a further probe is made after irrigation to ensure that a link has been established between the surface and the sub-surface moisture. An even distribution of 'wetness' will promote vigorous leaf and stem growth.

Irrigated water should be distributed evenly and only in quantities sufficient to provide the balanced needs of the turfgrass being irrigated. These needs will be different for different species and cultivars; therefore the physiology of the plants making up a sward has to be understood.

There is a current trend in Stadia, where it can be afforded, to water a playing area prior to a football match to quicken the pace of a ball over a turfgrass surface. That process is a different one from irrigating for horticultural reasons and may upon investigation be disadvantageous to turfgrass.

Beard points out that the preferred time to irrigate is just prior to wilting. He suggests that evidence of imminent wilting is the poor recovery of footprints on turf grass. Leaves possessing a negative water balance show a poor rate of recovery. However, in the confined conditions of a stadium probes would need to be taken to ascertain the water need over the depth of the rootzone.

Excessive irrigation is not only uneconomic it also results in waterlogging. Waterlogging reduces the supply of oxygen to the ground; that adversely affects turfgrass growth and vigour and increases ground compaction. Overwatering at times of day when free water is left on leaves for an extended period can result in increased disease problems. Beard draws attention to the influence of timing of irrigation application as follows:

- **Early morning irrigation** reduces the time when water droplets and leaf exudates persist on the leaves.

- **Midday irrigation** occurs at a time when evapotranspiration is usually the most rapid. This would therefore be the preferred time for irrigating from the standpoint of minimising disease development.
- **Late afternoon or early evening irrigation** permits free water droplets to remain on the leaf surface for the longest time.
- **Nocturnal irrigation** reduces evaporation losses but increases the possibility of pathogenic activity.

The supply rate and its duration are integral factors in delivering the water requirement in an economic manner. It is essential therefore, as previously indicated, to estimate the water requirements of a turfgrass species and additionally to know the rootzone rates of infiltration and percolation to avoid standing water. Rootzones in stadia should be designed to accept the irrigation requirements of a particular turfgrass species in a stadium.

Sprinklers can be set to deliver water at rates ranging from 0·1" to 1·0" per hour and can be delivered from fixed, rotary or oscillating heads. The spacing of the sprinkler systems is an important consideration as this influences water distribution and the need to avoid overlapping. The type of sprinkler head influences the droplet size: the finer the droplet, the less will be the ground compaction. Overhead sprinkling is the most common form of irrigation. However there are other forms such as a) surface b) subsurface c) sub rootzone irrigation. Only sub rootzone irrigation is an alternative to the overhead sprinkling system in stadia because the other methods would interfere with turfgrass maintenance and the sporting activities.

It is essential that the sprinkler water supply is analysed to determine the presence of any of the micronutrients or toxins.

In a stadium the irrigation distribution lines may be in situ with pop-up outlets, thus reducing ongoing labour costs. Sprinkling a multi-pallet system may have to be delivered through a manual method, unless a distribution system can be set out below the pallets or below the pallet-supporting floor. The latter arrangement may be more convenient for the processes of reconfiguration necessary for some multi-use activities.

CHAPTER FIVE

4.5.0 THE ROLE OF WATER IN TURFGRASS.

4.5.0.1. Introduction.

Water can be defined as-a colourless, odourless, tasteless liquid, m.p. 0°C b.p.100°C, whose molecules associate extensively through the hydrogen bonding, which gives it its unique properties. On electrolysis it yields two volumes of hydrogen and one volume of oxygen. It forms a large proportion of the Earth's surface, occurs in all living organisms, and combines with many salts as water of crystallisation. Water has its maximum density of 1000 kgm $^{-3}$ at a temperature of 4°C...... Besides being essential for life, water has a unique combination of solvent power, thermal capacity, chemical stability, permittivity and abundance.[47]

Water plays two important roles in the growth and maintenance of turfgrasses. Firstly, it combines with carbon dioxide and heat energy to drive the vitally important photosynthetic process **(Section 3.1.3).** Secondly, water serves to mitigate the effects of solar radiation on turfgrass plants by the process of evaporative cooling: it achieves this through two separate evaporative processes.

The description of the processes involved in the transportation of water from the plant roots through the stems and leaves are complex. However, a broad outline of these processes is provided to aid the understanding of the action of water on the turf plant.

Connellan *et al* outlines in simplified terms the complex action of the upward movement of water from the root to the leaf. This action comprises either a pushing or a pulling motion of water from the rootzone through tubes within the turfgrass plant. The plant water supply is therefore dependent on the retention and percolating factors of the rootzone sink. The factors are in turn dependent on the composition of the rootzone and the design of the drainage system that services it.

Connellan's outline explanation of the movement of water through the turfgrass plant is as follows.

> The movement of water through a plant system can be simplified to consider the water entering the roots and moving up through the trunk or stem to the leaves as a continuum of a solution as a liquid. Within the leaf there is a change from a liquid to a water vapour. This is the process of evaporation. When it specifically refers to the evaporation of water from within the foliage it is called transpiration. In order to maintain the plant in a healthy condition, all the water requirements of the plant need to be satisfied. This includes water that evaporates from the soil between the plants and also any water that may be on the plant surfaces. The total water use by a plant, including both transpiration

[47] Walker,P,Ed, Dictionary of Science and Technology. LAROUSSE, Edinburgh & NewYork, 1995, page 1180

> and evaporation and from other surfaces is referred to as evapotranspiration (ET). The (ET) rate is generally measured in millimetres depth of water per day (mm/day). [48]

The quotation indicates the two different forms of evaporation involved in the cooling process, from the plant and from the ground in which the plants may be growing. These processes are considered in sufficient detail to enable an interpretative evaluation of how evaporation influences the physiological and morphological structures of the turfgrass plant within a stadium with a retractable roof. This interpretative evaluation is set out in **(Section 5.3.0.1.).**

What is clear from these studies is how vital it is to manage the correct balance between the supply and demand for water to achieve both vigorous growth and maintenance of the turfgrass plant. "The ability of a plant to transport water and dissolved ions upward from the root enables a plant to supply nutrients to its stems and leaves while growing upwards and exposing its leaves to sunlight"[49].

Adams encapsulates in a few lines the major influence of water on the turfgrass plant and how outside factors impose their influence on the action of water within the plant.

> The water content of actively growing turfgrasses is generally from 75 to 85% by weight. The water content varies with the turfgrass cultivar, type of plant tissue, weather, location, intensity of culture, time of day and time of year. Young tissues are higher in water content than are mature tissues because of their lower dry matter content, thin wall cells and a highly hydrated protoplasm. The roots are lowest in water content; the leaves, intermediate; and the stems, highest.[50]

The important roles of the evaporation of water from the plant and the soil are discussed in some detail in the following sections.

4.5.1. Transpiration.

Transpiration can be defined as the loss of water by evaporation via the exposed surfaces of a plant: diffusion takes place through stomata which are the same mechanisms that play an important role in the gaseous exchanges involved in the photosynthetic process.

---

[48] Aldous, D.E Ed International Turf Management Handbook, Butterworth-Heinemann, 1999, Page 119.

[49] Walker.P. Ed. Dictionary of Science and Technology. LAROUSSE Edinburgh & New York 1995 Page 626.
[50] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 261.

Ninety percent of stomata are located in the turfgrass plant leaves; therefore they are the sites of the principal water exchange. Stem tissues where the residual stomata are located make only a secondary contribution to diffusion.

Stomata possess the unique ability to open and close through the action of the physiologically regulated guard cells. Light stimulates a carbon dioxide control system, which causes the stomata to open, while darkness causes closure. Other factors influencing the stomata aperture include temperature, internal plant water stress, pH and certain chemicals. Partial or complete closure of stomata may occur during mid-day owing to a plant water deficit or extremely high temperature.

Stomata are distinctly elongated and relatively small and are located on both faces of leaves but occupy only 2 to 3% of the leaf surface area. It is reported that stomata density typically ranges from, between 1,000-6,000 on the lower leaf surface, and on the upper surface between 4,000 and 10,000 stomata per sq cm. But Beard points out that "The stomatal density and distribution varies with the turf grass species, leaf position and surface and the environment under which the stomata developed."[51]

It is not only the differences of distribution and density of stomata within species that influence the ability of a plant to transpire. The varying physiological and morphological features within individual species or cultivars will also make transpiration rates vary. The pursuit of horticultural regimes will also influence transpiration rates. These pursuits include defoliation and the application of certain chemicals. Pesticides, soluble salts, copper-containing fungicides increase the transpiration rate and reduce drought tolerance. In contrast, some herbicides may cause a reduction in transpiration.

Water stress and high light intensities increase the number of functional stomata differentiated from epidermal cells. Stomata of turfgrass leaves are usually arranged in longitudinal rows interspersed among other epidermal cells. The spacing of stomata on a leaf results in a more rapid upward diffusion rate per unit of evaporating area than would occur from a free-water surface.

Beard suggests that the following variations in the physiological and morphological structure of turfgrass plants influence the rates of transpiration.

---

[51] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 273.

- Rooting depth.
- Total number of Roots.
- Root shoot ratio.
- Total leaf surface area.
- Cuticle thickness.
- Osmotic pressure of the cells of the leaf.
- Leaf morphology.
- Leaf orientation.
- Internal leaf structure.
- Structure, spacing, size and location of stomata.
- Leaf rolling or folding capability.

> The processes of stomatal transpiration involve the evaporation from the wetted surfaces of the mesophyll cells into the intercellular spaces. The water vapour then diffuses along a vapour pressure gradient through the intercellular into the stomatal cavity and eventually to the external atmosphere.[52]

The stomatal transpiration rate is a function of the vapour pressure gradient which increases with the following:

- A decrease in the atmospheric vapour pressure adjacent to a leaf.
- An increase in wind speed adjacent to a leaf.
- A high leaf moisture content.
- An increase in temperature.

However the rate of diffusion from a plant leaf depends on:

- Internal leaf resistance.
- The resistance set up by a leaf boundary layer.
- Vapour pressure gradient.

The internal diffusion resistance to water vapour for the turfgrasses according to Beard are approximately 0.4 seconds per cm and the external diffusion resistance is approximately 1.2 seconds per cm. The diffusion resistance values vary within species; drought resistant species have higher values.

[52] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 272.

4.5.2. Evapotranspiration.

Evapotranspiration is the product of the two forms of evaporation:

- Turfgrass transpiration.
- Water loss to the air from the ground in which a transpiring plant is growing.

In uniformly dense turfgrasses transpiration is the main contributor to evapotranspiration losses.

Evapotranspiration is influenced by

- Light duration.
- Temperature.
- Atmospheric vapour pressure.
- Wind.
- Water absorption rate.
- Soil moisture tension.
- Shade.

Solar radiation is the main source of energy for evapotranspiration.

> The amount of energy available for the process depends on the relative partitioning of incoming solar energy among evapotranspiration, reflection and heat transfer by conduction. The internal leaf vapour pressure increases as the leaf temperature rises owing to increased solar radiation. There is also a corresponding increase in the transpiration rate due to the increased vapour pressure gradient.[53]

The influence of atmospheric water vapour content and wind speed on the evapotranspiration rate can be substantial.

The evapotranspiration rates from perennial ryegrass turf have been compared for 2 days having similar solar radiation patterns.

Day A is comparatively cool, calm and humid with a low total evapotranspiration rate of 0.23.
Day B is characterised by dry, strong winds and a total evapotranspiration rate of 0.46 .

---

[53] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 274.

The water vapour diffusion rate from the leaf is influenced by the difference between the vapour pressure in the intercellular spaces and the vapour pressure in the external atmosphere. A decrease in the atmospheric water vapour content results in a more rapid transpiration owing to a large vapour pressure gradient. Transpired water vapour tends to accumulate in the boundary layer adjacent to the leaf in still air. The mixing action of the wind reduces the thickness of the water vapour boundary layer, which lowers the external pressure and increases transpiration.

4.5.3. Water Use Rates.

Water Use Rate can be defined as the total amount of water required for turfgrass growth plus the quantity of water lost by evapotranspiration. Beard reports that the water use rates in most turfgrasses are 0.1 to 0.3 inches per day but rates in excess of 0.45 inches occur occasionally.

The evapotranspiration rate per unit area of turf is much greater than the equivalent area of bare soil, owing to transpiration through the extensive area of leaf surface served by a root system capable of removing the available rootzone water.

A number of factors influence water use rate:

- Evapotranspiration.
- Length of the growing season.
- Growth rate.
- Turfgrass species or cultivar.
- Intensity of culture.
- Intensity of traffic.
- Soil type.
- Rainfall.
- Available soil moisture.

The total seasonal water use rate of a turf is a function of the length of the growing season. The longer the growing season, the greater the annual water use rate of a turf. The water rate also varies with the seasons of the year. Seasonal conditions favouring rapid shoot growth and transpiration cause an increase in the water use rate. Peak water use rates generally occur in early midsummer in most regions and decline to relatively low levels during the winter.

Turfgrass species and cultivars vary in the amount of water used. The water rate is not necessarily related to the drought tolerance of a turfgrass species.

Water use rates are influenced by cultural practices, for example, by lowering or increasing the cutting height. Reducing the leaf area causes a decrease in the total transpiration rate per plant but the water loss rate per unit of leaf area actually increases. Water use rate will increase and so will the propensity for disease if defoliation is carried out with a dull, improperly adjusted mower.

Nitrogen fertilisation increases the total water use of turfgrasses. "When expressed in terms of the water used per unit of growth produced, however, increasing the fertility results in more efficient water use".[54] Certain turfgrass diseases such as rust disrupt the leaf epidermis and can also cause an increase in the water use rate.

The water use rate declines as a result of a number of factors:

- A decrease in the moisture content of a soil.
- Turfs that are irrigated less frequently.
- The lowering of a water table.

The turfgrass must be irrigated to prevent a plant water deficit whenever the water use rate exceeds the effective precipitation for a period of time.

4.5.4. Water Deficits.

The water content of a turfgrass plant is determined by the balance between water absorption and transpiration. The plant balance is favourable as long as the absorption exceeds transpiration. Whenever transpiration exceeds water absorption, the water balance is negative, causing an internal water deficit or stress. These conditions may be transient or permanent, depending on the available soil moisture level. Water deficits most commonly occur during the months of summer, with the changes in the use patterns of stadia. These periods can coincide with maximum usage.

The growth rate and turgidity of a turfgrass plant declines under moisture stress. The effects of water deficits range from death to less severe morphological and physiological modifications of the turfgrass plant. A plant water deficit produces such morphological modifications as

- Increased rooting depth.
- Increased root-shoot ratio.
- Decreased tillering.
- Decreased leaf numbers.
- Reduced shoot elongation.

---

[54] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973 Page 277.

- Decreased size and total area of leaves.
- Thinner leaves.
- Smaller cells in the leaves.
- Thicker cuticle.
- Thicker cell walls.
- Smaller intercellular spaces.
- Smaller xylem cells.

The influence of water deficits on the physiological processes are not as obvious as the morphological modifications but the effects are just as important. Physiological changes resulting from a plant water deficit include

- Decreased succulence.
- Higher osmotic pressure.
- Decreased photosynthesis rate.
- Increased soluble carbohydrate.
- Decreased protein content.
- Increased bound water.

Turfgrass plants grown under a continual water deficit have a higher osmotic pressure and lower tissue water content. A water deficit causes a general reduction in physiological activity. The effect of water stress in decreasing the photosynthetic rate is quite striking. An internal water stress causes stomatal closure and increases mesophyll resistance to the inward diffusion of carbon dioxide needed for photosynthesis. Dehydration decreases respiration in seeds and certain mature tissues but stimulates respiration in actively growing tissues. Associated with the metabolic changes are increases in the soluble carbohydrate free amino acid, amide, and bound water content. A water deficit enhances the hydrolysis of starch, causing an increase in the water-soluble carbohydrates.[55]

4.5.4. Diurnal and Seasonal Variations.

A diurnal variation in the water content of grass plants is observed. The osmotic pressure of the leaves is usually lowest during the night and increases substantially during the daylight hours. The increased osmotic pressure during the daylight hours is caused by an increase in the concentration of soluble carbohydrates and other organic compounds resulting from photosynthesis.[56]

---

[55] Beard. J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 279.
[56] Beard. J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 279

A decrease in the water content of a plant is caused by the transpiration rate exceeding the absorption rate.

The leaf water content varies inversely with osmotic pressure with the highest turgidity usually occurring at night and the minimum at midday. Wilting is likely to occur during the latter period.

4.5.6. Leaf Wilt.

Leaf wilt is the visible drooping, rolling, or folding of turfgrass leaves resulting from a loss of turgidity.

> The first visible symptom of water stress is a grey to blue-green or slate coloration frequently evident on the leaves. Wilt occurs when the rate of water loss by transpiration exceeds the absorption rate of the roots. A restriction in the water translocation caused by increased resistance of the water flow may occasionally cause wilt. Wilt may occur as small-localised spots or may extend over a large turfgrass area. It may occur at any time during the growing season but is most common during midsummer.[57]

The loss of leaf turgidity can also be detected by visible signs of slow or partial standing recovery in response to casual foot traffic.

An alternative form of wilt occurs when the soil moisture level is both available and adequate but because of a limited root system or a poor water absorption capability of a species, a plant is unable to take advantage of the available moisture. This form of wilt is termed wet wilt.

Wilt in turf may occur while a plant is growing in waterlogged soil, thus limiting respiratory oxygen to the vital root hair zone causing death or serious injury to turfgrass. The consequence of these conditions is termed wet wilt.

The factors that stimulate transpiration or restrict water absorption increase the wilting tendency of turfs.

Conditions favouring transpiration and potential wilting are

- High temperatures.

---

[57] Beard, J, Turfgrass Science and Culture, Prentice Hall, New Jersey, USA, 1973, Page 280

- Wind movement.
- Solar Radiation.
- Low external vapour pressure.

Wilt of turf is usually a more frequent problem on ridges, knolls and high spots that are exposed to the drying action of winds and where infiltration is reduced.

Water absorption may be impaired by a lack of available soil moisture or a limited non-functioning root system. Shallow rooted turfs are more prone to wilt. Common causes of poor rooting include

- Lack of aeration.
- Compaction.
- Waterlogged soil.
- Excessive nitrogen fertilisation.
- Severe leaf defoliation.
- High soluble salt level in the soil.

Thatched turfs are more likely to wilt owing to the shallow root system.

Wilting Tendency	Turfgrass species.
Very low	Sheep fescue.
	Red fescue.
Low	Meadow fescue.
	Redtop.
	Chewing fescue.
Medium	Canada bluegrass.
	Kentucky bluegrass.
	Creeping bentgrass.
	Perennial ryegrass.
High	Velvet bentgrass.
	Timothy.

Temporary water stress inhibits many vital metabolic processes in the plant:

- Stomatal closure seriously restricts photosynthesis.

- Transpiration is also restricted by stomatal closure.

The resulting rapid rise in leaf temperatures may cause the temporary impairment of numerous metabolic processes or even death.

Vehicular traffic can cause death to wilted turfgrass and should be avoided until wilting has been corrected.

The most serious aspect is that wilt is the first stage leading to desiccation. Wilt and even desiccation can occur within a matter of hours on close cut bentgrass having limited roots.

4.5.7. Wilt Prevention.

The following measures will prevent or limit the extent of wilt.

- An adequate supply of available soil moisture.
- The frequency and supply of water adjusted to the evapotranspiration rate.
- Deep and extensive root system. Good soil aeration.
- High cutting height and proper mowing frequency.
- Balanced Nitrogen, Phosphorus and Potassium levels.
- Thatch control.

Wilt prevention involves a number of complex and interwoven cultural issues, as well as biological factors. If ignored it will produce mal-functioning turfgrass. Both sets of factors have been considered in this work and if systematically applied in the anticipated environmental conditions should produce healthy turfgrass and also generally control wilt. But Beard further suggests that syringing be applied in the case of the first suspicion of wilt. Syringing reduces the transpiration rate by decreasing the temperature and increasing the atmospheric water vapour levels surrounding the leaves.

Other methods of controlling transpiration at the leaf interface are being considered since wilt may occur even when the soil moisture is adequate. The methods being considered involve

- Chemically induced stomatal closure.
- Covering the mesophyll surface with a thin, monomolecular layer.
- Covering the leaf surface, including the stomata with a thick film that is relatively impermeable to water vapour.

It is essential to ensure that methods that control transpiration at the leaf surface do not impair gaseous exchange to the extent that growth is restricted. But a degree of growth inhibition of turfs can be tolerated. But care has to be exercised to ensure that the measures are not so successful as to cause leaf temperatures to rise to levels that are lethal to turfgrass.

INDEX PART FIVE.

CHAPTER ONE.

5.1.0. TURFGRASS DRAINAGE.

5.1.0.1. Introduction.
5.1.1. Playing Surface Drainage in a Stadium with a Retractable Roof.
5.1.2. Purposes of Horticultural Drainage in Stadia.
5.1.3. Installation of Drainage Systems.

CHAPTER TWO.

5.2.0. ROOTZONE COMPOSITION.

5.2.0.1. Introduction.
5.2.1. Soil Texture and Structure.

CHAPTER THREE.

5.3.0. SUB-SOIL WARMING.

5.3.0.1. Introduction.
5.3.1. Is there a requirement for Sub-soil warming in Retractable Roofed Stadia.
5.3.2. Sub-soil Heating Load.
5.3.3. Sub-soil Warming and the Incidence of Turfgrass Disease.
5.3.4. Relationship between Economics and Use of Subsoil Warming.

PART FIVE.

CHAPTER ONE.

5.1.0. TURFGRASS DRAINAGE.

5.1.0.1 Introduction.

The drainage of hard surfaces is not a matter for this thesis. Nevertheless, it is useful to define in principle the difference between the drainage of hard and soft areas. Most of the water falling on a hard surface is discharged from that surface which to all intents and purposes seals a compact sub-base. The ensuing problems of water disposal are resolved by engineering principles.

In contrast, most of the water falling on a soft surface infiltrates that surface and flows into the soil sub-base. The particle constituents of the soil should be cohesive but not totally compacted. The consequential problems of dealing with soil water are comparatively complex, involving a broad range of issues based on soil physics. Some of these resulting issues influence directly plant growth and maintenance.

The volume of water falling on a soft surface, its intensity, rates of water infiltration and retention are some of the issues that make draining soft areas complex. The texture and structure of a soil governs both water retention and infiltration. The material composition, arrangement, size, shape and juxtaposition of the particles leave spaces within the soil called pores. It is these spaces through which both soil /air and plant roots travel.

Other factors influencing water retention are soil depth, the presence at a substrata level of a fissure which forms a natural drainage outfall. Alternatively water retention can be influenced by the installation of a piped drainage system or a gravel drainage blanket discharging into a planned outfall. There are occasions when artificial drainage may be used to augment natural drainage. Adams and Gibbs suggest, however, that drain laying ought not to be required below 800mm.

Water is essential to the needs of plant growth. The volume of water retained by the soil is determined by the porosity of the soil and by the efficiency of the drainage which can be either natural or artificial. The aim of the rate of removal should be such as to allow a balanced water/air relationship. "The volume of air in the soil is largely determined by the soil water content. The greater the water content, the smaller the volume of soil air and the more quickly is the oxygen depleted by respiration"[1].

"The concentration of oxygen in the soil/air is less than that in the atmosphere..... but it does not usually limit the supply to the roots unless it falls to a low value, perhaps less than 10% by volume of air. It is the volume and distribution of soil air that are critical".[2]

Not all plants receive their oxygen in this way, for example wetland and bog plants which are adapted to being water saturated receive their oxygen internally.

Turfgrasses are amongst those plants that rely on soil pore passages for the oxygen that drives plant respiration. The composition of the rootzone material is an essential factor in that complex relationship and when rootzones are modified the make-up of the composition must be influenced by the drainage strategy.

Adams and Gibbs emphasise the importance of rootzone composition and the dual purpose it plays in turfgrass technology.

> ...... The growing potential of a soil is related to its being able to provide two important divergent physical characteristics: that of the drainage to allow aeration and that of water retention for the use of plant roots. From the plant point of view, the physical framework of a soil must therefore contain a system of pores stable enough to preserve its porosity, but so strong that the individual plant roots cannot enlarge and explore pores within the soil system. The continuity of pores is as important as the quantity.[3]

5.1.1. Playing Surface Drainage in a Stadium with a Retractable Roof.

European stadia with retractable roofs have natural playing surfaces incorporating various methods of drainage. Of these, the complex computer controlled P.A.T. drainage system installed at Amsterdam ArenA has never been used: it is unlikely it ever will be, **(8.0.4.)**. The Millennium Stadium drainage system is simple, but its efficiency has to be questioned. Drainage holes, set in groups are located at the base of each individual pallet. This

---

[1] Wild, A Soils and the Environment (An Introduction), Cambridge University Press, 1993, page 28.
[2] *Ibid page 118.*
[3] Adams W.A., Gibbs R. J. Natural Turf For Sport and Amenity: Science and Practice. CAB INTERNATIONAL, Wallingford, OXON,UK 1994. page 71.

arrangement may be a contributory factor to the current sour condition of the pallet soil. At Arnhem and Gelsenkirchen effective drainage arrangements are set up in single concrete pallets.

Most literature dealing with turfgrass drainage relates to agricultural conditions or equivalent open conditions. There is however, a body of literature covering drainage of sports turf for Racecourses, Golf Greens, Cricket Greens and areas for the Games of Football in various locations. As yet there is no published research dealing with the drainage of playing areas in stadia with retractable roofs. Two factors make draining playing areas of stadia with retractable roofs different from draining playing areas found in natural open conditions.

1) **Such a roof allows for the exclusion of precipitation.**
2) **The capital cost of providing drainage and a rootzone are insignificant in comparison with the overall capital costs of a stadium.**
3) **Such stadia may necessitate the consideration of a range of options in respect of modes of drainage, rootzone composition and methods of providing the playing surface,**

A rootzone will be automatically isolated when a stadium is built over other forms of development, or when turfgrass is set in a pallet system. An isolation layer will also be used where rootzone drainage is based on mechanical suction. A mechanical barrier also allows for the containment of any chemicals within the rootzone. Thus the polluted liquid can be taken to a settling tank before being passed into the main surface water drainage.

A rootzone may be modified either by replacing removed material with a new rootzone composition or by amelioration of the existing material through mixing into the soil the correct type of sand. Or change may be brought about by adding a surface layer after an initial surface has been stripped. Whatever the method adopted in rootzone provision it is essential to associate it with the method of drainage adopted.

Managing the opening and closing of a retractable roof in periods of precipitation offers the opportunity of controlling the volume of water falling on a playing surface. This, coupled with determining the rootzone composition through soil modification enables better control of the soil/air balance.

Adjusting the frequency and length of irrigation dosing can be used to adjust any shortfall or excess in the soil water available by roof management.

Despite the available facility to control the ingress of rainwater on a stadium playing surface, the idea of omitting drainage from such a location has not been considered. Where turfgrass is permanently fixed in stadia, a case for drainage inclusion can be made as can a case for its exclusion. There is evidence that ArenA Amsterdam operates without a functioning drainage system. Two major stadia with retractable roofs, scheduled for completion in the UK after the year 2000, will have drainage systems incorporated in their playing surfaces without the question of its need ever having been considered.

A turfgrass playing surface in a movable single pallet requires the same provision of drainage as the playing area in an open stadium. The rootzone may be 400 to 500 mm deep; the first 200-mm should be free of any form of obstruction. The residual depth for any piped drainage system will require either the pipe to be pressurised or laid to a suitable gradient to allow for the appropriate degree of water movement.

In the various pallet arrangements the drainage depth will be limited by the constraints imposed by the pallets. Fall, however, need not be a limiting factor in the single pallet configuration as there is potential to develop the pallet base to provide drainage outlets in numbers and locations to promote efficient drainage.

These outlets may be linked together by removable flexible connections to discharge into a separate drainage system at a lower level designed as a hard surface drainage system.

The rootzone depth should be considered as the zone in which the turfgrass roots develop and migrate; as a parallel consideration the depth and composition of the rootzone influences the rate of water infiltration and its removal. As such there must be a balance in determining its depth between the needs of drainage and of root development.

Draining a playing area made up of multi-pallets may be more complex than draining a playing area set in a single pallet. One reason for this is the influence of compaction. For practical reasons compaction is more difficult to relieve in a multi-pallet arrangement by mechanical slotting or "by the application of high pressure water injection"[4]. The

---

[4] Emmons, R, Turfgrass Science& Management, Delmar Thomson Learning,UK,& USA, 2000, page 384.

proliferation of the fibreglass sides of the pallets prohibit these methods. The options available for compaction relief in the multi-pallet arrangement are solid or hollow core tining carried out manually.

Draining a playing surface where the rootzone is not subject to artificial modification is well covered in the literature and will not be repeated. Both Adams & Gibbs and McIntyre & Jakobsen are relevant in the theory and practice of turfgrass drainage in the open condition.
In considering turfgrass drainage it is important to acknowledge the basic principles of soil physics which McIntyre & Jakobsen suggest are not understood by some of those who prepare drainage schemes for soft areas.

5.1.2. The Purposes of Horticultural Drainage in Stadia.

Sub-surface drainage removes excessive water from a rootzone. If that purpose fails and water ingress exceeds egress waterlogging will occur and the oxygen essential to plant roots will be unavailable. Under these conditions the subsoil will change its state.

Under unexceptional conditions rainwater will drain naturally to the level of an impermeable layer and there, it may add to a fluctuating water table or migrate to a point of natural discharge. The rate of discharge will depend on the soil texture and structure, the relationship of the impermeable layer to the surface level and on any gradient that layer may have to a discharge point.

In nearly all circumstances it is necessary to supplement natural drainage by the inclusion of a system of drainage pipes or by slit drainage systems. These arrangements are commonly considered the effective means of sports field drainage but McIntyre & Jakobsen express the view that piped drainage arrangements are misunderstood and comment as follows.

> People have assumed that if sub-soil drains are installed in certain locations, water will quite 'logically' flow into them through the soil. Some text books *[sic]* even tell us this. Once again it is often **wrong**, simply because the first assumption that 'water flowed sideways in the soil at a reasonable rate' was itself **wrong**.
> On the basis of this incorrect assumption, we see millions of dollars being spent all around the world by people installing sub-soil drains in playing fields, golf courses, race courses, garden beds and various other places. Unfortunately, these will never

drain anything effectively other than the area directly above the drainpipe itself, and perhaps with time a total width of about a metre, if the soil profile is deep enough.[5]

Where drainage is required, in a compact stadium with a retractable roof a piped system may not be the best or only solution. The following section looks at the possibilities of draining such a surface, considering the differing ways a rootzone may be housed.

5.1.3. Installation Drainage Systems.

Around the mid 20th Century horticultural drainpipes usually took the form of perforated clay pipes. These have been replaced by perforated PVC pipes which range in size from 35 to 200mm in diameter. The smaller size is used for sand slitting. Pipes are either corrugated or smooth; corrugated pipes are stronger but less efficient "the corrugated pipe has about 75% of the flow capacity of smooth bore pipes of the same diameter"[6].

A piped drainage system consists of main pipes with lateral connections. The effectiveness of the system depends on the ratio between the spacing and depth at which the pipes are laid. Water discharge rates relate to pipe size, efficiency of the flow and the gradient at which they are laid.

McIntyre and Jakobsen suggest that there may be a misconception prevalent at some levels in the turfgrass industry about the behaviour of water when in contact with soils. They restate working principles as follows:

> Water only moves sideways if there is a component of gravity pulling it, and this is usually achieved by the slope on the sub-grade. The steeper the slope, the higher the component of gravity. Water will move laterally towards a drain where it is being removed even though the base may be flat. Under these circumstances the gradient on the depth of the saturated free water zone, as it is being depleted, provides the gravitational component. For example, if the slope on the sub-grade is 1:100, then water is only being pulled sideways across that slope at one-hundredth of the rate that it can move downwards, or one-hundredth of its saturated hydraulic conductivity. .....
> If the slope on a base is only 1:100, then the maximum rate at which the water can move sideways is 0.2 millimetres per hour (20 x 1/100). Therefore even on a steep

[5] McIntyre, K&Jakobsen, B Drainage for Sportsturf & Horticulture. H. E. C. 5 Brimage Place Kambah ACT Australia 2902. 1998, page 1-2.

slope water cannot move very quickly sideways but on the more common gentle slopes, water moves sideways very slowly indeed.[7]

Whether stadia have retractable roofs or not, their natural playing surfaces will have modified rootzones, either by soil replacement or by adding rootzone material to an existing surface. Rootzone modification facilitates the control of soil composition, depth, and maybe gradient.

In certain circumstances there can be no alternative but to modify a rootzone, for example when turfgrass is contained in any form of pallet or where stadia are built over other forms of development.

A multi-pallet system like the single pallet can only be drained at the base level. An examination of the pallet drainage at the Millennium Stadium suggests that the arrangement is not working efficiently. The soil is over compacted and the removal of the turfgrass exposes sour odour typified by a lack of oxygen.

The rapid removal of surface water on a playing area can be aided by introducing surface gradients; the extent of these will differ with the different rootzone arrangements. The single pallet arrangement can be designed to produce efficient drainage. Nevertheless, it is advisable to build in surface gradients. The surface gradient, whatever that may be in the multi-pallet system, has to be reflected in the base on which the pallets are supported. This simplifies the setting out of the pallets and produces a continuous linear high point on the long axis of the playing surface.

The adoption of the traditional rootzone offers the possibility of providing gradients at the levels of the playing surface and the base of the rootzone. The surface gradient will be limited by the influence it has on the playing conditions. The base gradient will be determined by hydraulic conductivity of the soil. But the advantages offered to drainage efficiency by determining the base gradient have to be set against the advantages pallet systems offer in allowing turfgrass to be removed from a stadium. In most matters relating to delivery of healthy turfgrass it is not a matter of providing a satisfactory solution to one aspect of that problem that is multi-faceted. A balanced approach must be offered in order to

---

[6] Handreck, K Black, N,Growing Media, NUSW PRESS, 2002, Third Edition, ISBN 086840 796 8.
[7] Aldous D.E. Editor International Turf Management, Inkata Press, Australia , 1999. ISBN 0 7506 8954 4 page71.

achieve a holistic solution to the maintenance of turfgrass which may suffer from inadequate light, air movement, temperature, excessive wear and inadequate drainage.

Surface gradients are important in exceptional conditions in facilitating the shedding of water from a playing surface towards the surrounding margins of the pitch. This action reduces the volume of water entering a rootzone. The objective can also be achieved by closing a roof but if exceptional conditions occur during a game it might be difficult to arrange for the roof to be closed unless the rules of a Game permit that to happen.

McIntyre & Jakobsen suggest that the use of a surface fall can save drainage costs as drains will not have to be installed at close centres. "A much better strategy under these circumstances, would be to make sure there is sufficient surface fall of about 1in70 (1 in 100 is definitely not sufficient), as this will shed a large amount of water before it enters the soil in heavy or prolonged rain".[8]

Adams & Gibbs suggest that "slopes in excess of 2.5% are undesirable".[9] This statement relates to the influence gradients have on playing characteristics and not the removal of surface water.

It is important to set drainage costs within the context of capital expenditure of stadia construction; drainage and rootzone costs can represent a small percentage of the overall building costs. These costs ought to reflect the importance of the natural turfgrass playing surface as the internal focus of a stadium. As such it has to present a favourable visual impression and also a surface that is both firm but yielding and one that displays an even ball roll and optimum levels of ball bounce. To achieve these standards many factors are involved amongst which is an efficient drainage system.

Even with the inclusion of an efficient traditional drainage scheme, building in surface falls is advisable. This is especially so when a complete single pallet system is installed, which may be withdrawn from a stadium from time to time. Providing gradient falls will also reduce the effect of hollowing which can occur through soil settlement.

[8] McIntyre, K&Jakobsen, B Drainage for Sportsturf & Horticulture. H. E. C. 5 Brimage Place Kambah ACT Australia 2902. 1998, page 110-111.

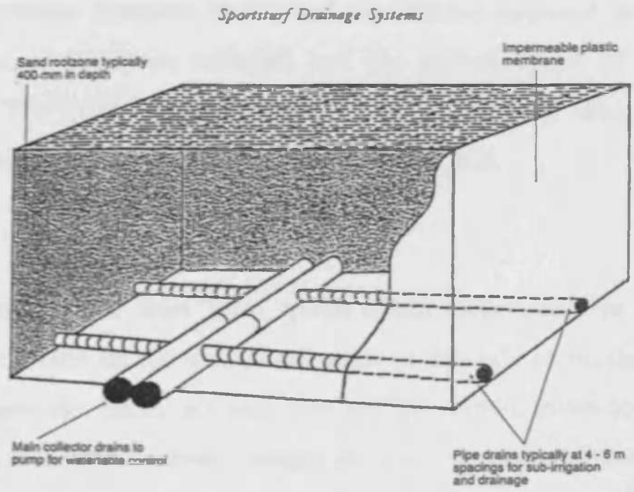
A method of providing turfgrass drainage without reliance on gravitation is with a system known as Prescription Athletic Turf. The PAT system was invented in the USA by "Daniel et al., 1974, USA Patent No 3908385"[10]. The system is composed of a network of pipes laid without falls at the base of a modified rootzone. Mechanical suction is used to extract water from the soil through the pipes at accurately controlled rates by computers.

The benefits are that balanced water/soil ratios can be maintained even in exceptional conditions. Control enhances turfgrass growth, maintains soil structure and through that, stable playing conditions. The suction process can be reversed to provide subirrigation and fertilisation. Plant roots feed directly at the rootzone base as well as from water percolation. The PAT system and the alternative "Vacudrain system employ extra features in addition to those used by the Cellsystem and Purr-Wick systems."[11]

The PAT system has advantages for use with shallow modified rootzone construction. The minimum depth of rootzone construction should, however, also be balanced with the requirements of migratory root development, which varies between turfgrass species. Where the PAT system is adopted for a single pallet arrangement the control system would have to be duplicated at both the stadium location and the outside location adjacent to the stadium.

Fig. 5.2.0.1.

An all-sand drainage system utilising one construction medium enclosed within an impermeable plastic membrane. In some highly specialised designs of this type, pumps are attached to the main drain for the very rapid removal of excess water. (After Adams and Gibbs)



---

[9] Adams W.A., Gibbs R. J. Natural Turf For Sport and Amenity: Science and Practice. CAB INTERNATIONAL, Wallingford, OXON,UK 1994. Pagel15.
[10] Ibid. page 93.

[11] Adams W.A., Gibbs R. J. Natural Turf For Sport and Amenity: Science and Practice. CAB INTERNATIONAL, Wallingford, OXON,UK 1994. Page96.

CHAPTER TWO.

5.2.0. ROOTZONE COMPOSITION.

5.2.0.1 Introduction.

Most turfgrass succeeds on what can be described in 'shorthand form' as pasture soil. Such soil will most probably not match the requirements of a rootzone suitable to nurture turfgrass used for the display of ball games.

Soil can be defined as a "loose material composed of weathered rock and other minerals, and also partly decayed organic matter".[12] Adams &Gibbs point out that "the essential property of soil is that it provides an environment for the biological cycling of carbon. There are two components to this cycling: (1) fixation of carbon by photosynthetic organisms (usually plants) (2) the decomposition of carbon compounds derived from heterotrophic organisms (mainly micro-organisms) living within the medium"[13].

Besides meeting the biological needs as a growing medium soil also facilitates the retention or release of water infiltration, a process essential to the soil/air balance required to aid biological activity. The proportions of the loose material and the particle sizes of that material define soil composition. The proportions and particle sizes make up what are termed soil texture and structure. These terms are expanded briefly in **5.2.0.2.**
Adams & Gibbs state that:

> in most soils it is the particles smaller than 2mm which affect behaviour. For this reason particle size classes are based on the size distribution of the fine earth, that is soil sieved through a 2mm aperture. Sand, silt and clay are the names given to the particle size categories; the size limits for these categories differ somewhat between different systems, as do the subdivisions between the categories."[14].

A turfgrass rootzone is that upper part of a 'cross-sectional slice' through a soil profile. The effective depth of a turfgrass rootzone can be between 250mm and 400mm. A rootzone has a

[12] Wild, A. Soils and the Environment an Introduction, Cambridge University Press, 1993, page 16.
[13] Adams W,& Gibbs R, Natural turf for Sport and Amenity Science and Practice, CAB International,1994.page1.

fourfold impact on turfgrass: 1) as a growing medium 2) as a root anchorage, 3) it influences rates of water percolation and retention; 4) it also influences surface compaction.

5.2.1. Soil Texture and Structure.

Soil texture refers to "the relative proportions of clay, silt and sand in a sample of soil. The dominant size fraction is used to describe the texture, for example as clay, sandy clay, silty clay etc. If no fraction is dominant the soil is described as a loam."[15]

Adams & Gibbs suggest that the term 'texture' is replaced by 'particle size class' because of the common confusion between the term soil texture and soil structure. There ought to be no confusion. The distinction between Soil Texture and Soil Structure is this: Soil Structure is the arrangement of the particles in a soil sample, and the dominant size fraction of those particles describes texture of the soil. A quotation from Wild also develops the definition of soil structure.

> A soil in which these *[the soil particles]* are unattached to one another is said to have a single-grained structure or be structureless; this occurs with coarse-grained materials as in sand dunes. At the other extreme is massive structure where all the mineral particles are packed tightly together, as occurs in some clay soils. More usually the particles form aggregates, which have a size and shape that are characteristic of the soil. For arable cropping soil should consist mainly of small aggregates or crumbs, which allow seedlings to emerge easily and provide a ready supply of water and oxygen to plant roots. This desirable state is brought about by judicious cultivation and is described as tilth. The aggregates should be sufficiently strong to avoid being broken down by the impact of raindrops, otherwise the soil surface may form a crust which can prevent seedling emergence and may also lead to run off and emergence of erosion.[16]

The visual and textural appearance of a soil can provide a guide to its performance in aiding the growth of turfgrass and also for its qualities as a drainage medium. The extent of the soil's potential can be confirmed by the tactility of a soil. Whilst the action of 'seeing and feeling' is insufficient to provide an accurate guide to its biological performance, it is

---

[14] Adams,W, Gibbs, R, Natural turf for Sport and Amenity: Science and Practice.CAB International 1994, page2.
[15] Wild, A, Soils and the Environment an Introduction, Cambridge University Press, 1993, page 16.

[16] Wild, A, Soils and the Environment an Introduction, Cambridge University Press, 1993, page 16

certainly helpful in providing an initial appraisal of the classification of a soil, but texture alone is insufficient in evaluating the properties of a soil.

Handreck & Black suggest ways of making a field assessment of the classification of soils by kneading samples of soil material with water and pressing the mixture through the thumb and forefinger.

> At one extreme are soils in which no individual particles can be felt. They are smooth and slippery and can be pressed into long ribbons- the clays. At the other extreme are the soils that cannot be pressed into ribbons; the particles in them can be easily felt and seen- the sands. Most soils fall between these extremes. We can feel sand in them, but they also contain finer material and they can be pressed into short ribbons- these soils are called loams.[17]

Wild suggested that 'if no fraction is dominant the soil is described as a loam. That statement is not contradicted by the Handreck & Black quotation. A loam is a composition as defined by Wild, but can also be classified as a Sandy Loam, Fine sandy Loam, Silty Loam, Sandy Clay Loam and Clay Loam. This indicates that there is some marginal emphasis toward either sand, silt or clay in what otherwise would be a composition without the dominance of any one of the three constituent elements. Loam can be distinguished because it "forms a coherent cast that feels spongy but with no obvious sandiness or 'silkiness'; it may feel greasy if much organic matter is present and forms a ribbon *[in the hand]* 25mm long."[18]

This wider classification of the composition of textural classes of soils is recorded in the Soil Triangle developed and used by the United States Soil Survey. This is shown in **Fig.5.2.0.2.**

[17] Handreck, K& Black, N,Growing Media for Ornamental Plants and Turf, 3rd Edt. UNSW Press,Sydney page 8.
[18] *Ib id* page9

Wild confirms a previous statement

> that whilst Texture is an indicator of other soil properties, used alone it has limited predictive value of those properties. For example, the ability to adsorb cations from solution depends on the mineralogy of the clay fraction as well as on the percentage of clay. It also depends on the amount and nature of the organic matter the soil contains. The permeability of soils to water depends more on the organisation of the mineral particles and organic matter into structural units with spore spaces between them than on texture itself.[19]

Soil texture indicates the way a soil will cultivate. Clay will need more energy for cultivation whereas the sandy soils will need less energy. Clay soils retain more water than sandy soils and consequently warm up later in the year than sandy soils.

It is the sand soils of varying composition which are currently being specified for sports turf being considered in this thesis.
Amongst the reasons that these mixes are being specified is that.

> due to absence of clay and silt in the rootzone, all-sand drainage systems should provide the fastest drainage rates for all intensive drainage solutions for sportsturf. However, it must be emphasised that the sand / soil drainage systems depend on the correct selection of sand to provide the hydraulic conductivity, air / water balance and physical stability. These requirements are to some extent contradictory and this considerably narrows down the selection of suitable sands.[20]

Table 5.2.0.2.1. Particle size grade categories for sports turf soils.

Description.	Very Coarse Sand.	Coarse Sand.	Medium Sand.	Fine Sand.
Particle size range (dia,in μm)	2000-1000.	1000-500.	500-250.	250-125.
	Very Fine Sand.	Coarse Silt.	Fine silt.	Clay.
	125-60.	60-20.	20-2.	< 2.

---

[19] Wild, A. Soils and the Environment an Introduction, Cambridge University Press, 1993, page 18.

[20] Adams,W, Gibbs, R, Natural turf for Sport and Amenity: Science and Practice. CAB International 1994, page93.

Table 5.2.0.2.2. Typical commercial grades for particles larger than 2mm in dia.,

Description	Fine Gravel.	Coarse Gravel.	Fine Stone.	Medium Stone.	Coarse Stone.
Particle size range (dia,in mm)	2-5	5-10	10-20	20-50	50-100

Tables 5.2.0.2.1 & 2.2 are extracted from page 3, Adams & Gibbs,Natural Turf for Sport and Amenity.

CHAPTER THREE.

5.3.0. SUBSOIL WARMING.

5.3.0.1. Introduction.

Subsoil warming by the means of thermal conduction is now the most common means of frost protection for football stadia. Historically, other means of avoiding ground freezing were employed such as siting coke braziers around a playing field or covering the pitch with straw bales.

Fig 5.3.0.1.1.
Stoke City Football Club UK. 1938.
Staff attempt to thaw ground.

Fig. 5.3.0.1.2.
White Hart Lane UK 1925.
3000 straw bales laid to protect pitch.

Beard suggests that the use of atmospheric methods of temperature control in low temperature turfs, such as smudging, artificial atmospheric heating, or forced convection wind machines to counteract temperature stratification are not particularly effective or practical for turfgrass areas.

The first subsoil warming system based on thermal conduction was installed at

> Everton's Goodison Park [*UK*] in 1958..... (though early experiments with such equipment had taken place at the club's practice ground back in 1937). Although Everton's system did not prove a success, similar systems were subsequently installed elsewhere in the UK and in other countries. [21]

Currently subsoil warming systems are activated when surrounding air temperatures reach 36°F on a falling thermometer. The aim is to enable ground temperatures to remain above freezing point, thereby allowing match fixtures to be played which otherwise would have to be postponed through the condition of the ground. However, factors other than the condition of the playing surface may make it necessary to postpone fixtures in adverse weather conditions. Nevertheless, the rules of the Premier League Section I Rule 20 indicated that each club " shall maintain at its registered ground an undersoil heating system or some other adequate system of pitch protection to the reasonable satisfaction of the Board"[22].

Investigations were undertaken to see if players were more vulnerable to sustain injuries in air temperatures around freezing point. The evidence from UK Premier League Physiotherapists and from the Professional Football Association suggests that players are not more vulnerable to injuries during freezing conditions than they are at other times.

The most common technique for subsoil warming is the passing of hot water or electrical cables through plastic pipes embedded in the rootzone. The current capital costs for these "schemes range around £150K in broad brush terms"[23]. It is also possible where single pallets are used to form a playing surface, to circulate warm air below the pallet containers to alleviate soil freezing.

5.3.1. Is there a requirement for Sub-soil warming in Retractable Roof Stadia?

Can the inclusion of a retractable roof in a stadium with in situ turfgrass obviate the need for subsoil warming systems? It can! Opening and closing a roof enables the climate within a cavea to be modified. In a multi-use stadium there ought to be provision when the roof is

---

[21] Pickering, D, Soccer The Cassell Soccer Companion, 1998 Edt. Cassell London 1998, page 316.
[22] The FA Premier League Handbook Season 2003-2004.

closed to temper the air when there is need to do so for some types of event. Under these combined circumstances, subsoil warming may be omitted. The decision to omit or include subsoil heating should be considered on both economic grounds and horticultural grounds. Humidity levels in enclosed conditions will increase and therefore so will the levels of evapotranspiration. A view will need to be taken as to whether the use of subsoil heating will increase the incidence of desiccation under those conditions.

If the playing area is contained in a single pallet, subsoil heating should be included in order to take account of situations when the pallet is moved from a stadium. The precedents for this assumption are the Gelredome Arnhem, Netherlands, Gelsenkirchen Stadium, Germany and the Sapporo Dome, Sapporo, Japan. It is relevant to consider the insulation values of the sides and base of the pallet as it will be exposed on all four faces in its stored position. This was not considered at Arnhem.

Where turfgrass is contained in multiple pallets and then moved to an outside location, the same problem arises: how to protect the turfgrass from frost. Other available options are using organic mulches or synthetic covers laid over the surface. Those covers made from "viscose rayon fibre cover, processed wood fibre cover, plastic screens, and polyethylene provide superior low temperature insulation"[24].

Beard also records a case for subsoil warming on agronomical grounds by indicating that a green, winter colour can be maintained during a normally dormant period by the use of soil warming. "Adequate colour of cool season grasses has been achieved even under intermittent periods of snow cover."[25] A significant amount of root growth of cool season turfgrasses occurs during the winter period if the rootzone temperature is maintained above 35°F. Thus the winter desiccation problem is reduced since the active root zone system is capable of absorbing water at all times. Higher levels of soil warming have actually induced leaf growth under relatively severe midwinter conditions.

However, it is unlikely that the benefits to be gained from this aspect of subsoil warming will be commercially considered by those who manage stadia because of the costs involved. The fundamental concern is to ensure that the playing surface is playable and for that to happen not only has the undersoil heating to be installed, it has to be used.

---

[23] Personal telephone communication with Hewitts. August 2003-2004.London. page 52.
[24] Beard, J,B, TURFGRASS SCIENCE AND CULTURE, Prentice Hall , 1973 page 243.

5.3.2. Sub-soil Heating Load.

The heating load for subsoil warming depends on the positional relationship between the heating element and the surface, efficient rootzone drainage, rootzone composition, climate, sward density and turfgrass height. Beard suggests that an input of 5 to10 watts has proven successful. But this assumption depends on the latitude and depth of the heating source. "A depth of 4" provides effective rapid surface warming with the additional advantage that the quantity of soil to be heated is smaller." [26]

Subsoil warming at a depth of 4" is not practical because of the need to aerate compacted turfgrass. A source suggests that " under soil warming cables or pipes should be set at 9" to10" to avoid the blades used for aeration".[27]

5.3.3. Sub-soil Warming and the Incidence of Turfgrass Disease.

Soil warming can influence the incidence of diseases in turfs during the winter period. Serious injury to turfs will arise when soil temperatures are maintained in a range that favours disease activity. On the other hand, "temperatures maintained at 32° F, resulted in no injury to Bentgrass from a low temperature, Basidiomycete or Fusarium".[28]

5.3.4. The Relationship between Economics and Use of Subsoil Warming.

The anecdotal evidence is that some UK groundsmen are not in favour of subsoil warming, but that management is in favour, if it can be afforded. There is no such option for those clubs in the UK Premier League, see **(5.3.1.)**.

None of these clubs have stadia with retractable roofs: only one club will have a stadium with a retractable roof by the year 2006. The horticultural consultant advising that club on their stadium horticulture design recommends the inclusion of under-soil warming.

Subsoil warming should be controlled by thermostats set between 5 and 6 ft above ground to measure the surrounding air temperatures. These should be linked to thermocouples set in the ground to control the ground temperature in relation to the air temperature. Most stadia

---

[25] *(ib id)* page 242.
[26] *(Ib id)* page 242.
[27] Kent,K, Interview, February 2001, Groundsman, Manchester United, AFC. Trafford Park, Manchester, UK.
[28] Beard, J,B, TURFGRASS SCIENCE AND CULTURE, Prentice Hall , 1973 page 243.

will have links with local weather stations to have advance notice of anticipated adverse weather conditions. The influence of subsoil warming should be introduced to the turfgrass plant on a gradual basis of heat build up rather than by a heat surge.

INDEX PART SIX.

CHAPTER ONE.

6.1.0. ALTERNATIVE WAYS OF SUSTAINING TURFGRASS IN STADIA.

6.1.0.1. **Introduction.**

CHAPTER TWO.

6.2.0. MULTI-USE PALLETS.

6.2.1. **Origins of Multi-pallet Systems.**
6.2.2. **Withdrawing Playing Surfaces in Multi-use Pallets.**

CHAPTER THREE.

6.3.0 SINGLE PALLET SYSTEMS.

6.3.0.1. **Introduction.**
6.3.2. **Withdrawing Playing Surfaces in Single Pallets.**
6.3.3. **Horticultural Influences on a Single Pallet System.**

CHAPTER FOUR.

6.4.0. RETURFING PLAYING SURFACES.

6.4.0.1. **Introduction.**
6.2.3. **Returfing as an Alternative to the Use of Multi-Pallet Systems.**

CHAPTER FIVE.

6.5.0 CURTAILING TURFGRASS USE.

CHAPTER SIX.

6.6.0. ARTIFICIAL PLAYING SURFACES.

PART SIX.

CHAPTER ONE.

6.1.0. ALTERNATIVE WAYS OF SUSTAINING TURFGRASS IN STADIA.

6.1.0.1. Introduction.

The most common playing surface for most traditional ball games is in situ natural turfgrass. "Most participants in field sports, except perhaps field hockey, would probably prefer to compete on a natural grass field if it is soft, has an abundance of grass with few weeds, no holes and ruts and is well maintained."[1]. The requirements for maintaining turfgrass in prime condition are heat, light, air movement, oxygen, carbon dioxide and horticultural attention. The detail of those conditions are set out in sections 3.1.0. to 3.8.0.

Both through observation and study it is clear that it is not always possible, through established horticultural practices, to maintain turfgrass in prime condition over the whole of the playing area in large compact stadia. There are a number of reasons for this: three of these are set out below.

- The impact a stadium cavea has in reducing levels of light and air falling on or moving over playing surfaces is detrimental to turfgrass.
- Better standards of weather protection for spectators has resulted in increased areas of shading for longer periods. This has reduced levels of light on areas of turfgrass.
- The maximisation of the use of arena surfaces through the introduction of multi-use activities is disadvantageous to turfgrass.

The following comment by Handreck and Black acknowledges the influence a stadium has on turfgrass failures:

> "A need to pamper patrons has led to a widespread construction of stadia that have roofs over the spectators. The grass has failed in most, mainly due to heavy shading. Promoters of stadia seem to have the same magical faith that gamblers have, but when such faith ignores basic plant physiology, disaster is the result"[2].

---

[1] Waddington D.V. *et al* Turfgrass No 32 Agronomy Madison , Wisconsin USA 1992 page 125

[2] Handreck, K, & Black, N, Growing Media for Ornamental Plants and Turf, 3rd Edn, UNSW Press, 2002, page 246.

This section examines a number of options available to provide and maintain in situ turfgrass in prime condition where horticultural practices are unable to do so. These options broadly fall under the term Pitch Replacement Methods. Most have been used; some have proved more successful than others in their practical application. These options are set out below.

1. **Withdrawing Playing Surfaces in Multi-Use Pallets.**
2. **Withdrawing Playing Surfaces in a Single Pallet.**
3. **Returfing Playing Surfaces.**
4. **Curtailing Turfgrass Use.**

CHAPTER TWO.

6.2.0 MULTI-USE PALLETS.

6.2.1. The Origins of the Multi-Pallet System.

The origins of the multi-pallet turf replacement methods did not begin with the research work carried out for the FIFA World Cup, USA, 1994. FIFA wanted some of their Cup matches to be played in the enclosed environment of the Silverdome Stadium, Pontiac, Michigan, USA. The detail of that research work forms an important impetus in the search for a method of providing movable in situ turfgrass. In the case of the Silverdome the object of portable turfgrass was to provide a playing surface of natural grass within the stadium when its environment could not sustain growth or maintenance of in situ turfgrass. **Case Study, 6.2.0.3,** sets out some of the detail of these multi-sized and multi-shaped pallets, which were placed together to make up the removable football pitch.

Other experimental work began prior to the Silverdome module development, with Ripley and Indyk in 1990. They worked on the concept of portable grass squares by connecting square metal trays; these modules were smaller in area but deeper than any of the Silverdome pallets. The success of the portable grass at the Silverdome in 1994 gave impetus to the concept.

"Ripley and Indyk installed a new plastic and wood version of modular turf as a practice tee that proved successful for the 1994 US Open in Springfield, New Jersey". [pan stadia July 60-61]

The next stage was the development of a high-density mould and with this came the possibility of the development of portable grass on a commercial scale.

The introduction in 1996 of the first commercial polyethylene pallets was at the Giants Stadium, New York, New York State, USA. The playing field of this open stadium was made up of approximately 6,100 pallets. The intention of installing the pallets was to allow the stadium a choice between natural turfgrass or an artificial playing surface. There is no evidence to indicate that the modules were installed to counter turfgrass failures through inappropriate environmental factors. Nevertheless, the facility was available to move individual pallets in the playing area to ease the impact made by wear when needed.

The pallets used at the Giants Stadium were 48" x 48"x 11". The grassed modules were installed on top of a 40mm plastic liner and a plywood layer that covered the stadium's synthetic playing surface. The sides of the modules were then folded down to allow a soil to soil compression joint with adjacent modules. "When the surface was required for concerts the modules were removed from the area required for the stage. The residual area of the playing field was covered with Terraplass decking to distribute the imposed loads from spectator seating". [Pan stadia inter July 1997 pages 60-61].

"However, since December 2000 the policy of removing all the pallets from the arena has been abandoned". [personal correspondence] The reasons for this were not revealed but it may be a combination of circumstances:

- the cost of moving the modules.
- the players' preference for playing on natural turfgrass.

The current policy is to limit pallet removal or replacement to those areas of wear.

The next prominent use of the multi-pallet system was at the Millennium Stadium, Cardiff, Wales, UK. **Case Study 9.4.5.** The decision to use pallets was taken after a confirmatory visit to the Giants Stadium, New York and it was taken for two reasons:

- Scientific tests indicated there was insufficient light and air to maintain turfgrass in some parts of the arena. The facility to interchange or replace pallets would alleviate the consequences of these environmental inadequacies.

- Removing the turfgrass would in addition allow events to be staged which would be hostile to turfgrass.

There was also the unforeseen advantage that the use of pallets allowed the installation of the playing surface to be delayed to the very end of the contractual programme. This eased site congestion and in doing so allowed the stadium to be opened on schedule.

This application of the multi-pallet system has not been an unqualified success as the area has been returfed on several occasions since the stadium opened. The detail of the system is set out in **(6.2.0.6.)**

6.2.2. Withdrawing Playing Surfaces in Multi-Use Pallets.

The same principle is involved in all pitch replacement methods using pallets. Turfgrass is grown in open conditions remote from the stadium in which the turfgrass is to be used.

The multi-pallet method consists of any number of pallets, that is, more than one in number. The pallets are filled with rootzone material, then seeded or most probably turfed. When required the filled pallets are brought into the stadium and laid out to form a playing surface. When the playing surface is not required the pallets are removed.

John and Sheard suggest three techniques available in providing pitch replacements:

> (i) a Canadian method of growing the turf in large boxes which can be then moved out of the stadium on rails; (ii) a German method of growing turf in pallets 4m square which are then moved on the hovercraft principle; and (iii) a Dutch concept of leaving the natural grass in place and constructing above it a new platform supported on remote-controlled hydraulic legs. In the UK, Odsal Stadium in Bradford has used a simple system of restoring the corners of a football pitch which had been cut off by a speedway track around the pitch: grass was grown on wooden pallets with a reinforced mesh sub-base and these were moved away to storage by forklift truck before speedway events.[3]

However, this work traces a multi-pallet system based on pallets formed of fibreglass. These are usually square, ·81sq.m.in area and 300mm deep. The number of pallets required for a playing pitch for Association Football falls between 7,400 and 7,800. It is advisable to add 1/6 to pallet numbers to allow for turfgrass failures. Therefore, the pallets required for the pitch and for those kept in reserve will number between 8633 and 9100. It is also considered good practice to keep one extra full size turfgrass playing area in reserve for turfgrass failures in the arena.

When pallets of this size are used they can in theory be conveniently interchanged between shaded or worn areas of a playing surface or alternatively, fresh turfgrass can be brought in from a turfgrass nursery in pallets to effect replacements.

The differences between technique (1)&(2) reported by John and Sheard centres on the means of pallet transportation and on the differences in pallet sizes. Technique (iii) appears to be experimental; there is no evidence of this work being carried out on a commercial scale.

The Odsal Stadium pre-Taylor was one of the largest stadia in the UK. It was principally known as a ground displaying Rugby League Football and Speedway Racing. "The speedway races lasted from the late 1940s to 1997. Stock Car racing was also held in the latter part of this period. The stadium was also used for football for two years after the Bradford City Football Ground fire"[4].

The Odsal 'pallets' are best described as timber trays. They were one yard square with a free depth of $1^{3}/4$". Therefore there could be no rootzone and consequently no space for root migration. The trays were used to restore the rectilinear shape of the football pitch from the shallow radius formed by the inner edge of the speedway track. The pallets were few in number, their application limited and their expectations modest. The turf they contained could not knit with adjacent trays for two reasons: principally the tray sides had to be thick enough to provide rigidity and they were in position for the duration of a game as the speedway usually followed a rugby game. This simplistic approach to a continuing problem made them wholly beneficial whilst incurring low capital expenditure. This was not a technique capable of wider applications.

CHAPTER THREE.

6.3.0. SINGLE PALLET SYSTEMS.

6.3.0.1. Introduction.

The failure publicised in August, 1996 of the Amsterdam Arena, Amsterdam, Netherlands, to maintain its in situ turfgrass, is recorded in **Case Study 6.2.0.5.** This failure led to the recognition by some developers that in large European stadia with centrally located retractable

[3] John G and Stroud R. A Design and Development Guide. Butterworth-Architecture 1994 pages 80-81.
[4] E Mail, Bradford Bulls Rugby, League Press Office. 18/1/2001.

roofs, the only acceptable way to maintain turfgrass without frequently returfing was to remove the in situ turfgrass from a stadium at intervals judged to secure its maintenance.

This led to the search for an alternative to the multi-pallet method of turfgrass removal. Thus this search reflected a lack of confidence in the ability of that system to provide an economic and convenient interchange between natural turfgrass and artificial surfaces in a stadium. The problem with the multi-pallet system relates to the number or size of pallets.

The numbers of pallets (called modules) used at the Silverdome was 194; at the Giants Stadium, New York, 6010 were used; at the Millennium Stadium, Cardiff, the number was approximately 6780. The number of makeshift pallets used at Odsall Park, Bradford is not recorded but they were relatively few in number; their function was to restore, radius corners to right angles after speedway events. These pallets were hand made and were manhandled into position.

The study of these early examples indicated that turfgrass transfer in principle to and from a stadium had been accepted as a method of providing a flexible surface for an arena and in addition a successful method for the maintenance of turfgrass. But ideas were now being focussed on how to achieve those objectives with economy and convenience.

6.3.2. Withdrawing Playing Surfaces in Single Pallets

Two ideas were to be considered in Europe: one was in the UK circa 1995 for the Kohlerdome, Luton; the other circa 1996 for the Gelredome, Arnhem, Netherlands.

However, the preliminary ideas for the concept of a removable turfgrass playing pitch in a single pallet had also been carried out during the development of the Toronto Skydome which opened 3rd June, 1989. Rod Robbie and Michael Allen, the Architect and Engineer for the building had, during its development work, invented and designed a system for a one piece concrete pallet enabling turfgrass to be removed from the stadium.

> The playing field is a concrete containment structure which holds the entire natural grass system including soil, turf, drainage and irrigation. The turf is crowned like normal football fields and the structure is on a series of steel-wheeled bogies which run on steel plate rails cast into the main concrete level floor. When not in use, the field is rolled out, with the electrically driven bogies, to an out door position where the grass can grow and be maintained in the natural outdoors...... The design includes the potential of a small

open air stadium constructed at the stored outdoor position of the field. Robbie R,Young &Wright, Architects Inc. Undated Abstract ,probably 1990 pages 27-38.

The Kohlerdome concept for a movable pitch was based on ten pallets. Each pallet was one tenth of the width of the playing area and ran its entire length. The steel pallets were 300mm deep. The upper part of the walls of the pallets had movable side flaps to provide for the seamless junctions of the turfgrass between adjacent panels. When filled, the estimated weight of each pallet was 600 tonnes.

The proposal was that the pallets were to be moved from the stadium through one of its corners. They were mounted on wheels and supported when in motion on cushions of air, based on the principle of the Hovercraft. The experimental work was based on 2·5m x 2·5m pallets, which weighed 3 tonnes[5]. This stadium did not proceed into the building stage, because Local Authority Planning Permission was not granted.

Subsequent investigations indicated that the experimental work perhaps did not reach the physical stages claimed for the original study. Hovair Systems USA, the company reported as being involved in the experimental work, have no records of any such involvement. They confirm that they were developing projects in the USA "where air film technology was used to float various sections of structures, but nothing in 1995"[6]. It was not until 2002 that Hovercraft technology was used successfully in assisting the horizontal movement of a single pallet playing pitch to and from a stadium. **Case Study 9.4.8.**

The second idea, circa 1996, was being developed for the Gelredome, Arnhem, Netherlands. The aim of this was to remove the turfgrass from that stadium in a single pallet. The system proved successful in use; other projects based on this principle have been built or planned. The details of the Gelredome development are recorded in **Case Study 9.4.7.**

Any system based on removing and returning a complete pitch by the means of one or more pallets poses the same questions: how to pass the pallet or pallets through the stadium superstructure and where to locate the pitch. The method used to move the pitch will be

---

[5] Phillips, J, The Environmental Influences of Roofing a Large Multi-use Stadium in the UK., The Welsh School of Architecture, University of Wales, Cardiff. Dec 1996, Pages 103-107

[6] E mail.- Gus Hart President Hovair Systems 20/12/2000. Gus Hart <hartg@hovair.com>

instrumental in determining the possible parking positions. A system based on traction by the use of hydraulic jacks, as at Arnhem, will dictate a straight-line relationship between the opening through which the pallet passes and the jacks. Thus the parking position will be as near as is possible to the superstructure. Where the method of retraction is based on wheels, combined with the hover air principles, the straight line no longer applies and more choice is available, within limits in determining the position of the pitch.

It follows from this that the land required to house the pallet must be taken into account at the site procurement stage. This essential requirement emphasises the need to determine a turfgrass strategy at the initial procurement stage of any stadium. It is also an essential requirement to park the pitch when it is outside the stadium on the sun path and not in the shadow of a stadium.

There may be no advantage in using more than one pallet provided the problem of physically passing one pallet through the base of a superstructure can be solved. Two methods of passing the width of the playing field through the stadium to its outside location have been so far used. These are as follows.

(1) Passing a single pallet through the base of a grandstand by forming an opening at its base 80 to 90 metres wide by 2·5 to 3·0 metres high: structural problems accompany this arrangement. Such spans generate large reactions requiring both complex reaction detailing and foundations. The solutions to these problems have so far been reflected in dictating the architectural expression, as at Arnhem, in the form of the building at each of the affected two corners. This arrangement disrupts what otherwise can be, in simplistic terms a symmetrical plan. Two other factors must be considered: the first, the varying dynamic loading imposed by spectators as a consequence of the excitement influenced by an event, which has led to structural vibration. Such movement has been psychologically disturbing to the occupants. Therefore the grandstand over the opening has to be propped when occupied. The second issue relates to spectator sight lines which require adjustments to match the sightlines of those grandstands not so affected by the opening through which the playing field passes.

(2) The second of these methods is to pass the pallet only through the superstructure wall, which is a simple structural problem. In order to achieve this, it is necessary to rotate the self supporting grandstand away from the opening in the wall and to achieve this it has to be divided into sections. The method is demonstrated at the Sapporo Dome. **Case Study 9.4.8.**

Thus far the largest multi-use stadium with a retractable roof and a removable single pallet which slides beneath a fixed grandstand has a spectator capacity of approximately 56,000. There is, however, the possibility demonstrated by the preliminary work carried out on the Kohlerdome to extend the spectator numbers beyond the present maximum. The experimental work on the Kohlerdome sought to divide the pitch into ten parts across its width. This had the advantage of reducing the width of the structural opening through which the panels had to pass.

If the present ideal of a single pallet could be divided into a three or five pallet system, the structural problems would be considerably reduced, leaving only the issue that the walls of the pallets could be sufficiently narrow to ensure the turfgrass from adjacent pallets could knit together.

The present experience of moving the pallet is based on pushing and pulling the pallets on steel sliders or alternatively wheeling the pallet supported on an air cushion based on the Hover air method. There have been fewer problems with the Hover method than with the sliding method.

Irrespective of the method of moving the pallets, the mechanism for doing so has to work every time. It is for this reason that pallet withdrawal systems are operated at least 24 hours before a surface change is actually required, having a hiatus for repairs to be carried out in the event of mechanical failure. The time taken to remove a single pallet from one position to another is approximately 6 hours.

The single pallet has up to this point been drawn through the narrow side of a stadium. Where a number of larger pallets are used they may be drawn through the narrow or the long side of a stadium. This strategy will be determined by the way the pallets are arranged and by the shape or orientation of a site.

The removal of the turfgrass from a stadium provides the most flexible arrangement for multi-use events and the maintenance of turfgrass. The single pallet system when compared with that of the multiple pallet arrangement offers the better solution for achieving convenience and speed in reconfiguring a stadium. However, research is required to see the effects on turfgrass horticulture and stadium superstructures to determine the impact of considering the use of between ten and twenty pallets.

6.3.3. The Horticultural Influences on a Single Pallet System.

A rootzone in a pallet is defined as a modified rootzone, therefore determining its depth is an important factor. This depth should be not less than 400mm; its composition may be based primarily on appropriate sands. Watson *et al* reinforces the desirability of rootzone depth " Too many fields are not properly drained and have seedbeds that are too shallow (<40 cm) to effect proper water movement." [7]

A single pallet drainage system should be designed for the appropriate open conditions. Unless the PAT type drain system is installed other drainage arrangements will be laid to falls as the water is gravity driven. The system will fall towards each corner of the pallet to the out-falls.

Irrigation points should be set to allow a water cover for the whole area of the single pallet or alternatively mobile sprinklers should be provided. The arrangement should work for both the inside and outside conditions.

Access outside the stadium has to be provided in order to feed the turfgrass and to defoliate it in its parked position. Consideration should also be given to the inclusion of soil warming because in the parked position the soil can be subjected to freezing conditions from the perimeter of the pallet. Where soil warming is installed the base of a pallet should be insulated and the upper surface tanked with an impervious waterproof lining.

CHAPTER FOUR.

6.4.0. RETURFING PLAYING SURFACES.

6.4.0.1. Introduction.

The practice of providing a sward for ornamental lawns and playing surfaces by turfing is common. One of the advantages of turfing is the immediacy of appearance; its disadvantage is cost. Once established, a sward established by turfing and one from planted seeds will respond equally provided the seeds, rootzone are identical and horticultural arrangements for each method is appropriate.

The most suitable option for maintaining in situ turfgrass in any stadium is a suitable environment, the application of appropriate methods of turfgrass husbandry and most importantly, curtailing the use of the turfgrass. These factors are rarely available in any large stadium, even in those not classified as multi-use stadia. These circumstances necessitated the introduction of returfing as a means of providing an acceptable playing surface. Even where a multi-pallet system has been incorporated as at the Millennium Stadium it has been found necessary to returf over the modules to seek a method of providing a satisfactory playing surface. Returfing has been adopted rather than the idea of sustaining a satisfactory playing surface by exchanging the worn turfgrass modules by new modules.

ArenA Amsterdam adopts the same policy only this stadium has a modified rootzone. The policy of returfing there has continued since 1996. Returfing of the playing area has been carried out several times a year since that date.

Returfing has become a commercially acceptable method of turfgrass replacement. Prior to that point, partial turfgrass replacement was sometimes used, at the end of a season on limited areas of high wear in stadia. This practice is still used but now may be carried out on more than one occasion during a playing season. In stadia where the use of the playing surface was not subject to multi-uses and therefore unused between seasons, restoration could be carried out by scarification and reseeding. This is a practice carried out by the Arsenal Football Club, London, UK.

In some cases the reason for the complete returfing has not only been poor surface qualities, but that these poor playing surfaces have been exposed to wider public scrutiny through television broadcasts. In this respect there is evidence that UEFA and the English Football Association are concerned about the image that poor turfgrass projects. These bodies have demanded from the management of the ArenA Stadium, Amsterdam, Netherlands and the Millennium Stadium, Cardiff, Wales, that their playing surfaces are re-turfed prior to the staging of showpiece events.

At the beginning of this section it was suggested that 'one of the advantages of turfing is the immediacy of appearance, its disadvantage is cost'. Immediacy of appearance will be short lived if the environmental standards and conditions of the replacement turfgrass match the conditions in which the original turfgrass failed. It stands to reason, therefore, that the replacement process will have to be repeated unless the environmental conditions are improved or the patterns of use are adjusted in favour of the turfgrass.

The cost of replacing a FIFA standard playing area is in the region of £80,000-£100,000. These prices are based on the year 2000. Nevertheless, for large stadia with spectator capacities of 40,000 and above and where an extensive programme of multi-uses is displayed, there may be no other option but to replace the turfgrass by turfing. This strategy may involve changing the

---

[7] Waddington D.V. *et al* Turfgrass No 32 Agronomy Madison , Wisconsin USA 1992 page 80

playing surface between three and four times a year at a total cost of between £320,000 and £400,000. **(Case Study 9.4.5).** Under the circumstances of an extensive programme of events, these costs can perhaps be absorbed. Where events are fewer, the need to change the playing surface will be less and the costs proportionally reduced.

6.4.1. Returfing as an Alternative to the Multi-Pallet System.

The multi-use stadia, of ArenA, Amsterdam and the Millennium Stadium, Cardiff, have been used as a base for comparative analysis in this section of the study. Both suffer from poor environmental conditions. Both have a modified rootzone; that is, their rootzones are isolated from a natural sub-stratum. The Arena rootzone is 600 mm deep and is set on a waterproofed suspended reinforced concrete slab. The Millennium Stadium rootzone is contained in individual fibreglass pallets set on a hard supporting surface. Within the pallet the rootzones vary in depth between 200 and 290 mm.

Both stadia have had to employ returfing on a regular basis to maintain their playing surfaces. In the case of ArenA Amsterdam there is no realistic alternative but to returf to provide a viable playing surface. But in the case of the Millennium Stadium there is an alternative to returfing. That alternative is to renew the playing surface with fresh grass in pallets on at least the same frequency as that of the returfing programme. But that policy is not carried out. It is not carried out presumably on the basis of a cost comparison between the two forms of turfgrass renewal.

The advantage the Millennium Stadium has over the ArenA is that its playing surface can be removed as a whole or in part from time to time for a specific purpose and then can be restored relatively easily as a playing surface when required. That same process at ArenA could be a more complex and costly operation so much so that it would not be undertaken unless a major retrofit of the stadium was to be undertaken.

Returfing cannot be an alternative to the Multi-pallet system but it can be an accompaniment to the system. Whether that arrangement can be successful is dependent on a number of horticultural factors.

The current arrangement at the Millennium Stadium is that the pallets forming the playing surface are covered, after scarification, with an additional lightly consolidated shallow rootzone. This area is then covered with 40mm thick turf. In order for this to be successful the turf and the new rootzone have to be compatible and also combine with the rootzone in the pallets in order that the turfgrass roots can stabilise the turf bed. This compatibility between the three elements is essential, as is an efficient drainage system within the pallets. Sufficient time has to be allowed for the different rootzones to unify or the turfgrass surface will not provide a firm foot-hold and the surface will also cut up.

The advantage provided by the multi-use pallets is the potential for the flexibility they offer. From the evidence of the Giants Stadium the full potential of that flexibility is no longer used there; it is now restricted to exchanging pallets where and when wear occurs. [personal correspondence] The experience at the Millennium stadium is that the pallets are removed from the perimeter for some events in the stadium. Sometimes pallets are removed from the centre of the playing area sufficient only to 'drop in' a cricket pitch for novelty cricket.

The experience from ArenA and the Millennium Stadium is that irrespective of how the rootzone is contained the playing surface in both stadia has to be renewed by turfing from time to time. The new turfing brings with it a green surface but this can be no more than a temporary feature. That greenness can only be a transient feature as long as the environmental conditions in the stadium remain unsatisfactory. The turfgrass, as a long-term feature, will remain as unsatisfactory as did the multi-use pallets in providing a green stable playing surface. The difference between the two is that re turfing is simpler to carry out.

CHAPTER FIVE.

6.5.0. CURTAILING TURFGRASS USE.

All the turfgrasses considered in this work are perennial plants. Their survival and their renewal can be assured for long periods provided the environment and their horticultural treatment is favourable to them. The environmental conditions in most large multi-use stadia with retractable roofs is usually unfavourable to in situ natural turfgrass but the horticultural treatment it receives will be beneficial.

However, a significant factor which will determine the duration of both plant survival and renewal, is the way in which turfgrass is used. The consequence of all use is wear. The duration of wear, its application and type will determine the extent of that wear. If plant roots are not eradicated during the processes of wear, which they can be, they will survive provided the affected areas are allowed appropriate periods of rest. The poorer the environmental conditions, the greater will be the effects of wear and the longer will be the necessary rest periods. Conversely, the better the environmental conditions the less will be the effects of wear.

But even in prime environmental conditions intensive or inappropriate turfgrass wear without turfgrass recovery periods will override even prime environmental conditions.

The consequences of any traffic on turfgrass will be compaction, soil displacement and divots. These factors are considered in **3.3.0.1.**

This section is included in order to speculate if there is a likelihood of the use of a turfgrass playing surface being curtailed to benefit turfgrass maintenance in multi-use stadia.

CHAPTER SIX.

6.6.0 ARTIFICIAL PLAYING SURFACES.

It is not the intention to record in any detail the desk studies carried out on the use and composition of artificial playing surfaces[8]. The reason for this is that artificial surfaces as they are currently constituted cannot be used in Europe as an alternative to in situ natural turfgrass where Association Football is played at the highest level. This follows the guidance issued by FIFA. This same principle is also followed in Europe by the authorising bodies of the other codes of football.

These desk studies were carried out to determine why synthetic surfaces as presently constituted are not acceptable for the games of football at the highest level. Synthetic materials provide playing surfaces that are true and accurate and also display low wear characteristics substantially superior to those same characteristics shown by in situ turfgrass. These surfaces also provide a flexibility in use, which can never be matched by natural turfgrass pitches.

The answer centres on two primary reasons:

- The consensus view is that synthetic surfaces change the playing characteristics of the various games of football as practised in Europe.

- Professional players both in Europe and North America perceive an artificial surface influences impact injuries in both the immediate term and long term.

Conversely, since the introduction of the artificial playing surface, the playing techniques of field hockey have developed to the game's advantage. This is because the synthetic material used for this game produces a smooth, true and accurate playing surface when laid on a firm unyielding foundation. These conditions allow the ball used to provide both an accurate roll and consistency of bounce. The composition of the hockey ball is solid whereas the balls used for football are larger and are plastic coated leather and are inflated.

Also the playing characteristics of hockey are intrinsically different from those of the various games of football. In hockey, player contact with the ball is made via a playing stick. Almost without reservation in the games of football a player is able to make direct physical contact with the ball. The one exception is that in Association Football the outfield players are not allowed to propel the ball by throwing.

It is however the high bounce produced by the ball on the artificial surface that inhibits the skills of footballers and consequently diminishes the spectacle of the game. This is especially so in the game of Association Football.

Until the bounce factors produced by artificial turf fall within the range of bounce standards produced by in situ natural turfgrass, artificial surfaces will not be considered for use in a stadia where the primary purpose is to display football. It could, however, be used as an auxiliary surface where the main in situ turfgrass can be withdrawn by some means from an arena.

UEFA has suggested through correspondence [1997] with a member of the UEFA Playing Pitch Committee that "ultimately they [UEFA] expected to see all games played on artificial surfaces". This statement is probably founded by the attraction to UEFA of the artificial turf providing a consistently visually satisfactory 'telegenic' playing surface. The statement was made before the first successful use of a natural turfgrass playing pitch, set in a single retractable pallet was developed in Arnhem, Netherlands. Such surfaces have the capability of showing similar standards of visual appearance to that of artificial turfgrass, with the application of proper maintenance regimes.

The appearance of in situ turfgrass will deteriorate during the progression of a game or other use whereas artificial turfgrass will normally remain constant during a period of activity. The artificial surface has the advantage of being able to absorb intensive use for long periods, without having to be replaced. Natural and artificial turfgrass require maintenance but the natural turfgrass requires intensive maintenance when compared with that of artificial grass.

---

[8] Waddington,Carrow,& Sherman Co Editors, Turfgrass, No 32 in the series Agronomy, Madison 1992 pages 115 127.

Both types of surfaces have to be replaced. The theoretical replacement period for artificial turfgrass is set between 5 and 10 years, whereas turfgrass surfaces are reported as being frequently replaced at Ajax ArenA, Amsterdam and at the Millennium Stadium, Cardiff.

Research is required to produce an artificial turf grass with its underlay and base, which would produce equivalent bounce factors imposed by inflated balls, to those produced on well-maintained turfgrass. Such successful research would allow the material to be used for other ball games played at the highest skill level besides those of hockey and tennis.

In order to allay the perception of players that the artificial surface is a greater cause of injuries than in situ natural turfgrass, parallel research would be required to determine how any new artificial surface stemming from that report would impact on sporting injuries.

Current research data available of comparative injury incidents between the natural and artificial surfaces is unreliable. The data shows in some studies little variation between the two surfaces: but in others differences that could be classed as significant. The reason lies in the inconsistent methodology used in conducting the research. One desk study suggests: .....

> Samples were not random but were restricted in terms of geographical region and the skill levels of participants. Rates of exposure were not calculated and few attempts were made to ascertain the possible causes of the injuries. For the purposes of analysis it is necessary to define injuries, classify them according to severity and at least estimate the exposure rates so that a denominator is available for the estimation of incidence.

As yet, there is little comparative research on the anticipated long-term effects on the ankle, knee and hip joints of professional players performing on natural or artificial surfaces in the USA. **Appendices 9.3.2.4** includes a survey of research so far carried out in the USA and Europe. However, until independent research is undertaken on the latest specifications of artificial surfaces the claim for their all round improvement cannot be verified. The qualities required in the artificial surface are those that improve the mode of play and in parallel ensure that the participating players are relieved from the rigid impact that previous players encountered from artificial surfaces. Until this research is undertaken the artificial surface ought not be used at the highest level of play in Europe.

However, the material will continue to be used in confined urban environments where pressure of use would make natural turfgrass inappropriate. It was for these conditions that the artificial surface was invented. . Its original introduction into stadia was a measure of expediency.

UEFA are also prepared to use the surface as an expediency as they currently allow games to be played on artificial surfaces only where there is no opportunity to grow and maintain natural turfgrass, for example, above the Arctic Circle where two Clubs play there in the Norwegian Football League.

INDEX PART SEVEN.

CHAPTER ONE.

7.1.0. DIRECT LIGHT, DIFFUSE LIGHT AND WIND RESEARCH.

7.1.0. 1 **Introduction.**

CHAPTER TWO.

7.2.0. DESCRIPTION OF RESEARCH EQUIPMENT.

7.2.1. **The Artificial Sky.**
7.2.1.1. **Technical Description of the Skydome.**
7.2.1.2. **Technical Description of the Heliodon.**
7.2.2. **The Wind Tunnel.**

CHAPTER THREE.

7.3.0. DESCRIPTION OF RESEARCH MODELS.

7.3.1. **Wind Tunnel Models.**

7.3.1.1. **Introduction.**
7.3.1.2. **Preparing the Wind Tunnel Base Model.**
7.3.1.3. **Preparing the Different Roof Types.**

7.3.2 **The Artificial Sky-Base Model.**

7.3.2.1. **Introduction.**
7.3.3. **Painting the Model.**
7.3.4. **Preparing the Playing Surfaces for the Different Experiments.**
7.3.4.1. **Recording the Turfgrass Grass Shadows.**
7.3.4.2. **Playing Surface Adjustments made to Record Turfgrass Lighting Levels.**
7.3.5 **The Roof Models.**

CHAPTER FOUR.

7.4.0. THE SHADOW DATA.

7.4.1. **Introduction.**
7.4.1.1. **The Tables.**
7.4.1.2. **The Graphs.**
7.4.1.3. **The Location Photographs.**

CHAPTER FIVE.

7.5.0. The DIFFUSE AND DIRECT LIGHT DATA.

7.5.0.1. **Introduction.**
7.5.0.2. **Detail of the Experiments.**
7.5.1. **Quantifying the Level of Lighting.**

PART SEVEN.

CHAPTER ONE.

7.1.0. DIRECT LIGHT, DIFFUSE LIGHT AND WIND RESEARCH.

7.1.0.1 Introduction.

This thesis has three strands of study: the first of these searches and reveals the essential literature related to turfgrass culture; the second strand is based on visits to Stadia, Turf Research Institutes and Turfing Companies. The third strand is the laboratory research which measures beam, diffuse light and wind found in stadia conditions and uses that data to judge their influence on turfgrasses in those environmental conditions.

These three strands provide a continuous thread from work carried out for an earlier degree. Visits to stadia at the earlier time suggested that turfgrass failures relate to reduced levels of light energy and air movement falling on a playing surface.

The earlier laboratory research in principle determined the detrimental influence a centrally located retractable roof had on turfgrass and how the superstructure of a large compact stadium disrupted airflow over a turfgrass playing surface.

It also became apparent during the original study that other factors also contributed to these failures such as turfgrass wear, the influence of the rootzone, drainage and turfgrass species selection. It was considered there was a need in this new thesis to understand the influence these aspects had on the light energy and air movement data collected from the laboratory.

The decision to carry out the research through the use of models rather than by computer graphics was deliberate. The candidate had experience in designing with three-dimensional models. Such modelling provides a tactile and visual understanding of the influence of shape and form. The other strong influence for using models was that a Wind Tunnel and a state of the art Artificial Sky and Heliodon were available.

The difference between architectural modelling and modelling used for laboratory research is the need for absolute accuracy in the construction of the latter. Any variation through unintended modelling inaccuracy is automatically reproduced in the data. Therefore the modelling process has to be controlled. Research models have to be compatible in size with the laboratory apparatus, the probable implication being, as it was in this case, models of different scales have to be constructed to satisfy scaling requirements of each apparatus. If this is necessary the scope of the work considerably increases.

It is sometimes necessary when using models for research to adjust a part of a model to increase the effectiveness of the whole design. Adjustments can take several variations before one arrives at the best solution. This also considerably increases the scope of the modelling.

Appraising the effectiveness of the design variations necessary to provide, the form of the funnelling between the concourse and the upper stand could have been more easily established by using computer-modelling techniques, rather than by preparing several three-dimensional models each requiring modifications during the experimentation development. The acceptable variation could then have been more rapidly incorporated in the overall three-dimensional model used for final wind tunnel testing. A retrospective view of the whole process is that it would have been beneficial to combine the techniques of computer modelling with three-dimensional modelling. In this way comparative results could have been appraised and analysed for all work carried out in a wind tunnel.

CHAPTER TWO

7.2.0 DESCRIPTION OF RESEARCH EQUIPMENT.

7.2.1. The Artificial Sky.

Some of the physical experiments carried out for this thesis were conducted in the Artificial SkyDome located in The Centre for Research in the Built Environment (CRiBE) located in theWelsh School of Architecture, Cardiff University, Wales, UK.

The room in which the Artificial SkyDome is installed is without daylight. The walls and ceiling are painted black, as is the structural frame of the Artificial SkyDome. The four-metre radius hemisphere, which forms the outline of the Artificial SkyDome is constructed from open geodesic units. In principle this system provides a stable and strong frame with a lot of flexibility in lighting mounting methods. However, a vertical slot had to penetrate the geodesic construction to provide clearance for the structural arc of the artificial sun which is placed on the rim of the dome. The artificial sun has a radius of 4·5 metres. This intrusion reduced the integrity of the structural system. This weakness is effectively countered by bracing and cabling: the strengthening of the structure was achieved without interfering with the technical performance of the Artificial Sky.

Access into the Artificial SkyDome is provided by a top hinged, truncated triangular door, developed from the dome surface. The door movement is hand activated by spring loaded arms. In the direct centre of the dome there is a two metre suspended, vertically adjustable turntable edge driven. In the area surrounding the turntable there is a one metre deep pit which may be used to house instruments used in experiments. The operations of the Artificial Sky are controlled from a working desk adjacent to it.

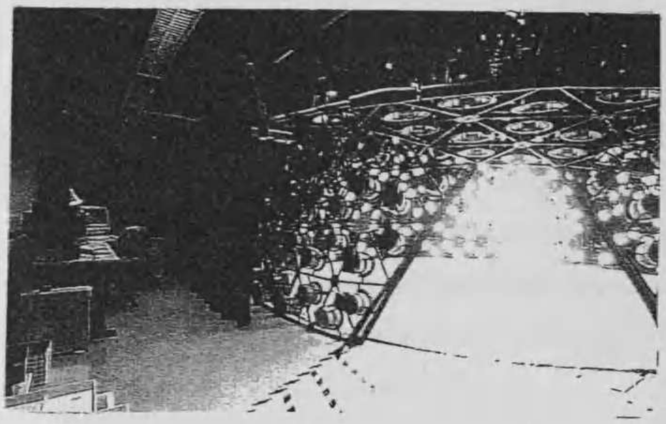


Fig. 7.2.1.
View into Artificial Sky through the open overhead hinged door. The console control is on the left set behind a black curtain.

7.2.1.1. Technical Description of the Artificial Sky.

The following quotation is taken from the literature prepared by The Centre for Research in the Built Environment to describe the technical details of the Artificial Sky.

> The lighting of the dome is a compromise between the desire for maximal coverage of its lit surfaces (so as to achieve a smooth luminance distribution) and the desire for minimal surface area (so as to reduce inter reflections and so make luminance control easier).
> Six hundred and forty luminaires containing low energy compact fluorescent lamps (Philips CL 4500K) are mounted within each triangle of the dome frame.
> Owing to the geodesic structure, this leads to an irregular spacing of the luminaries, but it was felt that this could be countered by luminance control software. The individual luminaires are between two and three degrees apart. Philips electronic dimmable ballasts are used with the luminaires; these provide a large dimming range of between 3-100% brightness. To achieve a greater brightness range for those positions near the sun path, selected units are double lamped.
>
> The luminaires were developed from the standard category one fittings, with extra baffling to control side spill and inter reflections….. Overall the dome lighting can produce up to 4500 lux at the model stage under simulated overcast sky conditions[1].

[1] Alexander, D Skydome Literature, The Welsh School of Architecture Cardiff, UK (undated)

tungsten or a 575 W HMI lamp. The latter gives us more light and a higher colour temperature, but is less easy to control. The Selecon provides a good even distribution over the two metre stage and gives sharp shadows, but as a 'point' source , there is some divergence. This has not proved to be a problem to date, but we are still looking for an appropriate mirror source to provide a technical parallel beam.

The big advantage of the Selecon for general use is its 'cold mirror design', which reduces the infrared heat load of the model. At the other end of the spectrum (literally) we also use a 4k w HMI source, adapted from a Desisti stage lantern. This provides over 80,000 lux at the stage and 600W/m^2 broad band irradiation overall. This has been used for testing solar panels systems. Goggles and high factor sun block are required safety equipment when it is in use.

The dome lighting and the heliodon mechanism are computer controlled, using standard industrial PC I/O interface cards under Windows 95. The interfacing and software were developed in-house, using visual basic.

The dome lighting is controlled through a DMX512 system. This system is an 8 bit resolution 0-10V control communication protocol. A standard in the world of stage lighting, the DMX system provided the most cost-effective solution for a number of control channels needed for the dome. Individual addressable receiver channels are grouped in modules about the dome, linked in a 'daisy-chain' by a single twisted pair cable. The 'universal interface' modules were produced by Pulsar. The PC based DMX transmitter (supplied by fPf Ltd.) is memory mapped , so that rapid changes to the Dome lighting can be achieved. The modelling of natural lighting dynamics is an area planned to be explored.

The heliodon uses high resolution quadrature encoders to determine altitude and azimuth of the track and turntable. Position and speed are controlled in real time. The heliodon positioning accuracy is better than half a degree and the accelerated day can be run in 2-3 minutes [2]

The Artificial Sky simulates external natural lighting conditions: those arising from the sun, sky, and clouds and from reflections from the ground and nearby structures. It can do so in principle for all weather conditions, seasons and locations. The luminaries can be selectively dimmed to

[2] Alexander, D Skydome Literature, The Welsh School of Architecture Cardiff, UK (undated)

model the luminous distributions of different types of skies: overcast, clear or mixed. The Artificial Sky heliodon sets the relative angles between the model and the artificial sun as appropriate for the time, date and location being studied. The artificial sun travels vertically in the slot visible in the images above; this sets the relative solar altitude. To set the relative azimuth, the model is placed on a rotating turntable. Under the computer controlled system an accelerated day can be run in only a few minutes.

7.2.2. The Wind Tunnel.

Some of the physical experiments carried out for this thesis were conducted in the Boundary Layer Wind Tunnel which is also located in The Centre for Research in the Built Environment in The Welsh School of Architecture, Cardiff University, Wales, UK.

The tunnel cross section is 2 metres by one metre and its internal length is 12 metres. The bell mouth entry area is 2·6 x 5·2 metres. A 6 metre upstream fetch uses a combination of blockages, fences and surface roughness (Lego Duplo blocks) to produce a simulation of the lower part of the atmospheric boundary layer. The working section of the tunnel is two metres long: models are usually placed on a 1·9 metre diameter turntable in that zone. For most of the experiments for this thesis the turntable was not used. The models were set in an airtight seal against the walls of the tunnel allowing only the passage of air above and below the models.

The tunnel is powered by two 13 hp fans, providing a maximum speed of approximately 11m/s. Instrumentation, some of which is controlled from a console adjacent to the tunnel, includes:

- Dantec hot wire and laser doppler anemometry equipment.
- Furnes low pressure transducers with Scanivalve scanners.
- Various video cameras, recorders.
- Image capturing equipment, the positions of which can be automatically adjusted horizontally and laterally at the roof level of the tunnel.
- Smoke diffusion equipment.

Fig. 7.2.2.
The Wind Tunnel & its Bellmouth.

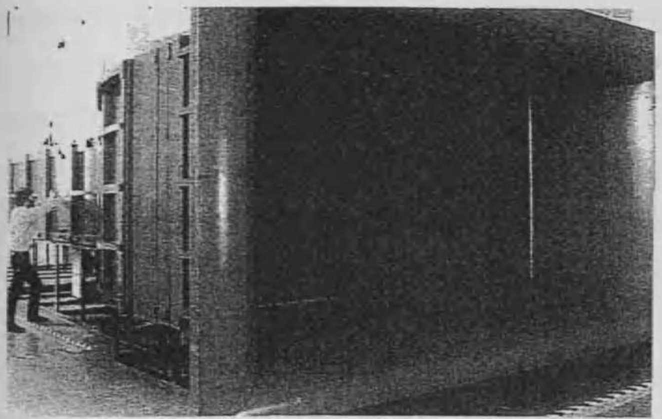


Fig. 7.2.2.
The Wind Tunnel & its Bellmouth.

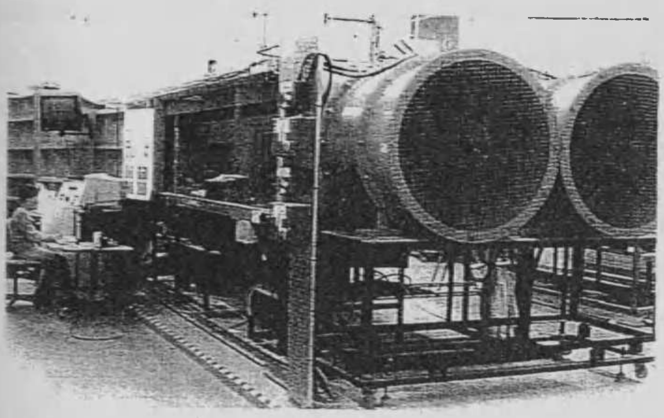


Fig. 7.2.3.
Illustrates the Fans and ControlConsole.

CHAPTER THREE.

7.3.0. DESCRIPTION OF RESEARCH MODELS.

7.3.1. Wind Tunnel Models.

7.3.1.1. Introduction.

A wind tunnel model of a stadium was developed which allowed airflow measurements to be taken across a playing surface which was surrounded by a superstructure with its retractable roof in an open or closed position. Previous experiments based on the model used for the Artificial Skydome were not suitable, being only appropriate for recording external pressure measurements on the superstructure.

The approach taken was to build a model which restricted the recorded measurements to a 'vertical slice' taken centrally through the cross section of the arena. This would make it possible to collect airflow data horizontally and vertically on that slice within a stadium's interior. To provide the conditions to achieve this objective it was necessary to build a model which fitted between the wind tunnel walls but allowed a free space between the top of the model and the wind tunnel ceiling to control air turbulence. The scientific supervisor suggested that a free space of 450mm would be sufficient to control the turbulence. The need to leave the free space determined the scale of the model which because of this became 1:150.

Fig 7.3.1.1. Illustrates the 'imaginary vertical slice' by showing three planes representing the horizontal and vertical planes situated on the centre line and each side of the centre cross section of the stadium playing surface. These planes extend between the playing surface and the underside of the various retractable roofs. Measurements were taken in identical plane positions on the gridlines either side of the central gridline.

Fig, 7.3.1.1.

Diagrammatically illustrates the 'Slice' arrangement. The three vertical planes represent the playing field centre gridline and the grid lines each side; these extend upwards to the underside of the roof line. The slices represent the imaginary plane on which the wind measurements are recorded. These positions are fixed by the intersection of the horizontal grid lines extended vertically with the vertical grid lines extended horizontally.

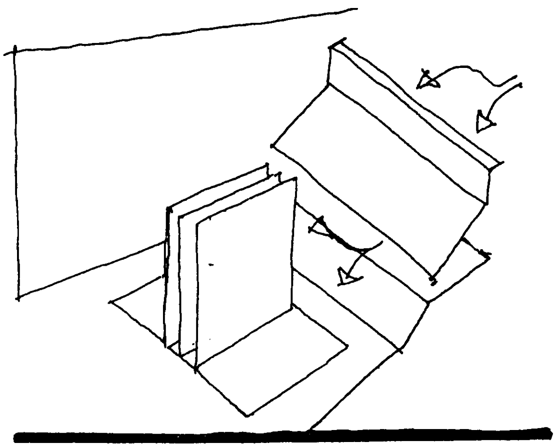
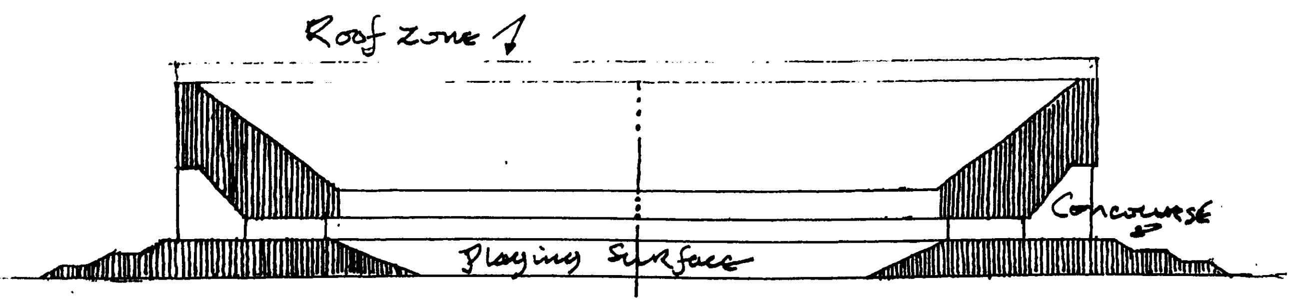


Fig. 7.3.1.2.

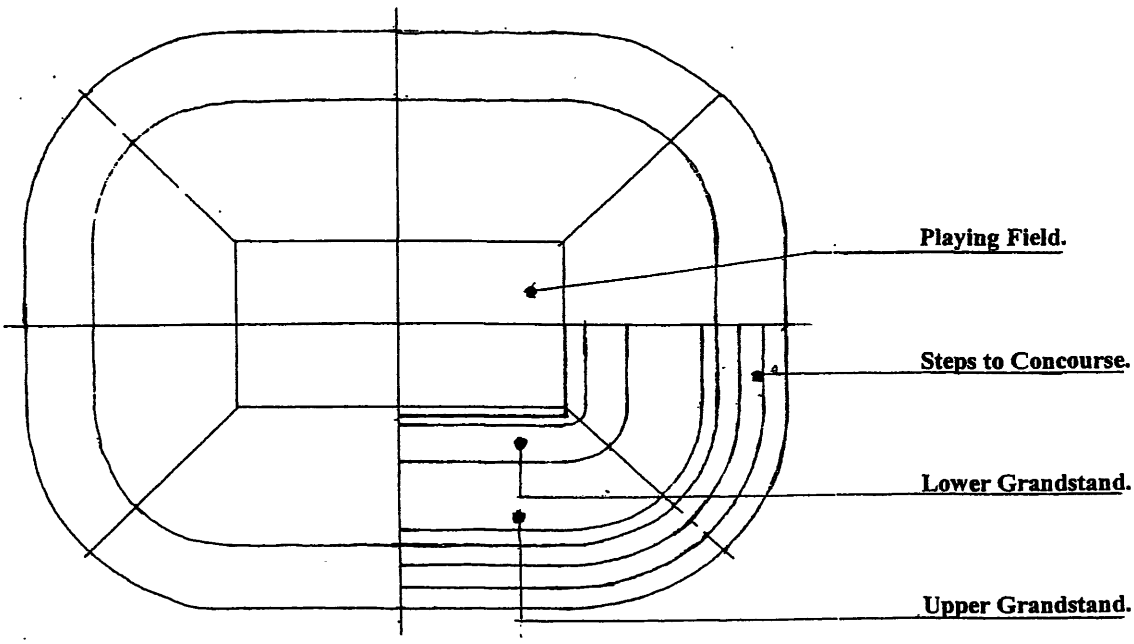
The cross section through the model shows opposite grandstands separated by the arena. The section also shows the upper stand separated from the concourse. This space acts as a funnel through which air can pass to the playing field turfgrass.



7.3.1.2. Preparing the Wind Tunnel Base Model.

The candidate built the base model together with the roof components. The model was 1800 mm long, 1500mm wide and 350mm high. It consisted only of the straight lengths of opposite grandstands, separated by the arena width. The working cross section of the model is set out in **Fig, 7.3.1.2. Figure 7.3.1.3.** illustrates the plan of the stadium at its various levels. The semi circular parts of the model played no direct role in the collection of the wind tunnel data.

Fig 7.3.1.3. Illustrates the plan of the model.



When work on the model began, access into the wind tunnel for the operator was cramped; setting up an experiment was an unpleasant experience. The access for the model was also insufficiently wide. Because of this fact, together with the problems of handling the model in manufacture, it was decided to divide each grandstand into two equal lengths. The overall length of the model was made 200mm less than the width of the wind tunnel. This would make the setting up of the model in the wind tunnel less problematic.

After the model was completed access into the wind tunnel was advantageously modified. The consequence was that a one piece model could slide easily into the tunnel. Had this been known, the model tolerance could have been reduced to 100 mm. Nevertheless, the right decision was taken to divide the model into two lengths, as a one length model would have been beyond the building and handling capabilities of one person working alone.

The grandstand profiles were made from 5mm Medium Density Fibreboard (MDF) cut, housed and glued onto38x20mm softwood runners. These then formed the structural skeleton of the grandstand profiles. The three dimensional profiles were covered with 5mm MDF facing boards. These were sealed internally to be airtight before the final surface was bedded and fixed. The profiles were set on accurately shaped 10mm MDF cradles, placed 15 metres apart, representing the structural supports for the suspended grandstand. In turn these were set into the solid softwood continuous concourse and lower terrace.

The choice of softwood for the concourse and terrace proved a poor one. The leading edge of the terrace was rebated to sit over the edge of the 5mm MDF board representing the arena. The residual edge thickness representing the up-stand between the arena and the terrace was so thin it twisted, necessitating remaking the front section in MDF. Otherwise this inaccuracy would be reflected in the data.

Where the grandstands abutted to form a single length, the construction was modified to allow that cradle thickness and spacing to match the remainder of the model. The initial decision to divide the model provided eventual difficulties in forming accurate junctions between the parts.

Three experiments were carried out to determine the rear profile of the grandstand above the concourse. The aim was to find a profile offering least air resistance between the lower leading edge of the superstructure and the funnel between the structure at concourse level. The one chosen was incorporated on the model.

The funnel space between the concourse level and the soffit of the upper grandstand can never be completely free of obstructions obviously because of the need for structural support and maybe for vertical access. However, the position of the vertical access may be set away from the concourse. Therefore for the purpose of these experiments only the structural obstruction to the passage of the air movement was taken into account.

During the experiments it became necessary to make a major adjustment to the model. It will be recalled that the model comprised two halves. Each consisted of a half of the left and right grandstands. These were joined in the middle to make the complete grandstand length. Despite the care taken to fit accurately the junction between the grandstands when these were fitted together in the wind tunnel air turbulence occurred at the centre junctions.

To counter this effect the model was adjusted to allow one whole section of a grandstand to occupy a central position on the centre line of the airflow. This process was repeated for the opposite side of the model. The remaining halves of the model were divided into two and fitted either side of the original half grandstand section. This arrangement meant that there ought to be no junction turbulence because there was no centre joint. But there was, although reduced in its extent.

The assumption was made that the problem of centre turbulence was the result of an imbalance in the airflow reaching the bell mouth air intake of the wind tunnel. This was tested with the model in position by the process of trial and error. Different sized baffles were introduced on each side of the wind tunnel room until the air reaching the wind tunnel bell mouth was balanced. When that occurred there was no centre turbulence on the model.

7.3.1.3. Preparing the Different Roof Types.

A requirement of the model was that its roofs had to be formed in a single span of 1600mm. It was not possible for the candidate to prepare calculations for an authentic roof structure. Therefore the concept for the roof structure is based on a combination of intuition and observation. There was also the absolute necessity to simplify the manufacture and assembly of the model. The roofs had to be made sufficiently rigid to allow them to be moved in and out of the tunnel and to withstand the wind forces within the tunnel.

To satisfy these constraints for this theoretical exercise, the construction of the model roof imitated vierendeel beams. These beams were to be made up of 12% of steelwork with 88% voids. This ratio applies to all beams and additionally all beams were to be the same depth. This uniformity allowed the placing of a representation of a waterproof skin above or below the structural frame. The skins and cheeks of the roofs were made from 2mm cardboard bonded to the roof members.

Structural members were introduced to judge the influence they would have on air moving through the members and reacting with the solid sections of the structural arrangements. Roof skins were introduced above or below the structural members in some experiments in order to judge the influence the different positions would have on air movement within the stadium.

The roofs were made to represent a centrally located retractable roof and an asymmetric arrangement. The bi-parting roof was represented by a no roof condition based on the logic that the wind tunnel measurements were recorded as a 'slice' of space running through the centre zone of the stadium.

Fig 7.3.1.3.1. shows the model set up to represent the condition of a centrally located retractable roof.
Fig 7.3.1.3.2. shows the model set up to represent the condition of a asymmetrical retractable roof.

Fig 7.3.1.3.1.

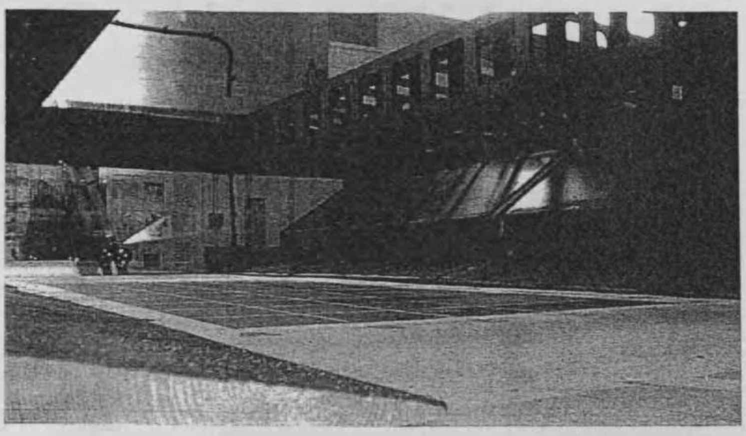
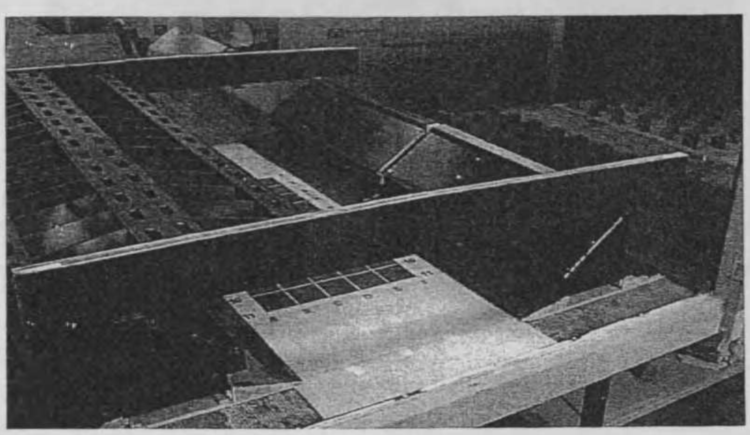


Fig 7.3.1.3.2.



7.3.2. The Artificial Sky - Base Model.

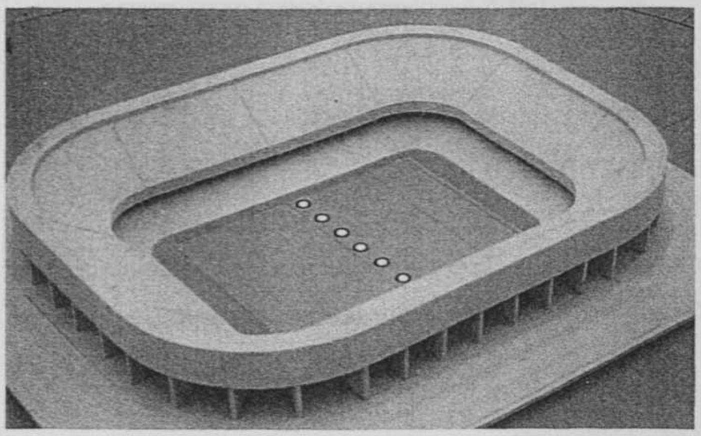
7.3.2.1. Introduction.

The 1:300 scale base model of the generic compact stadium recorded two types of experiments: 1) shadowing over the playing surface and 2) light intensity at selected positions over the playing surface. Experiments were conducted without a roof and with different roof configurations. The model playing surface had to be adjusted for the light intensity experiments.

The scale of 1:300 was agreed between the candidate and his Scientific Supervisor. The size of the resulting model fitted into the sunbeam produced by the Artificial Sky. **Fig 7.3.2.1.** illustrates the base model

Fig 7.3.2.1.

Photograph of the Base Model used for Collecting Shadow and Light level data. The playing surface in the photograph is set up to measure the lighting levels falling on the playing surface.



The other aim of the experimental work in this thesis was to determine airflow rates over the model's playing surface. That requirement dictated a superstructure which was suspended over a concourse running around the arena perimeter, and thus the greatest influence on the form of the model.

The spectator capacity of the model stadium cavea is 60,000. The form of the artificial sky model and the wind tunnel model is identical. The difference between the models is their scale and that the wind tunnel model represents only a horizontal slice through a central portion of the stadium.

The cavea space includes the conditions necessary to comply with good practice of current stadia design. Those conditions and standards are set out as follows:

- Statutory means of escape.[3]
- Seating standards that are marginally higher than those recommended.[4]
- Spectator sightlines free from any obstruction.[5]
- Viewing distances set to allow suggested visual acuity.[6]
- Allowance for disabled accommodation.[7]
- Space provision for 600 media representatives.
- Corporate boxes. (Included in 60,000 capacity).
- VIP accommodation. (Included in 60,000 capacity).
- Players' ingress and egress to and from the arena.
- Three vehicular openings at pitch level with access to the stadium outer zone.
- The playing area is set out for Association Football, Rugby Union, Rugby League and American Football.

The base model was built without a roof. A number of roof options were designed and built to assess the influence each would have on shade and the lighting levels falling on the playing surface. The roofs are later described.

7.3.2.2. Painting the Model.

- Three colours were used in painting the base model. These are as follows:
- The cavea seating. Grey.
- The playing surface. Green.
- The surrounding traffic route. Red / Brown.

To determine the impact colour makes on lighting levels within the cavea, the model was painted two different shades of grey. The lighter shade was applied by a spray gun, the darker was brushed on. Each coating presented a matte even surface.

Each colour value was adjusted to compensate for the fact that the cavea seating was not etched into the raked surfaces of the model. The colour values are described in the text relating to the research measurements.

The base model was professionally made from drawings prepared by the candidate.

---

[3] Guide to Safety at Sports Grounds, 4th Edition, HMSO London, The Stationary Office, 1997. pages, 55to 86 .
[4] *ibid* pages, 105 to 118.
[5] John G &Sheard R,Stadia A Design & Development Guide 1st Edt Butterworth Architecture, 1994, pages 114-119.
[6] *Ibid* 110 –114.

However, for light level experiments the playing surface had to be modified to facilitate an arrangement of light cells set into the playing surface.

7.3.4. PREPARING THE PLAYING SURFACE FOR THE EXPERIMENTS.

7.3.4.1. Turfgrass Grid used to Fix the Shadow Positions.

The full size area of the playing surface used in this study measures 132 x 73 metres. This size was determined to meet the spatial needs of a multi-use stadium. On the model this area was divided into sixty squares, five squares across the short axis and twelve along its long axis. The grid spacing was advised by Dr Brian Clifford of the Institute of Grassland Environmental Research, Aberystwyth, UK. (IGER) who suggested that he, "when measuring lighting levels on a playing surface would utilise a grid falling somewhere between ten and fifteen metre intervals". The resulting grid was etched onto the paintwork of the playing surface; this was used to define the location and extent of the shadows. The same grid was used to record air movement across the playing field.

7.3.4.2 Playing Surface Adjustments made to Record Turfgrass Light Levels.

The data for the levels of light falling on the playing surface was collected via six photocells, each being 22-mm diameter by 20-mm deep. To speed the measurement process, readings were taken across the playing surface in eleven groups of six. To do this it was necessary to cut out the playing area from the model used for the artificial sky and replace it with a new arrangement. This was formed from 11 equally sized strips covering the overall length and width of the playing area. The sum of these parts matched the template removed from the original playing area.

A jig was set up allowing the full width of a strip to be milled. The material used for the strips was 5mm Medium Density Fibreboard, (M.D.F). The length of the strips milled was 10mm longer than the length required and then adjusted to match the jig. The width of the jig was adjusted three times before the correct strip width was achieved.

The eleven strips were then clamped together to re-form the playing surface. The strips were fixed over the template baseboard with double-sided adhesive tape. It was found necessary to rub them individually again with superfine glass paper. The widths of the strips were collectively adjusted to match the template. The strips were brush painted the same colour as the original base.

---

[7] Guide to Safety at Sports Grounds, 4th Edition, HMSO London, The Stationary Office, 1997, page141.

One of the eleven strips was then drilled at each point of intersection on the original grid lines to receive the six photocells. This arrangement allowed for the holed strip to be substituted in turn for a non-holed strip at each grid line, allowing the 66 light level measurements to be recorded without changing the connections between the photocells and the computer at each exchange in any of the experiments.

The photocells were 10mm deeper than the depth of the model base. The base was therefore raised by that amount from the floor by adding a 10mm runner on each long side of the opening into which the 11 strips were fitted. The strips were supported on the long side of the base by a 5mm x 5mm soft wood strip.

Raising the base allowed the following:

- The cells to sit firmly on the base of the Artificial Sky, the level of which had been checked.
- The light receiving face of the cells to be set on the same plane as the playing surface.
- A cavity for the connecting wiring between the photocells and the computer.

7.3.5. The Roof Models.

Three roof options were designed for the basic model. Within that framework eight roof options have been developed which are recorded and illustrated in Figs **7.3.5.1-7.3.5.9.**

All versions of the roof models were coloured white; that colour remained unchanged irrespective of the cavea colour. The undersides of all roofs were spray painted and the upper surfaces brush painted. All roof models were made from 2 mm card. Where structural members have been replicated in the roof models, these have been built in modelling grade hardwood round or square sections. Junctions between wooden members have been shaped to fit together as far as possible within the restrictions of the scale. Then they have been bonded with an impact adhesive. In the case of the space frame construction, a number of jigs were made to replicate a roof curve.

The candidate could not calculate the roof structure, therefore was unable to arrive at accurate constructional depths for any of the roof options. Neither has it been possible to consider methods of structural appraisal available to produce optimum depths.

Fig 7.3.5.10.

A section of the longitudinal Beam set over the San Siro Stadium, Milan, Italy. The stadium provides a column free open roof.

With the exception of the option of the centrally located retractable roof, the roof structure required for the other options would be considerably more complex than the design of the roof for the San Siro. These roofs would in each of the options be subjected to additional forces imposed by structural elements that move or both move and fold. Therefore, a degree of exaggeration has been built into the assumed depths of the roof elements. This has been done in order to look at worst case considerations. However, two different structural depths have been modelled for the centrally located retractable conditions. The one depth is 30% shallower than the other. The purpose of this was to determine the influence depth has on the measurements of both shade and lighting levels on the playing surface. Each roof model fits over the base model at pre-determined locations.

The following figures illustrate the roof variations used in the lighting experiments but only roof numbers 1,2,3, 4 and 6 were used in the shadow experiments. The information contained in the residual figures was used to contrast and compare the detail of the roofs in the discussion set out in Chapter 8. The description accompanying each figure provides some detail of the various roof configurations set against the open roof.

The following figures illustrate the roof variations used in the lighting experiments but only roof numbers 1,2,3, 4 and 6 were used in the shadow experiments. The information contained in the residual figures was used to contrast and compare the detail of the roofs in the discussion set out in Chapter 8. The description accompanying each figure provides some detail of the various roof configurations set against the open roof.

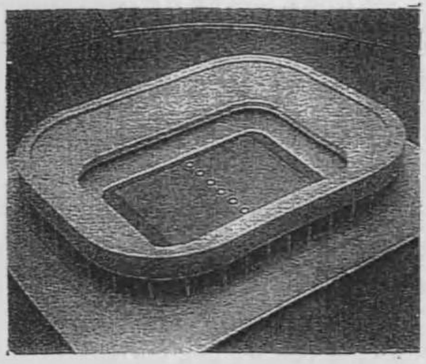


Fig. 7.3.5.1. (R1). Base Model - No roof.
The free to sky area provided by this option is 38,914. sq m. and is assumed to be 100% of that availability. The area is calculated within the 3 metre wide plane which represents the upper level of the superstructure structural zone. This plane also provides the structural seat for all roof models. The % of free lighting areas of all other roofs relates to the open area of R1.

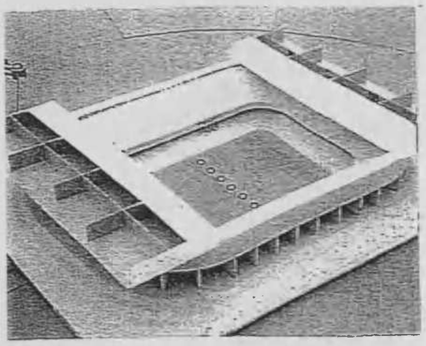


Fig.7.3.5.2. (R2). Longitudinal Bi-parting Roof.
The free to sky area provided by this option is 71.4% of R1. This figure is dependent on the structural depth of the roof folding and rolling mechanism. The free to sky area could also be increased by extending the folding and rolling roof sections to a line outside the outer perimeter of a stadium.

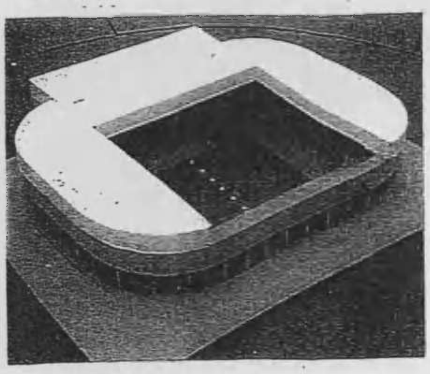
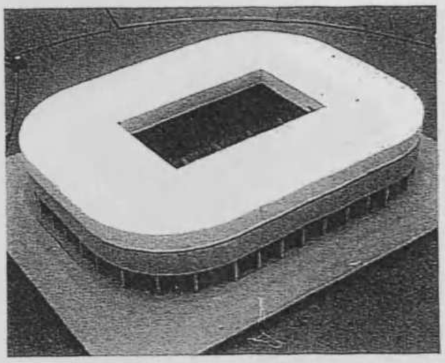


Fig 7.3.5.3. (R3) Asymmetrical Retractable roof. [Deep Structure]
The free to sky area provided by this option is 49.4% of [R1]. This figure may be increased by reducing the folding mechanism or by extending the roof further over the outer perimeter of the building, This roof type has an alternative North West and North East orientation.

Fig.7.3.5.4. (R4). Centrally located Bi-parting roof. With the roof in the open position. Surrounding surfaces opaque. [the structure is assumed to be Deep].
The free to sky area within this option is 23% on the model tested.



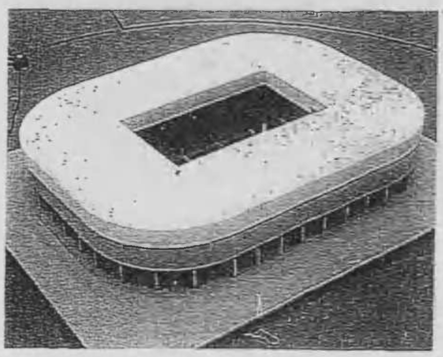


Fig.7.3.5.5. (R5). Centrally located Bi-parting roof. With the roof in the open position. Surrounding surfaces opaque. [the structure is assumed to be Deep].
The free to sky area within this option is 23% on the model tested.

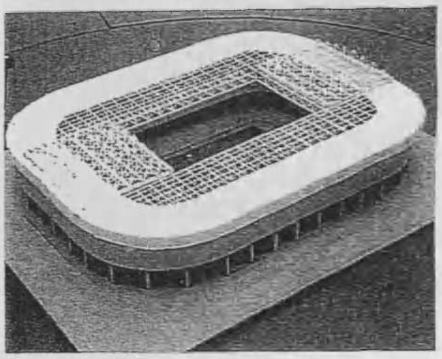
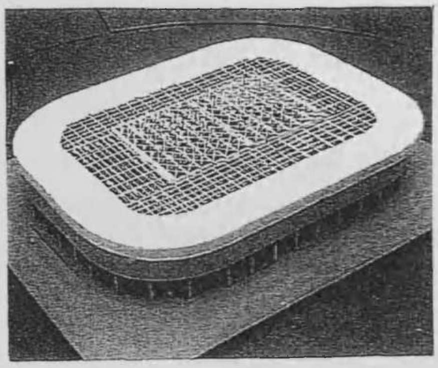


Fig.7.3.5.6. (R6). Centrally located Bi-parting roof. With exposed lattice construction [Shallow Structure]. The retractable roof is open and when open covers 12% of the adjacent glazed area. The free to sky area within this option is 23%; the lattice area is 27%; and the opaque area is 38% on the model tested. Surrounding lattice surfaces glazed with 1.5 mm clear plastic on the test model.

Fig.7.3.5.7. (R7). **Centrally located Bi-parting roof. With exposed lattice construction Shallow Structure]. The retractable roof is closed. The free to sky glazed area is 62%; the opaque area is 38% on the model tested. Lattice surfaces glazed with 1.5 mm clear plastic on the test model.**



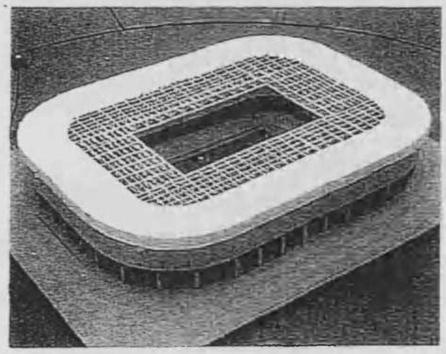


Fig.7.3.5.8. (R8). Centrally located Bi-parting roof. With exposed lattice construction;[Shallow Structure]. The retractable roof is removed. The free to sky open area is 23%; lattice area is 39%; the opaque area is 38% on the model tested. Lattice surfaces glazed with 1.5 mm clear plastic on the test model.

Fig. 7.3.5.9. (R9). Represents a roof with the central lattice structure and the retractable roof removed. The free area represents 62% of the roof area. The surrounding opaque area is 38%.

CHAPTER FOUR.

7.4.0. THE DIRECT LIGHT DATA.

7.4.1. Introduction

The extent and location of the areas of direct light falling on the modelled playing field may be deduced from the **Tables 7.4.1.1 to 7.4.1.7.** For simplicity and ease of reference the areas are shown in the form of graphs, **Figs 7.4.1.1 to 7.4.1.7.** Also provided are a set of photographs showing the comparison between areas in shadow and those in receipt of the direct beam for the differing retractable roof configurations. These photographs were taken during the period of measuring of the direct light and the diffuse light conditions in the Artificial Skydome. The photographs are presented in colour and appear as **Figs 9.6.1 to 9.6.7.1** in the appendices.

Twelve large scale photographs of the varying roof configurations are also included in the main text. The purpose of including these is that they help to clarify the method of constructing the the Tables and Graphs they also clearly show some of the difficulties in calculating the data which make up make some of the graphs especially those which relate to the roofs where the structure is exposed. The roofs in the photographs are grouped in the same way as they are found in the graphs. These photographs are listed under **7.4.1.3 the Location Photographs.**

7.4.1.1. The Tables

Each table records the data related to six different roof configurations. Beneath each roof type there are two columns: column one sets out, the percentage of the playing area not in shadow and column two the location of those areas. The data was collected at hourly intervals and when needed, at half hourly intervals on a particular day, during the months of December, January, February, March, April, May and June. The remaining months of the year are not recorded as the shadow free values from June to December are almost identical with those of the months from January to June.

To collect the data the playing field is divided into 60 rectangles, five across the field and twelve in the longer direction. The perimeter of theses rectangles is defined by grid lines which, when the lines occur across the pitch, are numbered and when in the long direction, are denoted by letters. The grid allows the shadow free areas to be fixed both in area and in location.

During the experiment 351 photographs were recorded in the Artificial Sky with a 'stills' camera located over the model at an identical point for each shot. The camera was set on a video tripod with an extension arm to avoid the influence of its shadow falling on the model. A delay mechanism was incorporated to avoid camera shake; the camera was activated from outside the

Artificial Sky. Each photograph was examined on a computer screen and the areas not in shadow calculated by counting the squares or parts of squares not in shadow.

The basis of the shadow calculation was that the 60 squares represent 100% of the playing field area. Therefore 1 square represents 1.67%. The number of squares of shadow free areas multiplied by 1.67% provides the total percentage for each reading.

The vertical gridlines are further divided to pinpoint more accurately the location of the shadow free areas across the playing area.

The same method was used to determine the influence of the shadows imposed by the structural filigree on the areas of direct light see Fig 7.4.1.9. From these imprints the shadow free areas were calculated. The way in which this was carried out was to estimate the percentage of interference of the shadowing in each of the grid spaces. Because of the difficulty in being reasonably accurate, this exercise was carried out three times and an average of the two readings nearest each other was recorded. The same exercise was undertaken in order to calculate the areas where sunlight entered the stadium between the concourse and the underside of the grandstand. In the majority of cases this method is sufficiently accurate for the purposes of these experiments. The difficulty arises in calculating areas where the filigree, imposed by the modelled structure, falls on the turfgrass or where sunlight enters the playing field from the space between the concourse and the underside of the grandstand.

In all cases the direct light areas were determined by transferring an imprint made of these areas to the chart shown in **Fig 7.4.1.** This chart presents the grid lines, as they appear on the model but this was an easier problem that deciding on the impact of the filigree on the playing surface.

7.4.1.2. The Graphs.

The graphs represent beam proportions on the playing field for the differing roof configurations and for each stated month. The roof configurations are grouped in pairs, selected to provide areas open to the sky that are as near as possible to each other.

The groups are presented in this way to establish quickly which roof configuration has the greatest advantage in admitting sunlight to the playing surface. The greater the area depicted within the graph boundaries, the greater the available sunlight. Some groups in some months clearly establish that the amount of sunlight entering a stadium is so insignificant as to be irrelevant to turfgrass growth. Part Eight will review the dependence of turfgrass growth on levels of sunlight but in addition, reviews the relationship of temperature and air movement to sunlight and tries to rank their interdependence in successful turfgrass establishment.

7.4.1.3 The Location Photographs.

The complete set of photographs are presented in the appendices as **Figs 9.6.1 to 9.6.7.1.** These are small-scale reductions and represent the photographs used to work on the data from which the Tables and Graphs were constructed. These photographs set trace the rising of the sun path and its falling back during a daily cycle on the 21st day of the months recorded. This trace shows the Direct and Diffuse lighting conditions in a stadium influenced by the differing roof configurations introduced during the study.

A limited number of location photographs are also presented to a larger size than the photographs in the appendices. But these photographs are ten percent smaller than the photographs used to produce the Tables and Graphs.

This group of photographs records the image of the Direct and Diffuse light for each of the six roof configurations. These photographic images are numbered as follows:

Fig 7.4.1.1.	**No Roof. Direct and Diffuse Light.**	**21st December 12:00 hrs.**
Fig 7.4.1.2.	**No Roof. Direct and Diffuse Light.**	**21st June 12:00 hrs.**
Fig 7.4.1.3.	**Longitudinal Bi-Parting Roof. Direct and Diffuse Light.**	**21st December 12:00 hrs.**
Fig 7.4.1.4.	**Longitudinal Bi- Parting Roof. Direct and Diffuse Light.**	**21st June 12:00 hrs.**
Fig 7.4.1.5.	**Centrally Located Retractable Roof. Direct and Diffuse Light.**	**21st December 12:00 hrs.**
Fig 7.4.1.6.	**Centrally Located Retractable Roof. Direct and Diffuse Light.**	**21st June 12:00 hrs.**
Fig 7.4.1.7.	**Centrally Located Retractable Roof. Lattice Construction. Direct and Diffuse Light.**	**21st December 12:00 hrs.**
Fig 7.4.1.8.	**Centrally Located Retractable Roof. Lattice Construction. Direct and Diffuse Light.**	**21st June 12:00 hrs.**
Fig 7.4.1.9.	**Asymmetrical Retractable Roof. (North West.) Direct and Diffuse Light.**	**21st December 12:00 hrs.**
Fig 7.4.1.10	**Asymmetrical Retractable Roof. (North West) Direct and Diffuse Light.**	**21st June 12:00 hrs.**
Fig 7.4.1.11.	**Asymmetrical Retractable Roof. (North East.) Direct and Diffuse Light.**	**21st December 12:00 hrs.**
Fig 7.4.1.12.	**Asymmetrical Retractable Roof. (North East) Direct and Diffuse Light.**	**21st June 12:00 hrs.**

These photographs are included to reinforce the written description between the relationship of the direct and diffuse areas with the grid lines on the playing surface. The photographs are recorded on the 21st day of December and 21st June at 12:hrs in most cases. The photographic images are linked by the same roof pairings in the photographs as they are in the Graphs.

In most cases the collection of the direct and diffuse lighting values are both easily and accurately gathered. However, the photograph the of Centrally Located Retractable Roof which incorporates Lattice construction illustrates the complexity of collecting data in this case. This complexity is repeated in all the photographs with this roof configuration.

Of the twelve larger scale images presented, ten were measured at 12:00 hrs and two, the Centrally Located Retractable Roof Lattice Roof and the Centrally Located Roof with Opaque finishes were recorded at 14:00 hrs on the 21st of December. This change was introduced to illustrate an additional problem of collecting data during early mornings or late afternoons or evenings these are times when the sun is either rising or setting. The stadium base model is novel, in that its design has an open concourse separating the upper grandstand from the lower grandstand.

This novelty allows the unanticipated affect of allowing the sun at low angles to penetrate through the space between the base of the concourse and the underside of the grandstand running over the concourse. The direct light is weak, its pattern of light does not readily conform to the rectilinear grid thus making it necessary to convert the polygonal shapes in the equivalent areas represented by the rectangular grid. This detail was not available on the 21st of December, until 14:00 hrs. The twelve larger photographs are shown because they are indicative of the photographs used in conjunction with **Chart 7.4.2** to determine the data for the Tables and Graphs.

Chart 7.4.2.

The Chart used to determine beam areas and their locations.

The areas are recorded on the charts to two Decimal places but on the graphs only whole numbers were used. The position of the beam areas is recorded across the width of the pitch by numbers and on the length of the pitch by letters. Where the shadow free area stopped less than half way into a rectangle it was recorded by the number or letter below the stopping point of the beam area. Where the stopping point exceeded half way in the rectangle the value of the number or letter above the lower value was taken.

The example shown is 21St April 08:00 hrs Roof One. (No Roof)

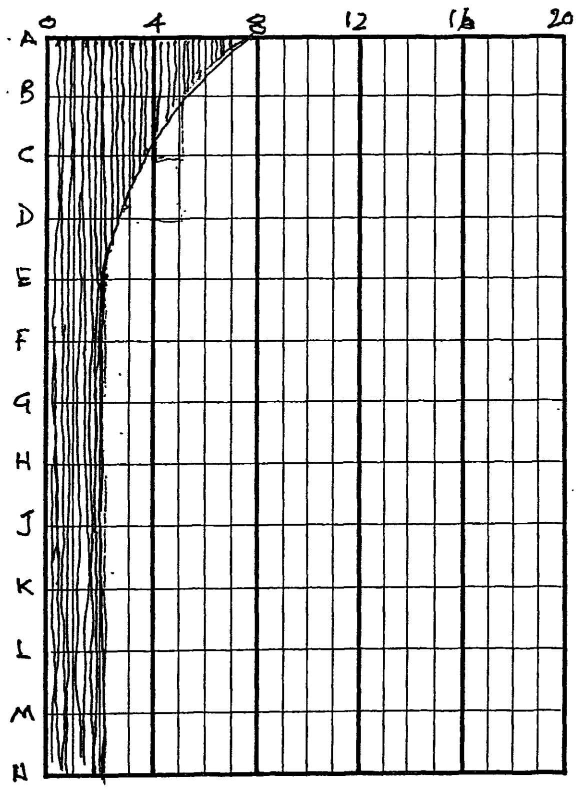


Fig 7.4.1.1 No Roof. Direct and Diffuse Light. 21st December 12:00 hrs.

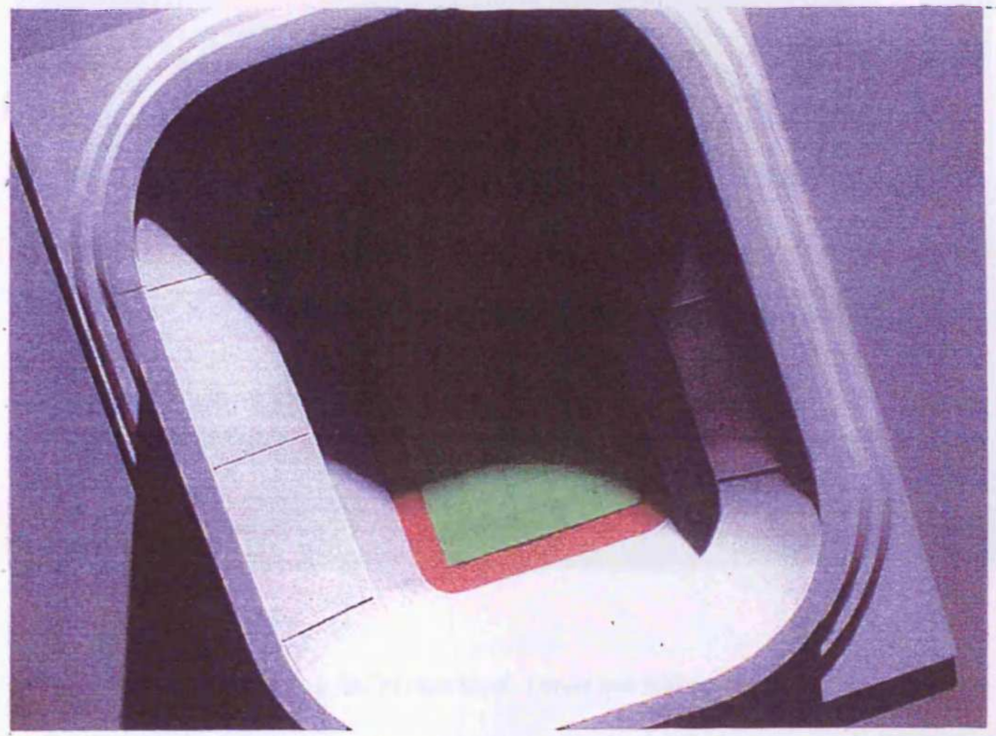


Fig 7.4.1.2. No Roof. Direct and Diffuse Light. 21st June 12:00 hrs

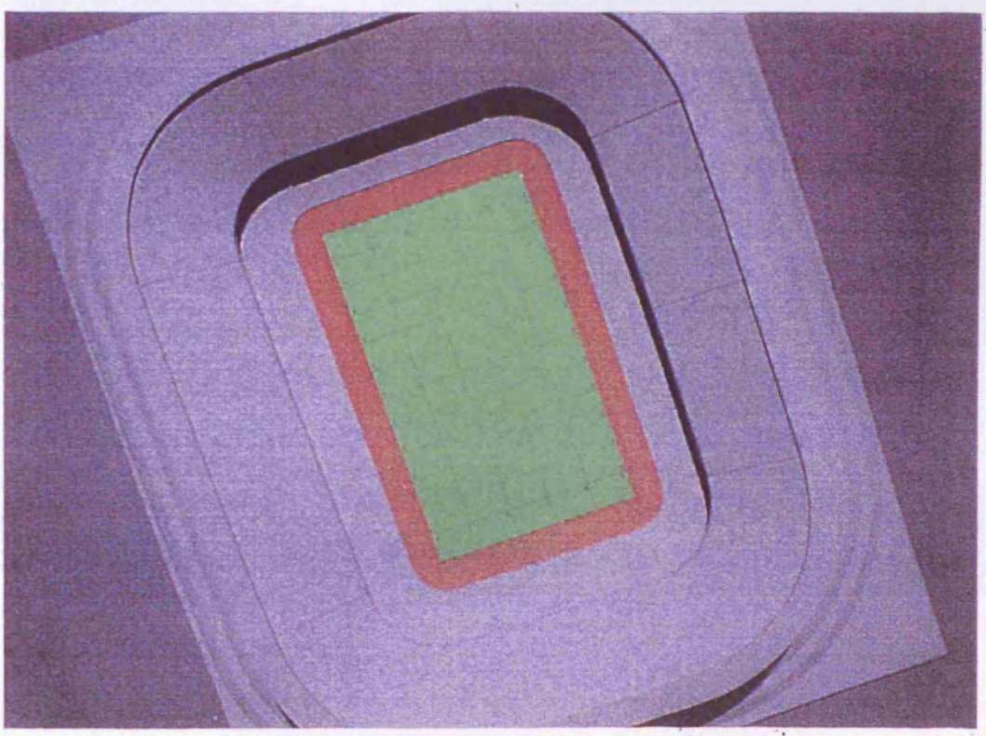


Fig 7.4.1.3. Longitudinal Bi- Parting Roof. Direct and Diffuse Light. 21st December 12:00 hrs.

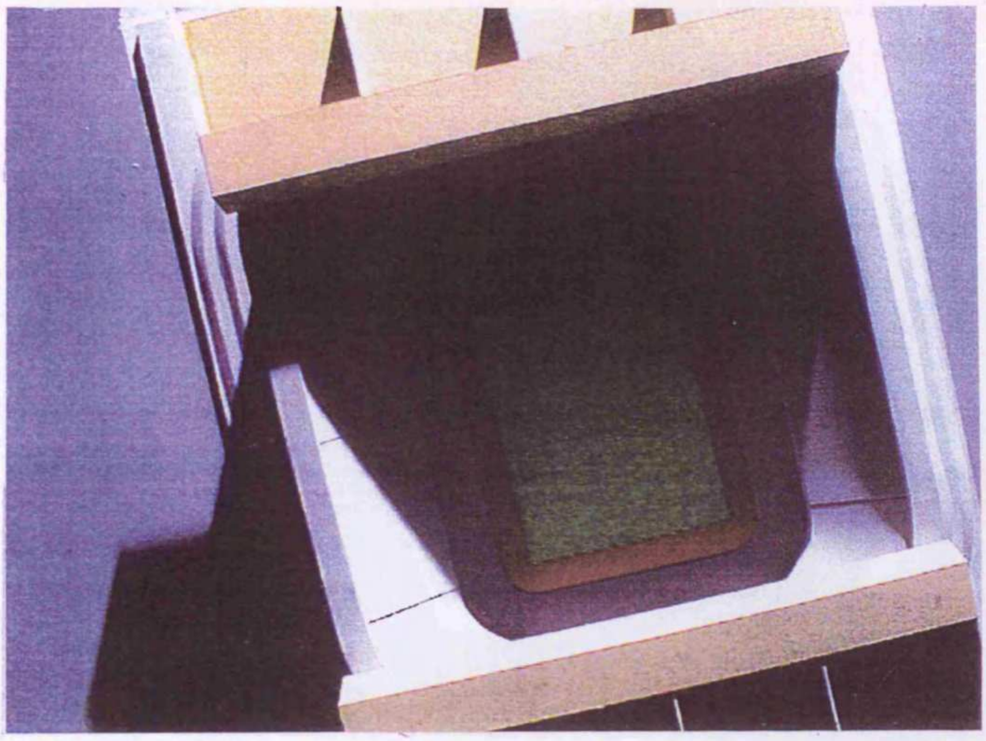


Fig 7.4.1.4. Longitudinal Bi- Parting Roof. Direct and Diffuse Light. 21st June 12:00 hrs.

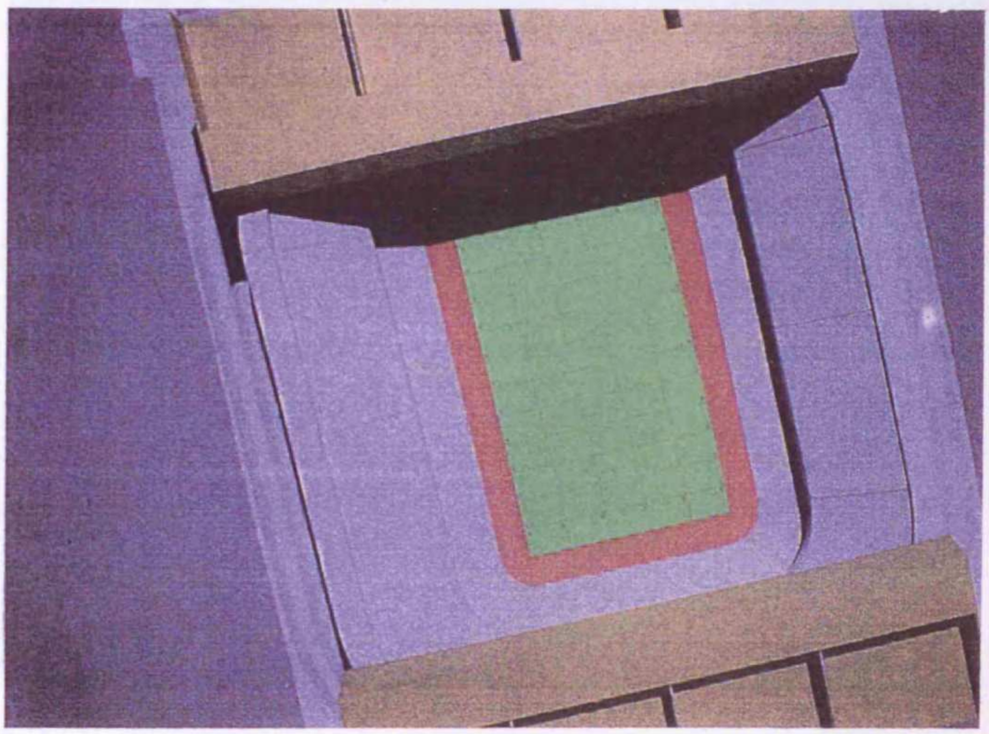


Fig 7.4.1.5. Centrally Located Retractable Roof. Direct and Diffuse Light. 21st December 12:00 hrs

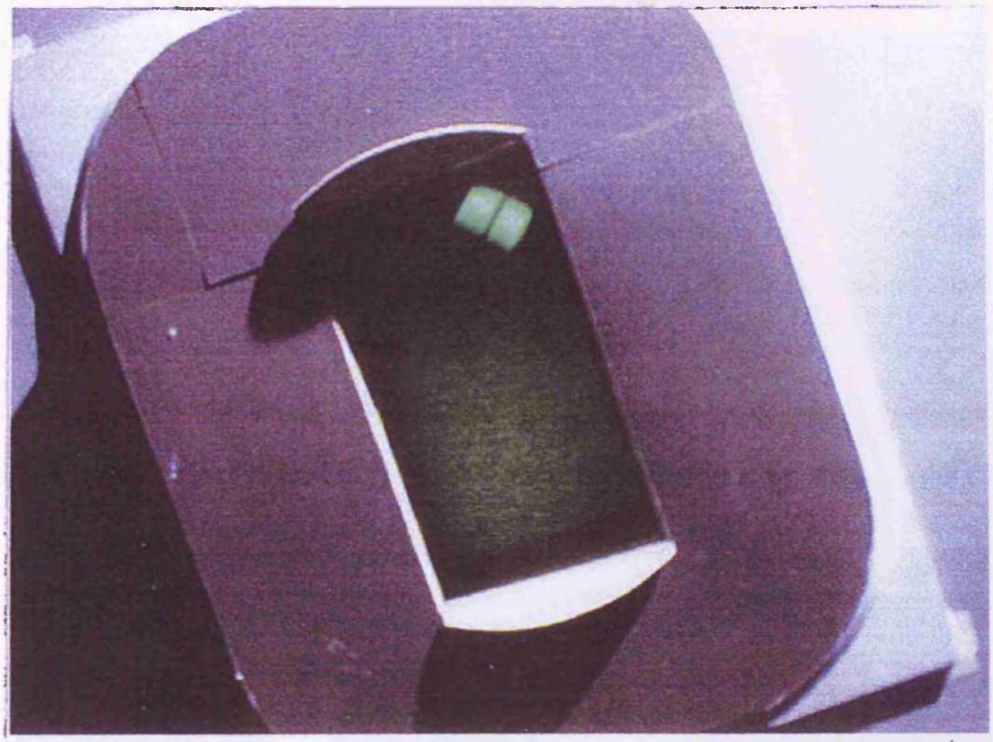


Fig 7.4.1.6. Centrally Located Retractable Roof. Direct and Diffuse Light. 21st June 12:00 hrs.

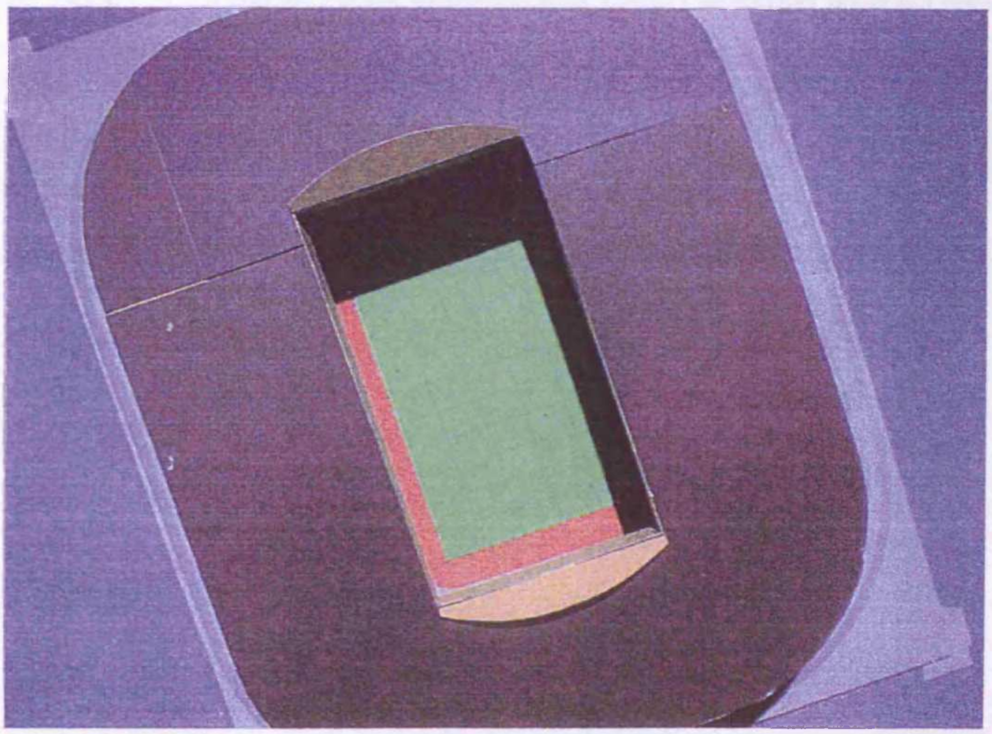


Fig 7.4.1.7. Centrally Located Retractable Roof. Lattice Construction Direct and Diffuse Light. 21st December 12:00 hrs.

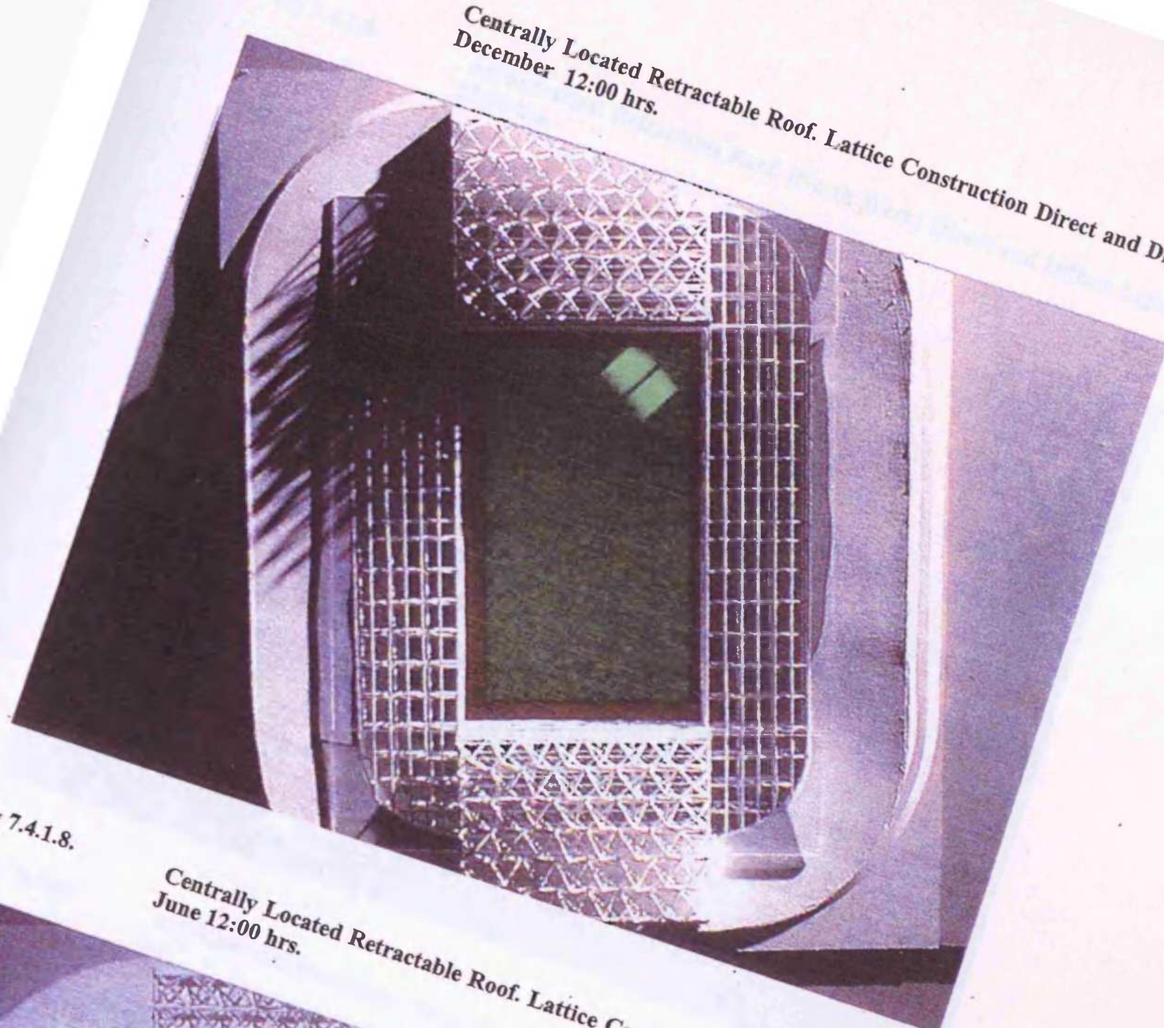


Fig 7.4.1.8. Centrally Located Retractable Roof. Lattice Construction Direct and Diffuse Light. 21st June 12:00 hrs.

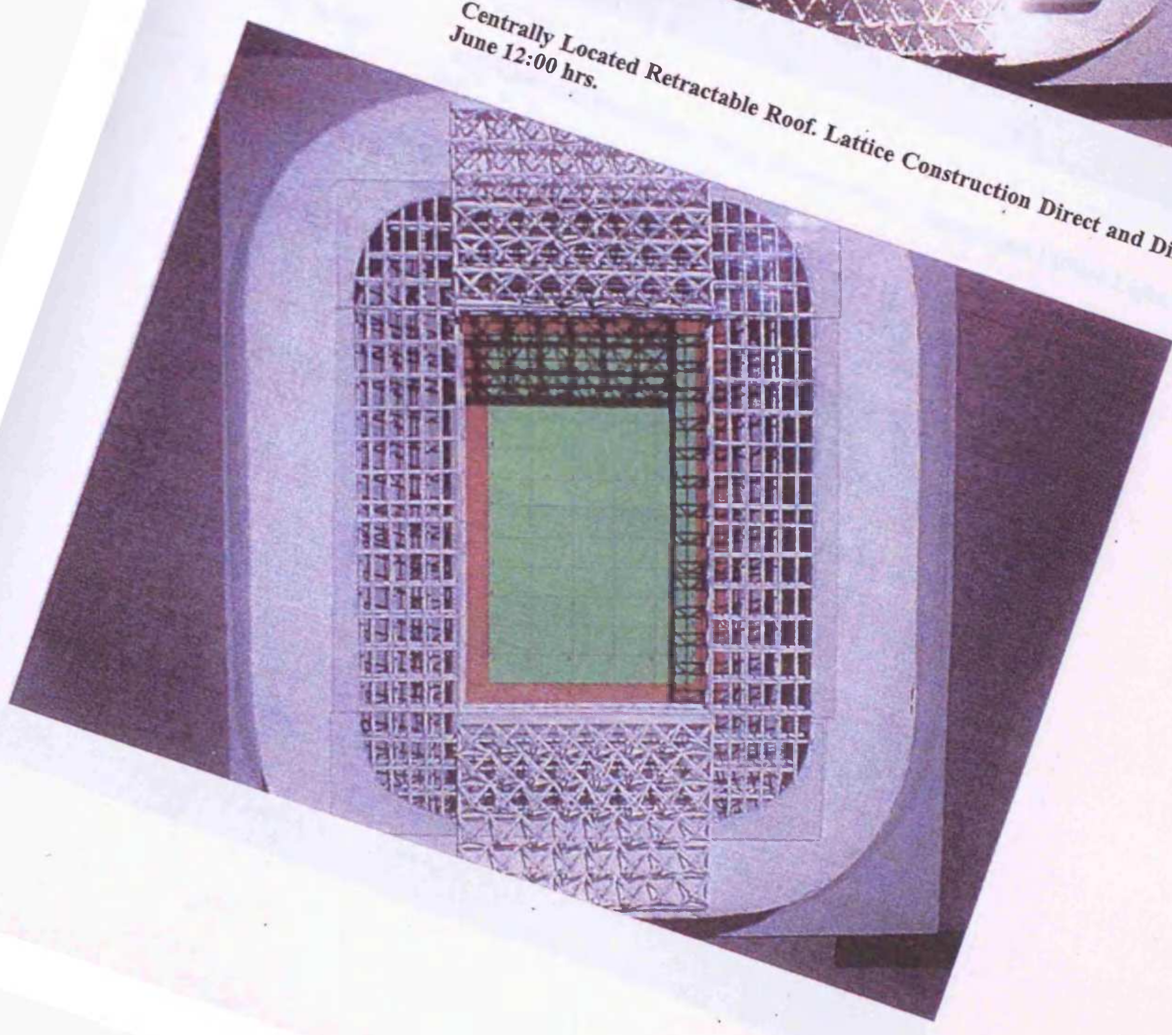


Fig 7.4.1.9. Asymmetrical Retractable Roof. (North West.) Direct and Diffuse Light. 21st December 12:00 hrs.

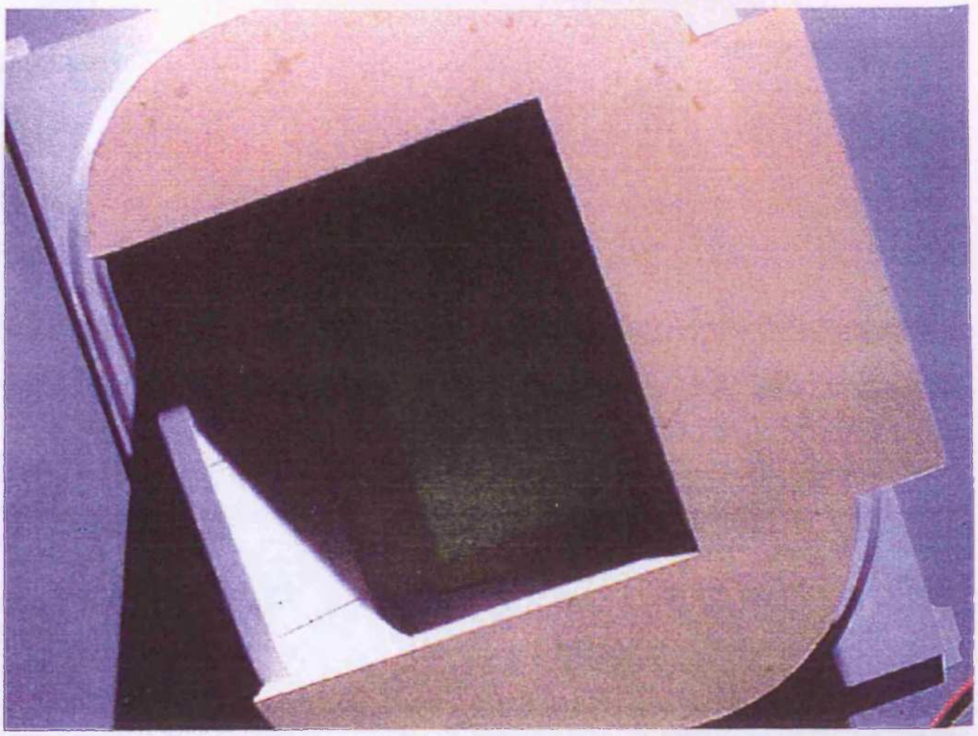


Fig 7.4.1.10 Asymmetrical Retractable Roof. (North West) Direct and Diffuse Light. 21st June 12:00 hrs.

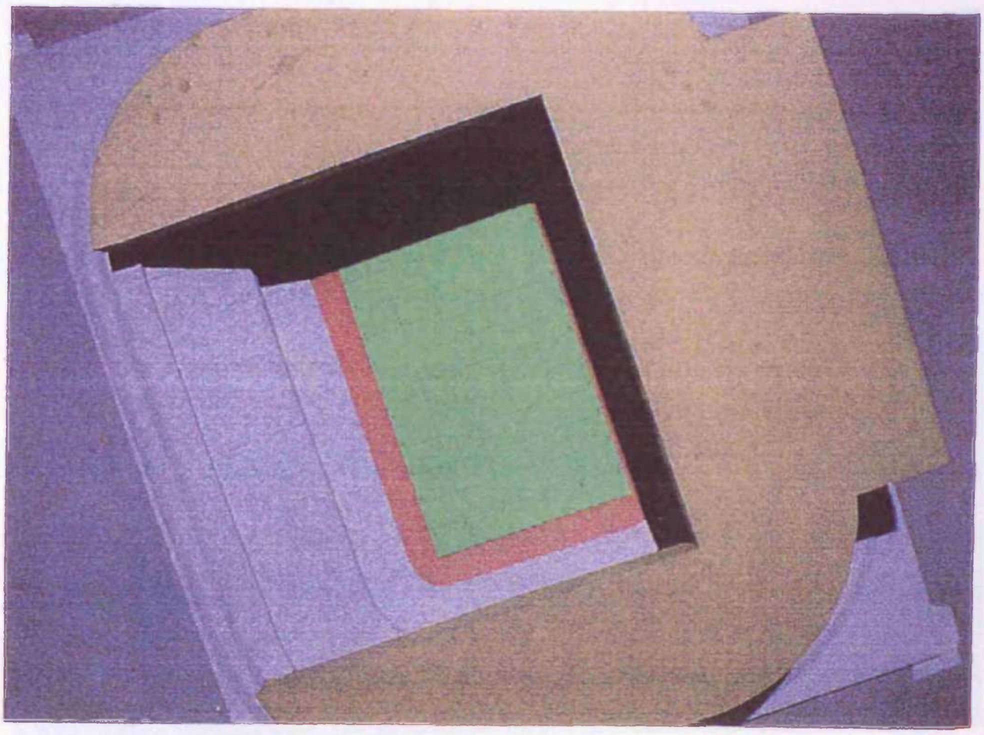


Fig 7.4.1.11. Asymmetrical Retractable Roof. (North East.) Direct and Diffuse Light. 21st December 12:00 hrs.

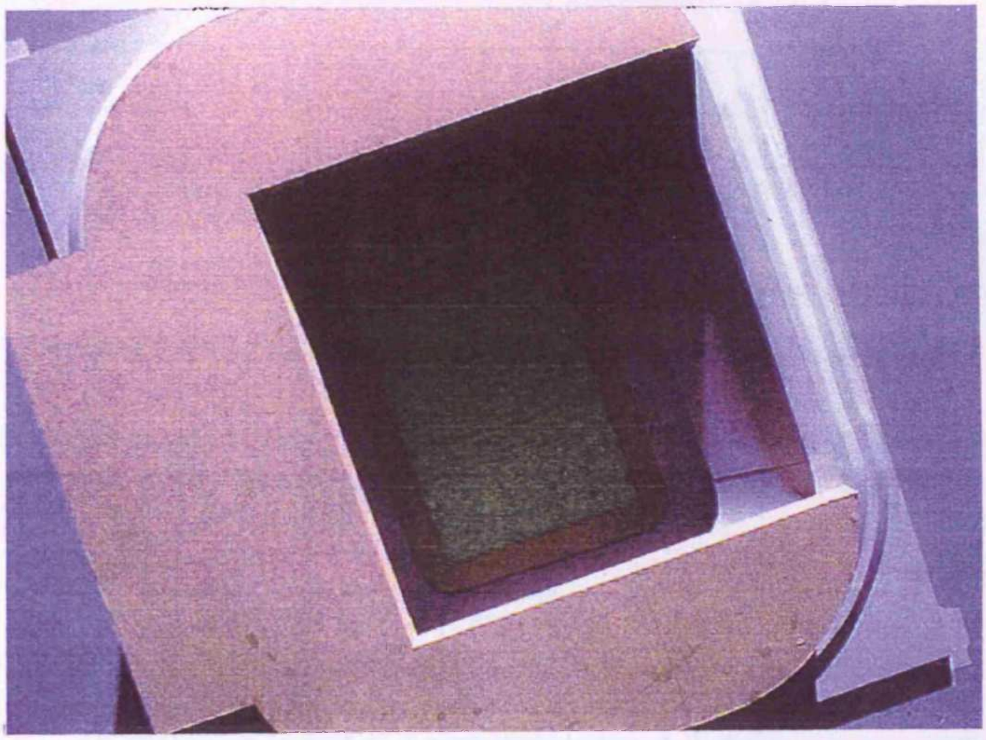


Fig 7.4.1.12. Asymmetrical Retractable Roof. (North East) Direct and Diffuse Light. 21st June 12:00 hrs.

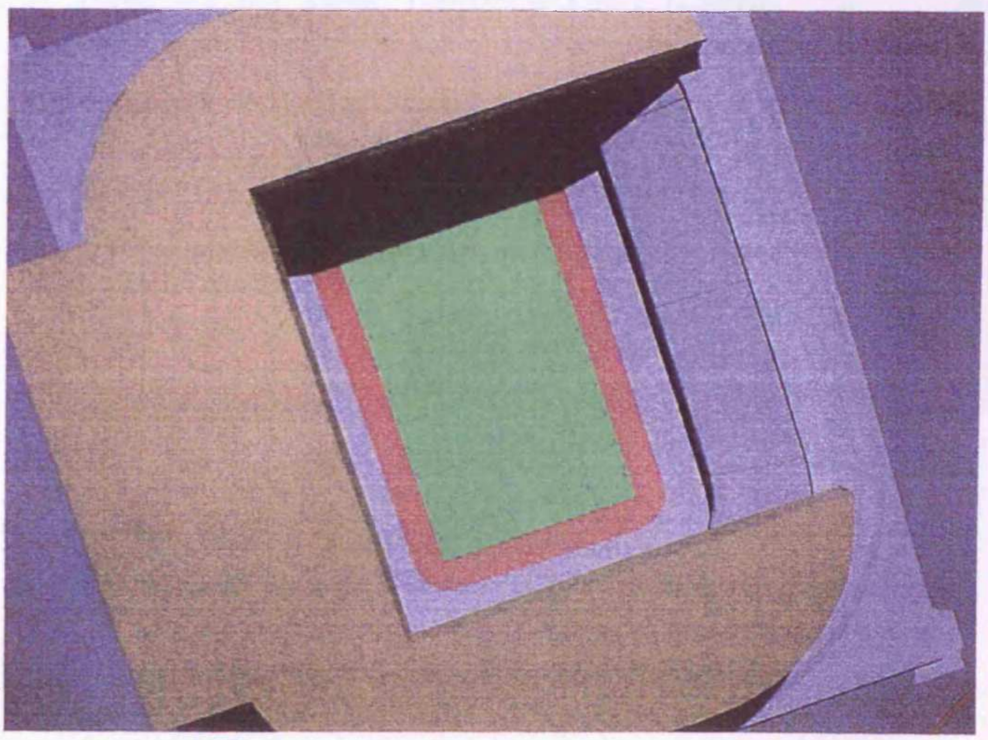


Table 7.4.1.1.

Percentage of Shadow free Areas and their Locations. All Roof Types. JANUARY.

Time	N. R.		C.L R.R.		C.L.R.R. (L.C.).		B. P.		Asy .(N.W).		Asy.(N.E.).	
(hrs)	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
06:00	0	0	0	0	0	0	0	0	0	0	0	0
06:30	0	0	0	0	0	0	0	0	0	0	0	0
07:00	0	0	0	0	0	0	0	0	0	0	0	0
07:30	0	0	0	0	0	0	0	0	0	0	0	0
08:00	0	0	0	0	0	0	0	0	7.5	6.20 CH*	10.0	6.20-BF*
08:30	13.3	4.18-DK*	10.5	4.19-CK*	10.5	4.19-CK*	0	0	0	0	0	0
09:00	6.7	0.18-BC*	5.8	0.18-BC*	5.8	0.18-BC*	0	0	6.6	0.18-AE*	6.2	1.16-BD*
10:00	0	0	0	0	0	0	0	0	0	0	0	0
11:00	37.3	0.20-FN	0	0	0	0	0	0	0	0	0	0
12:00	47.5	0.12-HN	0	0	0	0	0	0	0	0	0	0
13:00	33.0	0.16-HN	0	0	0	0	0	0	0	0	0	0
14:00	0	0	0	0	0	0	0	0	0	0	0	0
15:00	4.16	7.17-AE*	0	0	0	0	0	0	4.8	7-17AD*	0	0
16:00	0	0	0	0	0	0	0	0	9.6	0-8 AN*	0	0
16:30	0	0	0	0	0	0	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0	0	0	0	0
(hrs)	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
	N. R.		C.L.R.R.		C. L. R.R. (L.C).		B.P.		Asy .(N.W).		Asy.(N.E.).	

[1] Percentage of shadow free area on playing surface. [2]Location of shadow free area on playing surface.

**Sunlight enters the stadium at concourse level*

N.R. No Roof. C.L.R.R. Centrally Located Retractable Roof. C.L.R.R. (L.C.). (Lattice Construction).

B.P. Bi-Parting. Asy.(N.W.). Asymmetrical Roof. (North West). Asy.(N.E) Asymmetrical Roof. (North East).

Table 7.4.1.2.
Percentage of Shadow free Areas and their Locations. All Roof Types. FEBRUARY

Time	N. R.		C.L.R.R		C.L.R.R. (L.C.).		B.P.		Asy .(N.W).		Asy.(N.E.).	
(hrs)	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
06:00	0	0	0	0	0	0	0	0	0	0	0	0
06:30	0	0	0	0	0	0	0	0	0	0	0	0
07:00	0	0	0	0	0	0	0	0	0	0	0	0
07:30	12.6	7.20-BH*	12.6	7.20-BH*	12.6	8.20-BH*	0	0	0	0	0	0
08:00	4.8	0.7 -AC*	4.8	0.7 -AC*	4.8	2.8 -AC*	0	0	4.6	0.7 -AC*	4.6	0.7 -AC*
08:30	0	0	0	0	0	0	0	0	0	0	0	0
09:00	32.0	4.20-EJ	0	0	0	0	0	0	0	0	0	0
10:00	70.0	0.20-CJ	0	0	0	0	12.5	0.20-HJ	6.66	020-NM	5.5	7.20-MN
11:00	80.0	0.20-CJ	6.7	0.20-MN			26.0	0.20-GJ	20.87	0.20-KN	23.33	0.20 -KN
12:00	85.0	0.20-BJ	10.3	0.13-LN	14.0	0.20-FN*	Missing		37.57	0.16-JN	31.3	0.20 -JN
13:00	87.0	0.20-BJ	5.0	0.4 -KN	12.2	0.18-FN*	35.0	0.20-FJ	12.92	0.7-JN	36.7	0.20 -JN
14:00	62.0	0.16-BJ	0	0	4.4	0.4 -HN	34.7	0.16-FJ	0	0	27.4	0.15-HN
15:00	6.5	0.2 -CJ	0	0	0	0	6.0	0.2 -DJ	0	0	5.8	0.2 -FN
16:00	8.5	15.18-AN*	0	0	0	0	0	0	0	0	0	0
16:30	28.1	0.12- AN*	0	0	0	0	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0	0	0	0	0
	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
	N.R.		C.L.R.R.		C.R.R. (L.C.)		B.P.		Asy .(N.W).		Asy.(N.E.).	

[[1] Percentage of shadow free area on playing surface. [2]Location of shadow free area on playing surface.

**Sunlight enters the stadium at concourse level*

N.R. No Roof. C.L.R.R. Centrally Located Retractable Roof. C.L.R.R. (L.C.). (Lattice Construction).

B.P. Bi-Parting. Asy.(N.W.). Asymmetrical Roof. (North West). Asy.(N.E) Asymmetrical Roof. (North East).

Table 7.4.1.3.
Percentage of Shadow free Areas and their Locations. All Roof Types. MARCH.

Time	N.R.		C.L.R.R		C.L.R.R.(L.C.)		B.P.		Asy .(N.W).		Asy.(N.E.).	
(hrs)	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
06:00	0	0	0	0	0	0	0	0	0	0	0	0
06:30	0	0	0	0	0	0	0	0	0	0	0	0
07:00	0	0	0	0	3.33	2.6-AB*	0	0	0	0	0	0
07:30	0	0	0	0	0	0	0	0	0	0	0	0
08:00	28.82	12.20-DN	0	0	0	0	15.99	1020-KN	11.70	10.20LN	0	0
08:30	0	0	0	0	0	0	0	0	0	0	0	0
09:00	87.82	0.20-BN	2.66	1920-KN	19.2	8.20-DJ	40.41	0.20-HN	35.07	0.20-HN	9.85	1420-HN
10:00	96.66	0.20-AN	21.65	7.20-JN	34.98	0.20-CN	49.99	0.20-GN	44.67	0 20-GN	37.74	4.20-GN
11:00	100.00	0.20-AN	41.3	0.20-HN	43.31	0.20-CN	54.99	0.20-FN	51.93	0.20-GN	41.66	0.20-FN
12:00	100.00	0.20-AN	41.8	0.20-HN	44.91	0.20-CN	61.66	0.20-FN	52.24	0.17-FN	56.78	0.20 -FN
13:00	100.00	0.20-AN	19.8	0.12-GN	44.62	0.20-CN	67.49	0.20-FN	38.00	0.10-FN	64.00	0.20 -DN
14:00	98.66	0.20-AN	0	0	19.6	0.12-BN	73.33	0.19-BN	10.3	0.3-DN	7090.	0.20-CJ
15:00	59.68	0.12-AJ	0	0	0	0	1.8	0.2- EN	0	0	48.76	012-DN
16:00	0	0	0	0	0	0	0	0	0	0	0	0
16:30	0	0	0	0	0	0	0	0	0	0	0	0
17:00	26.72 *	8.16- AN*	0	0	0	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0	0	0	0	0
	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
	N R		C.L.R.R.		C.L.R.R (L.C.)		B.P.		Asy .(N.W).		Asy.(N.E.).	

[1] Percentage of shadow free area on playing surface.

[2]Location of shadow free area on playing surface.

**Sunlight enters the stadium at concourse level*

N.R. No Roof. C.L.R.R. Centrally Located Retractable Roof. C.L.R.R. (L.C.). (Lattice Construction).

B.P. Bi-Parting. Asy.(N.W.). Asymmetrical Roof. (North West). Asy.(N.E) Asymmetrical Roof. (North East).

Table 7.4.1.4.

Percentage of Shadow free Areas and their Locations. All Roof Types. APRIL.

Time	N.R.		C.L.R.R		C.L.R.R. (L.C.)		B.P.		Asy .(N.W).		Asy.(N.E.).	
(hrs)	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
06:00	0	0	0	0	0	0	0	0	0	0	0	0
06:30	0	0	0	0	0	0	0	0	1.25	1920-EN	0	0
07:00	15.32	15.20-BN	0	0	0	0	14.16	16.20-FN	13.36	1620-DN	0	0
07:30	0	0	0	0	0	0	0	0	0	0	0	0
08:00	86.13	2.20 -AJ	0	0	13.00	11.20-BN	60.33	2.20-EN	55.58	2.20 EN	0	0
08:30	0	0	0	0	0	0	0	0	0	0	0	0
09:00	100.00	0.20-AN	19.49	13.20.GN	42.00	2.20-BN	61.83	0.20-EN	61.83	0.20-EN	33.79	1020-EN
10:00	100.00	0.20-AN	38.90	6.20-FN	58.30	0.20-BN	70.81	0.20-DN	65.83	0.20-EN	60.00	2.20- EN
11:00	100.00	0.20-AN	60.41	0.20-FN	72.80	0.20-AN	74.16	0.20-DN	68.83	0.20-EN	70.00	0.20- EN
12:00	100.00	0.20-AN	51.66	0.20-EN	68.31	0.20-AN	77.49	0.20-DN	67.93	0.18 -DN	74.16	0.20 -CN
13:00	100.00	0.20-AN	34.58	0.10-EN	70.10	0.20-AN	83.33	0.20-CN	51.15	0.13 -DN	79.16	0.20 -CN
14:00	100.00	0.20-AN	15.41	0.4 - DN	38.20	0.16-AN	90.82	0.20-BN	29.75	0.7 -CN	86.66	0.20- CN
15:00	89.99	0.17-AN	0	0	36.20	0.14-AN	89.99	0.17-AN	0	0	83.13	0.17- AN
16:00	44.00	0.9 -AN	0	0	0	0	44.00	0 9 -AN	0	0	44.00	09 - AN
16:30	0	0	0	0	0	0	12.00	0.2 -AN	0	0.	12.03	0.2 - AN
17:00	0	0	0	0	0	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0	0	0	0	0
	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
	N. R.		C.L.R.R.		C.L.R.R.(L.C.)		B.P.		Asy .(N.W).		Asy.(N.E.).	

[1] Percentage of shadow free area on playing surface. [2]Location of shadow free area on playing surface.

**Sunlight enters the stadium at concourse level*

N.R. No Roof. C.L.R.R. Centrally Located Retractable Roof. C.L.R.R. (L.C.). (Lattice Construction).

B.P. Bi-Parting. Asy.(N.W.). Asymmetrical Roof. (North West). Asy.(N.E) Asymmetrical Roof. (North East).

Table 7.4.1.5.
Percentage of Shadow free Areas and their Locations. All Roof Types. MAY.

Time	N. R.		C.L.R.R.		C.L R.R. (L.C.).		B. P.		Asy .(N.W).		Asy.(N.E.).	
(hrs)	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
06:00	0	0	0	0	0	0			0		0	0
06:30	40.00	12.20-AN	0	0	0	0	37.20	13.20-AN	35.38	12-20 BN	0	0
07:00	63.00	6.20-AN	0	0	1.25	18.20-AN	64.74	6.20-BN	62.00	6-20 BN	0	0
07:30	0	0	0	0	11.3	12.20-AN	0	0	0	0	0	0
08:00	100.00	0.20-AN	5.99	19.20-CN	25.00	7.20 -AN	87.07	0.20-BN	81.79	0.20-CN	20.88	I 520-CN
08:30	0	0	0	0	0	0	0	0	0	0	0	0
09:00	100.00	0.20-AN	32.72	11.20-DN	46.00	1.20-AN	85.00	0.20-CN	79.32	0.20-CN	51.28	9.20-CN
10:00	100.00	0.20-AN	53.05	5.20 -EN	68.00	0.20-AN	85.09	0.20-CN	79.32	0.20-CN	78.56	2. 20-CN
11:00	100.00	0.20-AN	73.33	0.20 -DN	83.00	0.20-AN	90.00	0.20-BN	81.33	0.20-CN	81.80	0.20-CN
12:00	100.00	0.20-AN	63.6	0.17 -DN	76.00	0.20-AN	95.00	0.20-AN	83.46	0.19-CN	86.05	0.20-CN
13:00	100.00	0.20-AN	48.99	0.12 -BN	64.00	0.20-AN	96.00	0.20-AN	70.30	0.15-CN	91.01	0.20-CN
14:00	100.00	0.20-AN	32.99	0.90 -BN	53.00	0.20-AN	100.00	0.20-AN	51.01	0.11-AN	98.53	0.20-AN
15:00	100.00	0.20-AN	6.00	0.2 -AJ	35.00	0.1I- AN	80.00	0.16-AN	25.05	0.5 -AN	100.0	0.20-AN
16:00	81.66	0.16-AJ	0	0	26.00	0.8- AN	78.00	0.16-AH	0	0	88.16	0.16-AN
16:30	0	0	0	0	22.00	0.10- AN	0	0	0	0	0	0
17:00	39.33	0.80-AJ	0	0	0	0	33.33	0.8 -AG	0	0	30.39	08-AK
18:00	0.83	1920-MN*	0	0	0	0	0	0	0	0	4.7	02-AG
	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
	N. R.		C.L.R.R.		C.L.R.R. (L.C.)		B.P.		Asy .(N.W).		Asy.(N.E.).	

[1] Percentage of shadow free area on playing surface.

[2]Location of shadow free area on playing surface.

**Sunlight enters the stadium at concourse level*

N.R. No Roof. C.L.R.R. Centrally Located Retractable Roof. C.L.R.R. (L.C.). (Lattice Construction).

B.P. Bi-Parting. Asy.(N.W.). Asymmetrical Roof. (North West). Asy.(N.E) Asymmetrical Roof. (North East).

Table 7.4.1.6.

Percentage of Shadow free Areas and their Locations. All Roof Types. JUNE.

Time	N. R.		C.L.R.R.		C.L.R.R. (L..C.)		B.P.		Asy .(N.W).		Asy.(N.E.).	
(hrs)	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
06:00	15.00	17.20-AN	0	0	0	0	13.30	17.20-AJ	21.1	16-20AN	0	17.20-AJ
06:30	0	0	0	0	0	0	0		0	0	0	
07:00	77.60	5.20-AN	0	0	0	0	73.10	5.20-AN	41.4	6-20 CN	0	5.20-AJ
07:30	0	0	0	0	23.0	10.20-AN	0		0	0	0	
08:00	100.00	0.20-AN	7.49	17.20-CN	44.0	8.20-AN	91.66	0.20-AN	85.6	0.20-CN	26.6	1420BN
08:30	0	0	0	0	0	0	0	0	0	0	0	0
09:00	100.00	0.20-AN	35.33	12.20CN	60.0	0.20-AN	89.75	0.20-BN	83.5.	0.20-CN	55.5	7.20-CN
10:00	100.00	0.20-AN	56.24	6.20-DN	72.0	0.20-AN	87.49	0.20-BN	81.8	0.20-CN	78.3	2.20CN
11:00	100.00	0.20-AN	76.60	0.20-CN	86.O	0.20-AN	89.90	0.20-BN	85.17	0.20-BN	86.0	0.20-CN
12:00	100.00	0.20-AN	70.00	0.18-CN	84.0	0.20-AN	93.32	0.20-AN	88.51	0-20-BN	89.8	0.20BN
13:00	100.00	0.20-AN	55.83	1.14-CN	81.0	0.19-AN	97.91	0.20-AN	74.15	0.16-BN	94.4	0.20AN
14:00	100.00	0.20-AN	39.00	1.9 -BN	70.0	0.19-AN	100.00	0.20-AN	60.12	0,12-AN	100.0	0.20-AN
15:00	100.00	0.20-AN	18.33	0.4 -BN	55.0	0.14-AN	100.00	0.20-AN	35.10	0.7 -AN	100.0	0.20-AN
16:00	94.12	0.18-AN	0	0	26.7	0.10-AN	94.64	0.17-AN	4.0	0.1 -AN	96.2	0.19AN
16:30	0	0	0	0	0	0	0	0	0	0	0	0
17:00	59.10	0.12-AH	0	0	1.5	0.2 -AK	51.66	0.13-AL	0	0	47.3	0.12-AJ
18:00	3.00	0.2 -AJ	0	0	0	0	2.62	0.2 -AD	0	0	0.7	0.1 - AF
	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
	N. R.		C.L.R.R.		C.L R..R. (L.C)		B.P.		Asy .(N.W).		Asy.(N.E.).	

[1] Percentage of shadow free area on playing surface. [2]Location of shadow free area on playing surface.

**Sunlight enters the stadium at concourse level*

N.R. No Roof. C.L.R.R. Centrally Located Retractable Roof. C.L.R.R. (L.C.). (Lattice Construction)

B.P. Bi-Parting. Asy.(N.W.). Asymmetrical Roof. (North West). Asy.(N.E) Asymmetrical Roof. (North East).

Table 7.4.1.7.
Percentage of Shadow free Areas and their Locations. All Roof Types. DECEMBER.

Time	N.R.		C.L R.R		C.L.R.R. Lattice		B.P.		Asy .(N.W).		Asy.(N.E.).	
(hrs)	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
06:00	0	0	0	0	0	0	0	0	0	0	0	0
06:30	0	0	0	0	0	0	0	0	0	0	0	0
07:00	0	0	0	0	0	0	0	0	0	0	0	0
07:30	0	0	0	0	0	0	0	0	0	0	0	0
08:00	8.33	4.20-DK*	0	0	0	0	0	0	0	0	0	0
08:30	0	0	0	0	0	0	0	0	0	0	0	0
09:00	10.00	0.20-CE*	0	0	0	0	0	0	0	0	0	0
10:00	4.00	0.20-AB*	4.5	0.20-AB*	3.7	0.20-AB*	2.7	0.20- AB*	0	0	3.4	0.20-AB*
11:00	12.49	0.20- MN	0	0	0	0	0	0	0	0	0	0
12:00	20.83	0.20- KN	0	0	0	0	0	0	0	0	0	0
13:00	3.30	0.7- LN	0	0	0	0	0	0	0	0	0	0
14:00	3.60	15.18-AC*	2.5	17.20-AC*	2.5	13.17-AC*	2.5	13.17-AC*	2.5	11.18-AC*	0	0
15:00	7.00	0.10- BG*	7.0	0. 10-BG*	7.00	0.10- BG*	0	0	7.00	0.10-BG*	0	0
16:00	9.20	0.8 - AN*	0	0	0	0	0	0	0	0	0	0
16:30	0	0	0	0	0	0	0	0	0	0	0	0
17:00	20.00	0.7 - AN*	0	0	0	0	0	0	0	0	0	0
18:00	0	0	0	0	0	0	0	0	0	0	0	0
	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]	[1]	[2]
	N. R.		C.L. R.R.		C.L.R.R. (L.C.).		B.P.		Asy .(N.W).		Asy.(N.E.).	

[1] Percentage of shadow free area on playing surface. [2]Location of shadow free area on playing surface.

**Sunlight enters the stadium at concourse level*

N.R. No Roof. C.L.R.R. Centrally Located Retractable Roof. C.L.R.R. (L.C.). (Lattice Construction).

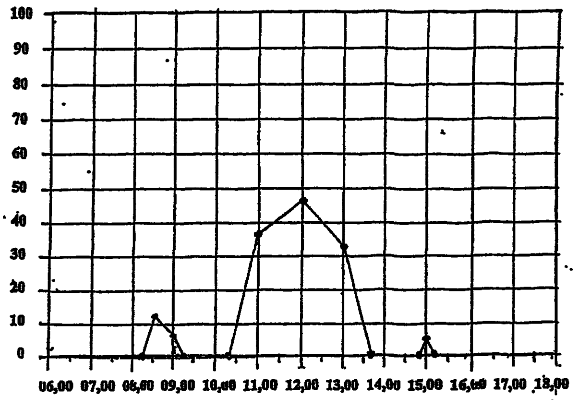
B.P. Bi-Parting. Asy.(N.W.). Asymmetrical Roof. (North West). Asy.(N.E) Asymmetrical Roof. (North East).

Fig 7.4.1.13. **JANUARY**

Illustrates graphically the shadow free area on the natural turfgrass playing surface as allowed by each roof configuration. The roofs are grouped in pairs. Each pair is made up of roofs with a common association in terms of their 'free to sky open area'. The vertical axis of each graph indicates the percentage of the shadow free area; the horizontal axis expresses time in hourly and half hourly intervals.

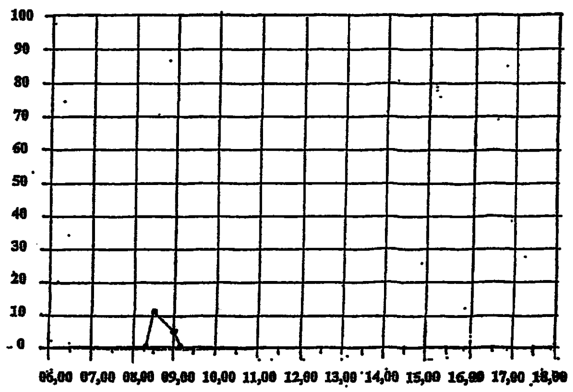
NO ROOF ————————

BI-PARTING
RETRACTABLE ROOF. - - - - - - - - - -
[Fig 7.4.1.1.1.



CENTRALLY LOCATED RETRACTABLE ROOF. ————————

CENTRALLY LOCATED RETRACTABLE ROOF. LATTICE CONSTRUCTION. - - - - - - - - - -
[Fig 7.4.1.1.2.]



ASYMMETRICAL
RETRACTABLE ROOF.
(N.W. ORIENTATION.). ————————

ASYMMETRICAL
RETRACTABLE ROOF.
(N.E. ORIENTATION.). - - - - - - - - - -
[Fig 7.4.1.3.]

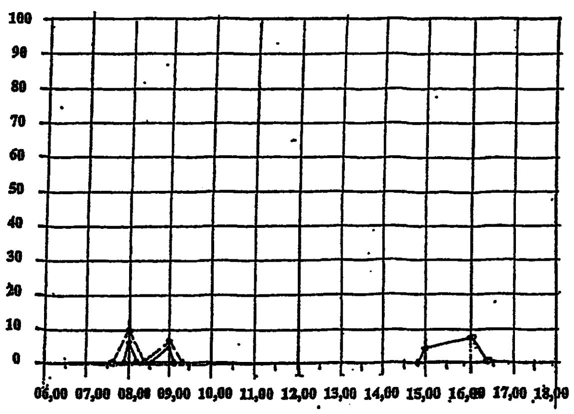
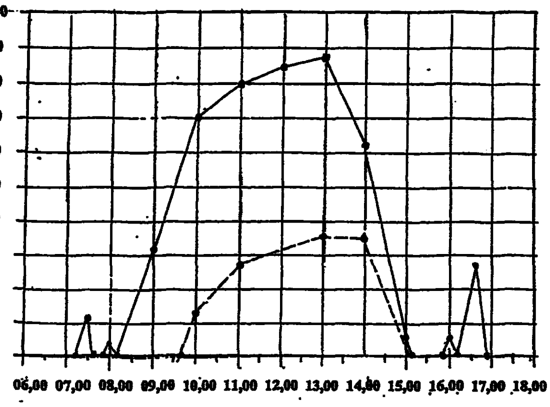


Fig 7.4.1.14. **FEBRUARY**

Illustrates graphically the shadow free area on the natural turfgrass playing surface as allowed by each roof configuration. The roofs are grouped in pairs. Each pair is made up of roofs with a common association in terms of their 'free to sky open area'. The vertical axis of each graph indicates the percentage of the shadow free area; the horizontal axis expresses time expressed in hourly and half hourly intervals.

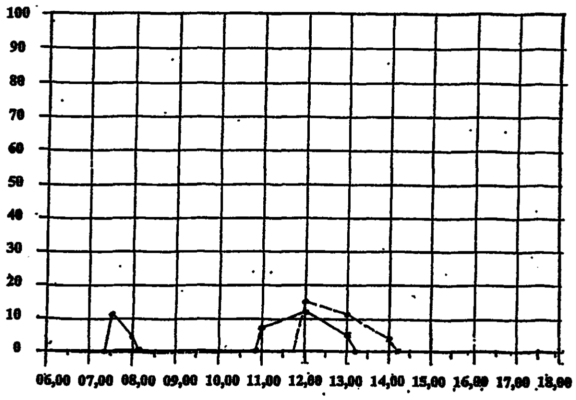
NO ROOF ————

BI-PARTING
RETRACTABLE ROOF. - - - - - - - - -
[Fig 7.4.1.2.1.]



CENTRALLY LOCATED
RETRACTABLE ROOF. ————

CENTRALLY LOCATED
RETRACTABLE ROOF. - - - - - - - - -
LATTICE CONSTRUCTION.
[Fig7.4.1.2.2.]



ASYMMETRICAL
RETRACTABLE ROOF. ————
(N.W. ORIENTATION.).

ASYMMETRICAL
RETRACTABLE ROOF. - - - - - - - - -
(N.E. ORIENTATION.)..
[Fig 7.4.1.2.3.]

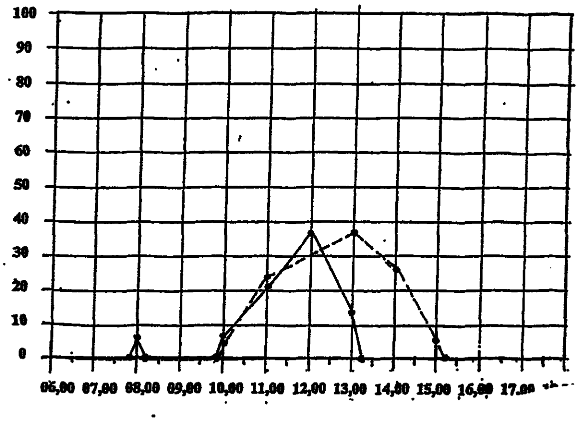
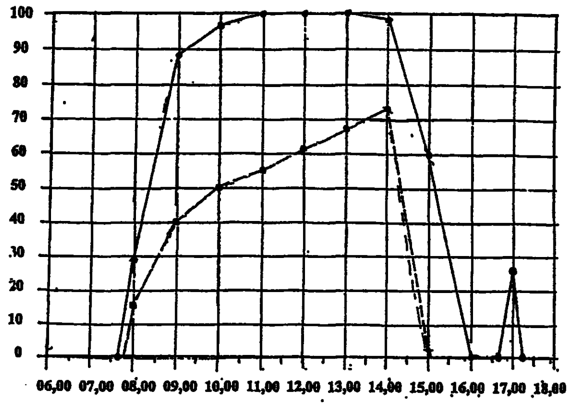


Fig 7.4.1.15. **MARCH**

Illustrates graphically the shadow free area on the natural turfgrass playing surface as allowed by each roof configuration. The roofs are grouped in pairs. Each pair is made up of roofs with a common association in terms of their 'free to sky open area'. The vertical axis of each graph indicates the percentage of the shadow free area; the horizontal axis expresses time in hourly and half hourly intervals.

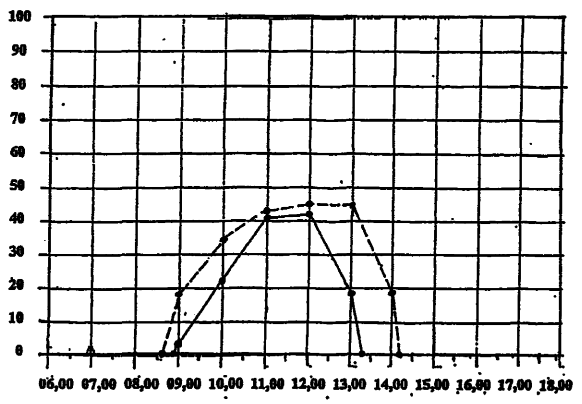
NO ROOF ————

BI-PARTING
RETRACTABLE ROOF. - - - - - - - -
[7.4.1.3.1.]



CENTRALLY LOCATED RETRACTABLE ROOF. ————

CENTRALLY LOCATED RETRACTABLE ROOF. LATTICE CONSTRUCTION. - - - - - - - -
[7.4.1.3.2.]



ASYMMETRICAL RETRACTABLE ROOF. (N.W. ORIENTATION.). ————

ASYMMETRICAL RETRACTABLE ROOF. (N.E. ORIENTATION.). - - - - - - - -
[7.4.1.3.3.]

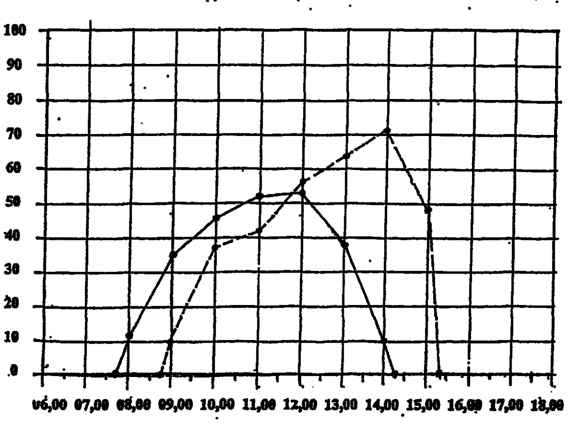


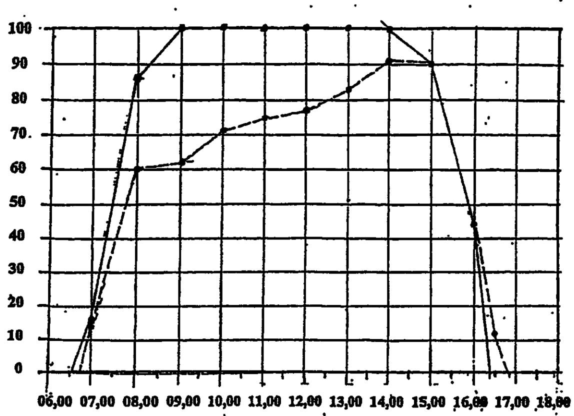
Fig 7.4.1.16.

APRIL

Illustrates graphically the shadow free area on the natural turfgrass playing surface as allowed by each roof configuration, The roofs are grouped in pairs. Each pair is made up of roofs with a common association in terms of their 'free to sky open area'. The vertical axis of each graph indicates the percentage of shadow free area; the horizontal axis expresses time in hourly and half hourly intervals.

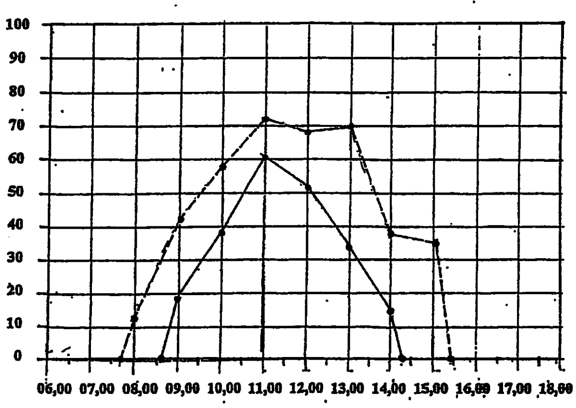
NO ROOF ————————

BI-PARTING RETRACTABLE ROOF. - - - - - - - -
[Fig 7.4.1.4.1.]



CENTRALLY LOCATED RETRACTABLE ROOF. ————————

CENTRALLY LOCATED RETRACTABLE ROOF. LATTICE CONSTRUCTION. - - - - - - - -
[Fig 7.4.1.4.2.]



ASYMMETRICAL RETRACTABLE ROOF. (N.W. ORIENTATION.). ————————

ASYMMETRICAL RETRACTABLE ROOF. (N.E. ORIENTATION.). - - - - - - - - -
[Fig 7.4.1.4.3.]

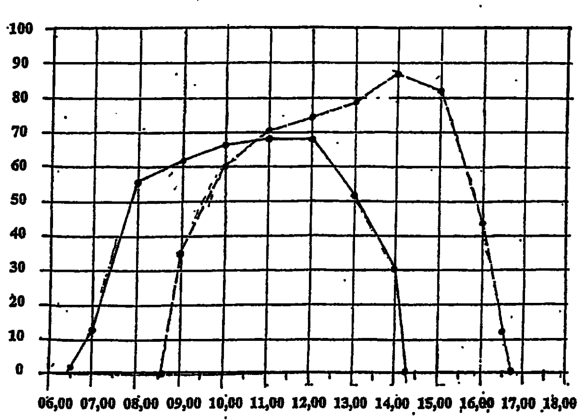


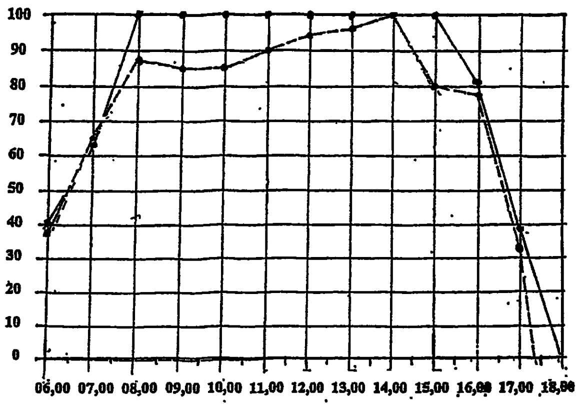
Fig 7.4.1.17.

MAY

Illustrates graphically the shadow free area on the natural turfgrass playing surface as allowed by each roof configuration. The roofs are grouped in pairs. Each pair is made up of roofs with a common association in terms of their 'free to sky open area'. The vertical axis of each graph indicates the percentage of shadow free area; the horizontal axis expresses time in hourly and half hourly intervals.

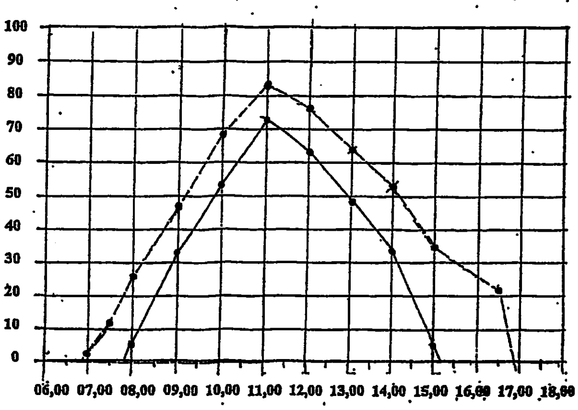
NO ROOF ————————

BI-PARTING RETRACTABLE ROOF. [Fig 7.4.1.5.1.] - - - - - - - -



CENTRALLY LOCATED RETRACTABLE ROOF. ————————

CENTRALLY LOCATED RETRACTABLE ROOF. LATTICE CONSTRUCTION. [Fig 7.4.1.5.2.] - - - - - - - -



ASYMMETRICAL RETRACTABLE ROOF. (N.W. ORIENTATION.). ————————

ASYMMETRICAL RETRACTABLE ROOF. (N.E. ORIENTATION.). [Fig7.4.1.5.3.] - - - - - - - -

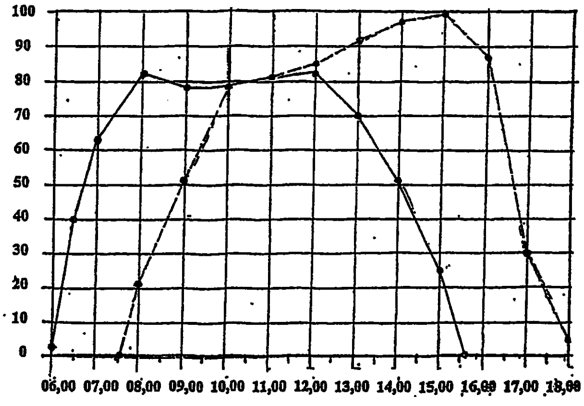


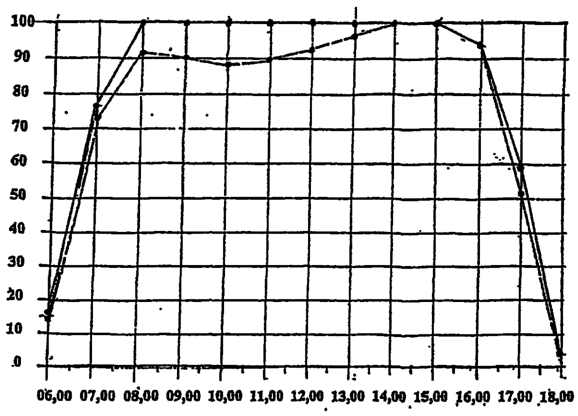
Fig 7.4.1.18.

JUNE

Illustrates graphically the shadow free area on the natural turfgrass playing surface as allowed by each roof configuration. The roofs are grouped in pairs. Each pair is made up of roofs with a common association in terms of their 'free to sky open area.' The vertical axis of each graph indicates the percentage of shadow free area; the horizontal axis expresses time in hourly and half hourly intervals.

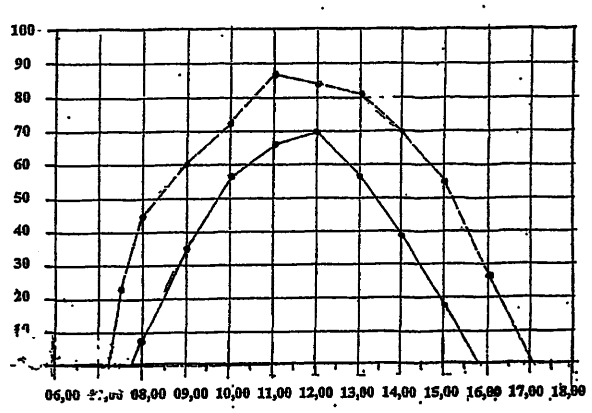
NO ROOF ————

BI-PARTING RETRACTABLE ROOF. - - - - - - -
[Fig 7.4.1.6.1]



CENTRALLY LOCATED RETRACTABLE ROOF. ————

CENTRALLY LOCATED RETRACTABLE ROOF. LATTICE CONSTRUCTION. - - - - - - - -
[Fig 7.4.1.6.2]



ASYMMETRICAL RETRACTABLE ROOF. (N.W. ORIENTATION.). ————

ASYMMETRICAL RETRACTABLE ROOF. (N.E. ORIENTATION.). - - - - - - - -
[Fig 7.4.1.6.3.]

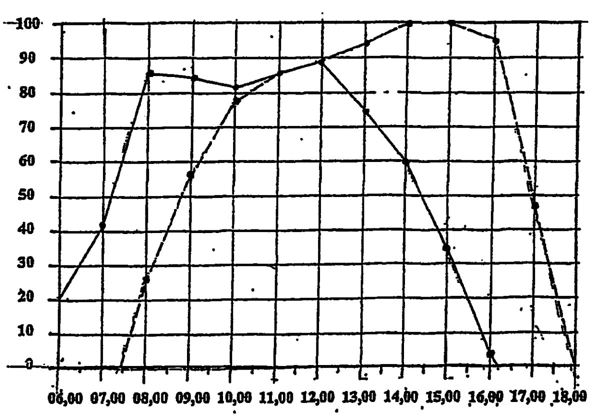
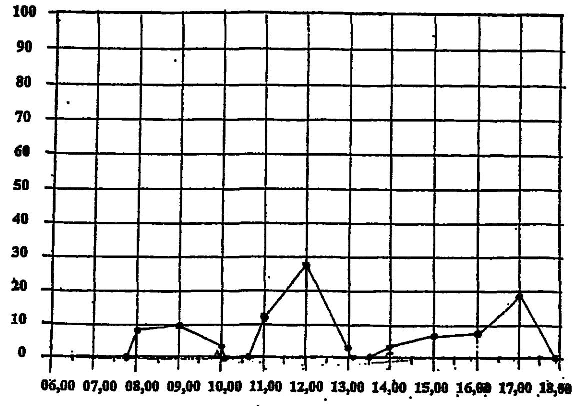


Fig 7.4.1.19. **DECEMBER.**

Illustrates graphically the shadow free area on the natural turfgrass playing surface as allowed by each roof configuration. The roofs are grouped in pairs. Each pair is made up of roofs with a common association in terms of their 'free to sky open area'. The vertical axis of each graph indicates the percentage of shadow free area; the horizontal axis expresses time in hourly and half hourly intervals.

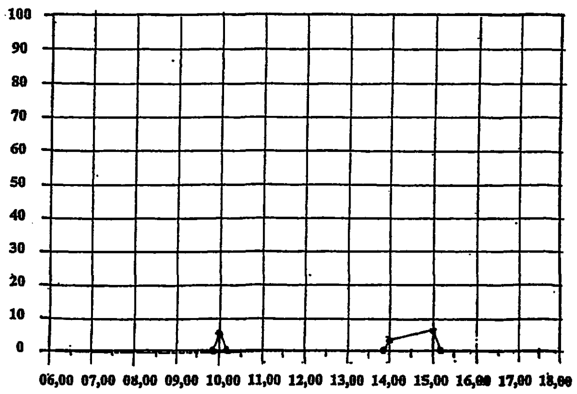
NO ROOF ————

BI-PARTING
RETRACTABLE ROOF. --------
[7.4.1.7.1.]



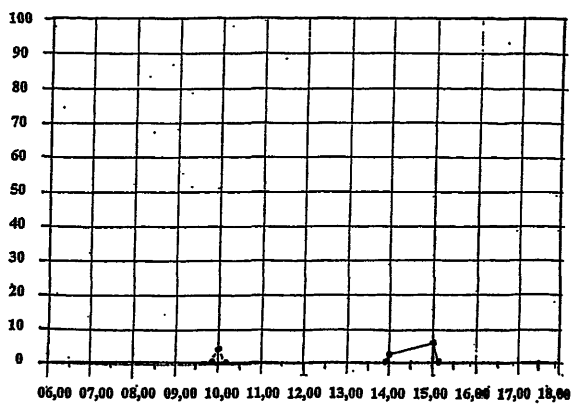
CENTRALLY LOCATED ————
RETRACTABLE ROOF.

CENTRALLY LOCATED --------
RETRACTABLE ROOF.
LATTICE CONSTRUCTION.
[7.4.1.7.2.]



ASYMMETRICAL ————
RETRACTABLE ROOF.
(S.W. ORIENTATION.).

ASYMMETRICAL --------
RETRACTABLE ROOF.
(N.W. ORIENTATION.).
[7.4.1.7.3.]



CHAPTER FIVE.

7.5.0 THE DIFFUSE AND DIRECT LIGHT DATA.

7.5.0.1 Introduction.

This data was collected to determine the light energy flux falling on the model playing surface of the stadium, occurring under the conditions imposed by the different roof configurations. To begin this process, the green area was divided by grid lines. The overall grid was composed of five spaces in the horizontal direction coded C2-C7, and eleven in the vertical direction, coded A to L with I not being used. The lettered codes were set in the centre of the grid spaces whereas C2-C7 were set directly on the grid lines.

This arrangement allowed flux levels to be recorded as lux values at fifty-five points, but in horticultural science energy values are expressed in Mega Joules m^{-2}.

The approach taken in compiling these measurements was that each of the six measuring cells represents one square metre of turfgrass set in the centre of each of the fifty-five spaces. Therefore the total energy falling on that square metre is the aggregated sum of the Hourly Irradiation expressed as Watt hours per square metre (later to be converted Mj m^{-2}) falling on each of the fifty-five positions. The data collected from the Artificial SkyDome coupled with the predicted data for hourly irradiation values taken from Page and Lubens was used to collect the data which is set out in **Tables 7.3.5.1 to 7.3.5.5.**

As indicated in **Part 3.2.5,** not all light available from the visible solar electromagnetic spectrum is useful to the photosynthetic process. That proportion which is useful is termed **Photosynthetically Active Radiation (P.A.R).** The PAR proportion represents approximately one half of the light available to a plant. Therefore to quantify that proportion of useful light it is usual to divide the value of the available light by 50%.

The explanation of the relationship of the visible light within the overall spectrum is repeated here for convenience. The numerical values used in this quotation differ marginally from the values stated in the Beard quotation. The differences are however insignificant.

> The solar spectrum can be divided into three main regions: ultraviolet (300-400nm) and the visible (400-700nm) and the infrared (700-3000 nm). Solar radiation (SR) or short-wave radiation originates from the sun with wavelengths between 300 and 3000nm. Short wave irradiance varies from 0 at night to over 900 and 1200 mW cm^{-2} at solar noon on clear days in temperate and tropical regions, respectively.

Photosynthetically active radiation refers to radiation in the visible (400-700nm) [380-780] region. About 45% of direct SR value is PAR. When both diffuse and direct components are combined PAR is about 50% of SR.[9]

7.5.0.2 Detail of the Experiments.

The lighting levels falling on the playing surface were collected in the Artificial SkyDome from six calibrated lighting cells set in a jig. The details of the cells and the jig are set out in **7.3.4.2.** The jig occupied the width of the green area of the arena and in the vertical direction one grid space. The jig was moved to predetermined positions as the measurements proceeded. The recorded measurements were subsequently transferred into percentage values as later described. The conditions under which the measurements were recorded in the Artificial SkyDome were those of an overcast sky.

Following the procedure as described in **7.3.4.2,** light values from 55 cell readings were digitally recorded in lux values. The cell positions were the same for all roof configurations. The variations in the data therefore are influenced by the differences in the roof configurations. The resulting data was tabulated and shown in the text.

All values relate to a reference cell coded as C1, the location of which is outside the model's sphere of influence. The reference cell records the illuminance level in the Artificial SkyDome during the periods of measurement. The position of the reference cell was constant during all tests.

Once the cell values were recorded the rig was moved to the next grid position on the length of the playing surface. This process is repeated for Roof 1 to Roof 9. However, only the No Roof Stadium and the Stadia with retractable roofs are the subject of the detailed experiments. The remaining roofs are referred to in the discussion in Part 8.

Whenever the experiments were interrupted, the reference cell reading had to be recalibrated. Interruptions were necessary to change the positions of the jig, to change roof configurations and at the end of working schedules. These interruptions made it impossible to provide comparative lux values between groups of cells because of the variations in the remeasured reference cell values.

---

[9] Waddington,Carrow,& Sherman Co Editors, Turfgrass, No 32 in the series Agronomy, Madison 1992 pages 271

To allow cell readings to become comparable it was necessary to convert the lux values of each cell group into percentage values. These values were based on the relationship between the cell lighting levels and that of the reference cell. The conversion to percentage values obviates the need to use Lux as the quantity of measurement and achieves the essential requirement of comparability between all the recorded values and for all roof configurations.

The aim of the lighting experiments is to determine the light flux available to the turfgrass throughout a particular day, during a particular month, in this case the 21st day of the months of December, January, February, March, April, May and June. The other months are not measured because their results will be almost identical to the months with which they correspond in the returning solar cycle.

The lux levels for each roof are individually tabulated **(Charts 7.5.0.1.-7.5.0.9.).** These values are converted to the percentage equivalent values of the lux values of the cells set out in the rows designated C2 to C7.

The light falling on the playing surface is derived from two sources:

Direct Beam (Solar Radiation) which is that portion of short-wave radiation received in a parallel beam 'directly' from the sun.

Diffuse short wave radiation is that which reaches the earth's surface having been scattered from the direct beam by molecules or other agents in the atmosphere.

The direct beam (Solar Radiation) is not always directly available between hours of sunrise and sunset. When the direct beam is absent the conditions are described as diffuse. When the direct beam is available light energy value will be made up of both direct and diffuse values.

Dual conditions can occur when the path of the main beam is disrupted in its direction by an intervention which causes a beam not to fall on a surface it would have fallen on had there been no such intervention.

The object of collecting the data is to aggregate the energy values falling on one square metre of turfgrass on each of the cell positions in each of the roof configurations considered.

Three pieces of information are necessary to calculate these values.

1) The direct beam contribution.

2) The diffuse light contribution.

3) The predicted Direct and Diffuse values measured in watt-hours between 1966-75.

The source for these three pieces of information are as follows:

(1) the photographic imaging of the beam and diffuse areas taken from the Artificial Sky. These areas were transferred for area assessment and location to **Fig 7.4.1.Shadow Free Area Location Diagram.**

(2) the percentage of available skylight reaching each cell is shown on **Chart numbers 7.5.0.1 to 7.5.0.9.**

(3) the predicted values for the Diffuse (D) and Beam (B) areas are taken from Climate in the United Kingdom, Page and Lebens. **The Hourly Incident Solar Radiation Averaged Over All Weather Conditions: Direct and Diffuse Conditions,** recorded between 1966-75, using the horizontal surface G and sunshine.

Besides the Page and Lebens data, the Availability of daylight, DRG Hunt, and the Availability of sunshine, Ne'eman and Light were also consulted. However, Page and Lebens provide a broader range of information in a convenient form. In addition to the direct beam and diffuse conditions for various locations and planes under differing sky conditions, Page and Lebens also provide information useful for turfgrass cultivation, such as: Direct Air Temperatures, Wet and Dry bulb temperatures, Ground temperatures, Wind movement and levels of Precipitation.

The Hourly Incident Radiation Averaged Over All Weather Conditions:DirectBeam (B), Diffuse(D) and Global(G) All Weather Horizontal London, Kew was used in the process of determining the lighting values and provides balanced values of the 'overall weather conditions measured in localities in the UK'. In these locations sky conditions are never consistently 'overcast' or 'clear'.

Table 7.5.0.1. Illustrates the comparison between the diffuse and beam values for various sky conditions. This information is compiled from information from Page and Lebens. Daily Totals in Kilowatt Hours

	1	2	3	4	5	6	7	8	9	10	11	12
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A	1.40	2.64	4.42	5.99	7.39	7.73	7.56	6.80	4.85	3.26	1.82	1.11
B	0.33	0.54	0.85	1.19	1.46	1.58	1.51	1.30	0.98	0.65	0.39	0.27
C	0.59	1.20	2.23	3.21	4.33	5.09	4.56	3.84	0.87	1.65	0.87	0.50

A – Clear Sky, London Horizontal. B – Overcast Sky, London Horizontal. C – All Weather Conditions. London Horizontal. The data used from Page and Lebens is based on London (Kew) 51° 28' N. The altitude of which is 5M.

In Page and Lebens the irradiation data is presented in two forms:

- Hourly totals expressed in Watt hours per square metre.
- Daily totals expressed in Kilowatt hours per square metre.

The Kilowatt hours per square metre will represent the total energy falling on that square metre over the hours of daylight.

Charts 7.5.0.1-7.5.0.9. record the lux values measured in the Artificial SkyDome. These charts are referred to on page 46. They show the readings converted into percentage values based on the cell readings with those of the reference cell.

Chart 7.5.0.1. Roof No. 1. Lux and percentage conversion values.

Roof 1

	Ref Cell	C2	C3	C4	C5	C6	C7
A	5020	3456	3696	3744	3639	3617	3564
		69	74	75	72	72	71
B	4931	4311	4556	4619	4511	4501	4399
		87	92	94	91	91	89
C	5029	4447	4639	4770	4622	4630	4522
		88	92	95	92	92	90
D	5062	4512	4758	4838	4670	4681	4574
		89	94	96	92	92	90
E	4929	4416	4639	4745	4580	4564	4469
		90	94	96	93	93	91
F	5039	4532	4737	4866	4670	4663	4574
		90	94	97	93	93	91
G	5059	4550	4770	4888	4685	4690	4528
		90	94	97	93	93	90
H	5067	4557	4770	4898	4695	4687	4529
		90	94	97	93	93	89
J	5396	4736	5077	5393	5126	4923	4712
		88	94	100	95	91	87
K	5061	4465	4692	4828	4621	4616	4482
		88	93	95	91	91	89
L	5065	4410	4632	4780	4555	4560	4329
		87	91	94	90	90	85

Chart 7.5.0.2. Roof No. 2. Lux and percentage conversion values.

Roof 2

	Ref Cell	C2	C3	C4	C5	C6	C7
A	5019	3457	3697	3745	3640	3618	3564
		69	74	75	73	72	71
B	4942	3740	3960	4008	3904	3907	3839
		76	80	81	79	79	78
C	5031	4009	4220	4285	4147	4162	4091
		80	84	85	82	83	81
D	5062	4172	4384	4446	4291	4303	4225
		82	87	88	85	85	83
E	4945	4159	4362	4461	4303	4299	4217
		84	88	90	87	87	85
F	5039	4272	4467	4557	4386	4393	4298
		85	89	90	87	87	85
G	5060	4275	4471	4577	4384	4395	4257
		84	88	90	87	87	84
H	5068	4213	4393	4498	4314	4327	4196
		83	87	89	85	85	83
J	5399	4208	4488	4711	4483	4376	4192
		78	83	87	83	81	78
K	5061	3882	4057	4147	3968	3997	3878
		77	80	82	78	79	77
L	5067	3601	3755	3843	3683	3710	3532
		71	74	76	73	73	70

Chart 7.5.0.3. Roof No. 3. Lux and percentage conversion values.

Roof 3

	Ref Cell	C2	C3	C4	C5	C6	C7
A	5026	3139	3306	3240	2988	2732	2319
		62	66	64	59	54	46
B	4951	3491	3628	3544	3269	2989	2527
		71	73	72	66	60	51
C	5037	3761	3893	3825	3500	3198	2697
		75	77	76	69	63	54
D	5062	3952	4075	4008	3662	3336	2814
		78	81	79	72	66	56
E	4958	3980	4102	4066	3699	3383	2846
		80	83	82	75	68	57
F	5039	4072	4178	4144	3754	3461	2887
		81	83	82	74	69	57
G	5063	4053	4158	4123	3735	3429	2841
		80	82	81	74	68	56
H	5070	3962	4052	4023	3644	3337	2761
		78	80	79	72	66	54
J	5404	3900	4075	4123	3660	3305	2733
		72	75	76	68	61	51
K	5065	3578	3667	3615	3289	3024	3505
		71	72	71	65	60	69
L	5068	3244	3323	3283	2975	2744	2236
		64	66	65	59	54	44

Chart 7.5.0.4. Roof No. 4. Lux and percentage conversion values.

Roof 4

	Ref Cell	C2	C3	C4	C5	C6	C7
A	5032	1217	1681	1860	1847	1694	1384
		24	33	37	37	34	28
B	4960	1496	1992	2184	2164	1941	1551
		30	40	44	44	39	31
C	5041	1698	2244	2503	2451	2205	1735
		34	45	50	49	44	34
D	5062	1841	2403	2694	2620	2325	1862
		36	47	53	52	46	37
E	4969	1879	2473	2751	2684	2415	1915
		38	50	55	54	49	39
F	5062	1912	2503	2818	2731	2501	1954
		38	49	56	54	49	39
G	5065	1931	2524	2817	2703	2454	1910
		38	50	56	53	48	38
H	5072	1868	2435	2724	2629	2387	1867
		37	48	54	52	47	37
J	5406	1846	2397	2615	2516	2285	1794
		34	44	48	47	42	33
K	5066	1637	2121	2310	2223	2025	1566
		32	42	46	44	40	31
L	5070	1448	1840	1991	1917	1757	1343
		29	36	39	38	35	26

Chart 7.5.0.5. Roof No. 5. Lux and percentage conversion values.

Roof 5

	Ref Cell	C2	C3	C4	C5	C6	C7
A	5037	1291	1770	1973	1990	1825	1507
		26	35	39	40	36	30
B	4971	1513	2025	2263	2276	2104	1698
		30	41	46	46	42	34
C	5045	1778	2372	2624	2584	2363	1876
		35	47	52	51	47	37
D	5062	1841	2463	2818	2798	2590	2100
		36	49	56	55	51	41
E	4983	1901	2546	2888	2871	2654	2141
		38	51	58	58	53	43
F	5062	1968	2625	2967	2933	2696	2155
		39	52	59	58	53	43
G	5067	1957	2598	2917	2896	2682	2115
		39	51	58	57	53	42
H	5073	1932	2550	2835	2794	2561	2023
		38	50	56	55	50	40
J	5053	1862	2435	2674	2611	2384	1853
		37	48	53	52	47	37
K	5067	1670	2202	2379	2339	2150	1704
		33	43	47	46	42	34
L	5070	1457	1881	2017	1995	1852	1441
		29	37	40	39	37	28

Chart 7.5.0.6. **Roof No. 6. Lux and percentage conversion values.**

Roof 6

	Ref Cell	C2	C3	C4	C5	C6	C7
A	5057	1822	2015	2044	1983	1975	1915
		36	40	40	39	39	38
B	4989	1877	2011	2044	1999	2031	1952
		38	40	41	40	41	39
C	5048	1988	2112	2137	2079	2069	1990
		39	42	42	41	41	39
D	5062	1980	2121	2188	2135	2113	2063
		39	42	43	42	42	41
E	5001	2002	2125	2183	2139	2083	2012
		40	42	44	43	42	40
F	5062	2079	2121	2164	2135	2131	2063
		41	42	43	42	42	41
G	5067	2023	2144	2135	2146	2097	2046
		40	42	42	42	41	40
H	5071	2057	2109	2145	2127	2125	2030
		41	42	42	42	42	40
J	5059	2006	2098	2152	2076	2095	1984
		40	41	43	41	41	39
K	5066	1993	2063	2120	2074	2028	1941
		39	41	42	41	40	38
L	5070	1889	2021	2065	1991	1987	1880
		37	40	41	39	39	37

Chart 7.5.0.7. **Roof No. 7. Lux and percentage conversion values.**

Roof 7

	Ref Cell	C2	C3	C4	C5	C6	C7
A	5057	2328	2653	2820	2773	2678	2517
		46	52	56	55	53	50
B	4993	2488	2843	3022	2951	2872	2646
		50	57	61	59	58	53
C	5049	2748	3105	3292	3204	3071	2823
		54	61	65	63	61	56
D	5062	2795	3214	3479	3409	3283	2997
		55	63	69	67	65	59
E	5004	2873	3295	3557	3471	3314	2988
		57	66	71	69	66	60
F	5062	2994	3357	3609	3524	3354	3033
		59	66	71	70	66	60
G	5067	2919	3351	3591	3498	3344	3010
		58	66	71	69	66	59
H	5071	2929	3286	3502	3418	3281	2960
		58	65	69	67	65	58
J	5058	2830	3167	3345	3230	3117	2787
		56	63	66	64	62	55
K	5066	2701	3013	3140	3035	2917	2660
		53	59	62	60	58	53
L	5069	2461	2745	2842	2772	2671	2412
		49	54	56	55	53	48

Chart 7.5.0.8. **Roof No. 8. Lux and percentage conversion values.**

Roof 8

	Ref Cell	C2	C3	C4	C5	C6	C7
A	5061	2005	2177	2219	2160	2157	2095
		40	43	44	43	43	41
B	5001	2066	2235	2261	2200	2238	2171
		41	45	45	44	45	43
C	5052	2182	2292	2321	2261	2254	2182
		43	45	46	45	45	43
D	5062	2178	2302	2402	2354	2307	2265
		43	45	47	47	46	45
E	5011	2200	2316	2405	2329	2288	2197
		44	46	48	46	46	44
F	5062	2278	2302	2354	2332	2307	2246
		45	45	47	46	46	44
G	5067	2232	2347	2390	2345	2303	2239
		44	46	47	46	45	44
H	5071	2231	2308	2357	2336	2328	2253
		44	46	46	46	46	44
J	5060	2187	2306	2346	2263	2288	2178
		43	46	46	45	45	43
K	5067	2186	2264	2301	2263	2195	2138
		43	45	45	45	43	42
L	5071	2067	2185	2242	2155	2125	2055
		41	43	44	42	42	41

Chart 7.5.0.9. **Roof No. 9. Lux and percentage conversion values.**

Roof 9

	Ref Cell	C2	C3	C4	C5	C6	C7
A	5060	3391	3789	3934	3819	3742	3499
		67	75	78	75	74	69
B	5007	3557	3930	4077	3939	3882	3641
		71	78	81	79	78	73
C	5053	3706	4065	4230	4069	4036	3769
		73	80	84	81	80	75
D	5062	3812	4157	4335	4150	4105	3858
		75	82	86	82	81	76
E	5016	3817	4160	4331	4160	4097	3834
		76	83	86	83	82	76
F	5062	3852	4198	4390	4197	4141	3876
		76	83	87	83	82	77
G	5066	3867	4202	4383	4188	4117	3804
		76	83	87	83	81	75
H	5071	3833	4165	4366	4164	4104	3788
		76	82	86	82	81	75
J	5061	3775	4104	4303	4090	4035	3717
		75	81	85	81	80	73
K	5065	3662	3989	4178	3978	3924	3620
		72	79	82	79	77	71
L	5070	3507	3840	4022	3830	3779	3424
		69	76	79	76	75	68

7.5.1. Quantifying the Levels of Lighting.

7.5.1.1. Introduction.

The purpose of this chapter is to quantify the sum of light energy falling on the playing surfaces influenced by the various roof configurations and to describe that methodology. Nevertheless, before setting out that essential purpose, it is useful to be reminded of the influence that light plays in the photosynthetic process which drives turfgrass growth and maintenance. It is also useful at this point to be reminded of the concept of PAR which halves the value of the light made available to turfgrass from the visible spectrum.

Activation by light is the significantly important factor in turfgrass growth. However, that factor cannot be considered independently from the other factors, some of which are air movement, water, oxygen, drainage, horticultural treatment and rest from being used. The absence or presence of these factors are influential in determining an increase or decrease in the efficiency of the photosynthetic process.

It may well be that even in some months of the year and in some roof configurations the light energy flux falling on the surface is considered acceptable for maintaining turfgrass; there can be no assurance that turfgrass acceptable for the games of football will result. The reason for this is that the consequences of continual wear will, in time, override satisfactory environmental conditions.

7.5.2. Method of calculation.

7.5.2.1. Preparing the grids

The areas of light and shade falling on the model playing surfaces were recorded for the charts and tables with the aid of **Fig 7.4.2. Shadow Free Area Location Chart.** This chart allowed shadow free areas to be recorded with acceptable accuracy even where shadow filigree from the structure could be seen on the photographs, indicating areas of light and shade.

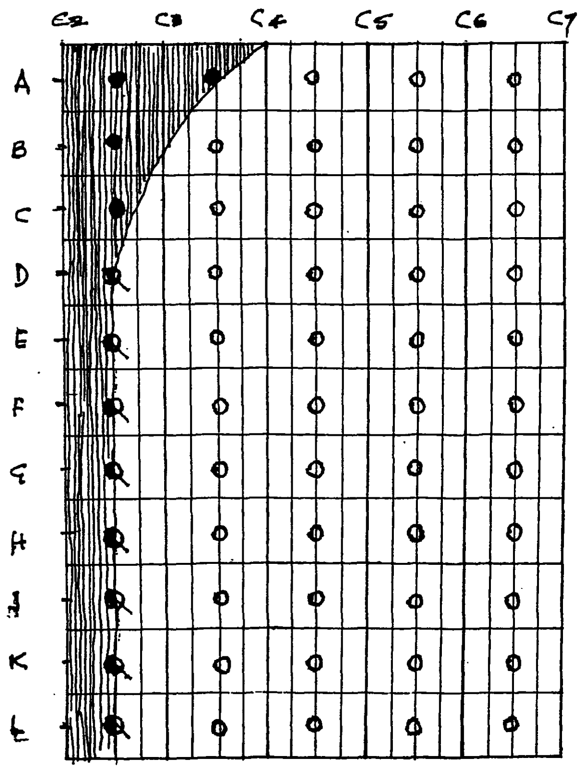
The same principles of using a grid chart were used in collecting the light energy data as was used in determining the areas of light and shade. But in this case the diagram shown as **Chart 7.4.2.1.** was divided into 5 grid spaces across the playing surface and 11 in the long direction of the playing surface, making a total of 55 spaces and consequently provided 55points for measurement.

The need to establish a different vertical grid was determined by the physical size of the light receiving cells. They could only provide cover over the whole green by dividing the vertical grid into eleven spaces and not the 12 spaces on **Chart 7.4.2.** The vertical divisions in both figs remained as five spaces.

The direct light and diffuse area profiles on **Chart 7.4.2.** were transferred to the grid arrangement shown on **Chart 7.4.2.1.**

Chart 7.4.2.1 **The Direct and Diffuse Light Location Diagram.**
This is a reduced size copy of the diagram used to locate the Direct Light and Diffuse Light, falling at hourly intervals on the prescribed area of one square metre of arena turfgrass at fifty five different locations.

Three symbols were used to record the types of light as follows:
Direct Light, represented by an open small circle.
Diffuse Light, represented by a circle closed in black.
There are occasions when the designated one square metre of turf grass can be equally divided between the receipt of Direct and Diffuse lighting conditions. Where this occurs the squares involved for the record were marked by a circle half of which was open and the other half of the circle was closed in black.



7.5.2.2. Cell Positions

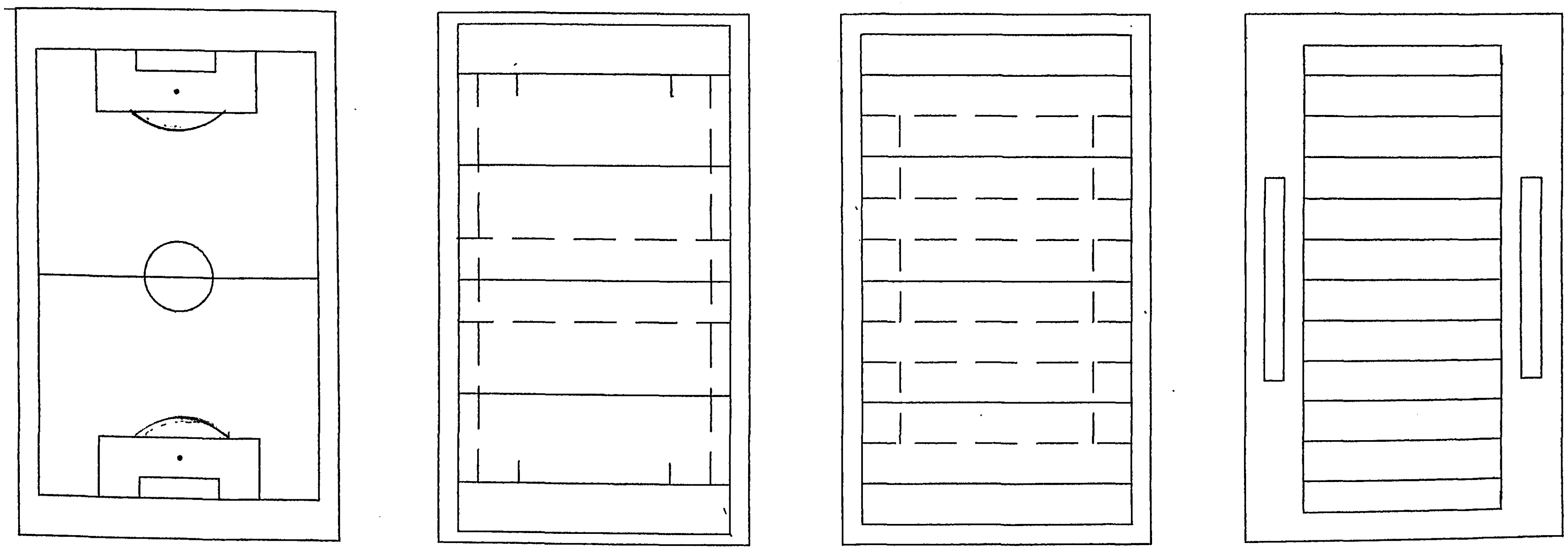
The cell positions relate to the overall green area. **Fig 7.5.2.2** shows the relationship of each pitch to that overall area.

The cells occupy a central position on each of the vertical grid lines. The experiment measures the amount of light falling on one square metre of turfgrass within each grid space. This space is designated at each of the 55 cell measuring positions on the green arena.

The vertical grid positions as previously reported are marked C2 to C7. However, to reflect a central position within the grid, an average was taken of the recorded readings C2 and C3. This process was repeated between adjacent pairs of readings until the reading between C6 and C7 was recorded.

This arrangement reflects a cell position approximately in the centre of each grid. To be more precise the measuring cells would need to be 5mm or less in diameter. These were not available. Neither was it possible to use the cells which could record directly in PAR.

A. Association Football | B. Rugby Union Football | C. Rugby League Football | D. American Football



The size of each pitch is as follows: Association Football 110m x 68m, Rugby Union Football 126m x 69m, Rugby League Football
American Football 112.7m x 51.8m. Each pitch is set within an overall arena size of 132m x 82m. The safety margins for each game are accommodated within this overall area.

Fig.7.5.2.2 The Relationship of the Playing Pitches of the various Games of Football in the multi- use stadium considered in this work.

7.5.3. Calculation Method.

The lighting calculations were prepared in the following manner.

The Direct Beam and Diffuse profiles were set up on recording sheets as **Fig. 7.4.2.** The plan profiles indicated which parts of the enclosing green area were receiving a mixture of diffuse or beam lighting conditions. Sometimes these areas recorded only direct beam or diffuse conditions. There were occasions when the centre square metre received 50% of its area in diffuse light and the other 50% in the beam condition. The only area of interest was the centre square metre of each grid.

Fig. 7.4.2. presents the photographic confirmation of the beam and diffuse light areas at 12:00 hrs April 15, for **Roof 4**, the **Centrally Located Retractable Roof.(CLRR)** These areas were transferred to the alternative grid shown on **Chart 7.4.2.1.**

The chart defined the different areas with symbols, solid dots for diffuse light and open dots for beam conditions. Where the light was equally divided within the defined square metre, open dots were used with a diagonal line striking through them.

The next stage applies the diffuse and beam values taken from Page and Lebens for 12:00hrs April 15, These values are 169 watts per hour per square metre for the Beam condition and 236 watts per hour per square metre for the Diffuse condition.

The amount of light falling on a designated square metre can either represent diffuse value or a beam value. When the area is covered by the beam condition, its measurement will consist of its beam watt value together with the watt value of the diffuse component. When the area is covered by the diffuse condition in these experiments, the principle remains the same but the diffuse values are adjusted by the reduction in the levels of light reaching the cells owing to the intervention of the superstructure.

The inference of this is that there are 55 different measurements being recorded for 1200:hrs on April 15, and for all other time steps during that day in April. This same process is repeated for the other months involved in Roof 4 and for the other roofs involved in the measurements.

A worked example for April 15, 12:00 would produce the following results:

Beam measurement **(B) 169 watts per hour per square metre.**

Diffuse measurement **(D) 236 watts per hour per square metre.**

Diffuse value position **A-C2/C3.** = (D) 236 W/hrs,m^{-2}

Beam value position **E-C2/C3** = (B)+(D x % light reduction).
Therefore total (B) +(D) = (169) + (236x45%) =(169+106) = 275 W/hrs,m^{-2}

The sum of the values collected at each corresponding point for each hour is totalled to provide the light falling on that particular square metre during that particular day.

The PAR Values expressed in Watt hours were converted into Mega Joules by the following method:
1 watt = 1 joule / second. 1 watt / hour = 1 x 60 x 60. = 3600 joules.
Therefore, 3600j*1,000000, = 0.0036 MJs. To Convert watt hours to MJs multiply W/hs by 0.0036.

Tables 7.3.5.1. to 7.3.5.5 show the mega joules values for 55 positions on the arena surface for the months of December to June for four stadia with retractable roofs and the stadium with the open roof. In the other roofs in the study the calculations were limited to the lux only. These configurations are considered in the Discussion in Part 8.

Table 7.3.5.1.

Values for Hourly Irradiation. Roof No 1. For January, February, March April, May, June and December.

Hourly Irradiation. January. Roof No. 1
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	306	319	317	310	306
	153	159.5	158.5	155	153
	0.55	0.57	0.57	0.56	0.55
B	194	202	202	199	193
	97	101	101	99.5	96.5
	0.35	0.36	0.36	0.36	0.35
C	389	408	401	397	390
	194.5	204	200.5	198.5	195
	0.70	0.73	0.72	0.71	0.70
D	391	406	403	393	390
	195.5	203	201.5	196.5	195
	0.70	0.73	0.73	0.71	0.70
E	393	406	405	400	393
	196.5	203	202.5	200	196.5
	0.71	0.73	0.73	0.72	0.71
F	442	440	423	418	428
	221	220	211.5	209	214
	0.80	0.79	0.76	0.75	0.77
G	459	473	472	435	426
	229.5	236.5	236	217.5	213
	0.83	0.85	0.85	0.78	0.77
H	459	504	503	481	456
	229.5	252	251.5	240.5	228
	0.83	0.91	0.91	0.87	0.82
J	457	512	515	497	445
	228.5	256	257.5	248.5	222.5
	0.82	0.92	0.93	0.89	0.80
K	485	498	497	487	452
	242.5	249	248.5	243.5	226
	0.87	0.90	0.89	0.88	0.81
L	486	513	510	503	462
	243	256.5	255	251.5	231
	0.87	0.92	0.92	0.91	0.83

Hourly Irradiation. February. Roof No. 1
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	572	602	584	572	567
	286	301	292	286	283.5
	1.03	1.08	1.05	1.03	1.02
B	877	903	842	743	644
	438.5	451.5	421	371.5	322
	1.58	1.63	1.52	1.34	1.16
C	840	940	940	884	904
	420	470	470	442	452
	1.51	1.69	1.69	1.59	1.63
D	935	1022	1016	954	939
	467.5	511	508	477	469.5
	1.68	1.84	1.83	1.72	1.69
E	1051	1075	1070	1069	998
	525.5	537.5	535	534.5	499
	1.89	1.94	1.93	1.92	1.80
F	1066	1077	1075	1090	1028
	533	538.5	537.5	545	514
	1.92	1.94	1.94	1.96	1.85
G	1066	1077	1105	1099	1025
	533	538.5	552.5	549.5	512.5
	1.92	1.94	1.99	1.98	1.85
H	1066	1077	1105	1090	1022
	533	538.5	552.5	545	511
	1.92	1.94	1.99	1.96	1.84
J	1060	1121	1124	1099	1004
	530	560.5	562	549.5	502
	1.91	2.02	2.02	1.98	1.81
K	1039	1099	1090	1075	1016
	519.5	549.5	545	537.5	508
	1.87	1.98	1.96	1.94	1.83
L	1042	1085	1081	1077	994
	521	542.5	540.5	538.5	497
	1.88	1.95	1.95	1.94	1.79

Hourly Irradiation. March. Roof No. 1
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	1564	1655	1614	1556	1487
	782	827.5	807	778	743.5
	2.82	2.98	2.91	2.80	2.68
B	1851	1936	1981	1886	1865
	925.5	968	990.5	943	932.5
	3.33	3.48	3.57	3.39	3.36
C	1859	1982	1993	1894	1875
	929.5	991	996.5	947	937.5
	3.35	3.57	3.59	3.41	3.38
D	1957	2001	2002	1894	1917
	978.5	1000.5	1001	947	958.5
	3.52	3.60	3.60	3.41	3.45
E	1960	2001	2005	1950	1925
	980	1000.5	1002.5	975	962.5
	3.53	3.60	3.61	3.51	3.47
F	1960	2008	2014	1950	1925
	980	1004	1007	975	962.5
	3.53	3.61	3.63	3.51	3.47
G	1960	2008	2014	1950	1922
	980	1004	1007	975	961
	3.53	3.61	3.63	3.51	3.46
H	1960	2008	2014	1950	1917
	980	1004	1007	975	958.5
	3.53	3.61	3.63	3.51	3.45
J	1952	2029	2131	1950	1891
	976	1014.5	1065.5	975	945.5
	3.51	3.65	3.84	3.51	3.40
K	1942	1991	1985	1927	1902
	971	995.5	992.5	963.5	951
	3.50	3.58	3.57	3.47	3.42
L	1923	1969	1973	1912	1871
	961.5	984.5	986.5	956	935.5
	3.46	3.54	3.55	3.44	3.37

Hourly Irradiation. April. Roof No. 1
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	2424	2559	2464	2435	2279
	1212	1279.5	1232	1217.5	1139.5
	4.36	4.61	4.44	4.38	4.10
B	2758	2904	2817	2790	2732
	1379	1452	1408.5	1395	1366
	4.96	5.23	5.07	5.02	4.92
C	2771	2916	2838	2808	2771
	1385.5	1458	1419	1404	1385.5
	4.99	5.25	5.11	5.05	4.99
D	2877	2943	2845	2808	2771
	1438.5	1471.5	1422.5	1404	1385.5
	5.18	5.30	5.12	5.05	4.99
E	2847	2943	2854	2826	2790
	1423.5	1471.5	1427	1413	1395
	5.12	5.30	5.14	5.09	5.02
F	2847	2951	2865	2826	2790
	1423.5	1475.5	1432.5	1413	1395
	5.12	5.31	5.16	5.09	5.02
G	2847	2951	2865	2826	2781
	1423.5	1475.5	1432.5	1413	1390.5
	5.12	5.31	5.16	5.09	5.01
H	2847	2951	2865	2826	2770
	1423.5	1475.5	1432.5	1413	1385
	5.12	5.31	5.16	5.09	4.99
J	2829	2979	2908	2826	2735
	1414.5	1489.5	1454	1413	1367.5
	5.09	5.36	5.23	5.09	4.92
K	2664	2927	2830	2793	2745
	1332	1463.5	1415	1396.5	1372.5
	4.80	5.27	5.09	5.03	4.94
L	2638	2895	2808	2771	2706
	1319	1447.5	1404	1385.5	1353
	4.75	5.21	5.05	4.99	4.87

Hourly Irradiation. May. Roof No. 1
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	3396	3478	3449	3413	3284
	1698	1739	1724.5	1706.5	1642
	6.11	6.26	6.21	6.14	5.91
B	3855	3976	3930	3889	3775
	1927.5	1988	1965	1944.5	1887.5
	6.94	7.16	7.07	7.00	6.80
C	3867	3990	3956	3918	3777
	1933.5	1995	1978	1959	1888.5
	6.96	7.18	7.12	7.05	6.80
D	3907	4025	3968	3918	3777
	1953.5	2012.5	1984	1959	1888.5
	7.03	7.25	7.14	7.05	6.80
E	3918	4025	3979	3943	3806
	1959	2012.5	1989.5	1971.5	1903
	7.05	7.25	7.16	7.10	6.85
F	3918	4041	3991	3943	3806
	1959	2020.5	1995.5	1971.5	1903
	7.05	7.27	7.18	7.10	6.85
G	3918	4041	3991	3943	3759
	1959	2020.5	1995.5	1971.5	1879.5
	7.05	7.27	7.18	7.10	6.77
H	3918	4041	3991	3943	3777
	1959	2020.5	1995.5	1971.5	1888.5
	7.05	7.27	7.18	7.10	6.80
J	3889	4071	4041	3943	3736
	1944.5	3964	2020.5	1971.5	1868
	7.00	14.27	7.27	7.10	6.72
K	3879	4006	3947	3891	3753
	1939.5	2003	1973.5	1945.5	1876.5
	6.98	7.21	7.10	7.00	6.76
L	3842	3964	3918	3867	3693
	1921	1982	1959	1933.5	1846.5
0.00	6.92	7.14	7.05	6.96	6.65

Hourly Irradiation. June. Roof No. 1
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	3967	4148	4119	3978	3994
	1983.5	2074	2059.5	1989	1997
	7.14	7.47	7.41	7.16	7.19
B	4445	4642	4628	4488	4488
	2222.5	2321	2314	2244	2244
	8.00	8.36	8.33	8.08	8.08
C	4461	4657	4657	4513	4515
	2230.5	2328.5	2328.5	2256.5	2257.5
	8.03	8.38	8.38	8.12	8.13
D	4501	4697	4666	4513	4515
	2250.5	2348.5	2333	2256.5	2257.5
	8.10	8.45	8.40	8.12	8.13
E	4513	4697	4684	4540	4540
	2256.5	2348.5	2342	2270	2270
	8.12	8.45	8.43	8.17	8.17
F	4513	4711	4697	4540	4540
	2256.5	2355.5	2348.5	2270	2270
	8.12	8.48	8.45	8.17	8.17
G	4513	4711	4697	4540	4528
	2256.5	2355.5	2348.5	2270	2264
	8.12	8.48	8.45	8.17	8.15
H	4513	4711	4697	4540	4515
	2256.5	2355.5	2348.5	2270	2257.5
	8.12	8.48	8.45	8.17	8.13
J	517	534	536	523	512
	258.5	267	268	261.5	256
	0.93	0.96	0.96	0.94	0.92
K	516	526	523	517	515
	258	263	261.5	258.5	257.5
	0.93	0.95	0.94	0.93	0.93
L	512	522	520	515	508
	256	261	260	257.5	254
0.00	0.92	0.94	0.94	0.93	0.91

Hourly Irradiation. Dec. Roof No. 1
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	270	283	278	292	251
	135	141.5	139	146	125.5
	0.49	0.51	0.50	0.53	0.45
B	321	327	325	341	336
	160.5	163.5	162.5	170.5	168
	0.58	0.59	0.59	0.61	0.60
C	324	343	336	324	322
	162	171.5	168	162	161
	0.58	0.62	0.60	0.58	0.58
D	336	346	335	324	329
	168	173	167.5	162	164.5
	0.60	0.62	0.60	0.58	0.59
E	332	343	332	327	324
	166	171.5	166	163.5	162
	0.60	0.62	0.60	0.59	0.58
F	324	337	336	327	324
	162	168.5	168	163.5	162
	0.58	0.61	0.60	0.59	0.58
G	324	337	336	327	322
	162	168.5	168	163.5	161
	0.58	0.61	0.60	0.59	0.58
H	324	337	336	327	322
	162	168.5	168	163.5	161
	0.58	0.61	0.60	0.59	0.58
J	356	376	376	327	314
	178	3964	188	163.5	157
	0.64	14.27	0.68	0.59	0.57
K	402	381	376	371	332
	201	190.5	188	185.5	166
	0.72	0.69	0.68	0.67	0.60
L	408	389	388	381	373
	204	194.5	194	190.5	186.5
	0.73	0.70	0.70	0.69	0.67

Table 7.3.5.2.

Values for Hourly Irradiation. Roof No 2. For January, February, March April, May, June and December.

Hourly Irradiation. January. Roof No. 2
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. m^{-2}d^{-1} = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	258	269	266	263	258
	129	134.5	133	131.5	129
	0.46	0.48	0.48	0.47	0.46
B	282	293	287	284	282
	141	146.5	143.5	142	141
	0.51	0.53	0.52	0.51	0.51
C	231	305	300	297	295
	115.5	152.5	150	148.5	147.5
	0.42	0.55	0.54	0.53	0.53
D	305	316	311	305	303
	152.5	158	155.5	152.5	151.5
	0.55	0.57	0.56	0.55	0.55
E	310	319	318	313	310
	155	159.5	159	156.5	155
	0.56	0.57	0.57	0.56	0.56
F	313	323	319	313	310
	156.5	161.5	159.5	156.5	155
	0.56	0.58	0.57	0.56	0.56
G	310	319	318	313	308
	155	159.5	159	156.5	154
	0.56	0.57	0.57	0.56	0.55
H	305	318	313	305	303
	152.5	159	156.5	152.5	151.5
	0.55	0.57	0.56	0.55	0.55
J	290	305	305	295	287
	145	152.5	152.5	147.5	143.5
	0.52	0.55	0.55	0.53	0.52
K	282	292	287	282	282
	141	146	143.5	141	141
	0.51	0.53	0.52	0.51	0.51
L	263	271	269	263	258
	131.5	135.5	134.5	131.5	129
	0.47	0.49	0.48	0.47	0.46

Hourly Irradiation. February. Roof No. 2
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. m^{-2}d^{-1} = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	424	444	438	430	424
	212	222	219	215	212
	0.76	0.80	0.79	0.77	0.76
B	464	478	476	470	468
	232	239	238	235	234
	0.84	0.86	0.86	0.85	0.84
C	488	502	496	488	488
	244	251	248	244	244
	0.88	0.90	0.89	0.88	0.88
D	502	520	512	506	498
	251	260	256	253	249
	0.90	0.94	0.92	0.91	0.90
E	512	528	518	518	512
	256	264	259	259	256
	0.92	0.95	0.93	0.93	0.92
F	533	530	526	571	512
	266.5	265	263	285.5	256
#0.00	0.96	0.95	0.95	1.03	0.92
G	580	581	579	571	508
	290	290.5	289.5	285.5	254
	1.04	1.05	1.04	1.03	0.91
H	644	645	641	629	568
	322	322.5	320.5	314.5	284
	1.16	1.16	1.15	1.13	1.02
J	686	699	699	681	612
	343	349.5	349.5	340.5	306
	1.23	1.26	1.26	1.23	1.10
K	676	675	669	661	604
	338	337.5	334.5	330.5	302
	1.22	1.22	1.20	1.19	1.09
L	691	692	690	680	617
	345.5	346	345	340	308.5
	1.24	1.25	1.24	1.22	1.11

Hourly Irradiation. March. Roof No. 2
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. m^{-2}d^{-1} = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	914	952	945	928	914
	457	476	472.5	464	457
	1.65	1.71	1.70	1.67	1.65
B	997	1029	1020	1008	1002
	498.5	514.5	510	504	501
	1.79	1.85	1.84	1.81	1.80
C	1127	1158	1138	1053	1050
	563.5	579	569	526.5	525
	2.03	2.08	2.05	1.90	1.89
D	1453	1500	1486	1388	1376
	726.5	750	743	694	688
	2.62	2.70	2.67	2.50	2.48
E	1542	1579	1572	1477	1465
	771	789.5	786	738.5	732.5
	2.78	2.84	2.83	2.66	2.64
F	1787	1817	1801	1710	1698
	893.5	908.5	900.5	855	849
	3.22	3.27	3.24	3.08	3.06
G	1851	1889	1904	1787	1768
	925.5	944.5	952	893.5	884
	3.33	3.40	3.43	3.22	3.18
H	1838	1875	1885	1800	1748
	919	937.5	942.5	900	874
	3.31	3.38	3.39	3.24	3.15
J	1781	1838	1859	1767	1734
	890.5	919	929.5	883.5	867
	3.21	3.31	3.35	3.18	3.12
K	1754	1786	1793	1719	1708
	877	893	896.5	859.5	854
	3.16	3.21	3.23	3.09	3.07
L	1683	1711	1725	1650	1634
	841.5	855.5	862.5	825	817
	3.03	3.08	3.11	2.97	2.94

Hourly Irradiation. April. Roof No. 2
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. m^{-2}d^{-1} = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	1580	1639	1552	1522	1445
	790	819.5	776	761	722.5
	2.84	2.95	2.79	2.74	2.60
B	319	317	310	306	1723
	159.5	158.5	155	153	861.5
	0.57	0.57	0.56	0.55	3.10
C	2260	2305	2209	2189	2124
	1130	1152.5	1104.5	1094.5	1062
	4.07	4.15	3.98	3.94	3.82
D	2708	2730	2631	2605	2564
	1354	1365	1315.5	1302.5	1282
	4.87	4.91	4.74	4.69	4.62
E	2795	2893	2804	2774	2738
	1397.5	1446.5	1402	1387	1369
	5.03	5.21	5.05	4.99	4.93
F	2813	2900	2804	2774	2738
	1406.5	1450	1402	1387	1369
	5.06	5.22	5.05	4.99	4.93
G	2795	2893	2804	2774	2731
	1397.5	1446.5	1402	1387	1365.5
	5.03	5.21	5.05	4.99	4.92
H	2779	2873	2774	2740	2700
	1389.5	1436.5	1387	1370	1350
	5.00	5.17	4.99	4.93	4.86
J	2692	2818	2722	2681	2618
	1346	1409	1361	1340.5	1309
	4.85	5.07	4.90	4.83	4.71
K	2649	2738	2640	2610	2585
	1324.5	1369	1320	1305	1292.5
	4.77	4.93	4.75	4.70	4.65
L	2537	2622	2535	2507	2458
	1268.5	1311	1267.5	1253.5	1229
	4.57	4.72	4.56	4.51	4.42

0.00

Hourly Irradiation. May. Roof No. 2
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. m^{-2}d^{-1} = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	2168	2275	2159	2119	1939
	1084	1137.5	1079.5	1059.5	969.5
	3.90	4.10	3.89	3.81	3.49
B	3101	3163	3071	3046	2885
	1550.5	1581.5	1535.5	1523	1442.5
	5.58	5.69	5.53	5.48	5.19
C	3597	3692	3588	3567	3404
	1798.5	1846	1794	1783.5	1702
	6.47	6.65	6.46	6.42	6.13
D	3658	3771	3669	3628	3451
	1829	1885.5	1834.5	1814	1725.5
	6.58	6.79	6.60	6.53	6.21
E	3698	3808	3716	3678	3503
	1849	1904	1858	1839	1751.5
	6.66	6.85	6.69	6.62	6.31
F	3721	3820	3716	3678	3503
	1860.5	1910	1858	1839	1751.5
	6.70	6.88	6.69	6.62	6.31
G	3698	3808	3716	3668	3492
	1849	1904	1858	1834	1746
	6.66	6.85	6.69	6.60	6.29
H	3649	3325	3668	3638	3429
	1824.5	1662.5	1834	1819	1714.5
	6.57	5.99	6.60	6.55	6.17
J	3558	3701	3628	3554	3337
	1779	1850.5	1814	1777	1668.5
	6.40	6.66	6.53	6.40	6.01
K	3509	3607	3504	3466	3300
	1754.5	1803.5	1752	1733	1650
	6.32	6.49	6.31	6.24	5.94
L	3356	3455	3366	3322	3132
	1678	1727.5	1683	1661	1566
	6.04	6.22	6.06	5.98	5.64

0.00

Hourly Irradiation. June. Roof No 2
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. m^{-2}d^{-1} = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	2859	3040	3024	2886	2913
	1429.5	1520	1512	1443	1456.5
	5.15	5.47	5.44	5.19	5.24
B	4140	4309	4296	4165	4205
	2070	2154.5	2148	2082.5	2102.5
	7.45	7.76	7.73	7.50	7.57
C	4243	4415	4388	4259	4297
	2121.5	2207.5	2194	2129.5	2148.5
	7.64	7.95	7.90	7.67	7.73
D	4313	4195	4469	4326	4353
	2156.5	2097.5	2234.5	2163	2176.5
	7.76	7.55	8.04	7.79	7.84
E	4353	4534	4520	4382	4407
	2176.5	2267	2260	2191	2203.5
	7.84	8.16	8.14	7.89	7.93
F	4382	4547	4520	4382	4407
	2191	2273.5	2260	2191	2203.5
	7.89	8.18	8.14	7.89	7.93
G	4353	4534	4520	4382	4400
	2176.5	2267	2260	2191	2200
	7.84	8.16	8.14	7.89	7.92
H	4326	4510	4484	4326	4353
	2163	2255	2242	2163	2176.5
	7.79	8.12	8.07	7.79	7.84
J	4207	4428	4428	4243	4236
	2103.5	2214	2214	2121.5	2118
	7.57	7.97	7.97	7.64	7.62
K	4049	4219	4194	4151	4194
	2024.5	2109.5	2097	2075.5	2097
	7.29	7.59	7.55	7.47	7.55
L	3892	4061	4047	4007	4021
	1946	2030.5	2023.5	2003.5	2010.5
	7.01	7.31	7.28	7.21	7.24

Hourly Irradiation. December. Roof No. 2
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	252	245	261	276	252
	126	122.5	130.5	138	126
	0.45	*0.44*	*0.47*	*0.50*	*0.45*
B	254	262	262	278	276
	127	131	131	139	138
	0.46	*0.47*	*0.47*	*0.50*	*0.50*
C	268	276	271	268	268
	134	138	135.5	134	134
	0.48	*0.50*	*0.49*	*0.48*	*0.48*
D	276	287	282	279	273
	138	143.5	141	139.5	136.5
	0.50	*0.52*	*0.51*	*0.50*	*0.49*
E	282	292	284	285	282
	141	146	142	142.5	141
	0.51	*0.53*	*0.51*	*0.51*	*0.51*
F	285	292	284	285	282
	142.5	146	142	142.5	141
	0.51	*0.53*	*0.51*	*0.51*	*0.51*
G	282	292	284	285	279
	141	146	142	142.5	139.5
	0.51	*0.53*	*0.51*	*0.51*	*0.50*
H	278	287	285	279	273
	139	143.5	142.5	139.5	136.5
	0.50	*0.52*	*0.51*	*0.50*	*0.49*
J	262	278	278	268	259
	131	139	139	134	129.5
	0.47	*0.50*	*0.50*	*0.48*	*0.47*
K	257	264	262	257	254
	128.5	132	131	128.5	127
	0.46	*0.48*	*0.47*	*0.46*	*0.46*
L	238	247	245	236	233
	119	123.5	122.5	118	116.5
	0.43	*0.44*	*0.44*	*0.42*	*0.42*

Table 7.3.5.3.

Values for Hourly Irradiation. Roof No 3. For January, February, March April, May, June and December.

Hourly Irradiation. January. Roof No. 3
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	274	279	264	241	214
	137	139.5	132	120.5	107
	0.49	0.50	0.48	0.43	0.39
B	306	313	294	269	237
	153	156.5	147	134.5	118.5
	0.55	0.56	0.53	0.48	0.43
C	333	332	316	281	251
	166.5	166	158	140.5	125.5
	0.60	0.60	0.57	0.51	0.45
D	348	348	323	294	261
	174	174	161.5	147	130.5
	0.63	0.63	0.58	0.53	0.47
E	350	353	336	306	269
	175	176.5	168	153	134.5
	0.63	0.64	0.60	0.55	0.48
F	351	353	336	306	269
	175.5	176.5	168	153	134.5
	0.63	0.64	0.60	0.55	0.48
G	348	350	331	322	264
	174	175	165.5	161	132
	0.63	0.63	0.60	0.58	0.48
H	338	341	323	294	256
	169	170.5	161.5	147	128
	0.61	0.61	0.58	0.53	0.46
J	314	323	306	276	241
	157	161.5	153	138	120.5
	0.57	0.58	0.55	0.50	0.43
K	306	306	291	269	276
	153	153	145.5	134.5	138
	0.55	0.55	0.52	0.48	0.50
L	279	279	264	241	209
	139.5	139.5	132	120.5	104.5
	0.50	0.50	0.48	0.43	0.38

Hourly Irradiation. February. Roof No. 3
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	490	498	468	407	381
	245	249	234	203.5	190.5
	0.88	0.90	0.84	0.73	0.69
B	556	554	524	476	421
	278	277	262	238	210.5
	1.00	1.00	0.94	0.86	0.76
C	578	580	549	501	444
	289	290	274.5	250.5	222
	1.04	1.04	0.99	0.90	0.80
D	603	608	572	524	462
	301.5	304	286	262	231
	1.09	1.09	1.03	0.94	0.83
E	618	624	597	542	475
	309	312	298.5	271	237.5
	1.11	1.12	1.07	0.98	0.86
F	624	624	592	542	476
	312	312	296	271	238
	1.12	1.12	1.07	0.98	0.86
G	668	671	641	625	471
	334	335.5	320.5	312.5	235.5
	1.20	1.21	1.15	1.13	0.85
H	761	764	733	684	563
	380.5	382	366.5	342	281.5
	1.37	1.38	1.32	1.23	1.01
J	826	840	815	757	643
	413	420	407.5	378.5	321.5
	1.49	1.51	1.47	1.36	1.16
K	810	810	784	743	704
	405	405	392	371.5	352
	1.46	1.46	1.41	1.34	1.27
L	762	766	792	750	639
	381	383	396	375	319.5
0.00	1.37	1.38	1.43	1.35	1.15

Hourly Irradiation. March. Roof No. 3
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	858	874	828	764	682
	429	437	414	382	341
	1.54	1.57	1.49	1.38	1.23
B	963	970	924	846	752
	481.5	485	462	423	376
	1.73	1.75	1.66	1.52	1.35
C	1090	1096	1047	886	790
	545	548	523.5	443	395
	1.96	1.97	1.88	1.59	1.42
D	1243	1246	1192	1031	930
	621.5	623	596	515.5	465
	2.24	2.24	2.15	1.86	1.67
E	1460	1471	1420	1255	1209
	730	735.5	710	627.5	604.5
	2.63	2.65	2.56	2.26	2.18
F	1658	1717	1660	1500	1390
	829	858.5	830	750	695
	2.98	3.09	2.99	2.70	2.50
G	1644	1760	1707	1650	1471
	822	880	853.5	825	735.5
	2.96	3.17	3.07	2.97	2.65
H	1623	1734	1683	1560	1484
	811.5	867	841.5	780	742
	2.92	3.12	3.03	2.81	2.67
J	1548	1683	1622	1503	1430
	774	841.5	811	751.5	715
	2.79	3.03	2.92	2.71	2.57
K	1524	1631	1599	1480	1542
	762	815.5	799.5	740	771
	2.74	2.94	2.88	2.66	2.78
L	1442	1552	1510	1401	1343
	721	776	755	700.5	671.5
0.00	2.60	2.79	2.72	2.52	2.42

Hourly Irradiation. April. Roof No. 3
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. m^{-2}d^{-1} = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	1273	1291	1147	1057	938
	636.5	645.5	573.5	528.5	469
	2.29	2.32	2.06	1.90	1.69
B	1692	1700	1555	1451	1192
	846	850	777.5	725.5	596
	3.05	3.06	2.80	2.61	2.15
C	1918	1928	1759	1653	1395
	959	964	879.5	826.5	697.5
	3.45	3.47	3.17	2.98	2.51
D	2316	2323	2162	2039	1777
	1158	1161.5	1081	1019.5	888.5
	4.17	4.18	3.89	3.67	3.20
E	2352	2427	2476	2346	2066
	1176	1213.5	1238	1173	1033
	4.23	4.37	4.46	4.22	3.72
F	2362	2513	2469	2346	2073
	1181	1256.5	1234.5	1173	1036.5
	4.25	4.52	4.44	4.22	3.73
G	2343	2495	2460	2418	2052
	1171.5	1247.5	1230	1209	1026
	421.74	449.10	442.80	435.24	369.36
H	2306	2460	2421	2298	2017
	1153	1230	1210.5	1149	1008.5
	4.15	4.43	4.36	4.14	3.63
J	2205	2384	2357	2215	1942
	1102.5	1192	1178.5	1107.5	971
	3.97	4.29	4.24	3.99	3.50
K	2165	2309	2279	2181	2100
	1082.5	1154.5	1139.5	1090.5	1050
	3.90	4.16	4.10	3.93	3.78
L	2043	2195	2167	2068	1812
	1,022	1,098	1,084	1,034	906
	3.68	3.95	3.90	3.72	3.26

Hourly Irradiation. May. Roof No. 3
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. m^{-2}d^{-1} = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	2084	2106	1953	1833	1564
	1042	1053	976.5	916.5	782
	3.75	3.79	3.52	3.30	2.82
B	2606	2617	2459	2306	2008
	1303	1308.5	1229.5	1153	1004
	4.69	4.71	4.43	4.15	3.61
C	2771	2782	2767	2609	2424
	1385.5	1391	1383.5	1304.5	1212
	4.99	5.01	4.98	4.70	4.36
D	3062	3076	3046	2887	2690
	1531	1538	1523	1443.5	1345
	5.51	5.54	5.48	5.20	4.84
E	3113	3137	3122	2942	2732
	1556.5	1568.5	1561	1471	1366
	5.60	5.65	5.62	5.30	4.92
F	3124	3137	3109	2942	2744
	1562	1568.5	1554.5	1471	1372
	5.62	5.65	5.60	5.30	4.94
G	3094	3113	3098	3061	2720
	1547	1556.5	1549	1530.5	1360
	556.92	560.34	557.64	550.98	489.60
H	3048	3062	3046	2887	2669
	1524	1531	1523	1443.5	1334.5
	5.49	5.51	5.48	5.20	4.80
J	2914	2972	2955	2779	2573
	1457	1486	1477.5	1389.5	1286.5
	5.25	5.35	5.32	5.00	4.63
K	2863	2863	2866	2732	2779
	1431.5	1431.5	1433	1366	1389.5
	5.15	5.15	5.16	4.92	5.00
L	2857	2872	2720	2584	2397
	1,429	1,436	1,360	1,292	1,199
	5.14	5.17	4.90	4.65	4.31

Hourly Irradiation. June. Roof No. 3
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J. m^{-2}d^{-1} = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	2467	2493	2400	2171	2032
	1233.5	1246.5	1200	1085.5	1016
	4.44	4.49	4.32	3.91	3.66
B	3338	3577	3583	3297	3284
	1669	1788.5	1791.5	1648.5	1642
	6.01	6.44	6.45	5.93	5.91
C	3434	3680	3775	3502	3458
	1717	1840	1887.5	1751	1729
	6.18	6.62	6.80	6.30	6.22
D	3526	3772	3844	3579	3525
	1763	1886	1922	1789.5	1762.5
	6.35	6.79	6.92	6.44	6.35
E	3574	3834	3926	3630	3566
	1787	1917	1963	1815	1783
	6.43	6.90	7.07	6.53	6.42
F	3585	3834	3916	3630	3575
	1792.5	1917	1958	1815	1787.5
	6.45	6.90	7.05	6.53	6.44
G	3562	3804	3902	3762	3549
	1781	1902	1951	1881	1774.5
	641.16	684.72	702.36	677.16	638.82
H	3510	3760	3848	3549	3497
	1755	1880	1924	1774.5	1748.5
	6.32	6.77	6.93	6.39	6.29
J	3265	3550	3708	3466	3399
	1632.5	1775	1854	1733	1699.5
	5.88	6.39	6.67	6.24	6.12
K	3217	3451	3556	3415	3573
	1608.5	1725.5	1778	1707.5	1786.5
	5.79	6.21	6.40	6.15	6.43
L	3048	3292	3400	3257	3215
	1,524	1,646	1,700	1,629	1,608
	5.49	5.93	6.12	5.86	5.79

Hourly Irradiation. December. Roof No. 3
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	180	184	175	162	127
	90	92	87.5	81	63.5
	0.32	*0.33*	*0.32*	*0.29*	*0.23*
B	183	184	176	160	141
	91.5	92	88	80	70.5
	0.33	*0.33*	*0.32*	*0.29*	*0.25*
C	192	192	184	168	149
	96	96	92	84	74.5
	£0.35	*£0.35*	*£0.33*	*£0.30*	*£0.27*
D	200	203	191	176	154
	100	101.5	95.5	88	77
	0.36	*0.37*	*0.34*	*0.32*	*0.28*
E	207	207	199	180	158
	103.5	103.5	99.5	90	79
	0.37	*0.37*	*0.36*	*0.32*	*0.28*
F	207	207	196	180	160
	103.5	103.5	98	90	80
	0.37	*0.37*	*0.35*	*0.32*	*0.29*
G	204	207	196	188	157
	102	103.5	98	94	78.5
	0.37	*0.37*	*0.35*	*0.34*	*0.28*
H	200	200	191	176	152
	100	100	95.5	88	76
	0.36	*0.36*	*0.34*	*0.32*	*0.27*
J	187	191	183	164	141
	93.5	95.5	91.5	82	70.5
	0.34	*0.34*	*0.33*	*0.30*	*0.25*
K	180	180	174	158	164
	90	90	87	79	82
	0.32	*0.32*	*0.31*	*0.28*	*0.30*
L	165	166	157	143	123
	82.5	83	78.5	71.5	61.5
	0.30	*0.30*	*0.28*	*0.26*	*0.22*

Table 7.3.5.4.

Values for Hourly Irradiation. Roof No 4. For January, February, March April, May, June and December.

Hourly Irradiation. January. Roof No. 4
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	112	137	146	140	123
	56	68.5	73	70	61.5
	0.20	0.25	0.26	0.25	0.22
B	140	153	175	163	137
	70	76.5	87.5	81.5	68.5
	0.25	0.28	0.32	0.29	0.25
C	163	195	197	183	152
	81.5	97.5	98.5	91.5	76
	0.29	0.35	0.35	0.33	0.27
D	153	179	190	174	149
	76.5	89.5	95	87	74.5
	0.28	0.32	0.34	0.31	0.27
E	156	190	197	185	156
	78	95	98.5	92.5	78
	0.28	0.34	0.35	0.33	0.28
F	156	190	197	185	156
	78	95	98.5	92.5	78
	0.28	0.34	0.35	0.33	0.28
G	156	209	217	197	171
	78	104.5	108.5	98.5	85.5
	0.28	0.38	0.39	0.35	0.31
H	168	202	209	197	166
	84	101	104.5	98.5	83
	0.30	0.36	0.38	0.35	0.30
J	152	183	188	176	149
	76	91.5	94	88	74.5
	0.27	0.33	0.34	0.32	0.27
K	146	172	177	165	140
	73	86	88.5	82.5	70
	0.26	0.31	0.32	0.30	0.25
L	128	149	149	143	120
	64	74.5	74.5	71.5	60
	0.23	0.27	0.27	0.26	0.22

Hourly Irradiation. February. Roof No. 4
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	196	250	256	244	213
	98	125	128	122	106.5
	0.35	0.45	0.46	0.44	0.38
B	250	299	302	285	228
	125	149.5	151	142.5	114
	0.45	0.54	0.54	0.51	0.41
C	271	325	339	317	269
	135.5	162.5	169.5	158.5	134.5
	0.49	0.59	0.61	0.57	0.48
D	285	345	362	336	285
	142.5	172.5	181	168	142.5
	0.51	0.62	0.65	0.60	0.51
E	302	362	375	354	302
	151	181	187.5	177	151
	0.54	0.65	0.68	0.64	0.54
F	297	362	379	354	302
	148.5	181	189.5	177	151
	0.53	0.65	0.68	0.64	0.54
G	302	364	375	348	296
	151	182	187.5	174	148
	0.54	0.66	0.68	0.63	0.53
H	291	351	364	339	290
	145.5	175.5	182	169.5	145
	0.52	0.63	0.66	0.61	0.52
J	339	317	325	306	257
	169.5	158.5	162.5	153	128.5
	0.61	0.57	0.59	0.55	0.46
K	401	377	309	290	247
	200.5	188.5	154.5	145	123.5
	0.72	0.68	0.56	0.52	0.44
L	437	405	408	320	281
	218.5	202.5	204	160	140.5
	0.79	0.73	0.73	0.58	0.51

Hourly Irradiation. March. Roof No. 4
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
M.J. $m^{-2}d^{-1}$ = P.A.R. x 0.0036.

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	351	430	457	437	382
	175.5	215	228.5	218.5	191
	0.63	0.77	0.82	0.79	0.69
B	430	525	545	512	430
	215	262.5	272.5	256	215
	0.77	0.95	0.98	0.92	0.77
C	486	586	609	568	480
	243	293	304.5	284	240
	0.87	1.05	1.10	1.02	0.86
D	512	617	649	604	512
	256	308.5	324.5	302	256
	0.92	1.11	1.17	1.09	0.92
E	545	649	672	636	545
	272.5	324.5	336	318	272.5
	0.98	1.17	1.21	1.14	0.98
F	663	775	678	398	545
	331.5	387.5	339	199	272.5
	1.19	1.40	1.22	0.72	0.98
G	863	972	864	816	721
	431.5	486	432	408	360.5
	1.55	1.75	1.56	1.47	1.30
H	909	1013	1019	974	883
	454.5	506.5	509.5	487	441.5
	1.64	1.82	1.83	1.75	1.59
J	864	952	951	913	867
	432	476	475.5	456.5	433.5
	1.56	1.71	1.71	1.64	1.56
K	841	929	920	883	848
	420.5	464.5	460	441.5	424
	1.51	1.67	1.66	1.59	1.53
L	784	848	839	819	779
	392	424	419.5	409.5	389.5
	1.41	1.53	1.51	1.47	1.40

Hourly Irradiation. April. Roof No. 4
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J.m^{-2} d^{-1}= P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	509	626	660	635	555
	254.5	313	330	317.5	277.5
	0.92	1.13	1.19	1.14	1.00
B	626	750	785	742	626
	313	375	392.5	371	313
	1.13	1.35	1.41	1.34	1.13
C	706	845	884	831	696
	353	422.5	442	415.5	348
	1.27	1.52	1.59	1.50	1.25
D	1129	1139	1102	956	823
	564.5	569.5	551	478	411.5
	2.03	2.05	1.98	1.72	1.48
E	1422	1433	1384	1250	947
	711	716.5	692	625	473.5
	2.56	2.58	2.49	2.25	1.70
F	1412	1577	1538	1509	1206
	706	788.5	769	754.5	603
	2.54	2.84	2.77	2.72	2.17
G	1422	1584	1528	1491	1188
	711	792	764	745.5	594
	2.56	2.85	2.75	2.68	2.14
H	1396	1547	1503	1474	1171
	698	773.5	751.5	737	585.5
	2.51	2.78	2.71	2.65	2.11
J	1333	1458	1401	1382	1091
	666.5	729	700.5	691	545.5
	2.40	2.62	2.52	2.49	1.96
K	1297	1422	1359	1340	1056
	648.5	711	679.5	670	528
	2.33	2.56	2.45	2.41	1.90
L	1219	1307	1245	1240	966
	610	654	623	620	483
	2.19	2.35	2.24	2.23	1.74

Hourly Irradiation. May. Roof No. 4
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J.m^{-2} d^{-1}= P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	615	754	793	762	667
	307.5	377	396.5	381	333.5
	1.11	1.36	1.43	1.37	1.20
B	939	1087	942	889	754
	469.5	543.5	471	444.5	377
	1.69	1.96	1.70	1.60	1.36
C	1555	1726	1585	1299	1108
	777.5	863	792.5	649.5	554
	2.80	3.11	2.85	2.34	1.99
D	1706	2076	1942	1810	1651
	853	1038	971	905	825.5
	3.07	3.74	3.50	3.26	2.97
E	1756	2128	1983	1865	1701
	878	1064	991.5	932.5	850.5
	3.16	3.83	3.57	3.36	3.06
F	1747	2128	1996	1865	1701
	873.5	1064	998	932.5	850.5
	3.14	3.83	3.59	3.36	3.06
G	1756	2136	1983	1844	1685
	878	1068	991.5	922	842.5
	3.76	3.84	3.57	3.32	3.03
H	1726	2096	1951	1822	1661
	863	1048	975.5	911	830.5
	3.11	3.77	3.51	3.28	2.99
J	1654	1987	1833	1717	1565
	827	993.5	916.5	858.5	782.5
	2.98	3.58	3.30	3.09	2.82
K	1607	1941	1780	1661	1521
	803.5	970.5	890	830.5	760.5
	2.89	3.49	3.20	2.99	2.74
L	1516	1806	1643	1545	1657
	758	903	821.5	772.5	828.5
	2.73	3.25	2.96	2.78	2.98

Hourly Irradiation. June. Roof No. 4
Expressed as Watt hours per sq metre.
P.A.R. = (Whm^{-2})/2.
M.J.m^{-2} d^{-1}= P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	903	870	922	882	773
	451.5	435	461	441	386.5
	1.63	1.57	1.66	1.59	1.39
B	1300	1281	1092	1035	870
	650	640.5	546	517.5	435
	2.34	2.31	1.97	1.86	1.57
C	2201	2320	2138	1900	1444
	1100.5	1160	1069	950	722
	3.96	4.18	3.85	3.42	2.60
D	2251	2500	2329	2178	1799
	1125.5	1250	1164.5	1089	899.5
	4.05	4.50	4.19	3.92	3.24
E	2308	2563	2377	2237	1857
	1154	1281.5	1188.5	1118.5	928.5
	4.15	4.61	4.28	4.03	3.34
F	2299	2563	2389	2237	1857
	1149.5	1281.5	1194.5	1118.5	928.5
	4.14	4.61	4.30	4.03	3.34
G	2308	2575	2375	2212	1835
	1154	1287.5	1187.5	1106	917.5
	4.15	4.64	4.28	3.98	3.30
H	2274	2523	2341	2192	1810
	1137	1261.5	1170.5	1096	905
	4.09	4.54	4.21	3.95	3.26
J	2187	2400	2203	2065	1701
	1093.5	1200	1101.5	1032.5	850.5
	3.94	4.32	3.97	3.72	3.06
K	2136	2346	2141	2004	1647
	1068	1173	1070.5	1002	823.5
	3.84	4.22	3.85	3.61	2.96
L	2025	2190	1978	1866	1524
	1012.5	1095	989	933	762
	3.65	3.94	3.56	3.36	2.74

Hourly Irradiation. December. Roof No. 4
Expressed as Watt hours per sq metre.
P.A.R. = $(Whm^{-2})/2$.
$M.J.m^{-2}\,d^{-1}$ = P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	109	124	121	135	92
	54.5	62	60.5	67.5	46
	0.20	*0.22*	*0.22*	*0.24*	*0.17*
B	105	128	134	134	115
	52.5	64	67	67	57.5
	0.19	*0.23*	*0.24*	*0.24*	*0.21*
C	118	142	150	141	118
	59	71	75	70.5	59
	0.21	*0.26*	*0.27*	*0.25*	*0.21*
D	124	152	160	147	124
	62	76	80	73.5	62
	0.22	*0.27*	*0.29*	*0.26*	*0.22*
E	134	160	161	155	134
	67	80	80.5	77.5	67
	0.24	*0.29*	*0.29*	*0.28*	*0.24*
F	131	160	166	155	134
	65.5	80	83	77.5	67
	0.24	*0.29*	*0.30*	*0.28*	*0.24*
G	134	160	165	152	129
	67	80	82.5	76	64.5
	0.24	*0.29*	*0.30*	*0.27*	*0.23*
H	129	155	160	150	128
	64.5	77.5	80	75	64
	0.23	*0.28*	*0.29*	*0.27*	*0.23*
J	118	139	142	134	113
	59	69.5	71	67	56.5
	0.21	*0.25*	*0.26*	*0.24*	*0.20*
K	111	134	136	128	106
	55.5	67	68	64	53
	0.20	*0.24*	*0.24*	*0.23*	*0.19*
L	97	113	116	110	92
	48.5	56.5	58	55	46
	0.17	*0.20*	*0.21*	*0.20*	*0.17*

Table 7.3.5.5.

Values for Hourly Irradiation. Roof No 5. For January, February, March April, May, June and December.

Hourly Irradiation. January. Roof No. 5.
Expressed as Watt hours per sq metre.
P.A.R. = (Whm-2)/2.
$MJm^{-2} d^{-1}$ = P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	151	158	156	152	151
	75.5	79	78	76	75.5
	0.27	0.28	0.28	0.27	0.27
B	156	163	163	160	158
	78	81.5	81.5	80	79
	0.28	0.29	0.29	0.29	0.28
C	167	172	163	162	161
	83.5	86	81.5	81	80.5
	0.30	0.31	0.29	0.29	0.29
D	163	169	208	206	163
	81.5	84.5	104	103	81.5
	0.29	0.30	0.37	0.37	0.29
E	162	165	172	168	162
	81	82.5	86	84	81
	0.29	0.30	0.31	0.30	0.29
F	163	168	174	165	162
	81.5	84	87	82.5	81
	0.29	0.30	0.31	0.30	0.29
G	162	165	165	163	160
	81	82.5	82.5	81.5	80
	0.29	0.30	0.30	0.29	0.29
H	163	165	165	165	162
	81.5	82.5	82.5	82.5	81
	0.29	0.30	0.30	0.30	0.29
J	160	165	165	162	158
	80	82.5	82.5	81	79
	0.29	0.30	0.30	0.29	0.28
K	158	163	163	162	152
	79	81.5	81.5	81	76
	0.28	0.29	0.29	0.29	0.27
L	151	160	158	152	149
	75.5	80	79	76	74.5
	0.27	0.29	0.28	0.27	0.27

Hourly Irradiation. February. Roof No. 5
Expressed as Watt hours per sq metre.
P.A.R. = (Whm-2)/2.
$MJm^{-2} d^{-1}$ = P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	288	311	299	297	293
	144	155.5	149.5	148.5	146.5
	0.52	0.56	0.54	0.53	0.53
B	306	316	307	307	304
	153	158	153.5	153.5	152
	0.55	0.57	0.55	0.55	0.55
C	312	320	315	311	304
	156	160	157.5	155.5	152
	0.56	0.58	0.57	0.56	0.55
D	312	332	398	394	315
	156	166	199	197	157.5
	0.56	0.60	0.72	0.71	0.57
E	311	320	330	322	311
	155.5	160	165	161	155.5
	0.56	0.58	0.59	0.58	0.56
F	315	322	322	320	315
	157.5	161	161	160	157.5
	0.57	0.58	0.58	0.58	0.57
G	337	320	320	315	307
	168.5	160	160	157.5	153.5
	0.61	0.58	0.58	0.57	0.55
H	342	320	320	320	311
	171	160	160	160	155.5
	0.62	0.58	0.58	0.58	0.56
J	404	355	355	346	304
	202	177.5	177.5	173	152
	0.73	0.64	0.64	0.62	0.55
K	400	350	350	346	297
	200	175	175	173	148.5
	0.72	0.63	0.63	0.62	0.53
L	388	342	339	332	288
	194	171	169.5	166	144
	0.70	0.62	0.61	0.60	0.52

Hourly Irradiation. March. Roof No. 5
Expressed as Watt hours per sq metre.
P.A.R. = (Whm-2)/2.
$MJm^{-2} d^{-1}$ = P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	505	537	519	512	475
	252.5	268.5	259.5	256	237.5
	0.91	0.97	0.93	0.92	0.86
B	576	539	533	533	526
	288	269.5	266.5	266.5	263
	1.04	0.97	0.96	0.96	0.95
C	715	735	675	670	592
	357.5	367.5	337.5	335	296
	1.29	1.32	1.22	1.21	1.07
D	649	677	809	747	738
	324.5	338.5	404.5	373.5	369
	1.17	1.22	1.46	1.34	1.33
E	839	799	818	790	771
	419.5	399.5	409	395	385.5
	1.51	1.44	1.47	1.42	1.39
F	910	872	910	850	777
	455	436	455	425	388.5
	1.64	1.57	1.64	1.53	1.40
G	1031	991	1030	969	827
	515.5	495.5	515	484.5	413.5
	1.86	1.78	1.85	1.74	1.49
H	1036	1098	1137	1083	941
	518	549	568.5	541.5	470.5
	1.86	1.98	2.05	1.95	1.69
J	1025	1098	1137	1070	965
	512.5	549	568.5	535	482.5
	1.85	1.98	2.05	1.93	1.74
K	1019	1090	1128	1070	951
	509.5	545	564	535	475.5
	1.83	1.96	2.03	1.93	1.71
L	997	1077	1109	1042	938
	498.5	538.5	554.5	521	469
	1.79	1.94	2.00	1.88	1.69

Hourly Irradiation. April. Roof No.5
Expressed as Watt hours per sq metre.
P.A.R. = (Whm-2)/2.
$MJm^{-2}\ d^{-1}$= P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	1032	1009	1001	862	773
	516	504.5	500.5	431	386.5
	1.86	1.82	1.80	1.55	1.39
B	1145	1170	1228	1112	1071
	572.5	585	614	556	535.5
	2.06	2.11	2.21	2.00	1.93
C	1227	1198	1246	1218	1129
	613.5	599	623	609	564.5
	2.21	2.16	2.24	2.19	2.03
D	1438	1417	1564	1416	1156
	719	708.5	782	708	578
	2.59	2.55	2.82	2.55	2.08
E	1,532	1564	1558	1405	1303
	766	782	779	702.5	651.5
	2.76	2.82	2.80	2.53	2.35
F	1623	1654	1621	1532	1452
	811.5	827	810.5	766	726
	2.92	2.98	2.92	2.76	2.61
G	1613	1645	1612	1524	1432
	806.5	822.5	806	762	716
	2.90	2.96	2.90	2.74	2.58
H	1623	1645	1612	1532	1441
	811.5	822.5	806	766	720.5
	2.92	2.96	2.90	2.76	2.59
J	1604	1645	1612	1483	1423
	802	822.5	806	741.5	711.5
	2.89	2.96	2.90	2.67	2.56
K	1595	1637	1604	1513	1406
	797.5	818.5	802	756.5	703
	2.87	2.95	2.89	2.72	2.53
L	1570	1619	1577	1488	1390
	785	809.5	788.5	744	695
	2.83	2.91	2.84	2.68	2.50

Hourly Irradiation. May. Roof No. 5
Expressed as Watt hours per sq metre.
P.A.R. = (Whm-2)/2.
$MJm^{-2}\ d^{-1}$= P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	1553	1524	1457	1301	1231
	776.5	762	728.5	650.5	615.5
	2.80	2.74	2.62	2.34	2.22
B	1567	1600	1468	1529	1465
	783.5	800	734	764.5	732.5
	2.82	2.88	2.64	2.75	2.64
C	1872	1830	1503	1449	1372
	936	915	751.5	724.5	686
	3.37	3.29	2.71	2.61	2.47
D	2187	2325	2485	2254	1958
	1093.5	1162.5	1242.5	1127	979
	3.94	4.19	4.47	4.06	3.52
E	2141	2182	2200	2032	1945
	1070.5	1091	1100	1016	972.5
	3.85	3.93	3.96	3.66	3.50
F	2027	2193	2176	2020	1958
	1013.5	1096.5	1088	1010	979
	3.65	3.95	3.92	3.64	3.52
G	2197	2314	2242	2009	1934
	1098.5	1157	1121	1004.5	967
	3.95	4.17	4.04	3.62	3.48
H	2211	2258	2242	2020	1945
	1105.5	1129	1121	1010	972.5
	3.98	4.06	4.04	3.64	3.50
J	2188	2313	2242	1997	1925
	1094	1156.5	1121	998.5	962.5
	3.94	4.16	4.04	3.59	3.47
K	2176	2224	2155	1996	1903
	1088	1112	1077.5	998	951.5
#0.00	3.92	4.00	3.88	3.59	3.43
L	2143	2204	2121	1955	1876
	1071.5	1102	1060.5	977.5	938
	3.86	3.97	3.82	3.52	3.38

Hourly Irradiation. June. Roof No. 5
Expressed as Watt hours per sq metre.
P.A.R. = (Whm-2)/2.
$MJm^{-2}\ d^{-1}$= P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	1828	1777	1765	1882	1637
	914	888.5	882.5	941	818.5
	3.29	3.20	3.18	3.39	2.95
B	2102	2101	1960	1904	1674
	1051	1050.5	980	952	837
	3.78	3.78	3.53	3.43	3.01
C	2387	2401	2345	2352	1847
	1193.5	1200.5	1172.5	1176	923.5
	4.30	4.32	4.22	4.23	3.32
D	2516	2660	2965	2971	2306
	1258	1330	1482.5	1485.5	1153
	4.53	4.79	5.34	5.35	4.15
E	2528	2647	2739	2733	2294
	1264	1323.5	1369.5	1366.5	1147
	4.55	4.76	4.93	4.92	4.13
F	2541	2660	2714	2721	2306
	1270.5	1330	1357	1360.5	1153
	4.57	4.79	4.89	4.90	4.15
G	2528	2647	2702	2709	2282
	1264	1323.5	1351	1354.5	1141
	4.55	4.76	4.86	4.88	4.11
H	2541	2647	2702	2721	2294
	1270.5	1323.5	1351	1360.5	1147
	4.57	4.76	4.86	4.90	4.13
J	2516	2647	2702	2696	2268
	1258	1323.5	1351	1348	1134
	4.53	4.76	4.86	4.85	4.08
K	2503	2635	2690	2696	2241
	1251.5	1317.5	1345	1348	1120.5
	4.51	4.74	4.84	4.85	4.03
L	2464	2610	2652	2644	2219
	1232	1305	1326	1322	1109.5
	4.44	4.70	4.77	4.76	3.99

Hourly Irradiation. December. Roof No. 5
Expressed as Watt hours per sq metre.
P.A.R. = (Whm-2)/2.
$MJm^{-2} d^{-1}$= P.A.R. x 0.0036

	C2-C3	C3-C4	C4-C5	C5-C6	C6-C7
A	154	150	157	176	145
	77	75	78.5	88	72.5
	0.28	*0.27*	*0.28*	*0.32*	*0.26*
B	141	143	143	152	160
	70.5	71.5	71.5	76	80
	0.25	*0.26*	*0.26*	*0.27*	*0.29*
C	150	157	144	144	141
	75	78.5	72	72	70.5
	0.27	*0.28*	*0.26*	*0.26*	*0.25*
D	147	154	186	181	144
	73.5	77	93	90.5	72
	0.26	*0.28*	*0.33*	*0.33*	*0.26*
E	151	153	153	151	144
	75.5	76.5	76.5	75.5	72
	0.27	*0.28*	*0.28*	*0.27*	*0.26*
F	144	151	151	150	144
	72	75.5	75.5	75	72
	0.26	*0.27*	*0.27*	*0.27*	*0.26*
G	144	150	150	144	143
	72	75	75	72	71.5
	0.26	*0.27*	*0.27*	*0.26*	*0.26*
H	144	150	150	150	144
	72	75	75	75	72
	0.26	*0.27*	*0.27*	*0.27*	*0.26*
J	143	150	150	144	141
	71.5	75	75	72	70.5
	0.26	*0.27*	*0.27*	*0.26*	*0.25*
K	141	144	144	144	138
	70.5	72	72	72	69
	£0.25	*£0.26*	*£0.26*	*£0.26*	*£0.25*
L	146	143	141	138	135
	73	71.5	70.5	69	67.5
	0.26	*0.26*	*0.25*	*0.25*	*0.24*

CHAPTER SIX.

7.6.0. THE WIND MEASUREMENTS.

Section **7.3.0** confirms the following:

- The description of the wind tunnel.
- That the airflow through the wind tunnel was symmetrical.
- That turbulence had been eradicated between the two adjoining sections of the wind tunnel model.

This chapter describes the methods involved in collecting the air movement data, the method of converting that data into actual wind speed values based on information from Page and Lebens and from a range of other assumed values.

The chapter also sets out the recommendation for minimum horizontal air speed movement at the turfgrass canopy level as being 0.2 m s $^{-1}$. The suggestion is that this requirement is an annual constant over the whole pitch. The suggestion is also made that the horizontal air velocity should not be more than 5 m s $^{-1}$ for more than 24 hours at a stretch over any part of the playing area without a 48 hour recovery period.

The airflow data used in this study was collected by an anemometer, which traversed the wind tunnel ceiling. The area of that movement centred on the area of the turntable and limits of its movements were defined by a rectangular area formed by the width of the wind tunnel and the diameter of the turntable. The ceiling above that area was adapted to allow the anemometer to traverse the area within fine limits longitudinally, laterally and vertically within the imaginary three dimensional box . This arrangement allowed airflow readings to be taken over the playing surface at prescribed points across the playing surface and at any height below the needle of the anemometer. The needle was set 200m below the wind tunnel ceiling.

The principal aim of testing was to record air speed movements at positions as near as possible to the upper surface of the model base. This surface represents turfgrass canopy level, which is the level at which field measurements would have been taken. However, care had to be exercised to ensure the needle tip was not damaged by making contact with the base of the model. Therefore, it was decided to record measurements at the scaled equivalent of 0.5m above the playing surface which was as near as practically possible to the surface, whilst controlling the relationship between the needle and the model surface.

Fig 7.6.0.1 and Fig 7.6.0.2 show the base model in the wind tunnel capped with different roof configurations.

Fig 7.6.0.1. The Wind Tunnel Model set in the mode to measure the influences imposed by the Centrally Located Retractable Roof.

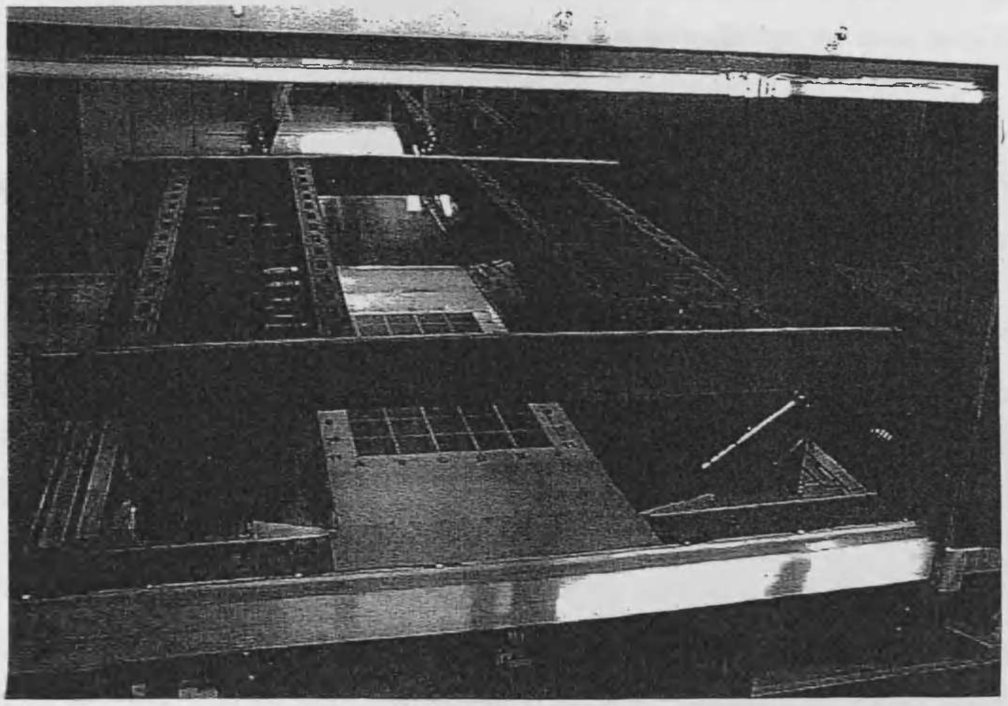
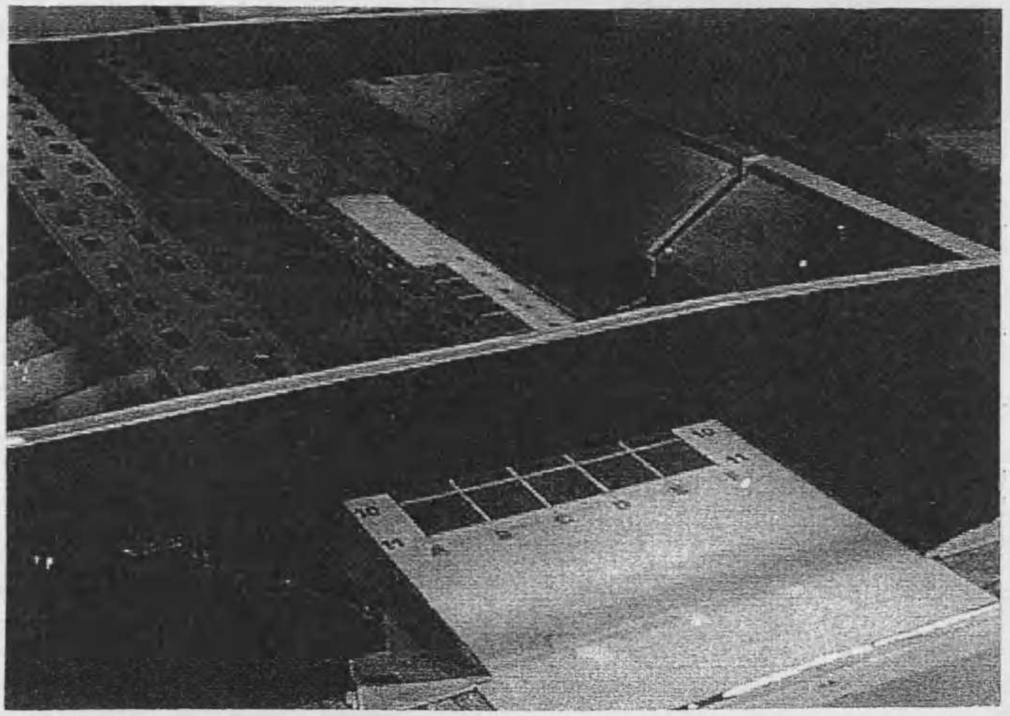


Fig 7.6.0.2. The Wind Tunnel Model set in the mode to measure the influences imposed by the Asymmetrical Retractable Roof.



Airflow measurements were taken on the grid intersections on the central grid line beginning at the **0.5 metre** position which represents the canopy level of the turfgrass. Other measurements were recorded at the following vertical positions above the canopy level: these positions were **2, 6.5, 8.7, 11, 17, 25, 31, 43,and 50 metres.** The measurements were repeated for each of the grid positions across the playing surface. This matrix of dimensions makes up the cross sectional slice referred to in **Fig 7.3.1.1.**

The wind levels which influence the turfgrass are those that occur at turfgrass canopy level. The canopy readings are taken at 0.5 of a metre and converted into real wind speed values measured in metres per second.

The remaining vertical levels on the section slice were taken only to judge the overall pattern made by the vertical wind profiles influenced by the varying roof configurations. These profiles are recorded on **Figs 7.6.0.4 to 7.6.0.15.**

The base model was modified at roof level by incorporating different roof configurations. The superstructure was also modified by closing the opening between the concourse and the soffit of the grandstand over the concourse. Measurements were also taken with the concourse space remaining open. This process was repeated on the grandstands on the extract side of the tunnel. These adjustments bring about the variations in the rates of airflow over the playing surface.

The wind tunnel reference height was set 50 metres, that reference relates to all the readings and for all models. The measurements were taken with adjustments being made to the superstructure and with the retractable roof in a range of configurations.

Turfgrass wind speeds are measured in $M\ s^{-1}$. In this case the lowest vertical measurements through the "slice" were taken at the equivalent of a scaled 200mm above the surface of the model playing field. If measurements had been attempted any closer to the surface than that, damage may have resulted to the anemometer needle.

7.6.0. Preparing the Calculations for the Different Roof Configurations.

Boundary layer velocity profiles can be created in Boundary Layer Wind tunnels by the introduction of features of varying heights on the tunnel base. These features produce surface roughness. In this case Lego blocks were used but other objects can serve the same purpose. The blocks were set some way from the air inlet and terminates in a straight line between the walls of the tunnel and just before the turntable edge. The turbulence and eddy structure of the wind was appropriate for the scale of the model being tested.

The wind profile suitable for the perceived siting of the stadium in the test is based on a terrain roughness based on a site in the open country with a flat landscape. This has a terrain coefficient of **0.14** and a **gradient height of 250 metres**. This profile is one of three wind profiles used in association with a Boundary Layer Wind Tunnel. The first of the other two profiles provide for Urban settings such as a small city or a dense forest. The third is the centre of a large city with many high rise buildings.

A planetary boundary layer is a region where mean wind speed increases with height above ground. Surface friction slows the flow at low level but this effect reduces with height until at gradient height the mean airflow equals that of free air stream velocity.

The rougher the terrain the deeper the boundary layer and the more gradual the increase in speed until it reaches its appropriate gradient height. Conversely the smoother the terrain, the shallower will be the boundary layer accompanied by an increase with height. This variation in height and wind speed can be realised by the velocity profiles formed by the different terrain conditions.

The velocity profile can be represented by a number of mathematical models. The Power Law Formula is one of the earliest approximations and is generally considered as being acceptable for the majority of wind tunnel simulations. The formula is set out in **Fig 7.6.0.3.**

Fig 7.6.0.3 The Power Law Formula.

All airflow measurements are recorded by the "slice"principle see **Fig 7.3.1.1.** The implication of this is that the stadium with the bi-parting roof will record the same readings as the stadium with no roof. The explanation for this is that where the slice cuts through the central cross section of the stadium there will be no roof cover in either of these cases.

The Centrally Located Bi-Parting roof performs well in terms of airflow rates at pitch level when the opening at concourse level is open, but is reduced significantly when either one or the other of the openings on either side of the stadium is blocked off.

The Bi-parting Roof performs in the same way as the Centrally Located Roof does when the opening at concourse level is open, but performs no better than the Centrally Located Bi-Parting Roof with either one or the other of the openings of the stadium blocked off.

The Asymmetrical Roof performs in much the same way as the Centrally Located Roof and the Bi-Parting Roof, when the opening at concourse level is in the open position on both sides of the stadium. The Asymmetrical Roof however performs better than the other two when one or the other of the openings on opposite sides of the stadium is blocked.

The study confirms the findings of a previous study that raising the underside of a superstructure does allow airflow across the playing surface and that only such a strategy will achieve that airflow by passive means.

By utilising the power law formula the wind velocity at 10 meters is reduced to 79.8% of the wind tunnel velocity at 50 metres in the wind tunnel. This value relates to the open country condition with a flat landscape, which attracts a terrain coefficient of **0.14.** Velocity values based on a 10 metres height are used because this is the altitude at which airflow data is published. Therefore the data produced in this work has a basis for comparison with published data.

The velocity of the air speed values at 50 metres in the wind tunnel tests were recorded at between 10 m/sec^{-1} and 13 m/sec^{-1}. Three air speed values were taken for each of the vertical levels recorded. These wind speeds which are marginally different from each other because the conditions in the wind tunnel vary between each run. These readings are averaged and the average is applied to the calculation used to determine the assumed real wind condition across the turfgrass at 0.5 metre level which is the only level appropriate to the turfgrass requirements.

An example of the calculation is as follows:
The wind tunnel reference speeds recorded at 50 metres height are adjusted to determine their percentage equivalent at a height of 10 metres.

If for example, the wind tunnel airflow level was recorded at 11 m sec^{-1}. That airflow value, is multiplied by 0.798. This adjustment will produce the reference wind speed in metres per second for a 10 metre level.

Therefore the appropriate reference speed is, 11m/sec x .0.798 = 8.778 m/sec^{-1}, to one decimal place 8.778 m/sec^{-1}.

The new reference speed now becomes the base figure, which is applied to produce a ratio; percentage of a real wind speed by dividing the reference speed is into wind tunnel velocities measured at 0.5 metres.

Assuming a wind tunnel velocity reading taken at 0.5m of 0.50, the airflow ratio/percentage is determined by dividing the 10 metre reference speed into the wind tunnel velocity reading at 0.5. Therefore the ratio between those values is 0.5/8.778 = 0,0569.

Assuming a wind speed outside the stadium of 5.0 m/sec the speed of airflow =2.8345 m/sec $^{-1}$. Expressed to two decimal places the final figure is 0.28 m/sec^{-1} airflow over the playing surface.

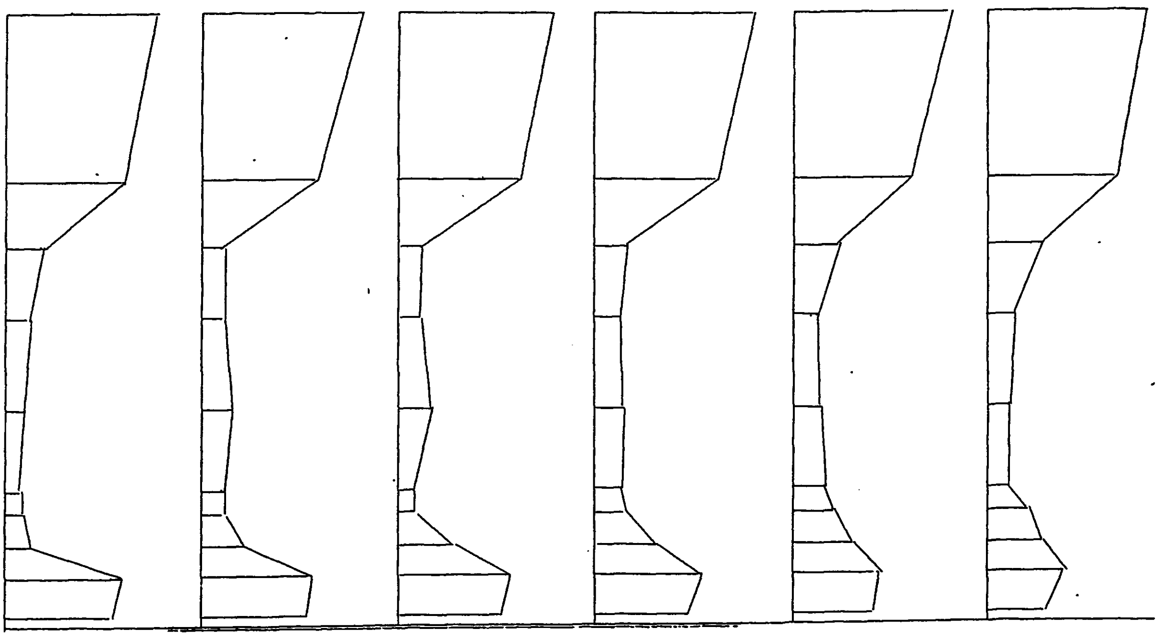
This figure exceeds the airflow speed recommended. The figure is 94.4% less than the airflow rate which if continuously applied, would require a natural turfgrass playing surface to be rested for 48 hours before use; that deleterious airflow rate is 5.0 m/sec^{-1}.

Fig 7.6.0.4. Asymmetrical Retractable Roof. Extract Closed. (A.R.E.C.)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.76	0.75	0.76	0.75	0.75	0.74
43	0.74	0.71	0.68	0.66	0.61	0.63
31.1	0.17	0.18	0.21	0.21	0.22	0.23
25	0.17	0.18	0.18	0.18	0.18	0.16
17	0.17	0.20	0.20	0.18	0.18	0.15
11	0.16	0.16	0.16	0.15	0.15	0.16
8.8	0.11	0.14	0.16	0.15	0.19	0.18
6.5	0.17	0.21	0.22	0.24	0.23	0.21
2	0.54	0.51	0.47	0.40	0.31	0.23
0.5	0.52	0.53	0.47	0.34	0.24	0.13

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Opening Blocked Extract End.

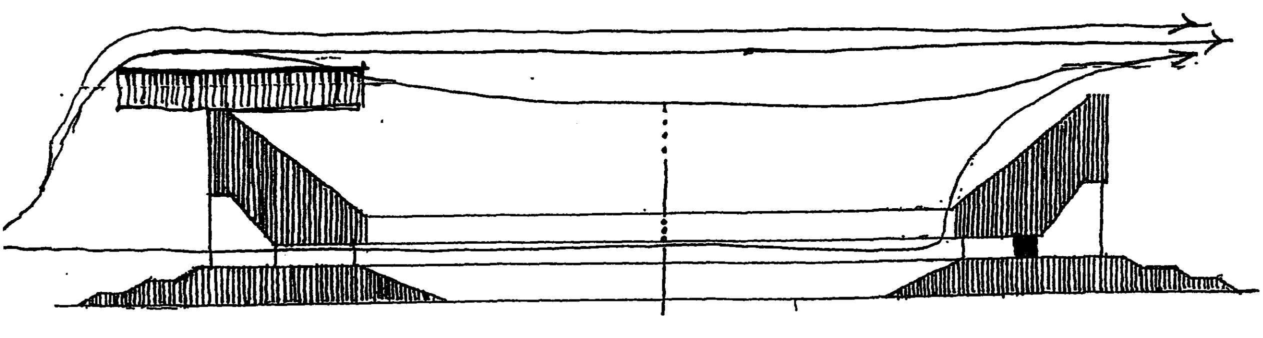
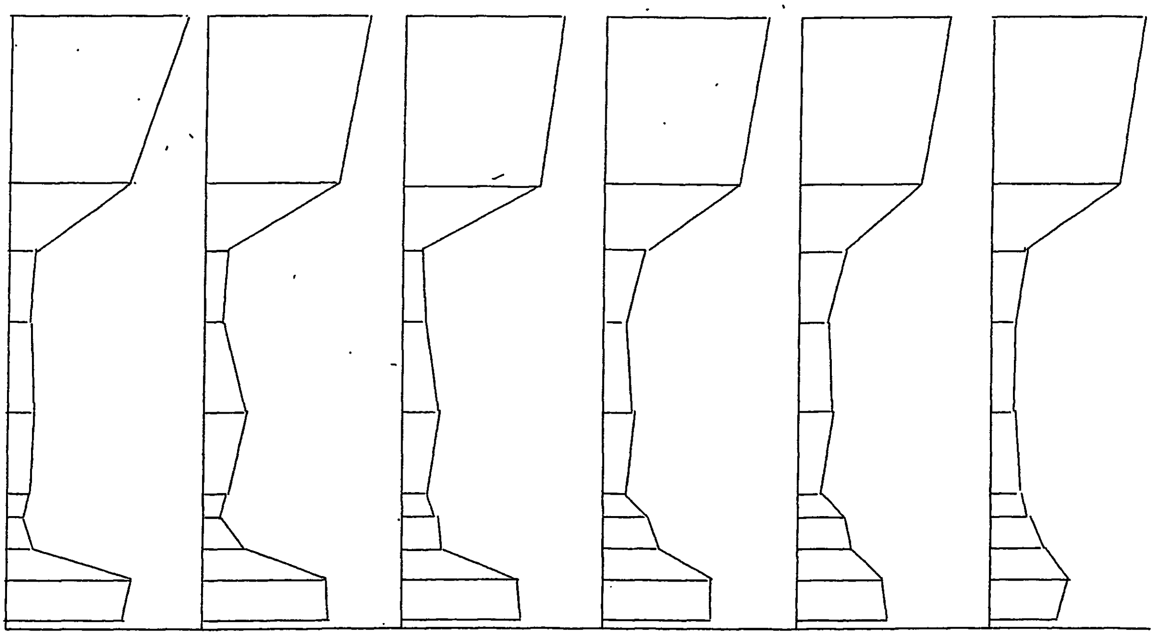


Fig 7.6.0.5. Asymmetrical Retractable Roof. Intake &Extract Open. (A.R.I.E.O)

Data Tabulated from Wind Tunnel Measurements.

	2a	2e	2i	2m	2q	2u
50	0.85	0.86	0.82	0.83	0.81	0.81
43	0.64	0.66	0.66	0.68	0.64	0.68
31	0.13	0.14	0.14	0.18	0.21	0.19
25	0.09	0.13	0.13	0.14	0.14	0.14
17	0.15	0.20	0.17	0.16	0.17	0.14
11	0.14	0.14	0.13	0.14	0.14	0.16
8.7	0.11	0.12	0.16	0.18	0.21	0.20
6.5	0.14	0.18	0.20	0.29	0.30	0.28
2	0.62	0.60	0.56	0.51	0.48	0.40
0.5	0.61	0.64	0.59	0.52	0.47	0.36

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Intake and Extract Open.

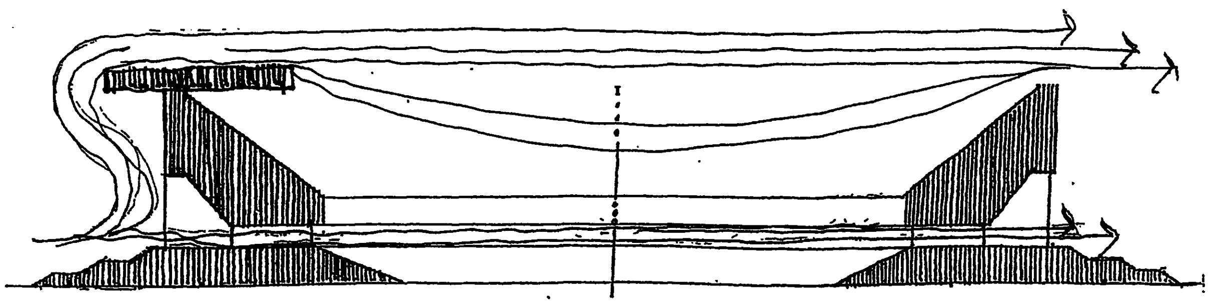
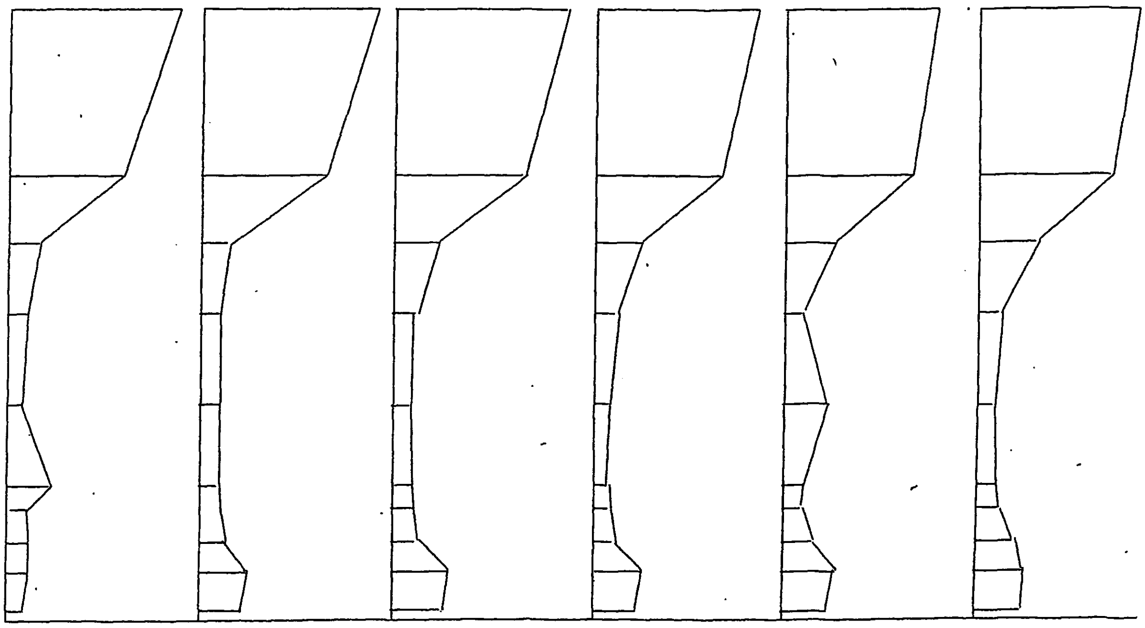


Fig 7.6.0.6. Asymmetrical Retractable Roof. Intake &Extract Closed. (A.R.I.E.C)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.79	0.79	0.79	0.79	0.78	0.77
43	0.76	0.75	0.71	0.65	0.67	0.65
31.1	0.22	0.23	0.25	0.25	0.31	0.28
25	0.11	0.12	0.11	0.12	0.17	0.24
17	0.12	0.09	0.08	0.09	0.12	0.24
11	0.15	0.15	0.15	0.13	0.15	0.25
8.8	0.15	0.19	0.16	0.15	0.16	0.24
6.5	0.20	0.22	0.23	0.20	0.21	0.22
2	0.25	0.27	0.29	0.29	0.25	0.17
0.5	0.21	0.29	0.30	0.31	0.26	0.14

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Intake and Extract Closed.

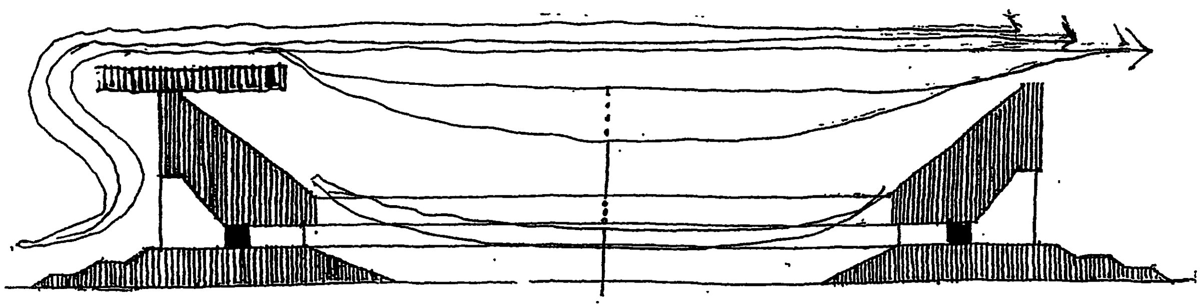
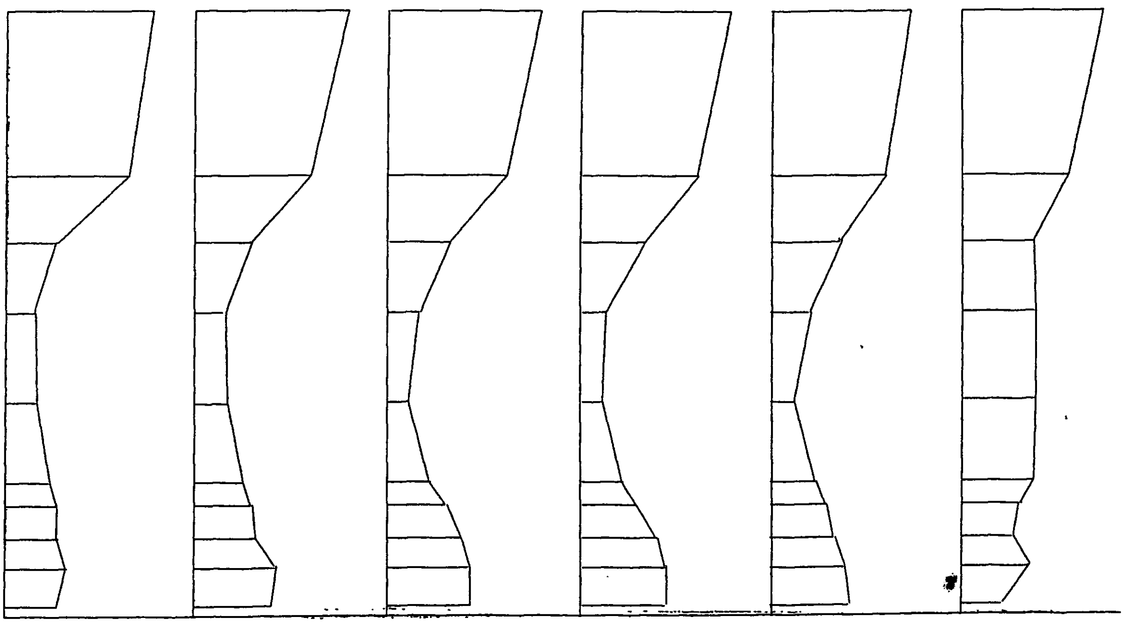


Fig. 7.6.0.7. Asymmetrical Retractable Roof Extract Open . (A.R.E.O.)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.81	0.81	0.81	0.80	0.78	0.77
43	0.73	0.70	0.71	0.67	0.63	0.60
31.1	0.20	0.21	0.24	0.25	0.27	0.27
25	0.13	0.11	0.14	0.12	0.16	0.28
17	0.14	0.12	0.09	0.08	0.13	0.28
11	0.19	0.19	0.16	0.16	0.17	0.27
8.8	0.21	0.21	0.23	0.20	0.20	0.23
6.5	0.22	0.23	0.27	0.28	0.24	0.21
2	0.26	0.34	0.34	0.34	0.29	0.27
0.5	0.20	0.31	0.34	0.34	0.31	0.14

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Intake and Extract Closed.

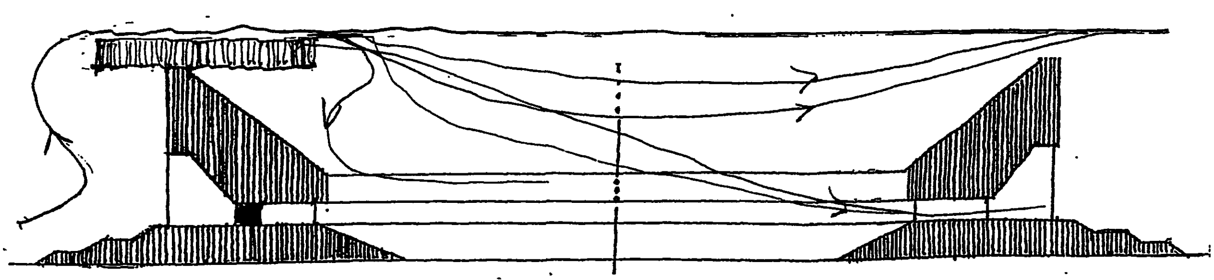
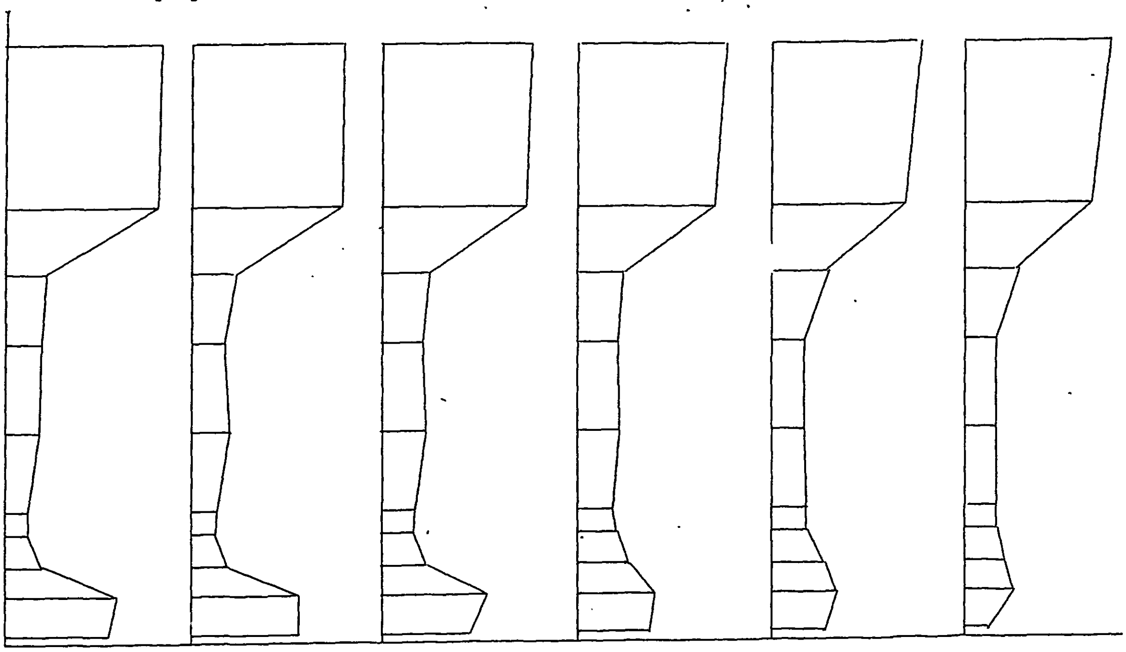


Fig. 7.6.0.8. Bi-Parting Retractable Roof. Intake &Extract Open. (B.P.R.I.E.O)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.83	0.81	0.79	0.79	0.78	0.79
43	0.82	0.80	0.77	0.71	0.71	0.69
31	0.22	0.23	0.23	0.23	0.27	0.27
25	0.19	0.18	0.20	0.19	0.17	0.18
17	0.18	0.20	0.21	0.20	0.17	0.18
11	0.14	0.16	0.17	0.17	0.18	0.18
8.7	0.14	0.15	0.16	0.18	0.18	0.18
6.5	0.18	0.21	0.24	0.23	0.25	0.20
2	0.60	0.56	0.52	0.40	0.33	0.22
0.5	0.56	0.56	0.49	0.38	0.26	0.14

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Intake and Extract Open.

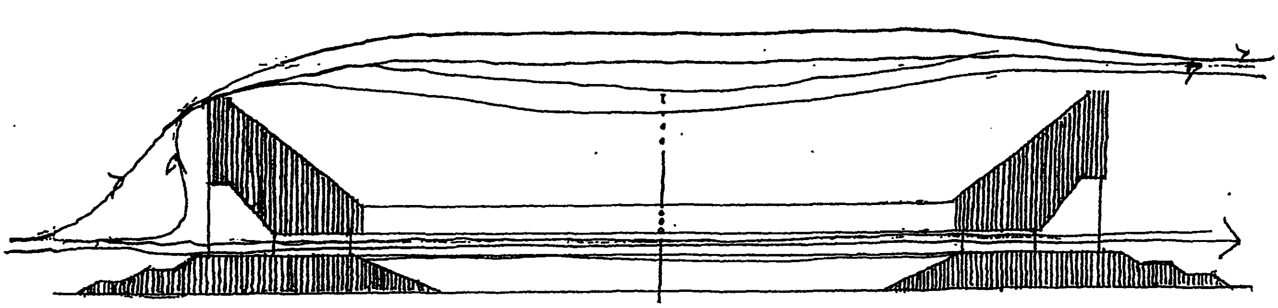
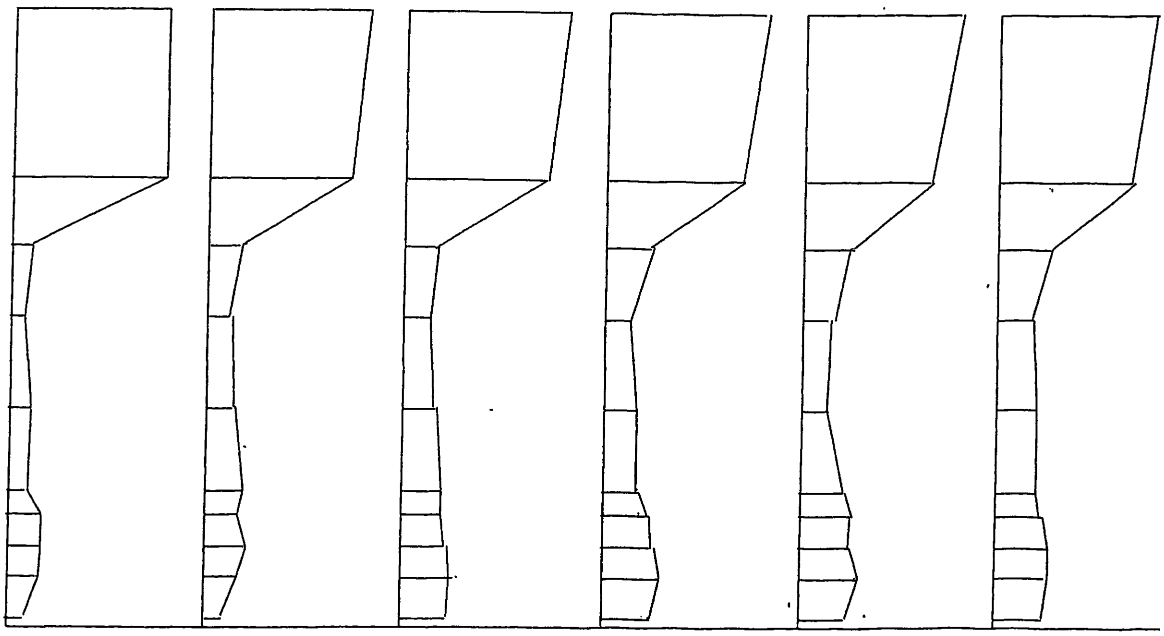


Fig. 7.6.0.9. Bi-Parting Retractable Roof. Intake Closed. (B.P.R.I.C.)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.81	0.82	0.82	0.82	0.82	0.81
43	0.81	0.75	0.71	0.69	0.66	0.68
31	0.15	0.17	0.16	0.23	0.24	0.26
25	0.10	0.12	0.13	0.12	0.15	0.17
17	0.14	0.13	0.16	0.16	0.14	0.18
11	0.13	0.18	0.18	0.18	0.21	0.18
8.7	0.17	0.17	0.18	0.20	0.22	0.21
6.5	0.17	0.21	0.19	0.21	0.21	0.22
2	0.15	0.17	0.20	0.23	0.24	0.22
0.5	0.10	0.13	0.19	0.19	0.20	0.20

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Intake Closed.

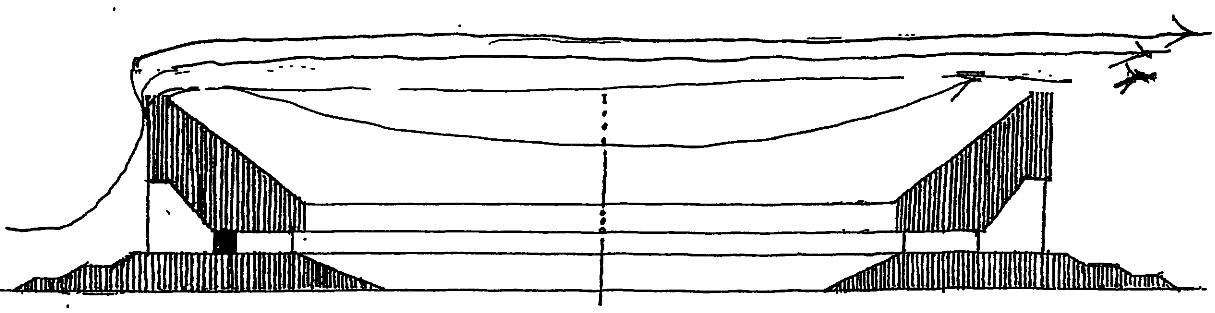
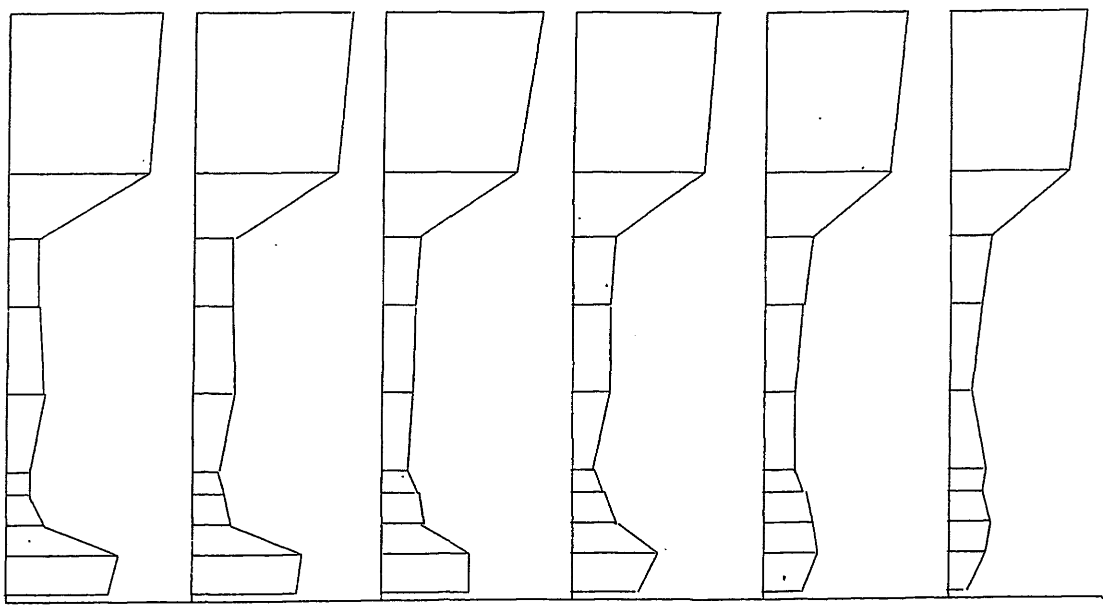


Fig. 7.6.0.10. Bi-Parting Retractable Roof. Extract Closed. (B.P.R.E.C.)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.80	0.80	0.81	0.78	0.78	0.78
43	0.78	0.77	0.72	0.72	0.70	0.65
31	0.16	0.20	0.20	0.24	0.24	0.24
25	0.16	0.20	0.18	0.19	0.19	0.16
17	0.18	0.21	0.21	0.19	0.17	0.15
11	0.13	0.15	0.15	0.15	0.17	0.19
8.7	0.13	0.16	0.16	0.17	0.20	0.18
6.5	0.18	0.21	0.22	0.25	0.24	0.21
2	0.57	0.55	0.47	0.41	0.30	0.19
0.5	0.53	0.53	0.47	0.35	0.18	0.09

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Extract Closed.

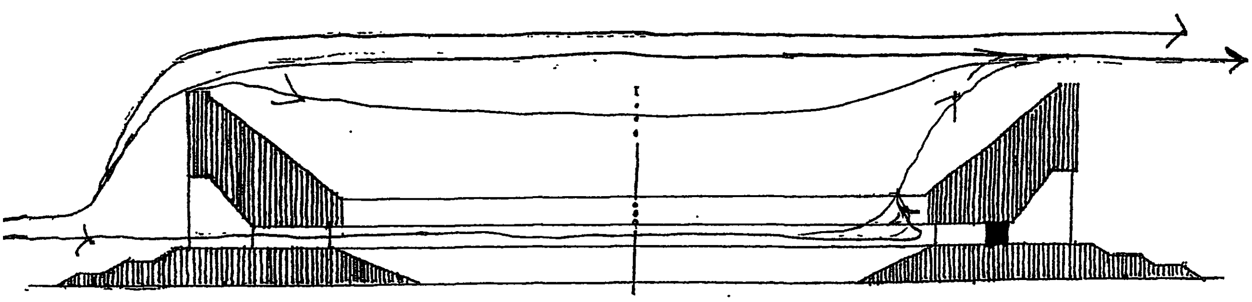
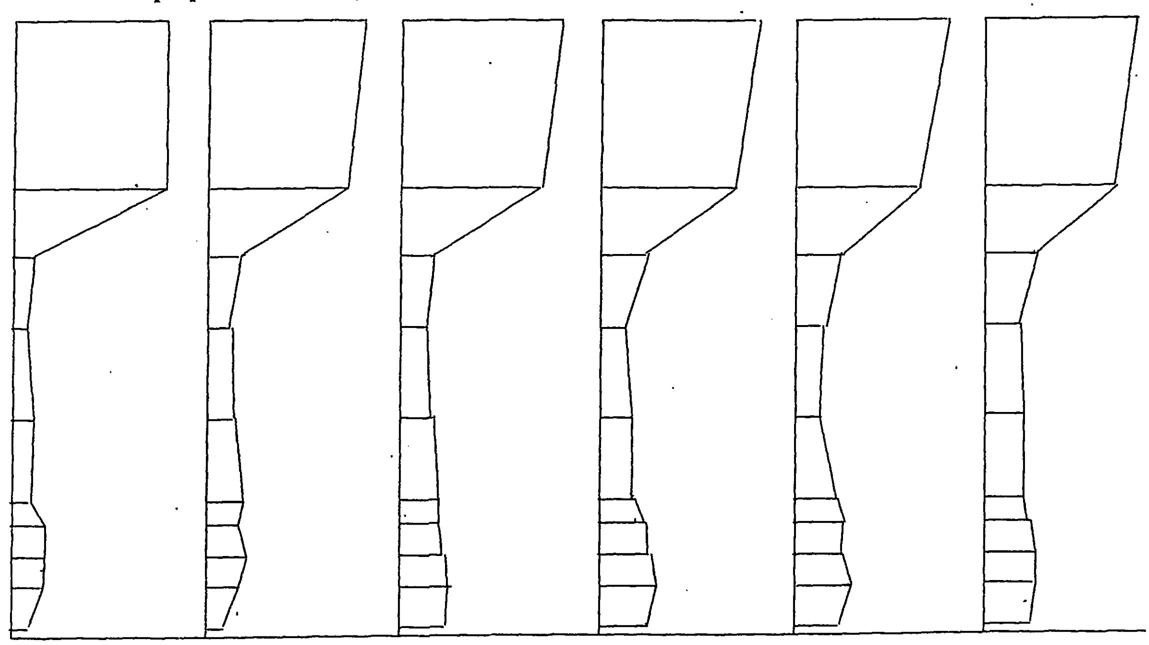


Fig. 7.6.0.11. Bi-Parting Retractable Roof. Intake, Extract Closed. (B.P.R.I.C.)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.81	0.82	0.82	0.82	0.82	0.81
43	0.81	0.75	0.71	0.69	0.66	0.68
31	0.15	0.17	0.16	0.23	0.24	0.26
25	0.10	0.12	0.13	0.12	0.15	0.17
17	0.14	0.13	0.16	0.16	0.14	0.18
11	0.13	0.18	0.18	0.18	0.21	0.18
8.7	0.17	0.17	0.18	0.20	0.22	0.21
6.5	0.17	0.21	0.19	0.21	0.21	0.22
2	0.15	0.17	0.20	0.23	0.24	0.22
0.5	0.10	0.13	0.19	0.19	0.20	0.20

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Intake Extract Closed.

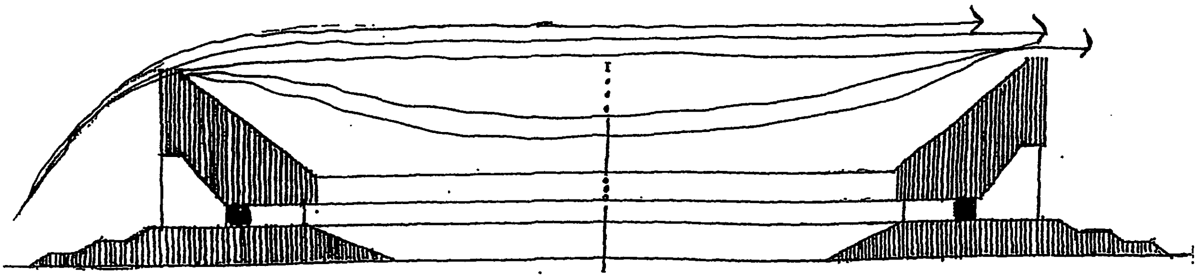
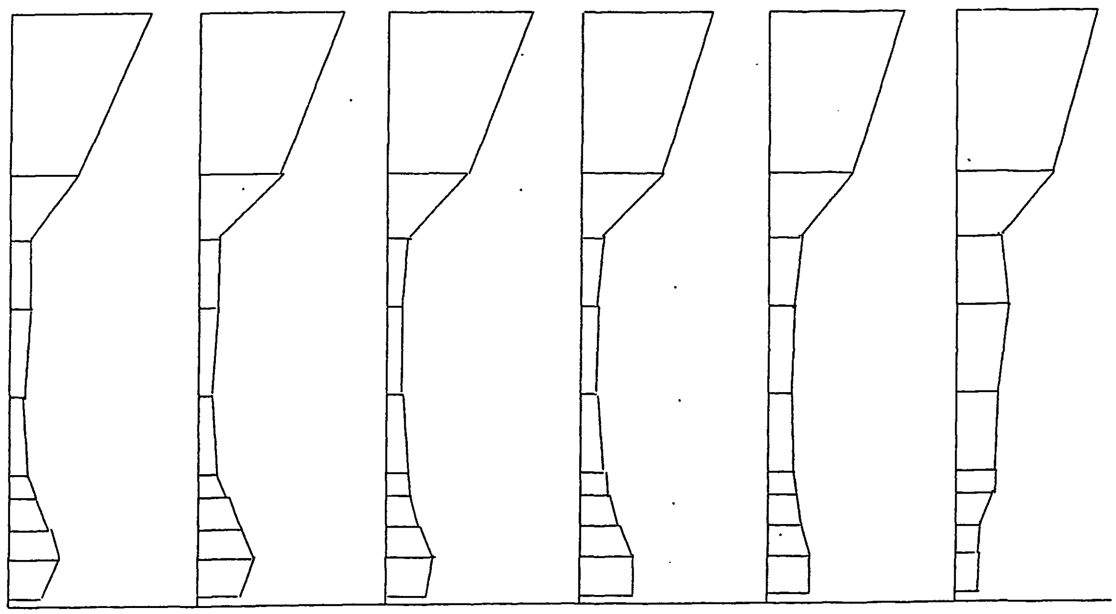


Fig. 7.6.0.12. Centrally Located Retractable Roof. Extract Closed. (C.L.R.E.C.)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.78	0.79	0.74	0.73	0.74	0.75
43	0.35	0.42	0.44	0.49	0.49	0.51
31	0.11	0.09	0.09	0.13	0.15	0.2
25	0.11	0.08	0.07	0.07	0.10	0.26
17	0.07	0.06	0.07	0.06	0.09	0.22
11	0.12	0.11	0.11	0.11	0.11	0.2
8.8	0.16	0.16	0.15	0.13	0.14	0.18
6.5	0.18	0.18	0.18	0.18	0.16	0.15
2	0.21	0.24	0.25	0.23	0.18	0.09
0.5	0.17	0.22	0.24	0.23	0.18	0.08

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Extract Closed.

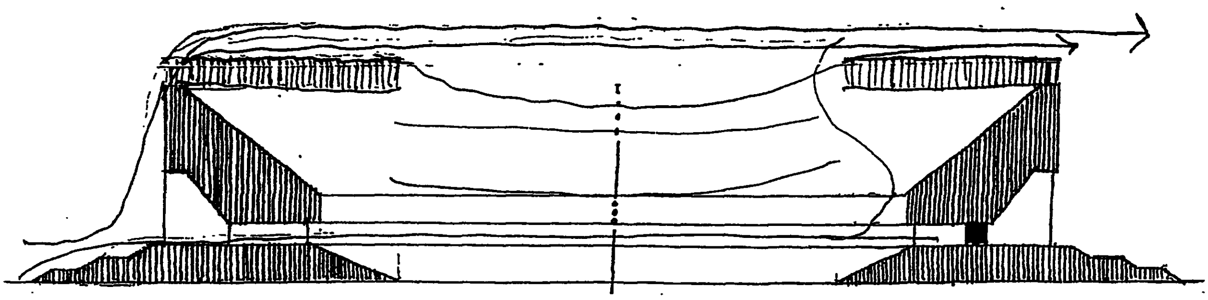
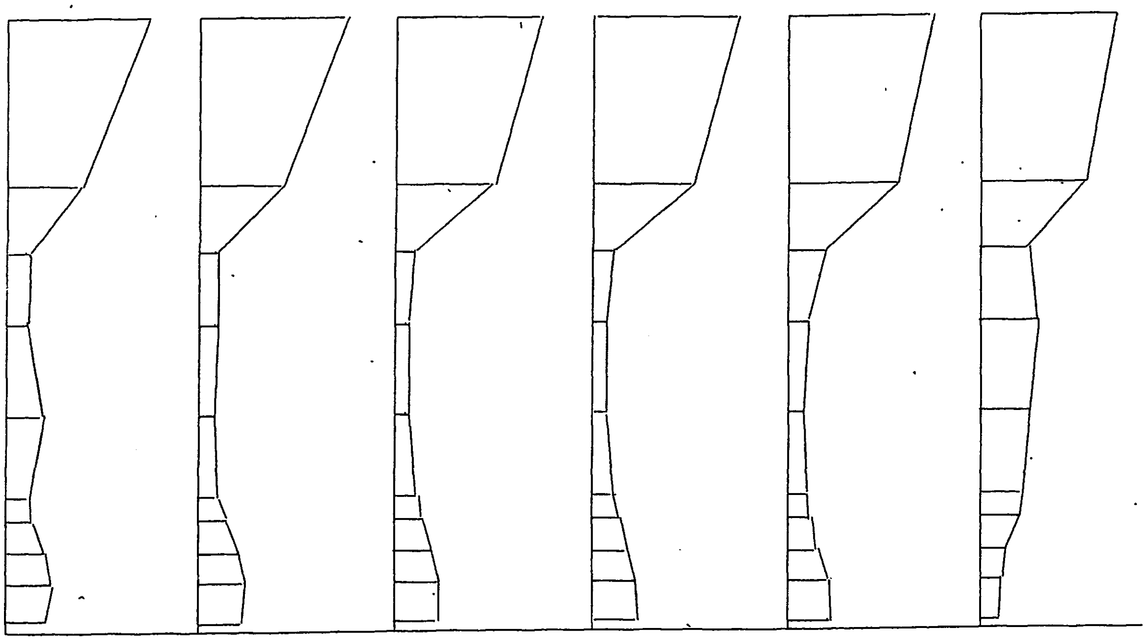


Fig. 7.6.0.13. Centrally Located Retractable Roof. Intake Closed. (C.L.R.I.C.)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.79	0.78	0.79	0.77	0.76	0.72
43	0.37	0.45	0.49	0.50	0.52	0.53
31	0.13	0.10	0.09	0.14	0.18	0.22
25	0.12	0.10	0.07	0.06	0.12	0.28
17	0.17	0.08	0.07	0.06	0.08	0.21
11	0.12	0.10	0.11	0.09	0.09	0.18
8.7	0.14	0.15	0.15	0.13	0.14	0.17
6.5	0.19	0.21	0.19	0.17	0.16	0.14
2	0.22	0.25	0.25	0.25	0.22	0.13
0.5	0.18	0.23	0.25	0.26	0.21	0.12

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Intake Closed.

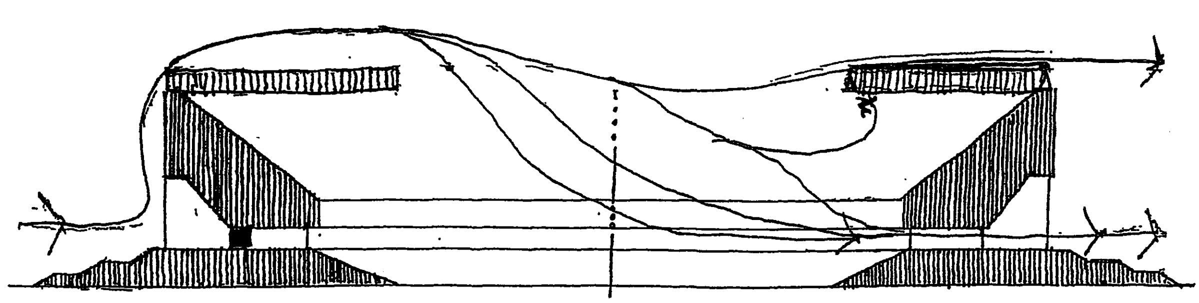
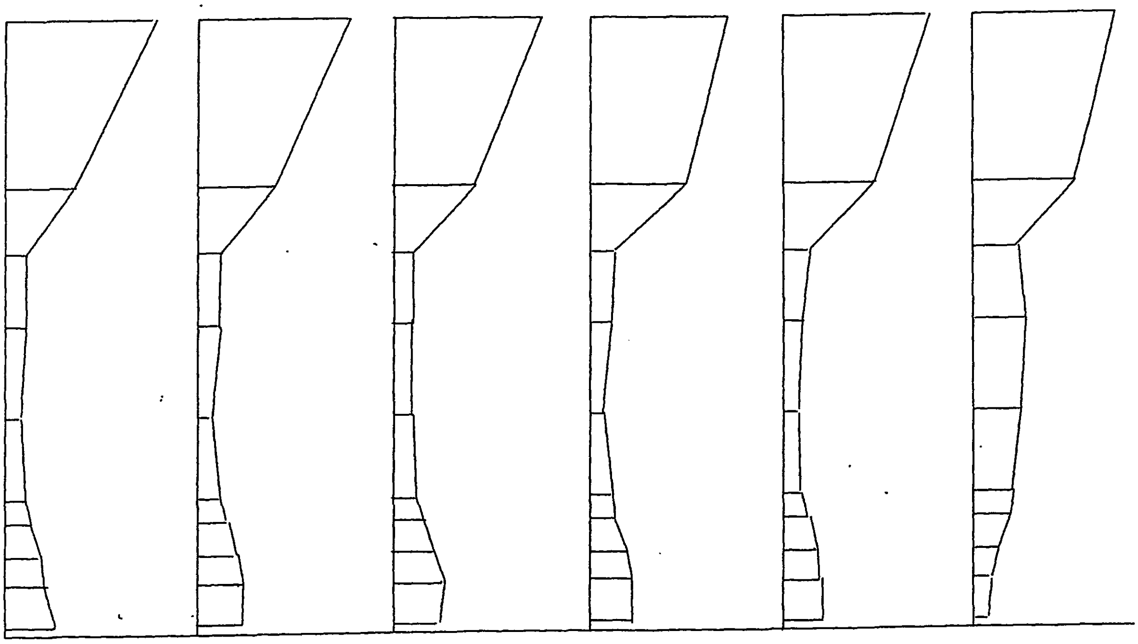


Fig. 7.6.0.14. Centrally Located Retractable Roof. Intake Extract Closed. (C.L.R.I.C.)

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.78	0.79	0.74	0.73	0.74	0.75
43	0.35	0.42	0.44	0.49	0.49	0.51
31	0.11	0.09	0.09	0.13	0.15	0.20
25	0.11	0.08	0.07	0.07	0.10	0.26
17	0.07	0.06	0.07	0.06	0.09	0.22
11	0.12	0.12	0.11	0.11	0.11	0.20
8.7	0.16	0.16	0.15	0.13	0.14	0.18
6.5	0.18	0.18	0.18	0.18	0.16	0.15
2	0.21	0.24	0.25	0.23	0.18	0.09
0.5	0.27	0.22	0.24	0.23	0.18	0.08

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse Intake Extract Closed.

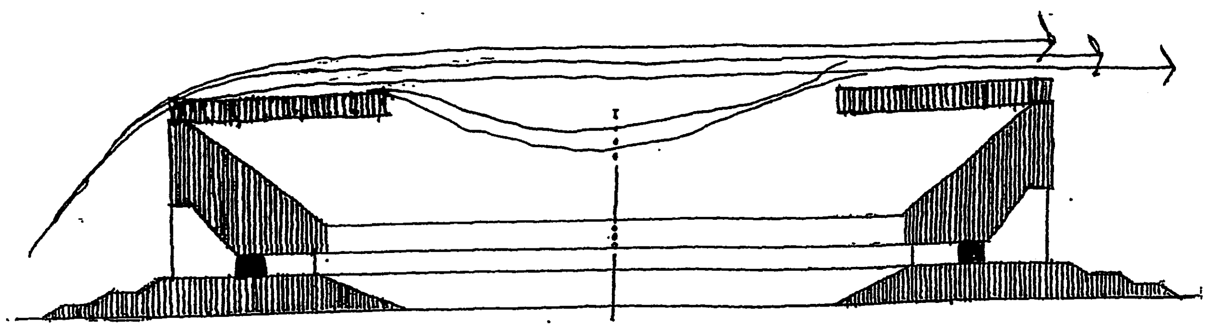
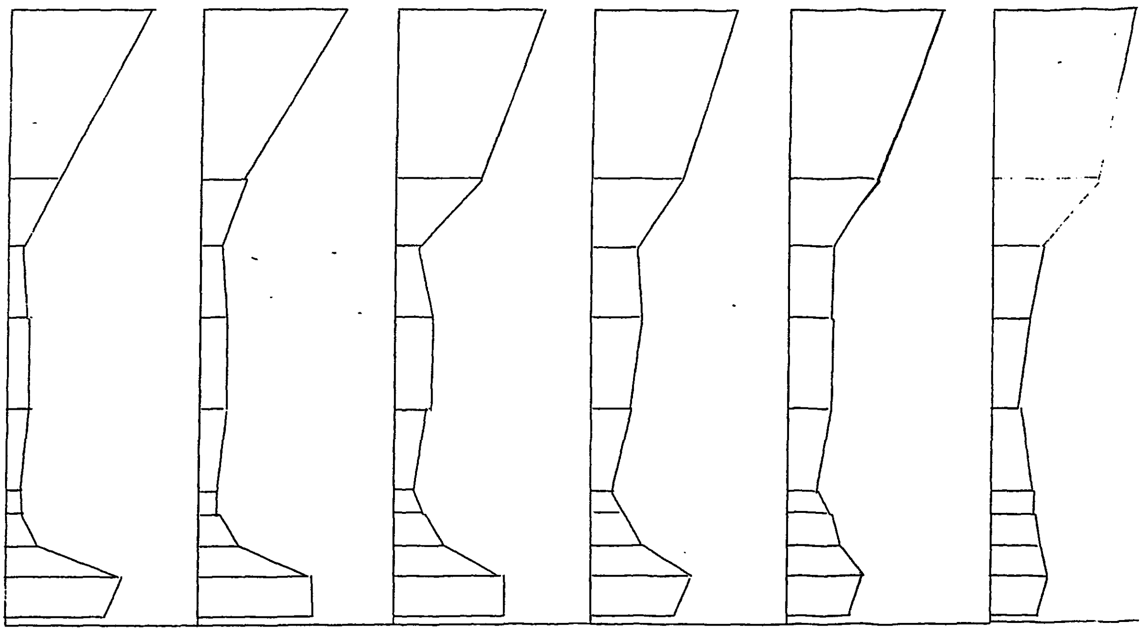


Fig. 7.6.0.15. Centrally Located Retractable Roof. Intake Extract Open. (C.L.R.I.F

Data Tabulated from Wind Tunnel Measurements.

	1a	1e	1i	1m	1q	1u
50	0.77	0.76	0.72	0.17	0.07	0.73
43	0.3	0.39	0.44	0.45	0.46	0.51
31	0.08	0.12	0.14	0.17	0.17	0.22
25	0.1	0.13	0.17	0.2	0.18	0.19
17	0.1	0.13	0.17	0.19	0.18	0.14
11	0.09	0.12	0.13	0.14	0.16	0.2
8.7	0.1	0.12	0.15	0.17	0.19	0.2
6.5	0.17	0.18	0.25	0.27	0.27	0.24
2	0.55	0.54	0.52	0.49	0.44	0.31
0.5	0.51	0.55	0.52	0.44	0.35	0.25

Wind Profiles prepared from Wind Tunnel Measurements



Cross Section Through Stadium. Concourse. Intake Extract Open.

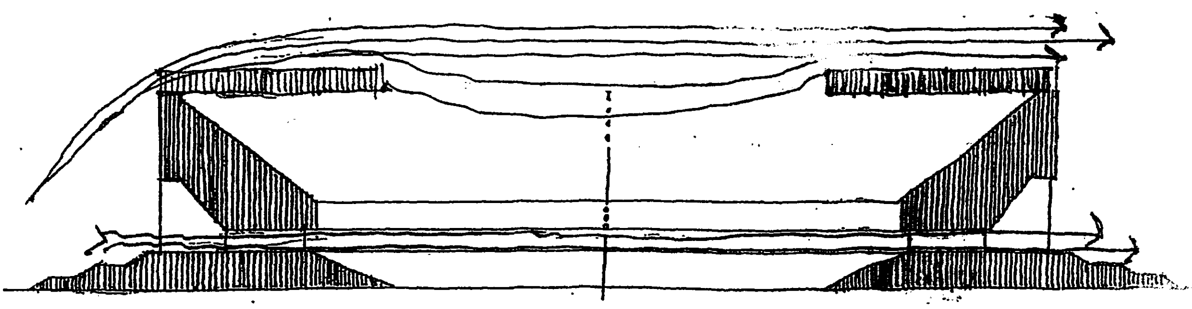


Fig no 7.6.0.16. Asymmetrical Retractable Roof. Extract Closed. Airflow Rates m/sec [-1]

Formula RS₁ 11.43	R/S.₁ x C.F. = R.S.₂ W.T.V./R.S.₂ = %/R. x W.S.₁ = W.S.₂						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.52	0.53	0.47	0.34	0.24	0.13
Wind Speed Measurements m/s	0.5	0.03	0.03	0.03	0.02	0.01	0.01
	1.0	0.06	0.06	0.05	0.04	0.03	0.01
	5.0	0.29	0.29	0.26	0.19	0.13	0.07
	10.0	0.57	0.58	0.52	0.37	0.26	0.14
	15.0	0.86	0.87	0.77	0.56	0.40	0.21

Asymmetrical Retractable Roof. Intake and Extract Open. Airflow Rates m/sec [-1]

Formula RS₁ 11.71	R/S.₁ x C.F. = R.S.₂ W.T.V./R.S.₂ = %/R. x W.S.₁ = W.S.₂						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m.		0.51	0.64	0.59	0.52	0.47	0.36
Wind Speed Measurements m/s	0.5	0.03	0.03	0.03	0.03	0.03	0.02
	1.0	0.05	0.07	0.06	0.06	0.05	0.04
	5.0	0.27	0.34	0.32	0.06	0.25	0.19
	10.0	0.55	0.68	0.63	0.56	0.50	0.39
	15.0	0.82	1.03	0.95	0.83	0.75	0.58

Asymmetrical Retractable Roof. Intake and Extract Closed. Airflow Rates m/sec [-1]

Formula RS₁ 11.31	R/S.₁ x C.F. = R.S.₂ W.T.V./R.S.₂ = %/R. x W.S.₁ = W.S.₂						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.21	0.29	0.30	0.31	0.26	0.14
Wind Speed Measurements m/s	0.5	0.01	0.02	0.02	0.02	0.01	0.01
	1.0	0.02	0.03	0.03	0.03	0.03	0.02
	5.0	0.12	0.16	0.17	0.17	0.14	0.08
	10.0	0.23	0.32	0.33	0.34	0.29	0.16
	15.0	0.35	0.48	0.50	0.52	0.43	0.23

Asymmetrical Retractable Roof. Extract Open. Airflow Rates m/sec [-1]

Formula RS₁ 11.70	R/S.₁ x C.F. = R.S.₂ W.T.V./R.S.₂ = %/R. x W.S.₁ = W.S.₂						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.20	0.31	0.34	0.34	0.31	0.14
Wind Speed Measurements m/s	0.5	0.01	0.02	0.02	0.02	0.02	0.01
	1.0	0.02	0.03	0.04	0.04	0.03	0.01
	5.0	0.11	0.17	0.18	0.18	0.17	0.07
	10.0	0.21	0.33	0.36	0.36	0.33	0.15
	15.0	0.32	0.50	0.55	0.55	0.50	0.22

R.S.₁ = Reference Wind Speed at 50 metres.
R.S.₂ = Reference Wind Speed at 10 metres.
C.F. = Power Law Conversion Factor.
W.T.V. = Wind Tunnel Velocity Measured at 0.5 metres.
%/R = Percentage Ratio Applied to W.T.V.
W.S.₁ = Wind Speed Measurement.
W.S.₂ = Actual Wind Speed m/5[1] at 0.5 metres. in Stadium

Fig. No. 7.6.0.17. Bi Parting Retractable Roof. Intake and Extract Open. **Airflow Rates m/sec $^{-1}$**

Formula RS$_1$ 11.1	**R/S.$_1$ x C.F. = R.S.$_2$ W.T.V./R.S.$_2$ = %/R. x W.S.$_1$ = W.S.$_2$**						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.56	0.56	0.49	0.38	0.26	0.14
Wind Speed Measurements m/s	0.5	0.03	0.03	0.03	0.02	0.01	0.01
	1.0	0.06	0.06	0.06	0.04	0.03	0.02
	5.0	0.32	0.32	0.28	0.21	0.15	0.08
	10.0	0.63	0.63	0.55	0.43	0.29	0.16
	15.0	0.95	0.95	0.83	0.64	0.44	0.24

Bi-Parting Retractable Roof. Intake Closed. **Airflow Rates m/sec $^{-1}$**

Formula RS$_1$ 10.9	**R/S.$_1$ x C.F. = R.S.$_2$ W.T.V./R.S.$_2$ = %/R. x W.S.$_1$ = W.S.$_2$**						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.10	0.13	0.19	0.19	0.20	0.20
Wind Speed Measurements m/s	0.5	0.01	0.01	0.10	0.01	0.01	0.01
	1.0	0.01	0.01	0.02	0.01	0.02	0.02
	5.0	0.06	0.07	0.11	0.11	0.11	0.11
	10.0	0.11	0.15	0.22	0.22	0.23	0.23
	15.0	0.17	0.22	0.33	0.33	0.34	0.34

Bi-Parting Retractable Roof. Extract Closed. **Airflow Rates m/sec $^{-1}$**

Formula RS$_1$ 10.9	**R/S.$_1$ x C.F. = R.S.$_2$ W.T.V./R.S.$_2$ = %/R. x W.S.$_1$ = W.S.$_2$**						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.53	0.53	0.47	0.35	0.18	0.09
Wind Speed Measurements m/s	0.5	0.03	0.03	0.03	0.02	0.01	0.01
	1.0	0.06	0.06	0.05	0.04	0.02	0.01
	5.0	0.30	0.30	0.27	0.20	0.10	0.05
	10.0	0.55	0.61	0.54	0.40	0.21	0.10
	15.0	0.91	0.91	0.81	0.60	0.31	0.16

Bi-Parting Retractable Roof. Intake and Extract Closed. **Airflow Rates m/sec $^{-1}$**

Formula RS$_1$ 11.2	**R/S.$_1$ x C.F. = R.S.$_2$ W.T.V./R.S.$_2$ = %/R. x W.S.$_1$ = W.S.$_2$**						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.10	0.13	0.19	0.19	0.20	0.20
Wind Speed Measurements m/s	0.5	0.01	0.01	0.01	0.01	0.01	0.01
	1.0	0.01	0.01	0.02	0.02	0.02	0.02
	5.0	0.06	0.07	0.11	0.11	0.11	0.11
	10.0	0.11	0.15	0.21	0.21	0.22	0.22
	15.0	0.17	0.22	0.32	0.32	0.34	0.34

R.S.$_1$ = Reference Wind Speed at 50 metres.
R.S.$_2$ = Reference Wind Speed at 10 metres.
C.F. = Power Law Conversion Factor.
W.T.V. = Wind Tunnel Velocity Measured at 0.5 metres.
%/R = Percentage Ratio Applied to W.T.V.
W.S.$_1$ = Wind Speed Measurement.
W.S.$_2$ = Actual Wind Speed m/5^1 at 0.5 metres. in Stadium

Fig. No. 7.6.0.18. Centrally Located Retractable Roof. Extract Closed. Airflow Rates m/sec $^{-1}$

Formula	R/S.$_1$ x C.F. = R.S.$_2$ W.T.V./R.S.$_2$ = %/R. x W.S.$_1$ = W.S.$_2$						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.17	0.22	0.24	0.23	0.18	0.08
Wind Speed Measurements m/s	0.5	0.01	0.01	0.01	0.01	0.01	0.00
	1.0	0.02	0.02	0.03	0.02	0.02	0.01
	5.0	0.09	0.12	0.13	0.01	0.10	0.04
	10.0	0.18	0.23	0.25	0.24	0.19	0.08
	15.0	0.27	0.35	0.38	0.23	0.29	0.13

Centrally Located Retractable Roof. Intake Closed. Airflow Rates m/sec $^{-1}$

Formula	R/S.$_1$ x C.F. = R.S.$_2$ W.T.V./R.S.$_2$ = %/R. x W.S.$_1$ = W.S.$_2$						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.18	0.23	0.25	0.26	0.21	0.12
Wind Speed Measurements m/s	0.5	0.01	0.01	0.01	0.01	0.01	0.01
	1.0	0.02	0.02	0.03	0.03	0.02	0.01
	5.0	0.09	0.12	0.13	0.14	0.11	0.06
	10.0	0.19	0.24	0.26	0.27	0.22	0.13
	15.0	0.28	0.36	0.39	0.41	0.33	0.19

Centrally Located Retractable Roof. Intake and Extract Closed. Airflow Rates m/sec $^{-1}$

Formula	R/S.$_1$ x C.F. = R.S.$_2$ W.T.V./R.S.$_2$ = %/R. x W.S.$_1$ = W.S.$_2$						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.27	0.22	0.24	0.23	0.18	0.08
Wind Speed Measurements m/s	0.5	0.01	0.01	0.01	0.01	0.01	0.00
	1.0	0.03	0.02	0.03	0.02	0.02	0.01
	5.0	0.14	0.11	0.13	0.12	0.00	0.04
	10.0	0.28	0.23	0.25	0.24	0.19	0.08
	15.0	0.42	0.34	0.38	0.36	0.28	0.13

Centrally Located Retractable Roof. Intake and Extract Open. Airflow Rates m/sec $^{-1}$

Formula	R/S.$_1$ x C.F. = R.S.$_2$ W.T.V./R.S.$_2$ = %/R. x W.S.$_1$ = W.S.$_2$						
Grid Lines		1a	1e	1i	1m	1q	1u
Wind Tunnel Reading at .05m		0.51	0.55	0.52	0.44	0.35	0.25
Wind Speed Measurements m/s	0.5	0.03	0.03	0.03	0.02	0.02	0.01
	1.0	0.05	0.06	0.05	0.05	0.04	0.03
	5.0	0.27	0.29	0.27	0.23	0.18	0.13
	10.0	0.53	0.57	0.54	0.46	0.37	0.26
	15.0	0.80	0.86	0.81	0.69	0.55	0.39

R.S.$_1$ = Reference Wind Speed at 50 metres.
R.S.$_2$ = Reference Wind Speed at 10 metres.
C.F. = Power Law Conversion Factor.
W.T.V. = Wind Tunnel Velocity Measured at 0.5 metres.
%/R = Percentage Ratio Applied to W.T.V.
W.S.$_1$ = Wind Speed Measurement.
W.S.$_2$ = Actual Wind Speed m/5^1 at 0.5 metres. in Stadium

The content of **Part Seven** had three purposes:

1) To describe the experimental equipment.

2) To describe the experiments.

3} To record the experimental data in the form of Tables, Graphs and Figures.

These experiments determined the extent of the influence the tested roof configurations had on the growth and maintenance of in situ turfgrass, in the environment produced by those conditions. The following factors were considered during the tests:

1) The extent of Sunshine and Shadow falling on a playing surface.

2) The availability of Photosynthetic Active Irradiance.

3) The extent of the air movement over a modelled playing surface.

The consequences of the experiments relating to Sunshine and Shadow define the extent of the direct beam availability for Photosynthetic irradiance on the areas of turfgrass. The more shadow there is on a turfgrass area, then the less will be the value of PAR on that area. The values of PAR and those of Air Movement can be seen from Tables, Graphs and Figures. The Hourly Irradiance values are set out in Tables 7.3.5.1-7.3.5.5; those values for Sunshine and Shadow are recorded in Tables 7.4.1.1-7.4.1.7; those for Air Movement in Figs7.6.0.4- 7.6.0,18.

The values for Hourly Irradiance and Air Movement should be set against the standards considered acceptable by the Turfgrass Industry. These standards sustain turfgrass in a reasonable condition in the long term. These standards are expressed as follows:

A daily minimum total of photosynthetic active irradiance of three MJm $^{-2}$ day^{-1} at pitch level throughout the year.[10]

Horizontal airflow at the minimum rate of 0.2 m s^{-1} immediately above canopy level is required over all parts of the playing field at all times of the year. Horizontal airflow

[10] Information produced by IGER in an unpublished Report relating to the Millennium Stadium. IGER 1997

INDEX. PART EIGHT.

CHAPTER ONE.

8.1.0. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS.
8.1.1. **Discussion.**
8.1.1.1 **Introduction.**
8.1.2. **Initial Approach.**

CHAPTER TWO.

8.2.0. ALTERNATIVE TURFGRASS ARRANGEMENTS.
8.2.1. **Single Turfgrass Pallet.**
8.2.2. **Multi-Pallet Arrangement.**
8.2.3. **Replacement by Returfing.**

CHAPTER THREE.

8.3.0. INFLUENCE OF THE RETRACTABLE ROOF ON TURFGRASS MAINTENANCE.
8.3.1. **Influence of the Retractable Roof on Stadium Use.**
8.3.2. **Sunshine and Shade.**
8.3.3. **Hourly Irradiance**

CHAPTER FOUR.

8.4.0. THE INFLUENCE OF AIR MOVEMENT.
8.4.1. **Appraisal of Wind Tunnel Experiments.**

CHAPTER FIVE.

8.5.0. Final Appraisal.
8.5.1. **Dosage Requirements for Turfgrass Irradiance and Airflow.**
8.5.2. **Conditions Beneath a Retractable Roof.**
8.5.3. **Other Ways of Maintaining Turfgrass in Stadia**

CHAPTER SIX.

8.6.0. Conclusions.

CHAPTER SEVEN.

8.7.0. Recommendations.

PART EIGHT.

CHAPTER ONE.

8.1.0. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS.

8.1.1. Discussion.

8.1.1.1. Introduction

The work began on this thesis sometime after the publicity surrounding the failure of the in situ playing surface of the Ajax ArenA, Amsterdam, Netherlands; it ends at a point where the turfgrass at the Millennium Stadium, Cardiff, Wales UK is receiving wide publicity for the same reasons. Both stadia are similar, in that they have retractable roofs, in situ turfgrass playing pitches and are designated as multi-use stadia. **Case Studies 9.4.5 and 9.4.6** provide some detail about their turfgrass failures. But both these large compact stadia are generally classed as successful venues for spectators. In this study large means stadia with spectator capacities of 50,000 and above.

The turfgrass failures in Ajax ArenA, Amsterdam, have been recurring since1996 and in the Millennium Stadium, Cardiff since 1999. Both dates coincide with the respective opening of each stadium.

The questions that must be asked are these. Can a stadium be classified as successful if its playing surface is adjudged to have failed? What constitutes a failed surface? What are the reasons for these failures?

The discussion will then extend to consider available solutions to the problem of turfgrass failures and whether these solutions have advantages and disadvantages in serving the primary function of a stadium and that of its display surface.

8.1.2. Initial Appraisal.

When a large stadium served only a single use, usually it displayed one of the several games of football. It was then a simpler process to define what constituted a successful playing surface, because those standards had to meet the sole requirements of a particular game.

Adams and Gibbs suggest that

> These surfaces would have at least three general factors which should be considered in relation to the performance criteria of natural turf winter games pitches, particularly those

used for soccer. These are: 1). Firmness of the surface influencing grip/traction and ball bounce. 2). Evenness of surface affecting the run of the ball. 3). Percentage grass cover.[1]

The factors considered in the Adams and Gibbs reported criteria for a successful playing surface remain valid for the ball games played in a multi-use stadium. But to meet the requirements of such stadia considered in this thesis, the number and range of those requirements needed for an acceptable playing surface must be expanded. The extended criteria have to meet the needs of those events which impose abnormal biological stresses on a turfgrass surface, which in most cases turfgrass plants are unable to withstand. Therefore, in such circumstances, to meet the Adams and Gibbs requirements, extensive restoration work or turfgrass in situ replacement has to be undertaken to maintain or restore the playing surface. Alternatively, turfgrass can be safeguarded by removing it from a stadium and replacing it with an artificial surface. The natural turfgrass surface can be brought back into a stadium when an artificial surface is no longer required. The methods of turfgrass removal and replacement are considered in some detail in **Part Six-Chapters Two, Three and Four.**

The last of these factors considered by Adams and Gibbs, that of percentage grass cover is an important visual consideration, now more than previously because of the influence television has on broadcasting surface defects. High density turfgrass cover also provides a cushioning effect for players when the surface is being used for the games of football. The higher the percentage figure will be for grass cover, the more the playing surface will be stabilised. This factor is relevant to all soils but especially those rootzones that are sand dominated, which may usually be the case in large compact stadia.

Playing surfaces that are uneven through the emergence of divots and surface tearing can adversely influence a player's skill through poor ball roll and uneven bounce. These factors diminish a player's ability to demonstrate ball control. Uneven surfaces may also influence the result of a game.

These surface defects should receive restoration treatment at the earliest time. The affected areas should be allowed time to recover before the surface is used again. Turfgrass tears and divots are usually the consequence of the speed of play, by players turning and twisting on the turfgrass and by players missing the object of a physical tackle which is to make contact with the ball. When such failure occurs the consequence is that players slide on the turfgrass and tear

[1] Adams W. Gibbs R .Natural Turf for Sport and Amenity :Science and Practice, CAB International, Wallingford, UK, 1994, Page 216.

the surface. Footwear is designed to impart a grip between the player and the surface. The studs facilitate grip but leave many surface indentations on the turfgrass surface. These indentations are the consequence of the simple act of running in a straight line but add to the damage inflicted by divots and tears. All indentations add to surface compaction. These factors are supported by conversations held with a number of respected Groundsmen with Association Football Clubs.

Turfgrass wear of the type described will occur even when environmental conditions are favourable to turfgrass. Wear occurs as the consequence of imposing uses on turfgrasses which differ from the historic and traditional pasture and landscape uses. Even in these categories, wear will be observed if turfgrasses are abused by overuse and there are insufficient periods of rest from those activities that cause wear.

It might be concluded from that that the absence of wear allows turfgrass to be maintained. That would be so, only if environmental conditions were beneficial to turfgrass growth. Beneficial conditions are those that allow the photosynthetic process to take place efficiently. Those conditions are the supply of carbon dioxide, water, light energy, glucose and oxygen. Where the photosynthetic process is retarded, the structure of the root and leaf of the plant will be weak and the consequence of surface wear will be even greater.

The problems of failed turfgrass usually occur in multi-use stadia with retractable roofs and with natural non-removable in situ playing surfaces. Other large compact stadia can display the same conditions. The reasons are usually poor environments and overuse. Many of the uses are inappropriate for turfgrass. Currently, the solution to these failures has been returfing as many as five times a year. The need to repeat turfing confirms that it is in principle not a long term solution.

Can these two significant stadia the Ajax ArenA and the Millennium Stadium, so dependent on returfing to provide an adequate playing surface, be classed as successful?

The problem they both demonstrate is that they have disregarded the historic requirements of a multi-use stadium. These requirements are a flexible display surface and a cavea that can be modified in form and size. If these are the criteria for a successful multi-use stadium, neither can be classed as successful because they provide none of these things. Although the Millennium Stadium has attempted to provide a flexible arena surface, that arrangement is only partially successful because that flexibility is not achieved with an economic simplicity.

But historically, no previous multi-use stadium had an in situ turfgrass arena and used that surface for some events as though the surface was inert. No previous multi-use stadium had to provide environmental conditions suitable for the maintenance of its arena surface. Both these stadia have used their surfaces with a disregard for the maintenance of turfgrass, demonstrating in doing so an understandable commercial bias. They have also both failed to provide optimum environmental conditions for in situ turfgrass within their environments.

Perhaps both stadia looked backwards at the commercial multi-use model of the then successful Harris Dome. However, this modern large multi-use stadium only became a success by default, a circumstance which allowed the stadium to provide a flexible display surface and a cavea that could be modified in form and size, thus including the elements which made up the traditional needs of a multi-use venue. The scale of this stadium had not been seen since the Roman Colosseum AD 80. Neither of these European stadia provide these basic elements. The Millennium Stadium could in principle change its playing surface but not with the simplicity and efficiency necessary to demonstrate commercial success.

The consequence was that both stadia overuse their playing surfaces, inappropriately causing subsequent turfgrass failures. The failures are ameliorated by returfing their surfaces wholly or partly. This technique has become both an acceptable and established remedial practice. The question must therefore be asked whether this technique can circumvent the need for the research carried out in this thesis and also whether the complex pitch removal methods discussed in this work are necessary. The frequency of replacing the turf depends on the extent to which the playing surface is used, the type of use and the environmental conditions in a stadium.

This makes clear the point that where a multi-use stadium displays football it should be provided with separate surfaces, hard and soft surfaces which should be rapidly interchangeable. The in situ turfgrass can then be released from the poor environment of a stadium to benefit from the influence of open conditions. The playing surface will then not only produce good playing conditions, it will also look healthy by producing the colour its cultivars were bred to produce.

CHAPTER TWO.

8.2.0. ALTERNATIVE TURFGRASS ARRANGEMENTS.

8.2.1. Single Turfgrass Pallet.

Influential in the European search for stadia was the discovery of the Vitesse Stadium, Arnhem, Netherlands. It is smaller than the other two European stadia mentioned but it incorporated a unique feature: it allowed the removal of the whole playing area from the stadium in a single pallet. In certain circumstances this arrangement could be applied to large stadia. **Case Studies 9.4.7 and 9.4.8** provide two methods of achieving this form of removal. This arrangement can allow a stadium to have a fixed roof and an in situ playing surface.

The single pallet solution frees the developer from problems of maintaining turfgrass in stadia environments, but introduces a different set of problems. These problems include increased initial costs, more complex site selection and the structural consequences of passing a pallet beneath a grandstand. The structural consequences may be significant enough to consider an alternative way of achieving the same objective. Ways of achieving the same objective are as follows:

1) Increase the number of pallets from one to six. This decreases the width of the structural opening beneath the grandstand. This arrangement can only be successful if the pallet design allows their upstands to discreetly lock together.

2) Follow the method used at the Sapporo Dome, Japan. This arrangement separates the grandstand from the main structure, thereby allowing the grandstand to move away from the pathway of the pitch, allowing it to pass through an opening in the wall rather than beneath the grandstand as the pitch has to do at Arnhem.

3) Adopt a multi-pallet system as used at the Millennium Stadium.

A perceived difficulty with any pallet removal by mechanical means is the concern that a mechanism might fail at the point of its need. To counter this, pallets are moved well in advance of the time they are required to be moved.

Because a single pallet contains a one-piece full size playing field it can more easily provide conventional irrigation, drainage, under soil heating (where used) and be treated horticulturally as can any other in situ turfgrass playing surface. The one-piece turfgrass surface allows treatment for compaction stress by mechanical means

.

The single pallet requires field research to appraise the opportunities that may exist in developing the potential of draining vertically at frequent intervals through the base of the pallet. The aim of this would be to investigate the possibility of producing a more efficient strategy than the current reliance on horizontal main drainage lines with lateral connections. Draining through the base of the pallet in multiple positions may provide the same opportunities for vertical drainage as exists in draining large flat roofs.

8.2.2. Multi-Pallet Arrangement.

This arrangement provides the same facility as the single pallet but does it less effectively and efficiently. It also brings problems in site selection but the choice of location for the 'turfgrass parking site' need not be contiguous with the stadium, provided there is a recognition that the further from a stadium that site is, the less economic will be the costs of exchanging surfaces.

The Millennium Stadium multi-pallet system may be considered a long-term failure as a means of maintaining turfgrass. The system was based on a similar pallet arrangement at the Giants Stadium, New York, USA. The Giants Stadium is an open stadium; the heat energy values are higher there than those values reaching the playing surface of the Millennium Stadium. The research for this Thesis has shown that the heat energy levels between the open stadium and the centrally located retractable roof exhibit the greatest contrast.

The probability was that the decision to use the multi-pallet arrangement at the Millennium Stadium was weighted towards its potential in providing a dual surface. There appears to have been no recognition that environments produced by the two stadia were a complete contrast. For the turfgrass to survive in the Millennium Stadium the pallets would have to be frequently removed from the stadium for environmental reasons: whereas the pallets in the Giants Stadium could stay in position until they were required to be removed, to accommodate an event requiring a non-turfgrass surface.

Whatever the long term consequences were of using multi-pallets, the short-term advantages were greatly beneficial. Their inclusion allowed the stadium to be completed on time and additionally provided the opportunity to use the stadium for events prior to the official opening.

There are over 7000 pallets used at the Millennium Stadium **(Case Study 9.4.6)** compared with 194 at the Pontiac Stadium, Michigan, USA **(Case Study 9.4.3)** and 1 pallet at the Geldredome Arnhem, Netherlands.**(Case Study 9.4.7)** The Pontiac experiment can be discounted because the pallets there were never intended for long-term use.

8.2.3. Replacement by Returfing.

In adopting returfing as a means of pitch renewal there are a number of factors which have to be taken into account. These are as follows :

1) The rootzone of the incoming turf must be compatible with the host rootzone.
2) The new turfgrass should not be used for at least 14 days to allow the rootzones to bond.
3) Continuity of the canopy mix is needed to ensure wear and colour properties are maintained.
4) The turfgrass must be in a fresh condition before planting.

These conditions can be met, and increasingly returfing has become a readily accepted option, providing an acceptable turfgrass playing surface over short periods of time. This strategy frees designers of stadia from having to consider ways of increasing light energy and air movement levels on and over their playing surfaces. An advantage turfing has is that parts of a playing field can be restored where wear has caused a difficulty in play.

It has been demonstrated at the enclosed Pontiac Stadium (1994) that turfgrass can be sustained for 30 days in a low lighting environment. The signs of senescence would take longer to emerge in the environment produced by a centrally located retractable roof than it would have taken in the enclosed Pontiac Stadium. Turfgrass senescence is inevitable but its presence is more pronounced in restricted environments because shoot renewal is both slower and weaker.

Returfing should perhaps not become an accepted option for providing in situ playing surfaces where new stadia are being considered. However, in some circumstances there may be no other option. This work has clearly inferred that non-removable in situ turfgrass is an inappropriate surface for a multi-use stadium. But in situ turfgrass is an essential surface in European stadia where the games of football are played. It is this stipulation that presents the stadia developer with a dilemma in judging the scale of the investment, what that investment ought to deliver for the benefit of the spectator, and the flexibility of the arena surface.

CHAPTER THREE.

8.3.0. INFLUENCE OF THE RETRACTABLE ROOF ON TURFGRASS MAINTENANCE.

The early retractable roofs were perhaps loosely associated with horticultural greenhouses. The method of retraction took the form of bi-parting integral sections of a greenhouse wall and roof. The purpose of retracting the roof was to passively modify the internal climate of a greenhouse.

Despite this possible horticultural association with retracting sections of buildings, there is no positive evidence to link using the retractable roofs in order to aid the biological requirements of turfgrass in stadia.

The Architect of the Toronto SkyDome, Canada in 1989, by the inclusion of the provision for dual surfaces, did recognise there was an issue regarding playing surfaces in stadia. But there are two reasons why a stadium may require dual surfaces.

1) To satisfy display needs.
2) In situ turfgrass cannot be maintained within a multi-use stadium environment without it being removed from that environment from time to time.

The probable reason for providing a roof which led to such complexity was almost certainly architectural: the site on which the Stadium stands has an urban significance. If the intention was simply to maximise the roof opening, that could have been achieved in a more direct manner. **(Fig 7.3.5.2)** The probable reason for providing dual surfaces was to satisfy display needs.

When open, the roof provided a free area of approximately 90% when compared with the same cavea without a roof. This degree of openness is obviously not possible with a centrally located retractable roof, the free opening of which on the test model is less than 23% of the free area on the roofless model. **(See Fig 7.3.5.4.)**

Judging from the research on the test models in this work, sufficient light energy should be available with that degree of free area to sustain turfgrass in the SkyDome. However, other factors such as latitude, superstructure height and the relationship of a roof in its opened parked position will have an influence on the increase or decrease in the direct light and diffuse light values falling on the arena surface.

The designer of the Toronto SkyDome suggested that European architects "got it wrong" by including centrally located retractable roofs in their stadia designs. This part of the discussion analyses whether or not they did get it wrong.

The centrally located roof configurations record lower levels of light energy falling on the stadium playing surface than any of the other roof configurations measured in this work. The less light energy reaching the playing surface, the more deleterious the effect will be on turfgrass wear..

Other configurations tested are certainly more sympathetic towards turfgrass maintenance. But are they as convenient for management and spectators as is the centrally located retractable roof? When the centrally located retractable roof is open, the opening will in most cases reflect the size of the playing surface below it. The light energy performance of this configuration may not be greatly dissimilar from that of a compact stadium with a high standard of weather protection. Where differences occur in this respect, it is usually because the structure associated with a centrally located roof is heavier and consequently the height of the stadium is increased.

The wholly bi-parting roof can offer in principle the same light energy performance as the roofless stadium. But it has the advantage of allowing a stadium to become enclosed. The fact that the roof is bi-parting indicates that there can be degrees of opening. However, when a stadium is being used, the roof will either be wholly open or wholly closed. Any other option would disadvantage a proportion of spectators and a game of football would be played in a changing environment, which would not be allowed. Consideration of the asymmetrical configuration will arrive at the same conclusions. The centrally located roof can remain open when an event takes place and this may be considered for some events an advantage. The advantage the centrally located roof has in a multi-use stadium is that the fixed sections of the roof can be more easily set up for mechanical services to control the environment.

If consideration is given to turf removal techniques it might be concluded that European architects have not got it wrong in including the centrally located retractable roof option. If turfgrass removal in a single pallet is adopted, the European architects have certainly not got it wrong.

8.3.1. Influence of the Retractable Roof on Stadium Use.

The Harris Dome led to a sea change in stadia development. Stadia were no longer principally composed of a cavea; they could become places of safety, comfort and resort. What is perhaps not always remembered is that these differences were founded on the introduction of the artificial surface. Because of this, stadia could be enclosed and air-conditioned. Capacity was limited only by economics and the consideration that there was a requirement to ensure that spectators with 20/20 eyesight could see a spectacle in visual comfort. Viewing distances affording this comfort will differ for different displays.

In Europe artificial surfaces were not accepted as playing surfaces for the major games of football. This makes European stadia essentially different from their north American counterparts.

In contrast, the tradition was that the games of football (baseball in the USA) were played on in situ natural turfgrass, before large crowds in the open air, mostly without weather protection. It appeared that spectators, almost anywhere, were willing to watch these games in adverse weather. Stadia were used generally for only one type of game and then used only seasonally. This form of use allowed a playing surface to remain unused until the following season's games. This arrangement afforded natural turfgrass long recovery periods at times advantageous to turfgrass recovery.

These periods of inactivity led to depleted cash flow situations, which in most cases in the UK led to ever-increasing rates of deterioration in stadia. The American example of stadia development was different: they increased investment in modern stadia, but in doing so, they used them more intensively. They could do this more easily where artificial surfaces were incorporated.

The technical success of the roof of the Toronto SkyDome, 1989 allowed the retractable roof to play a future role in stadia development. The reaction to the loss of control of the building costs of that stadium and the part the roof played in those costs, established a degree of financial caution towards the incorporation of retractable roofs in European stadia.

Nevertheless, the lessons of the Harris Dome and those of the Toronto SkyDome led European developers to consider stadia as places of entertainment on a broader scale, rather than simply places to display the games of football. The retractable roof became a part of that extended formula where multi-use stadia were being developed.

The inclusion of the retractable roof had three consequences.

1) It increased capital building costs over those of conventional stadia.
2) It generated the need to use a stadium as much as possible.
3) It increased turfgrass wear.

The evidence from Ajax ArenA, Amsterdam and The Millennium Stadium, Cardiff is that both fail to maintain in situ turfgrass. They incorporate centrally located retractable roofs but with different opening strategies and surface finishes. Both stadia also have different methods of rootzone containment and have different programmes of activity. These variables make comparisons between the turfgrass surfaces not possible, but it is clear their playing surfaces fail and fail consistently.

A comparison is made between the roof finishes of the Amsterdam Arena and those of the Millennium Stadium. The Millennium Stadium has an opaque roof, with the exception of relatively small triangular sections, set in each of its corners. Ajax ArenA has a wholly transparent roof except for the insertion of a continuous opaque strip set between the junction of the wall and roof. The reason for the inclusion of this opaque strip was the anticipation that the close proximity of the transparent surface with spectators would cause them heat stress when the transparent surface was subjected to sunshine. The opaque roof was included in the Millennium Stadium to save costs; the transparent triangles were incorporated to provide a minimal background lighting when the roof was closed and the stadium unoccupied.

This comparison emphasises that irrespective of the degree of transparency incorporated into these two roofs, both record turfgrass failures. The measurements recorded *(unpublished)* at Ajax ArenA by Dr Jeroen van Arendonk, an independent turfgrass scientist from De Haag Netherlands, and the measurements recorded by IGER (unpublished) at the Millennium Stadium, indicate that the turfgrass requirements for the receipt of light were not met in some areas of either stadium.

That evidence confirms the turfgrass failure in both stadia. The assumption in both locations is that a deficiency in the receipt of natural light has caused the failure. However, this thesis suggests that a reduction in lighting, although significantly influential, is not the only debilitating factor affecting turfgrass performance. Many other factors are involved in the success or failure of turfgrass maintenance. These are considered in **Parts Three to Seven.** It is not readily possible to appraise the comparative influence the reduction in lighting or the other factors impose on the turfgrass in each stadium. This is because whilst these influences are similar in principle in the effects they impose on the turfgrass, the differences in the form and detail in each stadium may alter the way these differing factors influence turfgrass maintenance. The differences between these stadia can be considered by referring to **Case Studies 9.4.5 & 9.4.6.**

The experiments recorded in **Part Seven** are designed to measure the factors of Shade, Light and Wind on various roof configurations set over a constant cavea and isolate those measurements from those other contributory factors which affect turfgrass growth but cannot be measured by the adopted modelling process. Both sets of factors can (under certain conditions and values) make a positive or negative contribution to turfgrass maintenance; the range of these factors is set out in **1.2.0.6.**

By separating Shade, Light and Wind from the other influences this allows an assessment to be made of the influence the shape and form of a roof may have on turfgrass growth, independent of those other influential factors.

The data relating to the influence of the varying roof forms are recorded in **Part Seven.** This data is analysed separately in this section under headings of **Sunshine and Shade, Hourly Irradiance and Air Movement.**

8.3.2. Sunshine and Shade.

The varying retractable roofs are ranked below in order of the extent to which they allow shadow free areas on the playing surfaces beneath them. These assessments are measured against the standard set by the roofless stadium **(R.1)** and are as follows:

1) **The Bi-Parting Roof. (R.2).** This roof fails to admit sunlight in January. The reason for this is that the structure adopted to span the stadium is of a depth that excludes the entry of sunlight into the stadium.

2) **The Asymmetrical Roofs. (R.3)** There is a variation between the aspects of these roofs which favours that of the North East orientation. The data points to the need to experiment with adjusting the orientation of this model to determine the advantages in respect of reducing the extent of turfgrass shading.

3) **Centrally Located Retractable Roof with Lattice Construction. (R.6)**
This roof arrangement includes the retractable section which is glazed as is the adjacent area. The arrangement confirms that transparency does reduce the extent of the shaded area in a stadium.

4) **Centrally Located Retractable Roof with Opaque Surfaces. (R.4)**
The moving part of this roof type may or may not be transparently glazed. The moving part of the roof must be open to allow full penetration of sunlight on the turfgrass. The advantage of glazing the moving roof section is that it increases the lighting levels when the roof is closed. The assessment is that an increase in the lighting level is of no significant value to turfgrass maintenance, but can be an advantage to the overall environment of the stadium.

8.3.3. Hourly Irradiance.

The varying retractable roofs together with those roof options tested which do not include retractable elements are ranked in order of the percentage light available reaching the playing surface when measured against the standards set by the roofless stadium **(R.1).**

One. The Bi-Parting option. **(R.2)** The level of light entering this arrangement may be increased by refining the structure, reducing its depth. The probability is that a lighter structural solution could be achieved by introducing arched beams. The outcome of this approach might be to increase the extent of the shadow areas and also reduce the availability of light to the turfgrass. It would be necessary to test this option to confirm this assumption.

Two. Roof (R.9). This option provides weather protection for a limited number of spectators; **R.1** provides none. This comparison confirms the deduction that the greater the extent of natural light on the playing surface, the lower will be the extent of spectator weather protection.

Three. Roof (R.3). Two aspects of the asymmetrical retractable roof were considered to assess the influence of turfgrass shadow; only one version was tested for lighting levels. This was because it was considered that the values would be superior on the western aspect arrangement.

Four. Roof (R.8). This arrangement dispenses with the retractable roof, thereby allowing the influence the retractable roof has on the light levels on the turfgrass to be measured. The inference of this test was that the lighter and shallower the structure of the moving roof would reflect in more light falling on the playing surface.

Five. Roof (R.6). This arrangement shows the retractable roof withdrawn and nestling over part of the adjacent glazed areas. The arrangement of the overlapping glazing reduces further the penetration of light on the playing surface.

Six. Roof (R.7). This arrangement shows the glazed roof and the glazed moving roof in the closed position.

Seven. Roof (R.5). This arrangement shows the marginal advantage of the shallower construction which is 20% shallower than the deep construction.

Eight. Roof (R.6). This arrangement shows the marginal disadvantage of a deep construction.

The way in which a retractable roof affects turfgrass maintenance is but one factor amongst a number which influences the operational requirements of a successful stadium. The concept of a modern stadium in the UK is that it must have healthy turfgrass and high standards of spectator weather protection. The research in this thesis has highlighted the inevitable conflict between these parameters.

Some of the Case Studies demonstrate these conflicts and the methods so far adopted to overcome them. The thesis has also recorded the opinion of some commentators that the extent of weather protection exceeds the standards that many spectators would be prepared to accept. This may be a viable argument for Association Football. But the stadium considered in this thesis has to display many events, other than Association Football, where extensive weather protection is a necessity.

This study began with the intuitive understanding that installing a centrally located retractable roof in a multi-use stadium was unsuitable for maintaining turfgrass. It ends by confirming that understanding. But a view has been formed through this study that a centrally located roof may have advantages for a stadium, if other options for incorporating in situ turfgrass are adopted. One advantage it has is its comparatively simple form of opening and closing mechanism when compared with the complexity of some North American examples of retraction methods.

An open roof of this central configuration provides a high standard of spectator weather protection and allows an event to be viewed in a more balanced natural light when the roof is open. Under some circumstances it is necessary to provide either artificial or natural lighting to the rear of spectator areas.

However, the experience of the user of such stadia is that when a roof is open, spectators have to be able to see the sky to enjoy the overall benefits provided by an open roof. Because of this it is advantageous to maximise the roof glazing.

If the inclusion of transparent finishes do not substantially aid the maintenance of turfgrass, what is the economic reason for their being used? This is especially when the chemical composition of the plastic material used for glazing will be subjected over time to the loss of transparency. This reduction will be further increased by the build up of atmospheric pollution which will vary in intensity from site to site. Therefore the decision to glaze a roof should be accompanied by the decision to include roof cleaning equipment.

An advantage a glazed roof has is that it will provide softer contrasts between those areas that are subjected to light and shade than the contrasts provided when there are opaque surfaces surrounding an open roof. Such sharp contrasts can be difficult for both players and television cameras.

A complete bi-parting system, on the other hand, provides a roof that can be made to be one hundred per cent completely open. This means that when the stadium is not in use its turfgrass can receive the same environmental benefits for turfgrasses provided by a roofless stadium. The Asymmetrical roof provides a lower percentage of those benefits than those provided by the Bi-parting roof.

Part of the argument against the Bi-parting and Asymmetrical roofs has already been made and centred on the probability that these roofs will have to be fully opened or closed. There are however, other arguments which relate to their use in hot climates where the range of temperatures are thus far not found in the UK.

In extreme conditions of heat the spectator requires protection from sunshine rather than from rain. The implications of climate, orientation, spectator capacity and use must be a part of the holistic thought process of appraising the needs of stadia design. The advantages these more open roof configurations have is that, on the basis of a 60,000 capacity stadium, they will allow turfgrass to be maintained, if the use of the turfgrass is restricted to appropriate patterns of use. The limitation of the height of a superstructure is an important factor in allowing the entry of light into a stadium. Height and spectator viewing distances and the arena perimeter are an integral part of determining the spectator capacity of a stadium and clearly spectator capacity has an absolute relationship to the height of a superstructure.

If a stadium includes a pitch removal system, turfgrass can be removed from it when it is not needed. Therefore the need for an environment suitable to sustain the photosynthetic process is no longer such a rigorous objective. Stadia can be built with or without a retractable roof. The advantage the retractable roof offers is the choice to partly provide outdoor conditions within a stadium. While the centrally located retractable roof is the least environmentally advantageous roof configuration, if the turfgrass is removed from the cavea, that disadvantage no longer matters, and a case can be made out that, that form of roof has advantages for the management of a stadium.

In practice, in Europe, the only options so far considered for sustaining turfgrass in stadia with retractable roofs are its removal or replacement of surfaces by returfing. Up to the year 2000 other forms of retractable roof configurations in large stadia had not been considered as a practical option.

If other options were to emerge, the probability will most likely remain that the roof will either be used for the games of football in the open or closed position. But openings that provide areas in excess of 70% free to sky ratio will enable turfgrass to be maintained when the cavea is not being used. This will be so when the height of a stadium superstructure is considered as one of the determining considerations in the maintenance of turfgrass.

A difficulty arises when the aim will be to use a stadium to its full commercial potential. The inference from the evidence of existing stadia is that the arena will be used for commercial gain, irrespective of the appropriateness of an event for an arena surface. This is also true of stadia without retractable roofs where football clubs are prepared to re-lay a playing surface in light of the financial advantage derived from a pop concert.

All methods of providing retractable roofs have the same advantage: when closed they reduce noise breakout from a stadium. This by inference intensifies the atmosphere within the cavea. The greatest flexibility in use will be achieved by providing an opaque retractable roof. It also has the following advantages over a glazed roof:

1) it maximises control over noise breakout.
2) the fixed part of the upper surface of the roof may be developed as an energy source.
3) the underside of both the fixed and moving roof can be acoustically developed.
4) the temperature of a cavea can be influenced by thermally adjusting the construction of the opaque roof covering.

The retractable roof has generally appeared in European stadia, (with one exception) where the aim has been to display multi-use activities. Except where turfgrass has been able to be removed from a stadium in a single pallet, stadia with movable roofs have developed turfgrass failures.

There is sufficient evidence, set out in the Case Studies, to argue that natural turfgrass is not a suitable surface for many multi-use activities. This is emphasised by those displays that require a surface to be covered for long periods; where activities transfer loads to the turfgrass surface that cause heavy surface compaction. Turfgrass surfaces often make reconfiguration difficult.

It is also evident that commercial pressures on stadia, irrespective of whether or not they include a retractable roof, will take precedence over the wellbeing of the turfgrass.

Not to accept these conclusions is to argue also against the fact that persistent wear will eventually overcome turfgrass growth. This can be the case even in the most advantageous environmental conditions.

CHAPTER FOUR.

8.4.0. INFLUENCE OF AIR MOVEMENT.

Air movement across a turfgrass canopy is but one of the contributory factors for the needs of turfgrass survival. The background study indicates that air movement is one of the factors which control the opening and closing of the stomata guard cells which are mostly sited in the turfgrass leaves.

The study investigated measures to ensure that natural air movement occurred across the turfgrass playing surface. The continuous opening through which air passed was formed by the separation between the upper superstructure and the concourse walkway. The cross section in **Fig 7.6.0.4** illustrates the position of the opening which is set at a minimum dimension of 3.5 metres. This opening allows airflow over the turfgrass which was never measured as excessive for the needs of turfgrass.

The control of airflow is essential, as the deleterious consequences to turfgrass of too much wind are the same as too little wind. Research work is required to determine the possibility of introducing airflow across turfgrass surfaces by mechanical means. A crude way of achieving this is by the use of surface fans. The problem with this simple arrangement is their management. The fans need to be distributed so that the face velocity across the fans is not too fast for the turfgrass immediately in the vicinity of the fan.

Airflow rates can also affect stadium spectators and also the flight of a ball used during a game. In the British climate the continuous opening which provided the conduit for the airflow would be disadvantageous to the comfort of those spectators sitting below the concourse level on the model used for this study. The wind tunnel studies suggest that like general airflow diagrams, wind speed increases with height and this principle is demonstrated by the airflow diagrams shown in **Part Seven.**

To alleviate spectator discomfort the concourse opening would on some occasions have to be closed when airflow levels were high and the cavea was in use. However, consideration should also be given to the fact that for long periods the cavea remains unoccupied, allowing advantageous airflow benefits to the turfgrass.

An alternative approach to provide airflow over the turfgrass would be to employ mechanical means. This strategy should not take the form of randomly placed individual fans, as these require careful management to achieve a balanced result. The approach should rather be to use a below ground arrangement feeding into a grid of pop-up fans distributed over the playing surface. This arrangement should be researched to consider the benefits not only in contributing to stomata control but also to ascertain if such an arrangement could assist the means of drying turfgrass and aiding frost protection.

8.4.1. Appraisal of the Wind Tunnel Experiments.

Chapter Six Part Seven describes the equipment and the methodology used to determine the wind tunnel airflow measurements. Differences between the models are defined by varying the roofing configurations and by opening or closing the space between the underside of the elevated superstructure and the upper surface of the surrounding concourse. The data from these varying combinations are shown in the form of Wind Diagrams. **Figs 7.6.0.4 -7.6.0.15.** The information from the Wind Diagrams is then converted into airflow rates in m/sec^{-1} by applying the Power Law Theory. **Figs 7.6.0.16-7.6.0.18.**

The diagrams and table listed under the above figures are divided into three groups of four roof configurations and are divided into the following categories:
The asymmetrical roof.
The bi-parting roof and the roofless stadium.
The centrally located retractable roof.

Because of the 'slice' principle of measuring airflow, the bi-parting roof and the roofless stadium were measured on the same model. Within these three categories there are four combinations of controlling the air intake and air extraction between the underside of the superstructure and the upper surface of the concourse.

The Airflow data in m/s^{-1} collected at 0.5 metres from the turfgrass canopy extracted from **figs 7.6.0.16.to 7.6.0.18** have been analysed in the following way:

Intake and Extract Open.

Asymmetrical Roof.	0.03. 0.03. 0.03. 0.03. 0.03. 0.02.
Bi-Parting & Roofless.	0.03. 0.03...0.03. 0.02. 0.01. 0.01.
Centrally Located Roof.	0.03. 0.03. 0.03. 0.02. 0.02. 0.01.

Intake and Extract Closed.

Asymmetrical Roof.	0.01. 0.02. 0.02. 0.02. 0.01. 0.01.
Bi-Parting & Roofless.	0.01. 0.01. 0.01. 0.01. 0.01. 0.01.
Centrally Located Roof.	0.01. 0.01. 0.01. 0.01. 0.01. 0.00

Intake Open and Extract Closed.

Asymmetrical Roof.	0.01. 0.02. 0.02. 0.02. 0.02. 0.01.
Bi-Parting & Roofless.	0.03. 0.03. 0.03. 0.02. 0.01. 0.01.
Centrally Located Roof.	0.01. 0.01. 0.01. 0.01. 0.01. 0.00.

Intake Closed and Extract Open.

Asymmetrical Roof.	0.01. 0.02. 0.02. 0.02. 0.02. 0.01.
Bi-Parting & Roofless.	0.01. 0.01. 0.01. 0.01. 0.01. 0.01.
Centrally Located Roof.	0.01. 0.01. 0.01. 0.01. 0.01. 0.01

From this analysis it will be concluded that the type of roof within this range of experiments is not of significance in determining the airflow rates. What does influence the air movement is the controlling of the intake and extract positions. The airflow rates are not as high as anticipated. The theory for this may be that the airflow is impeded by the depth and form of the funnel, through which the wind has to travel before reaching the turfgrass. This is one reason why it has been suggested that consideration should be given to simplifying the form of the underside of the superstructure by limiting the ancillary accommodation normally reserved for that position in most stadia designs.

CHAPTER FIVE.

8.5.0. The Final Appraisal

As previously stated this study began with the intuitive understanding that it was not possible to maintain turfgrass in a Multi-Use Stadium with a retractable roof in the UK. It also began with a bias against installing centrally located retractable roofs. It ends by developing a view that a centrally located roof may have advantages for stadia, if other options for incorporating turfgrass are adopted.

It also began by asking the question: if a centrally located roof is transparent as opposed to being opaque would that assist turfgrass maintenance? Yes, it would. But the increase in irradiance values in the experiments indicate that at certain times of the year, the differences between the readings are insufficient to maintain turfgrass, over certain areas of a playing surface.

A general statement is often made that natural in situ turfgrass will not grow in multi-use stadia. Visits to large stadia have indicated that in some areas of stadia, turfgrass can be maintained at certain times of the year to an acceptable playing standard. But in other areas it will not be maintained to that standard. In those areas of failure there is usually environmental deprivation, the influences of which are often reinforced by heavy turfgrass wear. Where turfgrass failure is more widespread, the probability is that the playing surface has been the subject of hostile uses and additionally, the drainage and rootzone systems are unable to provide a healthy subsoil environment.

The complete range of the photographic visual assessment of shade can be seen in **Figs 9.6.2-9.6.7.** A limited number of these images are illustrated to a larger scale in **Figs 7.4.1.5-7.4.1.12.** The information contained within the images are translated into **Tables 7.4.1.1-7.4.1.12** and **Graphs** in **Figs 7.4.1-7.4.7.** The irradiation patterns produced by the experiments can be accessed by referencing **Tables 7.3.5.1 to 7.3.5.5.**

8.5.1. Dosage Requirements For Turfgrass Irradiance and Airflow.

The following are the dosage rates of irradiation and airflow for maintaining healthy turfgrass.
A daily minimum total of photosynthetic active irradiance of three M Jm^{-2} day^{-1} at pitch level throughout the year is required to sustain turfgrass in reasonable condition in the long term.

Horizontal airflow at the minimum rate of 0.2 m s^{-1} immediately above canopy level is required over all parts of the playing field and at all times of the year.

Horizontal airflow should not continuously exceed 5m s^{-1} at canopy level for more than 24 hours, without a 48 hour recovery.

8.5.2. Conditions Beneath a Retractable Roof.

The discussion in this thesis has inevitably centred around the two European examples of large stadia with in situ turfgrass and centrally located retractable roofs. The centrally located roof is the current European response to the moving roof. It represents in its simplicity of movement the counter to the complexity of the North American examples of roof retraction.

The environmental conditions prevailing in the Millennium Stadium and the Amsterdam ArenA will in principle follow the pattern of the conditions recorded in those model experiments relating to the centrally located retractable roof. They relate 1) to a roof in the open position with its surrounding area opaque (comparable with the Millennium Stadium) and 2) the retractable roof in the open position with the adjacent areas glazed over the lattice construction. (comparable with Amsterdam ArenA). However, in the model the residual glazed area represents 38% of the total free roof area of **(R.1). Fig 7.3.5.4 and Fig 7.3.5.6.** The former has an opaque roof, the latter is extensively glazed.

The cost of plastic double glazing may be two to three times the cost of some opaque surfaces. The introduction of glazing with its accompanying environmental advantages, confirmed in principle by the experiments, produced reduced areas of shadow and higher levels of irradiation over a greater turfgrass area when compared with those results from an opaque roof. Despite these benefits, there may be only a small advantage to turfgrass in glazing a roof.

This assumption however, may be an incorrect one to draw, if the basis for this assumption is taken from the performance of the turfgrass at the Millennium Stadium when compared with failures at the Amsterdam ArenA. It is necessary to take into account a range of other factors which may influence the turfgrass performance in these stadia. For example, the turfgrass under glazed conditions may improve both its vitality and appearance but the improvements may be insufficient to avoid turfgrass failure. However, the reduction in shade and the increase in irradiance values may allow turfgrass replacements to take place at longer intervals than would be the case under an opaque roof. This would be so if the playing surface in each stadium is subjected to the same conditions of wear.

8.5.3. Other Ways of Maintaining Turfgrass in Stadia.

There are other ways of maintaining turfgrass in a stadium such as its temporary removal or its turfgrass replacement. These ways have been described in **Part Six**. The availability of these options may be crucial in deciding whether or not to install a retractable roof. Or if one is installed, is it to be finished with an opaque or a glazed surface?

The decision to remove turfgrass from a stadium is one that is fundamental to the strategy of stadium planning. The view taken at the end of the study is that the multi-pallet system in its present state of development may not be used again as a complete solution. It may be used in small areas in a stadium where wear is a persistent problem. However, groundsmen usually adopt the returfing method as an adequate method of surface replacement. It is possible to returf during a hiatus between fixtures during a playing season.

Pitch removal as a management tool, has proven to be successful judging from correspondence between the Stadium Manager and the Writer. The initial difficulty has centred around structural problems in passing the playing pitch under the stadium and also in the method of physically moving the pitch. Case Studies 9.4.7 and 9.4.8 deal with both these issues.

Pitch removal may also be another factor which can impose limits on the size of stadia. For this reason research is needed to address the problem of examining the problems of marginally increasing the number of pallets as was proposed for the abandoned Luton Town Stadium, Luton ,UK.

The costs of the single pallet technique have to be appraised against returfing costs. These can occur on an annual basis. The costs for each complete turfgrass replacement can be between £80,000 and £100,000 based on the year 2000 costs. These costs considered against the use of the playing surface over a number of events may be insignificant, when there may be little or no competition to stage events. Even if the cost of returfing became significant, there may be no alternative but to returf to provide a satisfactory natural in situ turfgrass surface, a surface which has also to be telegenic. It will, however, be a surface not suitable for Multi-use activities. The single pallet system will provide in theory, a consistently good playing surface, capable of easy configuration so essential to the needs of an arena used for Multi-Use activities.

An advantage of the turfgrass removal systems is that they can shorten a site's contractual programme in two respects: 1) divorce the turfgrass from the ongoing building programme which allows the contractor essential space for the fabrication process and 2) it allows the turfgrass to establish itself.

A decision may be taken to accept the situation that returfing is a viable option to maintain a playing surface for the games of football. The question then to be asked relates to the continuity of supply and to seek to experiment with the turfgrass species to improve its longevity performance. A view may be taken outside the turfgrass industry that the turfgrass plant is indestructible. It is not, but it does have the characteristic of renewing itself. Part Three discusses some of the issues concerning turfgrass culture.

An assumption may also be made that Artificial Turf is everlasting. It is not; but it is certainly more durable that Natural Turfgrass. Both surfaces require treatment and replacement after use but Natural Turfgrass requires more treatment and replacement at more frequent intervals.

The replacement or removal of turfgrass from a stadium may bring into question the need to collect environmental data. However, environmental data remains an essential tool in understanding the microclimate in and around the stadium. The data collected will help to determine turfgrass species, cultivars, rootzone composition, horticultural treatment and rates of irrigation.

These, and other matters, draw attention to the new complexity of stadium design. A stadium in this study is a building type composed of two principal elements: seating and the turfgrass playing area. It is no longer an open air building with a turfgrass playing field surrounded by seating, some of which is protected from the weather by a cantilevered roof.

The question to be asked is: is this complexity absolutely necessary? Has the search for comfort, which began with the absolute necessity for establishing safety, gone too far. Stadia have to be put to the maximum use and when they are the cavea still remains unused for long periods. It is not the aim of this thesis to discuss stadium economics, but it does point to **Chapters 9,12 and 13 The Stadium and the City** [2] for a preliminary insight into the reality of the economics in high profile stadia.

The lessons of the Olympic Movement should be learnt. We must provide stadia suitable for the events which they display. The discerning spectator will want eventually to add ambience to

[2] Bale & Moen Edts, The Stadium and the City Keele University Press Keele Staffordshire, 1995

those recently gained benefits of comfort, amenity and safety. A large stadium cannot provide ambience for the range of events that are being forced into the large cavea volume.

The inappropriate activities carried out on turfgrass are forcing the need to cover turfgrass. This will not allow the essential requirement of light and air to reach the turfgrass in an environment already reduced by the intervention of the superstructure. The cover, despite having some advantages, if left in position for long periods, about 15 days, will weaken or even destroy the turfgrass.

Ways are being sought to introduce the use of artificial light to supplement reduced levels of natural light but they remain principally as discussions. There are reports that in the north of England experiments are being used to carry out researching the use of supplementary lighting rigs under stadia conditions.

However, it may be significant that Philips Electrical, the original main sponsor for the Amsterdam ArenA, has not used this form of remedial action on the turfgrass of that Stadium. They also would not engage in the discussion requested during the course of this study, to exchange ideas on the application of artificial lighting for the maintenance of turfgrass.

Extensive studies on the use of artificial light on plant growth have been carried out by the Institute of Grassland and Environmental Research Institute, Aberystwyth, Wales UK. IGER confirm that supplementary light can provide a solution applicable to sports turfgrass. However, the problem is perhaps not related to the acceptance of the science, but rather with its application in stadia conditions. The lamps have to be as near to the turf as is practical to achieve an economic distribution of light energy. The problem of the acceptance of this method of turfgrass maintenance is probably not one of cost, but rather of setting up a rig, which can traverse the playing area in sections and in a way which will still facilitate a horticultural programme and also the commercial use of a stadium.

IGER suggest *et al* that Metal Halide Lamps, mercury lamps with selected metallic halides added, to give virtually continuous emission spectra from 350-750 nm could be used for turfgrass maintenance. These would be efficient but the spectral quality of the light may change with age because of the differential condensation of the metal halides. Metal halide lamps used alone may be suitable, although there is some evidence that they are better mixed with high pressure sodium lamps.

These innovations involving moving roofs, pitch removal methods, turfgrass covers and the possibility of supplementary artificial light are all symptoms of forcing uses into stadia for which they were not designed. The cost of these innovations has pushed the costs into ever increasing spirals. It was necessary to reform the form of stadia in the UK. The consequences of these often over elaborate standards are such that in certain stadia, the working class sport organised in the second half of the19th Century is being lost to corporate bodies.

At the present time the use of turfgrass is essential to display the games of football in Europe. We have seen through this study that failures through inadequate environments and hostile use are inevitable. Some methods of overcoming these factors have been discussed. That discussion has focussed on the playing area. It would, however, be productive to concentrate research on two issues 1) that the cavea is only occasionally used and 2) the roof is not required at all times. This thinking leads to the issue that the cavea could be opened at all times when not in use. This understanding is not the same thinking that produces the fully bi-parting roof **fig 7.3.5.2** which would be centred on bridge construction. But it is a thought process that turns back to the study of the Roman Colossuem where temporary awnings were erected when required.

It is essential to understand that turfgrass is not an entirely suitable surface for a multi-use stadium with absolute standards of weather protection. But it is entirely suitable if a pitch removal system is incorporated in such stadia. Alternatively, an artificial surface will provide a smooth, true surface but unsuitable at present for the games of football

.

CHAPTER SIX.

8.6.0. CONCLUSIONS.

This theoretical and experimental study considers the essential requirements needed to maintain in situ natural turfgrass in a multi-use compact stadium with a retractable roof in the United Kingdom. The study finds that in a large compact cavea, for in situ turfgrass playing surfaces to be maintained in optimum playing conditions, they require prescribed doses of heat, light and air movement. Turfgrass also requires the application of high standards of horticultural treatment based on the results of the research of turfgrass science. Even with the application of these essential requirements, turfgrass cannot be maintained, if subjected to uses that are inappropriate for the healthy structure of the plant or to any use which may be classed as continuous. Sufficient periods of rest are necessary for turfgrass maintenance between any uses.

The study concludes that maintaining turfgrass in a large compact multi-use stadium is a complex matter, the satisfactory solution of which requires more than the receipt by the turfgrass of the environmental factors of heat energy and air movement. The factor which appears unappreciated by those who manage stadia commercially is that the equally vital requirement is to rest it from use.

The methodology used in this study for the measurement of the values of Sunshine and Shaded areas and Airflow rates is to assume that the stadium is set in an open country position with the latitude set for Cardiff UK. But quantifiable differences in measured results would occur through differing site classifications, changing latitudes, differing day lengths, varying temperature values, cloud cover, precipitation rates and wind speed variations. Those influences will produce differing results which may be reflected in the choice of turfgrass species, cultivars and horticultural regimes.

To establish data for individual stadium sites, it is essential to build both physical and computer models of those sites. The models should reflect the topography and urban fabric of an area in which a stadium may be sited

A site on which a stadium is located may be surrounded with obstructions; the height, density and layout of the obstructions may intervene between the climate and the mass of the stadium: thus a surrounding microclimate may develop. This may have a modifying influence on the conditions within a stadium, which in itself will be large enough to develop its own internal microclimate. This climate will be influenced by the size of the superstructure, the way it is configured and by its height and the type of retractable roof used. The size and form of the superstructure will be one of the factors which will influence the capacity of a stadium. Spectator capacity will influence the microclimate by increasing both the temperature and air-borne carbon dioxide.

These factors will influence turfgrass behaviour. The increase in temperature and probable decrease in air movement will increase the rates of transpiration and evapotranspiration, thereby influencing horticultural regimes and the frequency and rates of irrigation.

The effective way of reducing the complexities of turfgrass maintenance in what may be considered as hostile conditions in multi-use stadia is to remove the turfgrass when it is not required. Removal obviates the need to consider the provision of an environment suitable for in situ turfgrass. The arrangement also allows the inclusion of an artificial surface and a stadium with either a fixed or retractable roof.

Clearly, forms of roof retraction other than those of the centrally located type produce more light energy falling on greater areas of a playing surface and for longer periods. Regardless of those benefits, this study concludes that the other forms of roof retraction tested may produce in adverse weather, poorer comfort standards for spectators. This is because with their roof configurations it may be necessary for them to be set only in the open or closed position. However, a centrally located retractable roof can remain in the open position during adverse weather conditions and in doing so, allow the majority of spectators to remain protected during adverse weather.

In situ natural turfgrass, which is not removable, is in general terms an unsuitable surface for a multi-use stadium on two counts. 1) it fails to maintain turfgrass areas and 2) it fails to provide the degree of commercial flexibility that such stadia require.

If there is no alternative to an in turfgrass surface, that surface has to be protected by some means. There are limitations in the time during which turfgrass surfaces can be covered without affecting turfgrass plants. After being covered, the plants require long time periods for recovery. Also, in the conditions of fixed in situ turfgrass surfaces, events programmes should be limited in range to those events that are similar in character and similar in the type of wear they impose.

However, commercial pressures are such that the likelihood of imposing such a restricted regime in large multi-use stadia is probably rare. Therefore, the most advantageous remedial action is to returf a playing surface. The frequency of that operation should be dependent on the environmental conditions, frequency and the type of use to which the surface is subjected.

The study argues that the performance of the multi-use pallet system used at the Millennium Stadium, Cardiff is unsatisfactory. It is not that a multi-pallet system is wrong in principle. If there is no other way to remove turfgrass from a stadium, the high costs involved in removing and reinstating the pallets have to be accepted. But the pallets appear to fail in providing satisfactory pallet drainage which may be a factor in poor turfgrass performance. The consequence of turfgrass compaction may be a contributory factor to this problem. It is unlikely that this system, on this scale, will be used again without long term field research being undertaken.

The study also notes that stadium costs have escalated by increasing the complexity of stadia design, including those design facilities that extend beyond the essential requirements of comfort and safety. The retractable roof and movable pitches are high cost provisions, which may be acceptable in national and some geographically distributed regional centres but are not required as a general accompaniment to all new build stadia. The increase in costs of complex stadia has led to the need to increase the use of stadia and consequently turfgrass wear is increased to levels that require turfgrass to be frequently replaced.

This study has demonstrated that one way of providing airflow across a playing surface was to lift the base of a stadium superstructure to allow air to pass beneath it. That approach provides innovative design possibilities but is also accompanied by perceived difficulties. These difficulties relate to spectator comfort when air has to pass directly over spectators in order that the air can reach the playing surface. It is also important to ensure that any means of closing down the flow of air does not interfere with spectator movement and means of escape. An alternative approach would be to supply air from a number of mechanically served pop-up outlets distributed over the playing surface. These fans could be concealed below individual turfgrass pallets.

The study suggests that the design of a stadium should be considered as two separate parts. The first part includes those features that can be considered as being permanently occupied and the second part is the cavea which attracts only occasional use. The latter part should be designed so that it can provide an open environment when it is not being occupied in order to help turfgrass maintenance. It is on the occasions when the cavea is not occupied that the benefits of raising the stadium would be an advantage.

This study also notes that more attention should be paid to turfgrass drainage. Taking into account the capital costs of stadia, the amount spent on turfgrass drainage is insignificant and the results are often inadequate in the long term. Research is required to determine the longevity of the efficiency of turfgrass traditional drainage.

Consideration should be given to the opportunities provided by the single pallet arrangement to determine a strategy for turfgrass drainage. This strategy need not rely on the traditional horizontal drainage runs. The single pallet concept can allow consideration of a vertical concept of field drainage, which is not a dissimilar approach to that of draining a flat roof building. Because the pallet is always separated from the floor that supports it, it is possible to connect the drain outlets by flexible tube connections. This also has the advantage that one can judge the efficiency of the drainage system.

CHAPTER SEVEN.

8.7.0. Recommendations.

Prior to commissioning a stadium there should be an initial strategic feasibility study. This study should be founded on a client statement setting out how the stadium will be used.

On commissioning a stadium environmentalists must be allowed sufficient time to gather data appropriate to turfgrass maintenance.

Sufficient time also must be allowed to enable data to be considered and evaluated at a time when it can influence a stadium design.

Stadia design teams should include at the outset turfgrass specialists as full members of those teams.

A distinction should be made between the qualities of Horticultural Contractors and Turfgrass Scientists and proper evaluations of their contributions must be made prior to appointments being made.

Specialists must be allowed time to bring their essential scientific and horticultural disciplines to bear on matters directly related to turfgrass and on other elements of that stadium that may exert an influence on turfgrass maintenance.

The turfgrass specialists team should have a single leader able to manage the integration of the broad issues of turfgrass management within the general contractual framework. He or she should also be able to evaluate the long term implications of accepting or rejecting recommendations made by turfgrass specialists.

It is recommended where in situ turfgrass playing surfaces are included that initial decisions are immediate concerning whether the surface is to be provided by turfing or seeding. This decision is influential in determining the period of the main contractor's construction programme.

When a playing field is established during the contractual period of a building programme, the grass area must be isolated from the remainder of the building site, except for the purposes of maintenance by a specialist contractor.

Where practical, where the games of football are played in a large multi-use stadium, an ideal arrangement is for the in situ turfgrass to be removed from that stadium at other times.

Further research is recommended in assessing if it is possible to consider other options to that of the single pallet arrangement to reduce the problems of passing the single pallet outside a stadium.

Research is recommended to consider other ways of passing airflow over turfgrass other than by passive means. Other methods of passing air over the turfgrass may allow greater design opportunities.

Where returfing has become an accepted turfgrass replacement method, it must be understood that for the arrangement to be satisfactory the rootzone of the donor turf must be compatible with the composition of the receiving rootzone.

Sufficient time must be allowed for the turfgrass roots to bind with the receiving rootzone. This may be a minimum period of 14 days. Specialist advice should be sought for different locations.

When turfgrass in a stadium is not required for immediate use, the turfgrass cut level should not be less than 50mm or exceed 75 mm. When a surface is used for Association Football the turfgrass cut level should be not less than 25mm. The turfgrass cut level for the games of Rugby Football should not be less than 40 mm. Upon the completion of these games, the grass leaves should be allowed to recover to a light interception length of not less than 50mm or more than 75 mm.

Any retractable roof system should remain open as much as it is practical so to do. This will ensure air exchange between the inside and outside of a stadium. The consequences of this will be to maintain adequate fluxes of water vapour and carbon dioxide.

Consideration should be given to not installing undersoil heating in stadia with in situ turfgrass in multi-use stadia with a retractable roof. It ought to be possible to anticipate conditions on a falling thermometer and to control the climate within a stadium by closing the roof and tempering its air.

Research should be undertaken to establish whether maintaining a controlled temperature of a rootzone will enhance turfgrass growth and development.

Where turfgrass can be removed from a stadium, other precautions should be taken to prevent the turfgrass from being frozen. This may take the form of covered tents with an intake of warm air.

Research should be carried out into the effects of covering turfgrass for varying periods of time. In the meantime where turfgrass is protected by a covering, upon its removal the turfgrass should be allowed to remain unused except for horticultural treatment for at least 10 days for every five days the turfgrass was covered. Turfgrass should not be covered for more than 15 consecutive days without understanding the consequences of doing so.

Research is required into the development of artificial surfaces which could provide the same playing advantages as natural turfgrass.

There is little apparent perception outside the turfgrass industry that turfgrass is a living plant. As such it requires careful treatment and in addition, essential periods of rest to recover from uses that are hostile to its maintenance.

A daily minimum total of photosynthetic active irradiance of three $MJm^{-2}\ day^{-1}$ at pitch level throughout the year, is required to sustain turfgrass in reasonable condition in the long term.

Horizontal airflow at the minimum rate of $0.2\ m\ s^{-1}$ immediately above canopy level is required over all parts of the playing field and at all times of the year.

Horizontal airflow should not continuously exceed $5m\ s^{-1}$ at canopy level for more than 24 hours, without a 48 hour recovery.

INDEX PART NINE APPENDICES

APPENDIX ONE
9.1.0. DISASTERS IN FOOTBALL GROUNDS BETWEEN 1888-2000.

APPENDIX TWO
9.2.0. CONCLUSIONS OR RECOMMENDATIONS ON THREE SIGNIFICANT REPORTS ON UK STADIUM DISASTERS.

9.2.0.1. Conclusions: The R.T. Lloyd Wheatley Report.
9.2.0.2 Recommendations: Mr Justice Popplewell Report.
9.2.0.3 Recommendations: Lord Justice Taylor Report.

APPENDIX THREE
9.3.0. THE DEVELOPMENT OF PLAYING SURFACES.

9.3.1. Ninian Park Football Ground, Cardiff, Wales, UK.
9.3.1.1. Introduction.
9.3.1.2. The Development of the Ground.

9.3.2. Artificial Playing Surfaces.
9.3.2.1. Introduction.
9.3.2.2. Composition of Artificial Playing Surfaces.
9.3.2.3. Artificial Surfaces in Stadia.
9.3.2.4. Artificial Surfaces and the Link with Injuries.
9.3.2.5. Comparative Use Factors Between Artificial and Natural Turfgrasses.
9.3.2.6. A European Overview of Artificial Turfgrass.

APPENDIX FOUR
9.4.0. CASE STUDIES

9.4.1. HARRIS COUNTY DOME, HOUSON, TEXAS, USA.

9.4.1.1. Introduction.
9.4.1.2. The Case Study.
9.4.1.3. The Natural Playing Surface.
9.4.1.4. The Artificial Surface.

9.4.2. THE MONTRAL OLYMPIC STADIUM, MONTREAL, QUEBEC, CANADA

9.4.2.1. Introduction.
9.4.2.2. The Case Study.
9.4.2.3. The Original Roof. ***(Background Information).***
9.4.2.4. The Replacement Roof.

9.4.3. THE SILVERDOME STADIUM, PONTIAC, MICHIGAN, USA.

9.4.3.1 Introduction.
9.4.3.2. The Case Study.
9.4.3.3. Outline Detail of the Experiment.
9.4.3.4. The FIFA Inspection.
9.4.3.5. Schedule of Events for the FIFA World Cup.

9.4.4. THE TORONTO SKYDOME, TORONTO, CANADA.

9.4.4.1. Introduction.
9.4.4.2. The Case Study.
9.4.4.3. Outline Technical Details of the Skydome.
9.4.4.4. The Retractable Roof.

9.4.5. THE AMSTERDAM ARENA, AMSTERDAM, NETHERLANDS.

9.4.5.1. Introduction.
9.4.5.2. The Case Study.
9.4.5.3. Work on Site.

9.4.6. THE MILLENNIUM STADIUM, CARDIFF, WALES, UK.

9.4.6.1. Introduction.
9.4.6.2 Case Study.
9.4.6.2.1 The Condition of the Arms Park Turfgrass.
9.4.6.2.2 The Millennium Stadium Turfgrass.
9.4.6.2.3 The Removable Pallets.

9.4.7. THE GELDREDOME, ARNHEM, NETHERLANDS.

9.4.7.1. Introduction.
9.4.7.2. The Case Study.

9.4.8. THE SAPPORO DOME, SAPPORO, KOKKAIDO, JAPAN.

9.4.8.1. Introduction.
9.4.8.2. The Case Study.
9.4.8.2.1. The Context.
9.4. 8.2.2. Fixed Roof.
9.4.8.2.3. 'Letter Box' Construction.
9.4.8.3. Moving the Pallet.
9.4.8.4. The Function of the Building.

APPENDIX FIVE

9.5.0. AN OUTLINE OF THE PHOTOSYNTHETIC PROCESS.

APPENDIX SIX

9.6.0. THE SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY.

APPENDIX SEVEN

9.7.0. VISITS TO STADIA.

PART NINE.
APPENDICES.

APPENDIX ONE.

9.1.0. DISASTERS IN FOOTBALL GROUNDS BETWEEN 1888-2000.

Disasters that have occurred in the UK are highlighted in bold type; those that have occurred elsewhere are shown in plain type. The numbers of the injured have not always been recorded. The following are the sites of the most notable accidents in stadia:

1888, Valley Parade, Bradford, England UK. 1 died and 3 injured, during a Rugby Match. Cause: collapse of wooden railings.

1902, Ibrox Park, Glasgow, Scotland, UK. 26 people died and 517 injured. Cause: collapsed section of a timber stand.

1914, Hillsborough, Sheffield, England, UK. 75 injured. Cause: collapsed wall.

1946, Burnden Park, Bolton, England, UK. 33 dead and 400 injured. Cause, invasion of hundreds of spectators into the ground after gates were closed.

1961, Ibrox Park, Glasgow, Scotland, UK. 2 people died. Cause: collapsed barrier Stairway 13.

1964, Lima, Peru, 340 dead and 500 injured. Cause: riot, Referee disallowed home team goal.

1967, Ibrox Park, Glasgow, Scotland, UK. 8 people were injured. Cause:collapsed barrier Stairway 13.

1969, Ibrox Park, Glasgow, Scotland, UK. 24 people injured. Cause: collapsed barrier Stairway 13.

1971, Ibrox Park, Glasgow, Scotland, UK. 66 people died and 145 injured. Cause: collapsed barrier Stairway 13.

1979 Riverfront Stadium, Cincinnati, USA. 11 died and many injured. Cause: surge into a tunnel during a pop concert.

1982, Lenin Stadium, Moscow, Russia. The accident "remained unreported until 1989. Official death roll recorded as 69; some foreign newspapers meanwhile reported 340 deaths. Some of the 15000 spectators were leaving the game early via an icy ramp, tried to turn back when the home team scored a goal and a fatal crush ensued." (Football Grounds of Europe, Simon Inglis, Collins Willow, London 2nd Edition 1986. Page 187.) Date not known.

1985, Valley Parade, Bradford, England, UK. 56 people died and 200 were injured.

1985, St Andrew's Stadium, Birmingham, UK. Cause: riot between the supporters of Birmingham City and Leeds United, during which a wall collapsed. "1 died. 96 policemen and one innocent fan were injured".

1985, Stade Du Heysel, Brussels, Belgium, Europe.38 people died, and 100 injured. Cause: riot.

1985, Mexico University Stadium, Mexico, South America. 10 people died and 70 were injured when crowds tried to enter the stadium through a tunnel which was locked.

1989, Hillsborough Stadium, Sheffield, England UK. 96 died. Cause: over-crowding in a spectator pen.

1991, Johannesburg, South Africa. 40 died and 50 injured. Cause: riot, Referee allowed an own goal at a friendly soccer match.

1991, Nairobi National Stadium, Kenya, Africa. 1 died and 20 injured. Cause: stampede. 15000 fans allowed into the ground without tickets, after kick off.

1992, Corsica, France. 17 died. Cause: collapse of temporary grand stand.

1996, Guatemala City. 83 died, between 127 and 180 injured. Cause: stampede, after entrance door kicked down, causing spectators inside to cascade down to lower levels.

1999, The Millennium Stadium, Cardiff, Wales, UK One died. Cause: whilst sitting in a seat, a spectator was hit by a flare shot from an opposite stand.

2000, Rotherham, England, UK. 1 died. Cause: a person was trampled by police horse during crowd unrest outside Rotherham Stadium prior to match.

APPENDIX TWO.

9.2.0. CONCLUSIONS OR RECOMMNENDATIONS OF THREE SIGNIFICANT REPORTS ON UK STADIUM DISASTERS.

9.2.0.1. Conclusions: R. T. Lord Wheatley Report.

66.] I recognise that a decision to introduce a licensing system for grounds along the lines I have recommended may cause anxiety to some football clubs and football administrators. As I see it, their misgivings are associated with a fear that such stringent conditions might be attached to the granting of a licence that many clubs may not be able to afford the cost and some may have to go out of business.

67.] My answer to that is this. My task was to consider the problem of crowd safety at the grounds. Clubs which charge the public for admission have a duty to see t hat their grounds are reasonably safe for spectators. This is a primary consideration. It is accordingly necessary that some standards should be imposed and observed. This has been recognised by the football authorities themselves. Hence their introduction of the certificate procedure. That, in my view, has been proved to be deficient and requires to be replaced by some other system. I have canvassed all the alternatives that have been proposed or which I personally thought were reasonable to consider, and the one which I decided was best to meet the situation in the interest of the public is the licensing system by a local authority. There is nothing new in this proposal. It has been mooted for almost fifty years. It can come as no surprise to the football world, and in the light of happenings over the years the demand for an independent appraisal and determination of the safety of grounds becomes almost irresistible. I certainly cannot resist it.

68.] At the same time I am not unmindful of the financial problems involved. I have had them clearly in mind when working out the system which I recommend. In the first place I have proposed that the introduction of the licensing system should be spaced out, so that clubs in the lower echelons, and presumably with the smaller financial resources, will have the opportunity of spreading their necessary ground improvements over a longer period before the licensing system applies to them. I have not suggested that there should be introduced a statutory Code of Regulations which must be observed in every particular and in every case. I have tried to envisage a much more flexible system under which the requirements of each ground can be individually considered. This leaves the door open to a sensible identification of what is required in a particular ground to secure a proper standard of safety for people patronising it, and a reasonable imposition of necessary requirements. The granting of a licence subject to conditions such as crowd limitation may be the answer in some cases. And if on the odd occasion this results in a drop in revenue, that would be the price the club would have to pay for its ground not being up to the proper standard. As in other spheres, the satisfactory working of the scheme will depend on the willingness of clubs to deploy their financial resources to the best of their ability on the one hand, and on a reasonable and sensible approach to requirements by the licensing authority on the other. It has worked in other fields, and I see no reason why it should not work in this.

69.] While not seeking to set out a code of practice in the sense of statutory regulations which have to be observed in all cases I have, with the assistance of the Technical Support Group, provided what should be regarded as guidelines towards a proper standard. I trust that these will be of benefit both to clubs in deciding what they should do in making improvements, and to licensing authorities in deciding what should be looked for.

70.] In the event of it being decided to introduce a licensing system, some time must elapse before the necessary legislation is passed and the system becomes operative. This, as I have indicated, will give both clubs and the ruling bodies time and opportunity to get ahead with changes which may be required to meet what may be reasonably anticipated as being necessary. The clubs will have to guide them not only the report of the Technical Support Group but also the recommendation of the Lang Report which some clubs have not implemented as they ought to have done. They will have the opportunity of making arrangements for such things as the provision of proper facilities for the police, first-aid and ambulance services, and the co-ordination of all personnel involved in crowd control and crowd welfare under the supervision of, say, the senior police officer in attendance. Consultations between the club and the police (and the first-aid and ambulance services as well) to see what is required for the efficient discharge of their duties should be held at least at the beginning of each football season.

71.] On the financial side, clubs may have to re-appraise their priorities. It may be that some of the money spent at present in other directions will have to be spent on necessary ground improvements. The rules governing the distribution of moneys from the Association and Leagues to clubs may require re-examination. A club may be able to do without a ground for a matter of weeks. It cannot do so indefinitely. A ground to play on is just as important as a team to play with.

72.] I trust that this report may be of assistance to you in deciding what should be done to solve this important question of crowd safety in football grounds. One thing is certain. The public demand for something to be done has been growing over the years. I am sure I am reflecting public opinion when I say that something must be done now. The evidence certainly supports that view. I am, Yours Faithfully, Wheatley.

9.2.0.2. Recommendations: Mr Justice Popplewell Report.

STRUCTURE OF THE GREEN GUIDE

Rec 1 E6. The Working Group was dissatisfied with the structure of the current Guide and recommends that *the Green Guide should be reorganised so as to reflect more closely the needs of its target audience.*(The Group agreed that the target audience of the Guide comprises : (a) sports ground management in designated and undesignated grounds; (b) engineers, designers and others engaged in the improvement, design appraisal or refurbishment of sports stadia to certifiable standards; and (c) local authorities responsible for enforcing the Safety of Sports Ground Act of 1975.) The Group considered that, following a general introduction which describes the scope of the Guide, sets the scene and briefly discusses the nature and extent of risks to the public at sports grounds, the guidance should be re-arranged so as to deal first with general management responsibilities and major planning and design matters. (Guidance on these matters should, where practicable, include methods for assessing the general safety condition of a ground and the need for detailed drawings and plans.) The succeeding categories of detailed guidance should each be preceded by a statement of the general functional requirement or aim and should include as much appraisal, flow and other diagrams as may conveniently be arranged. The Group considered that a possible scheme for the categories of advice in the Green Guide was : Fire (to include a checklist and appraisal flow diagram and reference to the need for professional advice), Structural Appraisal (to include a method for appraising existing structures and reference to the need for professional advice), Ground Control and Ground Management(to identify responsibilities and duties), and Inspections, Tests and Maintenance.

Rec 2, E7 The group also recommends that *consideration should be given to the production by the Home office, or other appropriate body, of a summary documents, training aids and seminars for sports ground management explaining the provisions of the Green Guide and their application.*

INTRODUCTION

E8. The current Guide is aimed at soccer and rugby grounds (GG (Green Guide,1976 Edition, paragraph): 1:1).

The Group decided that many of the recommendations in the Green Guide are relevant to outdoor sports other than football and recommends that the Introduction should say that the *Guide is applicable as a code of good practice for all sports grounds.* The Green Guide should make it clear, however, that *it does not cover measures to ensure the safety of spectators from hazards presented by the sport itself.* Rec3

Rec 4

E9. The Group noted that the references in the Guide to the Building Regulations for England and Wales would need to be revised and brought up to date. It was further noted that in Scotland the Building Standards (Scotland) Regulations gave requirements for the construction, alteration, extension and change of use of buildings, and included standards in respect of means of escape from fire, including emergency lighting, access for fire-fighters as well as structural fire precautions. The Group recommends that full account should be taken of national Building Regulations in the Green Guide.

IDENTIFICATION OF PROBLEMS

E10 The current Guide discerns three particular types of safety problem to be considered within a football ground and its immediate surroundings (GG: 2.1 to 2.4): (a) those physical hazards which may cause individuals to trip, slip or fall; (b) crowd pressures which may be built up in normal circumstances (particularly on terraces and exit routes); and (c) crowd pressures which may be built up under abnormal conditions. The Group considered that this analysis was correct. However, it felt that the need to tackle these problems should be covered in a new self-contained section defining, in general terms, good safety design in sports stadia and enumerating other important needs such as managing and controlling crowds, maintaining effective fire precautions, making proper provision for the disabled and achieving a reasonable standard of comfort and convenience for spectators. Accordingly the Group recommends the *incorporation of a new self-contained section on good safety design in sports stadia.*

GENERAL CONSTRUCTION

E11 The current Guide recommends that all components and installations should be designed, constructed, installed and maintained so as "to perform safely their required functions" and that they should be in accordance with good engineering and building practice, especially as set out in all relevant British Standards and Codes of Practice (GG: 3.1).

The Group approved this recommendation but felt that the reference to British Standards might be improved so as to identify those parts of the British Standards which are wholly applicable in the circumstances of the case. The Group recommends that *references in the Guide to British Standards and Codes of Practice should be improved* accordingly

E12 The current Guide recommends that all electrical installations should comply with the current edition of the regulations of the Institution of Electrical Engineers (GG:3.2). The Group considered that it would be reasonable in some circumstances for *the enforcing authority to accept a certificate of satisfaction from a chartered electrical engineer in lieu of full compliance with current IEE Regulations* and recommends that the Guide so advises. The Group also recommends a *reference to BS 5266: Pt 1 in respect of emergency lighting.*

E13 The current Guide recommends that all parts of the ground used by the general public should have a minimum headroom of 2.4 metres (GG:3.5).

The Group could find no clear foundation for this advice and, accordingly, recommends that *in respect of headroom the Guide should simply advise conformity to appropriate building regulations.*

INSPECTIONS AND TESTS.

E14 The current Guide recommends:

(i) A detailed annual inspection to ensure compliance with the Green Guide (GG:4.1);

(ii) A general visual inspection following each event for damage which might create a potential hazard(GG:4.2); and,

(iii) Testing of crush barriers in accordance with the Guide on installation and subsequently, normally, at intervals of several years (GG:4.3).

The group recommends that the routine *general visual inspection by management advised in the Guide should also cover features which might reduce the degree of fire protection offered* and that *there should also be a warning in the Guide against storing hazardous materials under or near stands.* The Group also recommends that *consideration should be given to the inclusion of additional guidance to certifying authorities as to the frequency and content of inspections*

E15. The Group recommends that *regular emergency evacuation drills for members of staff should be recommended in the Guide.*

E16. On the testing of crush barriers (GG: 4.3 and Appendix C of the Guide) the group had before it no evidence that the current guidance had permitted dangerous or defective crush barriers. However, it seemed to a minority of the Group that certain anomalies exist in the current recommendations in the Green Guide as to load factors and testing (for example, the table of strengths for new crush barriers permitted a different design strength for the bars and posts than for the foundations); and there was some evidence that the enforcing authorities were unclear as to the correct procedures. The Group recommends that *representatives of the local authorities, the Home Office and appropriately qualified advisers should, together, review the Guide's recommendations on the design and testing of crush barriers* in more detail with a view to clarifying the guidance in future editions of the Guide (see paragraph 28 below).

E 17. The Group further recommends that the Guide should advise that *any automatic fire protection equipment or emergency lighting equipment or emergency lighting systems should be tested regularly in accordance with the relevant British Standard Codes of practice.*

INGRESS TO THE GROUND

E 18. The Guide currently recommends that the number and location of turnstiles should be planned to achieve the smallest crowd waiting for admission that is consistent with the rate that spectators can be distributed inside the ground(GG: 5.1). The Group recommends that *more detailed guidance to management as to contingency planning in the event of unusual pressures and frustrations (including a reference to the value of centralised computer-based monitoring)* should be given. The Group further recommends that the Guide emphasise that *turnstiles are not acceptable as a means of escape from a ground.*

E 19. The Group considered it desirable that the Guide should specify a notional maximum free flow rate past a turnstile. The Group recommends that *further consideration be given to defining a maximum notional flow rate past turnstiles for incorporation in a future edition of the Green Guide.*

E 20. The Guide currently recommends that fences forming a boundary to a ground should be of " appropriate height and strength" to avoid spectators gatecrashing (GG: 5.2). The Group recommends that *boundary walls and gates and any other structure forming part of the boundary should also be of appropriate height and strength to avoid gatecrashing.*

EGRESS FROM THE GROUND

E 21. Currently, Section 6 of the Guide makes a number of general recommendations as to egress from a sports grounds (GG:6.1to 6.13). The Group was generally content with these but recommends that the wording in paragraph 6.13 of the Guide should be revised to make it clear that *escape routes are not to be regarded as an alternative provision only for use in emergency.* The Group further recommends that guidance should be included to the effect that *doors on exit routes should always open outwards; and that where practicable exit gates should be sited adjacent to entrances.*

E 22. The Group recommends that *a study should be undertaken of the current use and effectiveness of the exit route signposting and exit marking systems recommended in the Green Guide (GG: 6.6),* and that consideration should be given to commissioning further research in this area.

TERRACES AND STANDS

Safe Capacity of Terraces

E 23. The Guide currently suggests that the exits from each area of spectator accommodation should be so designed that the spectator can leave that area in eight minutes or less (GG: 6.5). The Group concluded that this so-called *"eight minute rule" was concerned solely with the effect of crowd turbulence* (arising from delays in evacuating spectator accommodation) *on the rate of flow.* It is not related to emergency evacuation time criteria (see paragraph 32 below) and the Group recommends that *the Guide should make this clear.*

Terrace Packing Densities

E 24 The guide recommends packing densities of between the limits of 27 and 54 persons per 10 m2 depending on the condition of the terrace or slope and on the extent to which crush barriers conform to the Green Guide guidelines on spacing (GG: 15.4). Recommended flow rates from the terraces are given at paragraph 16 of the Guide.

The Group concluded that the flow rates and permissible spectator densities in the Guide were satisfactory and reasonable when taken as a whole and that they accorded with experience. However, the Group recommends that *flow rate and packing criteria and their relationship (if any) with those criteria given in respect of emergency evacuation and crowd turbulences should be set out and explained more clearly in the Guide and that further advice should be given as to how interpolation between the wide limits suggested in respect of terrace packing densities may properly be carried out.* The Group further recommends that *consideration be given to the possibility of a separate detailed study of the possible casualties which might be attributable to high packing densities.*

Terrace Steps and Viewing Slopes

E 25. The Group was content with the Guide's recommendations in respect of terrace steps and viewing slopes (GG: 7.4). The Group recommends, however, *that the surfaces of terrace steps and viewing slopes should be even as well as non-slip and that the way in which the maximum desirable gradient is specified in the Guide should be improved.*

Terrace Gangways

E 26. The Guide states that the aim in respect of terrace gangways should be to ensure that every spectator on a terrace is within twelve metres of a gangway or of an exit. (GG: 7.5). The Guide further indicates that gangways should be sunk.

The Group felt that although these recommendations were generally satisfactory, reasons should be given for the basic aim stated in paragraph 7.5 of the Guide. Furthermore, it would be *preferable to state the safety objective behind the current recommendations to sink gangways so that it could be met in other ways.* The Group recommends accordingly.

Division of spectator accommodation

E 27. The Guide currently recommends the division of a ground into sections to prevent major migrations by spectators, and into sub-sections to minimise the sway and surge of spectators (GG: 7.6). The Group recommends that the Guide *should limit the application of its guidance on segregation to terraces at football grounds* (see recommendation 57 below)

Crush barriers and other physical restraints on movements

E 28. The Group recommends that the Guide should explain *that brick walls and similar structures lacking mass or tensile strength are poorly suited to withstand horizontal pressures and that the Guide should strongly recommend regular structural appraisal by appropriately qualified personnel.* The Group also recommends that *consideration should be given to mounting a more detailed review of current literature on the strength of crush barriers and the effects of the various types of loading that might be applied to them* (see also paragraph 16 above)

The Group further recommends that *the aim of the guidance on migrations be restated as " to prevent potentially hazardous migrations "* rather than mass migrations as currently indicated in the Guide (see paragraph 43 below)

PITCH PERIMETER FENCES

E 29. The advice on pitch perimeter fences in the current Guide deals mainly with the crush barrier aspects (GG: 7.9). Access to playing pitches and the need for "anti-hooligan" or other protective devices is however, referred to in the section on crowd behaviour (GG: 18)

The Group recommends that *the Guide should explain more clearly, preferably by reference to standardised specifications, the different functions perimeter fencing may serve* and that appropriate cross referencing is incorporated in any future edition of the Guide. The Group further recommends that *the importance of allowing full access to the pitch where this is likely to be used as a place of safety in emergency should be made plain.* (It was noted that Scottish Building Regulations required that protected zones such as stairways led to a place of safety, ie an unenclosed space in the open air at ground level or an enclosed space in the open air at ground level with access (of defined widths) to an unenclosed space. A pitch could be accepted as a place of safety only if it met that requirement. If however, it was subsequently fenced off, circumstances could arise, under Scottish Building Regulations, where a change of use would deemed to have taken place.)

Stairways and ramps

E 30. The Group recommends that the *current guidance on stairways and ramps (GG: 9) should contain appropriate cross references to advice on egress from the ground* (GG: 6). The Group further recommends that *the Guide should advise that, ideally, the rising and going of steps should be uniform throughout an entire escape system.* A minority of the Group felt that the method of the calculation for access to stairways (GG: 9.4.5) of the Guide was anomalous and should be reviewed.

FIRE PRECAUTIONS

E 31.Guidance on fire precautions is currently contained in section 10 of the Green Guide. It covers a variety of important matters including fire resistance, emergency lighting and fire-fighting equipment.

The Group was not wholly satisfied with the general advice on fire precautions offered by the Guide. So far as existing structures were concerned, the Group recommends *that detailed advice should be given on means of reducing the rate of fire growth in existing stands.* The Group believes that consideration should be given in incorporating appropriate references to recent work in this area commissioned by the inquiry from the Fire Research Station. In particular, the Group recommends that the *Guide should emphasise the hazards of developed fires breaking into spectator accommodation and the consequent need for fire separation under stands to be* *imperforate.* In addition the *dangers of fires spread across adjoining stands should be emphasised* and half-hour fire resistance might need to apply to vertical sections dividing spectator accommodation from other areas.

Evacuation times

E 32 On notional emergency evacuation times, the Guide currently recommends interpolation between 2.5 and 8 minutes, with the higher figure applying where a stand is of non-combustible fire resisting structure and presents generally a low fire risk (GG: 8.3).

The group was satisfied that there was no case for reducing the 2.5 minutes lower evacuation time as recommended in the Guide. The lesson of Bradford was the need for adequate measures to inhibit the rate of fire development and spread and to improve the efficiency of the fire procedures rather than to stipulate more stringent criteria in respect of notional values. However, representatives of the Fire Research Station felt that the 2.5 minutes should be regarded as a maximum; they believed that although individual circumstances might conceivably justify increasing the figure, it was not currently possibily to assign quantitative values to active or passive fire protection measures with sufficient precision to enable specific relaxations to be advocated in the Guide with any degree of confidence. A majority of the Group believed that the notional 8 minutes upper limit indicated in the Guide, although lacking any very clear or relevant technical rationale, was reasonable and should be retained. Nevertheless, it was the firm view of a minority including Mr Platt that 8 minutes is too long a period to allow for the evacuation of any stand under emergency conditions and that, although relaxation of the 2.5 minutes figure might be reasonable in individual circumstances, it would be misleading to specify the upper limit in the Green Guide.

The concensus was that the enforcing authority should decide on relaxations in the light of professional experience and individual safety circumstances of a particular ground, but that the Green Guide *should offer more guidance as to what latitude was permissible on evacuation times and the circumstances to take into account.* In particular, the Green Guide should emphasise that *escape routes should be designed or chosen so that they provide progressive reduction in difficulty or danger to people using them and regard should be had to the likely accumulation of smoke and combustion products in those routes.* The Group recommends that *consideration should be given to devising a more scientific method for assessing the evacuation of a stand under emergency conditions.*

Fire protection and fire-fighting equipment.

E 33. The Group considered that there was currently *insufficient evidence as to the value of life safety of automatic fire protection equipment for the Green Guide to encourage trade-offs between such equipment and structural fire precaution measures.* Any implications that such trade-offs were permissible should be removed from the current Guide (GG: 10.2). A majority of the Group rejected also the idea that the Green Guide should suggest similar relaxations where management expertise and vigilance were at a high level.

On fire detection and fire-fighting equipment, the Group recommends *that reference should be made to relevant British Standards such as BS 5839: Part 1, BS 5306: Parts 1and 3 and BS 5423.* The Group considered that it was an inefficient and undesirable use of resources for manned fire appliances to attend all matches.

E 34. On roof venting, the Group felt that with some stand roof configurations, appropriate venting and curtain arrangements might offer a means of reducing the spread of fire. It was agreed however that the science of fire and smoke venting was highly complex and that it was not appropriate for the Guide to offer more than a general reference to the issue. However, the Group felt that *some advice on roof venting should be offered in the Green Guide* along the lines of that proposed by the Fire Research Station in work commissioned by the Inquiry. It was agreed that the priority in the Guide was to recommend effective fire precautions relating to the early stages of a fire.

Access for emergency vehicles

E 35. The Group agreed that the Guide's recommendations as to access for emergency vehicles (GG: 11.30) were soundly based. It was noted that the Interim Report recommendation that vehicular parking be banned within a quarter of a mile of a sports ground (when it was in use) had been made on a " where practicable" basis. The Group recommends that *the qualification " where necessary" should be added to the current Guide's recommendations on access for emergency vehicles.*

Hazardous materials

E 36. The concensus was that it was not practicable for the Guide to offer detailed advice on fire spread hazards associated with particular materials. Nevertheless, the Group recommends that *consultation with expert fire advisers should be indicated in the Guide where substantial use of, for example, polymer seating is contemplated or of artificial pitches where forward escape onto the pitch might be necessary.* (See also recommendation 35 above).

COMMUNICATIONS

E.37. The Green Guide currently recommends that precise requirements for communications within a particular ground be determined after consultation with the police (GG:17). The Guide goes on to give examples of the arrangements likely to be needed at larger grounds. The Group considered that this advice and the way in which it was expressed was generally satisfactory. However, the Group recommends that the advice as to *central control points should not be confined to the largest grounds and that the Guide should emphasise the need for ground management and responsibility to be centralised accordingly.* The Group also believed that it would be *desirable in larger grounds if public address systems permitted messages to be directed towards specific zones of the ground.* The Group recommends accordingly.

E.38. On emergency audible alarms, the use of coded messages found little support in the Group. The need was rather to communicate essential information effectively to the crowd. For that purpose, *a clear system of communications covering all the various conceivable crises, including the facility to strop the event, should be devised in consultation with the emergency services.* The Group recommends that guidance to this effect should be incorporated in the Green Guide. Further study was required before pre-set formulae messages could be recommended in the Guide. However, it was clear that such messages should be in the active mode, that they should be directed towards persons from whom a response is required, and that they should be delivered authoritatively by trained controllers. The Group considered that there was a need for *standard guidance covering the use of public address systems for emergency purposes. The Group recommends that consideration be given to this.*

E.39. The Group considered that the development and operational experience of closed circuit television (CCTV) facilities was too little advanced to enable the Guide to be prescriptive as to particular systems. However, it was noted that CCTV appeared to have significant value in crime prevention and detection and that it had a considerable role to play in aiding emergency evacuations, police management information and crowd control. The Group therefore recommends that the *provision of CCTV systems should be encouraged* in the Guide.

Crowd Behaviour.

E.40. Advice on crowd behaviour is currently set out in the Green Guide in the form of recommendations of an earlier working party on crowd behaviour (GG: 18). The Group recommends that the *advice for management* currently presented at paragraph 18 of the Guide *should be re-organised and expanded* so as to explain more fully the major problems and principles of crowd control and then go on to elaborate the various methods available which may be relevant in certain situations at sports grounds and of the circumstances under which these might be appropriate (see also recommendation (1) above).

E.41. The Group also recommends that the *Guide should emphasise the value of effective planning before events, debriefing exercises and full liaison with the police*, in order to predict and prevent trouble. In particular, the Guide should stress the desirability of identifying in advance, against the local historical background and known travel arrangements, the likely size and nature of the crowd.

E.42. The Group further recommends that the Guide makes it clear that the *responsibility for pre-planning and liaison lies with club management,* subject only to the point that the disposition of operational police resources is the sole responsibility of individual chief constables.

E.43. There was considerable discussion in the Group of the segregation issue which, it was agreed, had major implications for planning. The consensus was that clear differentiation of opposing fans (with ancillary facilities) remained the only viable and prudent course so long as crowd violence remained at current levels; and that the best way to achieve such differentiation was by spatial separation and physical containment of opposing groups. The Group was anxious, however, that segregation should not be encouraged other than where local circumstances made it absolutely necessary. In particular, at the present time segregation should not be advocated for sports other than soccer. The Group recommends accordingly. (See also paragraph 27 above).

E.44. The Group agreed that *certain fire precautions measures*, for example plasterboard fire separation and fire protection equipment, *might be vulnerable to vandalism* and that certificating authorities should be advised to take this into account where appropriate. The Group recommends accordingly.

E.45. On ticketing, the Group agreed that this was not an effective means of crowd control unless clubs ensured that their *arrangements for the issue and allocation of tickets was as efficient and effective as possible*. The Group recommends that this latter point be strongly emphasised in the Green Guide.

E.46. On alcohol, the Group *recommends that the guidance on alcohol (GG.18.4) should be reworded* to make clear that an important objective was to reduce potential missiles and also that the police should be consulted over arrangements for the sale of alcohol at grounds. A reference to the Sporting Events (Control of Alcohol etc) Act 1985 was also needed.

E.47. The Group were content with the material on police facilities given in the Green Guide (GG: 17.8) but considered that the Guide should advise adequate *vehicular access for the unobtrusive removal of detainees and secure detention rooms at appropriate grounds*. The Group recommends accordingly.

OTHER MANAGEMENT RESPONSIBILITIES

E.48. The Group was strongly in favour of the creation of a new section in the Green Guide on management responsibilities and recommends that consideration should be given to this. The Group considered that it would be helpful if such a section could incorporate a form of checklist of necessary tasks organised under broad headings such as: Pre-planning for Emergency Procedures, Training of Stewards and First-aid Facilities/Other Medical Provisions. A reference to the need for management structure to reflect such responsibilities, preferably including the designation of a named individual to take responsibility for the proper execution of such duties, was also highly desirable.

E.49. On the question of the relative responsibilities of the police and stewards, the Group felt that the Guide ought to make it plain that it was the *club's responsibility to control and manage spectators in normal circumstances* and that the police presence (if there was one) was to deal with the law and order problems and provide support and leadership in emergencies. The Group recommends accordingly. It was noted that there now existed considerable material on the training and deployment of stewards and staff likely to be involved in emergency situations.

10.2.3. TAYLOR REPORT RECOMMENDATIONS.

All-Seated Accommodation

1]The Secretary of State should ensure that spectators are admitted only to seated accommodation at matches played at sports grounds designated under the Safety of Sports Grounds Act 1975 in accordance with the timing set out in Recommendations 2 to 4 below.

2.]Recommendation 1 should apply with effect from the start of the 1993/4 season at high-risk matches as defined under the UEFA Regulations set out in paragraph 82 above.

3.]Subject to Recommendation 2 above, Recommendation 1 above should apply with effect from the start of the 1994/5 season to all matches at grounds in the first and second divisions of the Football League, the Premier Division of the Scottish Football League, and at national stadia, subject to a reasonable extension of time in the case of a club promoted to the second division of the Football League or the Premier Division of the Scottish Football League. Standing accommodation at these grounds should be reduced annually by 20% of the present standing capacity (such present standing capacity to be calculated according to Recommendation 8 below), the first 20% deduction being effective from August 1990 so as to eliminate standing by August 1994.

4.]Subject to Recommendation 2 above, Recommendation 1 should apply with effect from the start of the 1999/2000 season to all matches at all other grounds designated under the Safety of Sports Grounds Act 1975. Standing accommodation at these grounds should be reduced annually by 10% of the present standing capacity (such present standing capacity to be calculated according to Recommendation 8 below), the first 10% deduction being effective from August 1990 so as to eliminate standing by August 1999).

Advisory Design Council

5]The Football Association and the Football League should establish an Advisory Design Council whose functions should be:

a] To conduct and marshal research into the improvement and design of football stadia;

b] To disseminate regularly such information and expertise as they acquire in this field to members of the Football League and, on request, to other football and sports clubs in England, Wales and Scotland.

National Inspectorate and Review Body.

6] a.]If Part I of the Football Spectators Act 1989 is implemented, section 13 should be brought into force giving the Football Licensing Authority the functions and powers therein specified (power to review the discharge of functions by local authorities). If Part I of the Act is not implemented or is substantially delayed, other arrangements should be made for the discharge of the functions and powers in section 13 of the Act by the appointment of a body to exercise them.

b.] In either event, the body exercising those functions and powers in relation to Association Football should also be entrusted with similar functions and powers regarding the discharge by local authorities of their certifying and licensing functions in relation to other sports grounds and sports entertainments pursuant to the Safety of Sports Grounds Act 1975 and Parts III and IV of the Fire Safety and Safety of Places of Sport Act 1987.

Maximum Capacities for Terraces

7.] Where a viewing terrace is divided into pens or areas which are self-contained, the Safety Certificate should specify the maximum number of spectators to be admitted to each such pen or area.. A pen or area is deemed 'self-contained' notwithstanding that it has a gate or gates affording access to another pen or area and whether such gate or gates be open or shut.

8.] Each figure for maximum capacity should be assessed in accordance with Chapter 16 of the Green Guide ('the Green Guide figure') subject to the following qualifications:-

a.] The maximum density permitted under paragraphs 221 and 222 of the Green Guide (when the terrace or viewing slope is in good condition) should be 47 not 54;

b.] The minimum figure specified in paragraphs 221 and 222 (when the terrace or viewing slope materially deviates from the recommended guidelines, so as to constitute a possible hazard to individuals closely packed) should be 0 not 27;

c.] In arriving at 'the Green Guide figure', proper and realistic allowance must be made for all factors which should reduce the permissible density including those specified in paragraphs 220 to 224 inclusive of the Green Guide.

9.] Arrangements should be made:-

a.] To limit the number of spectators entering each self-contained pen or area to the maximum capacity figure assessed in accordance with Recommendation 8 above either electronically, mechanically, by a ticketing arrangement, by counting or otherwise, and

b.]To close off further access to such pen or area when its maximum capacity is about to be reached.

10.] The maximum notional rate at which spectators can pass through a turnstile should be 660 persons per hour, not 750 per hour as stated in paragraph 47 of the Green Guide. The maximum rate for any particular turnstile must take full account of all circumstances including those given as examples in paragraph 47.

Filling and Monitoring Terraces

11.] There should be a written statement of intent, agreed between the club and the police, setting out their respective functions as to crowd safety and control and in particular as to the filling of each self-contained pen or other standing area and the monitoring of spectators in each such pen or area to avoid overcrowding. Any variation of the document in respect of an individual match should be agreed in writing in advance.

12. a.] At each match, there should be on the perimeter track, for each self-contained pen or other standing area (subject to (b) below), a steward (if the club is monitoring that area) or a police officer (if the police are monitoring it) whose sole duty is to check crowd conditions in that area for possible overcrowding or distress throughout the period the area is occupied by spectators. Whoever is so appointed should be in addition to any other steward or police presence. He should have ready access to a police officer who can authorise access through gates to the pitch under Recommendation 20 below.

b.] This Recommendation need not be applied to any self-contained pen or other standing area where the spectators present, or reasonably to be expected, during a particular match do not exceed one third of the area's maximum permitted capacity, or 2,000, whichever is the lower.

Gangways

13.]Gangways should be kept clear, in accordance with paragraphs 97 to 99 of the Green Guide. Gangways should be painted in a conspicuous colour whether they are sunk or not. The Safety Certificate should require that no standing be allowed in gangways and that they be painted.

Fences and Gates

14.] All spikes or similar constructions on perimeter or radial fences, and any sections overhanging or returning inwards towards spectators, should be removed.

15.] Perimeter fencing should be no higher than 2.2 metres, measured from the top of the fence to the lowest point at which spectators may stand, and including any wall or other foundations forming part of the perimeter boundary.

16.] All police officers and stewards with duties in relation to the standing areas and especially those with duties under Recommendation 12 above, should be fully briefed and trained with regard to the recognition of crowd densities, to the recognition of signs of distress and to crowd dynamics. Training should include demonstrations at the ground and photographs, designed to enable stewards and officers to recognise different crowd densities.

17.] There must be provided in any perimeter fence of a pen or other self-contained area sufficient gates of a minimum width of 1.1 metres to enable that pen or area to be evacuated onto the pitch in the time prescribed for an emergency evacuation of that pen or that area.

18.] All gates in radial or perimeter fences or pens or other self-contained areas should be painted in a different colour from the rest of the fence and marked "Emergency Exit."

19.] Where there is a perimeter fence in front of a pen or enclosure, all gates to the pitch should be kept fully open during the period when spectators are in the pen or enclosure, wherever those in command feel that this can safely be done. Whether they be fully open, partially open or closed, they should be kept unlocked throughout the period when the pen or enclosure is occupied.

20.] Each gate in a perimeter fence affording access to the pitch from a pen or enclosure should be manned by a steward or by a police officer when the pen or enclosure is occupied. Whether such manning should be by a police officer or by a steward should be decided by the Police Commander. In either event, the Police Commander should appoint one or more police officers with power to authorise access through gates to the pitch immediately in the event of an emergency.

21.] Suitable and sufficient cutting equipment should be provided by the club at each ground where there are perimeter fences to permit the immediate removal of enough fencing to release numbers of spectators if necessary. Agreement should be reached as to whether the equipment should be used by police, the fire brigade or stewards. Whoever is to use it should be trained to do so. Whether to use it should be a decision of a nominated senior police officer at the ground.

Crush Barriers

22.] All crush barriers should be visually inspected each year for signs of corrosion. Any barrier found to be affected by a significant degree of corrosion should be repaired or replaced.

23.] The layout of barriers in each pen or terraced area should be reviewed immediately (if this has not been already done following the Interim Report) to ensure that it complies with the criteria contained in Chapter 9 of the Green Guide. If it does not, the assessment of the maximum capacity figure for that pen or terraced area, in accordance with Recommendation 8 above should reflect that fact.

Safety Certificates

24.] The Secretary of State should exercise his powers under either section 6(2) or section 15A of the Safety of Sports Grounds Act 1975 so as to make mandatory in Safety Certificates those conditions specified in the original section 2(2) of the 1975 Act. So far as the original section 2(2)(b) is concerned "shall" should be substituted for "may".

25.] In assessing these mandatory requirements in the Certificate for a particular ground, the local authority should follow the Green Guide criteria. Once that is done, the resultant figures and terms for that ground should be specified in the Safety Certificate and no variation from them should be permitted other than by formal revision.

26.] Where a local authority incorporates any provision of the Green Guide into the Safety Certificate, other than one within the scope of Recommendation 25 above, it should be made clear whether that provision is to be complied with absolutely or with discretionary flexibility.

27.] There should be an immediate review of each Safety Certificate (if this has not already been done following the Interim Report) by the responsible local authority, which should consult the club in respect of which the Certificate is issued, the police, the fire service, the ambulance service and the building authority. Such a review should include an inspection of the stadium. Its object should be to ensure that the operative conditions of the Certificate are complied with and to add or substitute any condition shown to be necessary as a matter of urgency following the findings and Recommendations in this Report.

28.] Any local authority within whose area there exists a sports ground designated under the 1975 Act for which no Safety Certificate has yet been issued should proceed forthwith to remedy the situation.

29.] Every Safety Certificate should be reviewed by the local authority at least once annually and each Certificate should require to be renewed annually.

30.] Each local authority should review its arrangements for issuing, monitoring, enforcing, reviewing, amending and renewing Safety Certificates (if this has not already been done following the Interim Report). Such review should require that there exists or is provided an accountable administrative structure whereby the functions of the local authority are regularly and effectively supervised by senior officers and elected members and decisions are properly taken in accordance with the local authority's rules.

31.] To assist the local authority in exercising its functions, it should set up an Advisory Group (if this has not been already done) consisting of appropriate members of its own staff, representatives of the police, of the fire and ambulance services and of the building authority. The Advisory Group should consult representatives of the club and of a recognised supporters' organisation on a regular basis. The Advisory Group's terms of reference should encompass all matters concerned with crowd safety and should require regular visits to the ground and attendance at matches. The Advisory Group should have a chairman from the local authority, and an effective procedure. Its resolutions should be recorded and it should be required to produce regular written reports for consideration by the local authority.

Duties of Each Football Club

32.] Each turnstile should be inspected and its potential rate of flow measured (if this has not already been done following the Interim Report). Thereafter, regular inspections should be made to ensure that each turnstile remains capable of admitting spectators at the rate anticipated.

33.] The correlation between each viewing area in the stadium and the turnstiles serving it should be such as to ensure that all the spectators intended to be admitted to that viewing area can pass through the turnstiles within one hour. If that cannot be done, the capacity of that viewing area should be reduced accordingly. Since this Recommendation includes terms and conditions within the scope of the original section 2(2)(c)(I) of the Safety of Sports Grounds Act 1975 it should be given effect in the Safety Certificate (see Recommendation 24 above)

34.] Turnstiles should be closed when the permitted capacity of the area served by them is about to be reached and arrangements should be made to ensure quick and effective communication with turnstile operators for this purpose.

35.] Close circuit television should be so installed as to enable crowd densities outside the ground, within concourse areas and in pens and other standing areas, to be monitored before, throughout and at the end of a match.

36.] All signposting for spectators both outside and inside the ground should be comprehensively reviewed (if this has not already been done following the Interim Report). It should, in relation to the arrangements for each match, be unambiguous, eye-catching, simple and clear and should be designed to ensure the rapid movement of spectators to their appropriate viewing areas. Any redundant signs should be removed.

37.] Information on tickets should be unambiguous, simple and clear and should correlate absolutely with the information provided in respect of each match both outside and inside the ground. Retained ticket stubs should contain information necessary to guide spectators once inside the ground.

38.] Information on tickets requesting spectators to be in position by a particular time should be reviewed (if this has not already been done following the Interim Report) by clubs in conjunction with the police to ensure that it corresponds with the planned arrangements for admitting spectators to the ground.

39.] Clubs should consider maintaining a record on computer of ticket sales before the day of the match, for season tickets and tickets for all-ticket matches for seated areas, containing the names and addresses of those purchasing tickets.

40.] All-ticket matches should be confined to those at which a capacity or near capacity crowd is expected. When a match has been designated all-ticket, clubs should not sell tickets at the match and should take steps to advise the spectators of both clubs accordingly.

41.] Each club should consult with a recognised supporters' club as to the provision of pre-match entertainment aimed at attracting spectators to the ground in good time.

42.] Clubs should recruit and retain sufficient competent stewards. They should be fit, active and robust and preferably between the ages of 18-55. Clubs should ensure that stewards are fully trained, aware of their duties under Annex B of the Green Guide and under the statement of intent (see Recommendation 11) and are able to perform them.

43.] The club should provide a police control room which is :-

a.] well placed, so as to command a good view of the whole pitch and of the spectator area surrounding it;

b.] sufficient for the commander, his deputy and enough officers to operate theradios, telephones and CCTV screens. There should be space for others who may need from time to time to visit the room *eg* other senior officers, club management or a member of the emergency services;

c.] Well equipped with CCTV, radio and telephone facilities and where necessary, sound-proofed against excessive crowd noise.

It should be the duty of the club to provide a room and equipment to the satisfaction of the chief officer nominated under Recommendation 44 below.

Police Planning

44.] The Chief Constable of each police force in whose area there is one designated sports ground or more should nominate a chief officer to liase with the management of each football club and local authority concerned in respect of the safety and control of crowds.

45.] The Operational Order for each match at a designated sports ground, and the pre-match briefing of all officers on duty there, should alert such officers to the importance of preventing any overcrowding and, if any is detected, of taking appropriate steps to remedy it.

46.]The Operational Order for each match at a designated sports ground should enable the police to cope with any foreseeable pattern in the arrival of spectators at a match and in their departure. It should provide for sufficient reserves to enable rapid deployment of officers to be made at any point inside or outside the ground.

47.] Police planning should provide that ticketless fans should not be allowed to enter a designated sports ground except in an emergency.

48.] Arrest procedures inside and outside designated sports grounds should be reviewed so as to keep to the minimum the period during which an arresting officer is away from his post.

49.] The option to postpone kick-off should be in the discretion of the officer in command at the ground. Crowd safety should be the paramount consideration in deciding whether to exercise it.

50.] Consideration in consultation with the club should be given, especially for high-risk matches, to the possibility of an early kick-off or a Sunday fixture.

51.] There should be available in the police control room the results of all close circuit television monitoring outside and inside the ground and the record of any electronic or mechanical counting of numbers at turnstiles or of numbers admitted to any area of the ground. Officers in the control room should be skilled in the interpretation and use of these data.

52.] Consideration should be given to the provision of a specific training course for senior officers presently acting as Police Commanders and those in line to do so. Such a course should include training in the basic strategy of policing football matches.

53.] Police authorities should review the charges they make to clubs for the costs of policing inside grounds so as to ensure that realistic charges are made. The Home Office should take steps to ensure consistency of practice, subject to local discretion and the need to have regard to local circumstances.

Communications

54.] There should be sufficient operators in the police control room to enable all radio transmissions to be received, evaluated and answered. The radio system should be such as to give operators in the control room priority over, and the capacity to override, others using the same channel. Additional channels should be used, where necessary, to prevent overcrowding of the airwaves.

55.] There should always be a command channel solely reserved for the Police Commander to communicate with his senior officers around the ground.

56.] To complement radio communications, there should be a completely separate system of land lines with telephone links between the control room and key points at the ground.

57.] Within the control room, there should be a public address system to communicate with individual areas outside and inside the ground, with groups of areas or with the whole ground. Important announcements should be preceded by a loud signal to catch the attention of the crowd despite a high level of noise in the ground. This arrangement should be prominently advertised on every programme sold for every match.

58.] Use should be made where possible of illuminated advertising boards to address the crowd.

Co-ordination of Emergency Services.

59.] The police, fire and ambulance services should maintain through senior nominated officers regular liaison concerning crowd safety at each designated sports ground.

60.] Before each match at a designated sports ground the police should ensure that the fire service and the ambulance service are given full details about the event, including its venue, its timing, the number of spectators expected, their likely routes of entry and exit, and any anticipated or potential difficulties concerning the control or movement of the crowd. Such details should be readily available in the control rooms of each of the emergency services.

61.] Lines of communication, whether by telephone or by radio, from the police control room to the local headquarters of all emergency services should be maintained at all times so that emergency calls can be made instantly.

62.] Contingency plans for the arrival at each designated sports ground of emergency vehicles from all three services should be reviewed. They should include routes of access, rendezvous points, and accessibility within the ground itself.

63.] Police officers posted at the entrances to the ground should be briefed as to the contingency plans for the arrival of emergency services and should be informed when such services are called as to where and why they are required.

First Aid, Medical Facilities and Ambulances

64.] There should be at each sports ground at each match at least one trained first aider per 1,000 spectators. The club should have the responsibility for securing such attendance.

65.] There should be at each designated sports ground one or more first aid rooms. The number of such rooms and the equipment to be maintained within them should be specified by the local authority after taking professional medical advice and should be made a requirement of every Safety Certificate.

66a] At every match where the number of spectators is expected to exceed 2,000, the club should employ a medical practitioner to be present and available to deal with any medical exigency at the ground. He should be trained and competent in advanced first aid. He should be present at the ground at least an hour before kick-off and should remain until half an hour after the end of the match. His whereabouts should be known to those in the police control room and he should be immediately contactable.

b.] At any match where the number of spectators is not expected to exceed 2,000, the club should make arrangements to enable a medical practitioner to be summoned immediately to deal with any medical exigency at the ground. He should be trained and competent in advanced first aid. The arrangements made should be known to those in the police control room.

67.] At least one fully equipped ambulance from or approved by the appropriate ambulance authority should be in attendance at all matches with an expected crowd of 5,000 or more.

68.] The number of ambulances to be in attendance for matches where larger crowds are expected should be specified by the local authority after consultation with the ambulance service and should be made a requirement of the Safety Certificate.

69.] A "major incident equipment vehicle", designed and equipped to deal with up to 50 casualties, should be deployed in addition to other ambulance attendance at a match where a crowd in excess of 25,000 is expected.

Offences and Penalties

70.] Consideration should be given to creating an offence of selling tickets for and on the day of a football match without authority from the home club to do so.

71.] Each of the following activities at a designated sports ground should be made a specific offence:-

i. throwing a missile;

ii. chanting obscene or racialist abuse;

iii. going on the pitch without reasonable excuse.

72.] Consideration should be given to extending the courts' powers to make attendance centre orders for football related offences on occasions of designated football matches. The provision should be capable of imposition on an offender aged 21 or over and subject to a maximum of 72 hours in the case of an offender aged 17 or over.

73.] Consideration should be given to the use of electronic monitoring (tagging) in the sentencing of offenders convicted of football related offences.

Green Guide

74.] As a matter of urgency, the Home Office should set up a body to revise the Green Guide in accordance with this Report, these Recommendations and the Report of the Technical working Party (Appendix 3).

75.] In any revision of the Green Guide, the values to be achieved by way of percentage recovery after the required loading tests on crush barriers should be specified. Acceptable values for various materials should be specified.

76.] When the Green Guide is revised, the need to inspect crush barriers for possible corrosion should be specifically mentioned and emphasised.

APPENDIX THREE.

9.3.0. DEVELOPMENT OF PLAYING SURFACES.

9.3.1. Ninian Park Football Ground Cardiff Wales UK.

9.3.1.1. Introduction.

The purpose of this paper is not to outline the history of Cardiff City Football Club which has played at Ninian Park since 1910 when the development of the ground began. The Club's history has been set down in the 'Official History of the Bluebirds, Crooks, J (Yore 1992)' and in C'mon City, Lloyd G, Seren, 1999. Simon Inglis has also set out a compact introductory history of the Club, in his book, Football Grounds of Britain. Collins Willow, 2nd Edition 1987.

The purpose of this paper is to trace specifically the development of the playing surface and some aspects of the accommodation for spectators. The assumption has been made from tracing the development of football grounds in the UK that the development at Ninian Park is not dissimilar in the earlier stages of its development to many other football grounds around that time.

9.3.1.2. The Development of the Ground.

In 1910, Cardiff City Football Club had been accepted into the Second Division of the Southern League. The club found a five-acre site, a former rubbish tip, which had to be transformed into a playing pitch within three months to meet the Club's playing commitments. Volunteer labourers helped to finish the pitch. The following is an account, by one of those volunteers, of what happened from June to September:

> It had been decided that the area which sloped away from the railway should be built up to form an embankment along the length of the playing pitch, the site of which had been staked out and ran parallel to Sloper Road. We proceeded to dig and level the site of the pitch, wheeling the spoil in barrows where it was tipped onto the bank, while local factories and the gasworks on Penarth Road sent along ashes and clinker from their furnaces, until enough had been tipped to form a quite substantial bank. The spectators who later came to stand on this bank suffered whenever there was a stiff wind, since the dust and ashes flew up causing them to resemble coal-miners who had worked hard at the

pit. To complete the embankment, large wooden hoardings were built along the top to prevent free viewing and access from the railway.[1]

Eventually, low ash banks were raised on all four sides of the pitch which was enclosed by a white picket fence. A small wooden grandstand with a canvas roof and room for about 200 spectators was built and turnstiles were installed at the Canton End. Dressing rooms and offices were provided in a wooden building in the corner of the field at the Canton End. The pitch, having been laid out on an old rubbish dump, was rough and needed a lot of rolling. On match days, players and spectators would have to remove pieces of coke and glass, which had worked their way to the surface.

One of the players recalls, "when our first-ever professional team reported for training, we were told we would be paid 6d an hour for picking up glass from the playing pitch: everyone jumped at the offer".

During the close season of 1920 the Canton stand with its unique bench seating was begun and completed a year later..... The condition of the playing surface was improved by re-turfing the surface with sea-washed turf by expert men, the pitch now being equal to the best in the country. An appeal was therefore made to all not to run over the field after the match. Thousands of tons of ashes etc. have been utilised to improve the banks especially at the Grangetown end of the ground, whilst the new stand has been covered and many other improvements executed at a cost involving thousands of pounds.

Re-turfing with sea-washed turf was to prove a failure, as the playing surface became "increasingly troublesome". Tons of dressing had been used to induce a better growth of grass and to remove the treacherous surface caused by the sea-washed turf with which the pitch had been laid a couple of years before.

Despite this work, the poor quality of the playing surface remained a great concern. Tons of virgin soil and sand, together with large quantities of special grass seed, have been strewn over it to bring about its present state. The pitch is better today than it has ever been in the history of the club.

The Shilling bank has been properly raked, the depressions filled in, and other work has been done for the comfort and convenience of spectators. Much has also been done in other

[1] Source unknown. Pages 41-42. Lloyd, G, C'mon City!, Poetry Wales Press Ltd, Bridgend, 1999.

directions, such as painting, maintaining and making good. A great deal of this is not visible to the majority of spectators.

> The City directors have invited Messrs Sutton & Co, the great seed specialists to send an expert to Cardiff to advise them. An interview has been arranged for next week and it is highly probable that in the near future some drastic measures will be taken for the improvement of the ground.

The poor state of the pitch was offered as a possible reason for the 0-0 draw with Darlington in a Cup tie at Ninian Park. Its 'deadness' made accurate passing almost impossible. After the return game at Darlington, which was again drawn, the Cardiff players described that playing surface as worse than Ninian Park had ever been. A third leg of this Cup tie was played at the neutral ground of Anfield in Liverpool. The suggestion was that, that playing surface was the best pitch Cardiff City had played on since September.

Large crowds were attracted to Ninian Park when the team was successful; the poor conditions for the majority of the spectators were not a deterrent. This was the case for most grounds in the Football League. But the issue that attracted the attention of the Directors was the poor condition of the playing surface. This issue remained relevant until the end of the period under review. There is sufficient evidence that there was both intent and endeavour on the part of the Directors to solve this problem.

The problem with the playing surface could not have been related to the absence of light energy or air as the configuration of the ground was too open for that to have been a cause. The Club Directors suspected the turfgrass species as the cause of the failure. But in all probability the main contributory factor related to the rootzone. " The pitch, having been laid out on an old rubbish dump, was rough and needed a lot of rolling. On match days, players and spectators would have to remove pieces of coke and glass, which had worked their way to the surface".

There are no records of the rootzone work or sub-soil drainage. What is clear is that the base of the original playing surface would have been toxic, being derived from refuse made up of ashes from coal or coke used in either domestic fires or industrial furnaces. The pitch surface would have also been heavily compacted. Photographic evidence shows that the level of the playing surface was raised over the years up to 1965. The original picket fence of 1910 had been replaced probably by 1922 with a concrete retaining wall.

When Cardiff City won the FA Cup in 1927 the Directors spent their share of the proceeds on covering with a roof the Grangetown raised terrace. The stand opened in1928 which coincided with a decline in team performances.

At this stage in its development the ground had five standards of accommodation:

- the open "Bob" bank.
- the covered Grangetown end.
- the Canton stand with bench seating.
- the stand located on the centre line facing north, in front of which there was an open enclosure.

In 1937 the centre stand burnt down and was subsequently replaced and extended in the late 1950s. The enclosure was at the same time remodelled by the formation of a concrete terrace. By 1965 the ground was complete. Its accommodation remained unchanged and was becoming dilapidated until Taylor was partially implemented.

Fig 9.3.1.2.1 Ninian Park circa 1910, showing the white picket fence separating the spectator area from the playing area. There are both spectators and club officials on the playing side of the fence.

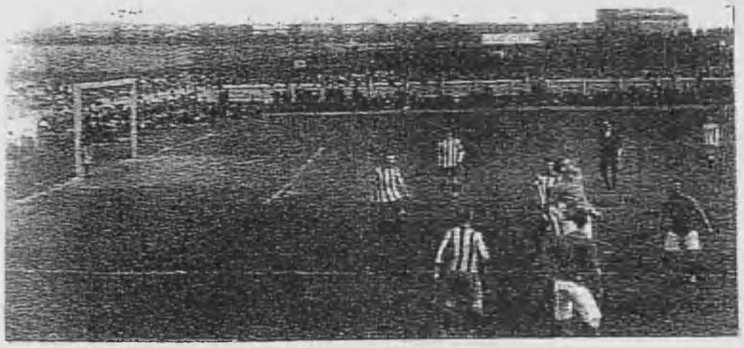


Fig 9.3.1.2.2 Ninian Park circa 1922. The white picket fence had been replaced by a concrete wall. The photograph shows the level of the playing field raised probably to increase the depth of the rootzone. This may have been carried out to alleviate the deleterious effect the toxic waste filling had on the turfgrass.

9.3.2. Artificial Playing Surfaces.

9.3.2.1. Introduction

Artificial Turf was originally developed incidentally as a playing surface for professional sport. The roots of its development started in the 1950s, when the Ford Foundation sought ways to improve the physical fitness of some sections of young Americans. Their concern began through observing the physical differences between youths from rural areas and those from urban areas.

> Youngsters from the country and small towns had ample grassy areas to run and play on without fear of falling and seriously injuring themselves. On the other hand, the city children had only limited areas on which to play and these were covered with asphalt or concrete surfaces which were hard and abrasive so falls often resulted in painful injuries. Consequently, it was concluded that the city children played with greater caution and their levels of fitness were lower. [2]

In the early 1960s, the Foundation's Educational Facilities Laboratory was considering with a subsidiary of the Monsanto Corporation called Chemstrand, the use of synthetic fibres for carpeting school buildings.

Because of the Foundation's involvement in the fitness programme Chemstrand were asked to develop a playing surface which would provide urban youth with more opportunities for recreational sport. The material had to be easy to maintain and retain its playing characteristics for a number of years: in 1964 a synthetic grass surface called Chemgrass was installed in Field House, Moses Brown School, Providence, Rhode Island, USA.

The failure of the natural turfgrass at the Harris County Dome, Houston, Texas, USA, (1964) prompted the need for a replacement surface. There was no option but to use an artificial playing surface. The Monsanto Corporation was asked to develop a version of Chemgrass. This material became known as Astroturf.

---

[2] Waddington, D.V. et al, Agronomy No 32, TURFGRASS, Madison, Wisconsin, USA. 1992, page 89

By April,1966 AstroTurf had been developed and installed on the baseball infield and by the summer the outfield was laid with it. The area for American Football was laid by the early fall of that year. The addition of 4.9 km of zippers made it possible to remove the turf and its underpad, which was installed directly over the earth floor. Removing the turf allowed rodeos, circuses, midget automobile races and cattle shows on the floor of the Dome. [3] **(Case study 9.4.1.)**

9.3.2.2. Composition of Artificial Playing Surfaces.

Two layers usually make up artificial turfgrasses. The upper layer can be woven, tufted or knitted; techniques and materials employed may vary with each manufacturer. The artificial surface is usually laid on a separate underpadding. Artificial surfaces may be used indoors and out.

The manufacturing techniques equate with those of the carpet industry. Mat widths will therefore be limited to 4·6 metres, determined by weaving techniques. The widths are linked to make up the playing area.

Materials used in the upper layer range from Polypropylene, Nylon, Polyolefin or Polyester. The surface fibres formed from these materials are attached to a high strength synthetic mat formed of the same material used in the artificial grass blades.

The second layer, the underpadding is separate from the top layer and has the purpose of absorbing load shock. It is made up from either polyvinylchloride or polyethylene. The under padding is an influential factor in the performance and durability of a playing surface. The underpadding is laid over a sub-base.

The sub-base has to withstand loads imposed on the artificial surface. The composition of the material used in it will depend on the factors of loading and its location. If the surface has to be waterproofed, the sub-base construction will equate to that of a lightweight road. The sub-base construction for an indoor location can be formed of consolidated hardcore with a blinding layer of medium to fine sand, or it may even remain as rammed earth depending on the bearing capacity of the soil. In a multi-use stadium with a retractable roof the sub-base may be

[3] Waddington, D.V. et al, Agronomy No 32, TURFGRASS, Madison, Wisconsin, USA. 1992, page 90

considered as a wholly external location, thereby allowing the greatest degree of flexibility in its use.

9.3.2.3. Artificial Surfaces in Stadia.

Artificial turf allowed the Astrodome to display football and baseball. But the artificial surface did more: it was influential in allowing a change in the design of stadia. Stadia could now be completely enclosed, incorporate high standards of comfort, safety and environmental control. Artificial surfaces also increased the range of multi-use activities in stadia. Between 1966 and 1987, John and Sheard report: of 13 large stadia built in the USA, 7 had artificial surfaces and 6 had closed roofs.[4]

The material originally intended to meet recreational standards in a fitness programme was now being used by professional sportsmen playing games at an energy intensity not envisaged when the original material was conceived.

The capital costs for artificial turfgrass are significantly higher than those for in situ turfgrass but by comparison, artificial surfaces need less maintenance. There are three simple rules for its maintenance[5].

- Keep it clean.
- Do not abuse it with vehicular traffic, heavy static loads, fireworks or open flames.
- Make all repairs promptly.

The extent and frequency of maintenance depends on whether the playing surface is knitted or tufted or woven. "Cost of maintenance of the synthetic surface, originally touted as minimal, has since proven to be as great or greater than natural turfgrass surfaces."[6] Artificial surfaces require protection from loads which fall outside the loading limits of the surface material. "The surface, subject to the degree of wear, should have a service life of at least five years. Many installations have been in use for 8 to10 years or longer without needing replacement"[7].

9.3.2.4. Artificial Turf and the Link with Injuries.

The increase in the speed at which games were played on the surface led to an anecdotal view by professional users in the USA in the mid 1970s that the use of artificial surfaces would

[4] John G &Sheard R.Stadia, A Design & Development Guide, Butterworth Architecture, Oxford,. 1994. Page 14
[5] Waddington, D.V. et al, Agronomy No 32, TURFGRASS, Madison, Wisconsin, USA. 1992, page 95.
[6] Waddington, D.V. et al, Agronomy No 32, TURFGRASS, Madison, Wisconsin, USA. 1992, page 83.
[7] *Ibid* page 94

increase injuries. Watson reports that "It [an artificial surface] lacks the resilience of natural turf and produces more wear and tear on the athletes, causing concern about career longevity by athletes, agents, and team managers. (G Toma, 1986, personal communication)"[8]

The American experience of injuries was that

> the knee and ankle injuries had reached near epidemic proportions particularly in tackle football..... The basic mechanism that results in many of these lower extremity joint injuries,.....is that the foot becomes fixed as a result of excessive traction and the shoe becomes locked into the turf when changing directions. The momentum of the body then places considerable stress on the ligaments of the joints, which frequently cause severe sprains or even ruptured ligaments.[9]

Since 1983 there have been three extensive European studies comparing player injuries on artificial and natural turfgrass.

> In 1983 the Federation of Ball Games in Berlin conducted comparative studies of injuries sustained on natural grass fields, synthetic pitches and hard porous surfaces. A total of 784 injuries were reported by soccer teams that played in all districts of Berlin. To make a valid comparison of the incidence of injury on the three different types of fields because of the varying number of fields of each type, coefficients of injury were calculated based on 1000h of field use per year. These injury coefficients were 2582 for natural turfgrass, 1863 for hard porous surfaces and 400 for synthetic turf. In this study, the higher numerical value indicated a relatively higher injury rate.[10]

The Winterbottom Study, England 1985, involved 1125 games on natural grass and 889 games on artificial turf.

A study two years later included 49 games played on natural grass and 153 games on a synthetic surface. In both these studies, injury rates were reported as the number of player exposures per

[8] Waddington, D.V. et al, Agronomy No 32, TURFGRASS, Madison, Wisconsin, USA. 1992, page106

[9] *Ibid,* page 83.

reportable injury, where a reportable injury was defined as one that kept a player from participation for 4 days or longer.

> The injury rates reported in the initial study conducted during the 1978 season were 1:80 on the natural grass and 1:90 on artificial turf. In games played during the 1980 season the injury rates reported were 1:49 and 1:56 for games played on natural turfgrass and artificial turf, respectively. [11]

The significant increase in the factors of use of artificial surfaces has little impact on the professional game. Scheduling of games would not allow it. In any event the surface is not acceptable for games played at the highest level [to various governing European bodies]. The exception to this is Field Hockey. Despite the doubts raised about the impact the surface has on injuries, the surface allows hockey players to develop their skills in the certainty of a pitch, which is true, devoid of rutting, surface tearing and when watered, very fast.

Beard and Sifers reported their conclusions after carrying out tests on a wide range of surfaces including concrete, asphalt, artificial turf and natural turf: "that natural turf is between 40% and 75% less hard than artificial turf ".

This work follows the 1994 survey conducted by the National Football League Players Association of 965 professional American football players in the USA. The findings of this report are as follows:
85% preferred to play on natural turfgrass.
93% believed that artificial turf was more likely to contribute to an injury.
54% identified an artificial turf injury they believe would not have occurred on grass.
70% said they would rate a grass pitch very or somewhat important in selecting a team for which they would play. *Source of information. Turf Management, June 1995.*

Richard Dodds, Captain of the Great Britain 1988 Olympic gold medal team, is reported to have said that

> There has been a shift away from plastic pitches in National Football League (NFL) stadiums following a cluster of injuries. Of the 30 NFL teams, 16 now play on artificial surfaces and 14 on natural grass. Most users accept that abrasions are more common on

---

[10] Waddington, D.V. et al, Agronomy No 32, TURFGRASS, Madison, Wisconsin, USA. 1992, page 120.
[11] *Ibid*. page 120.

synthetic surfaces than on grass. If players slide on the plastic pile of sand they will scrape their skin more severely than on natural turf "[12].

9.3.2.5. Comparative Use Factors Between Artificial and Natural Turfgrasses.

Subsequent studies show that artificial turfgrass demonstrates its superiority over natural turfgrass in its factors of use.

1975 the British Sports Council reported that where floodlighting was available 35 matches could be played over a weekly period, whereas the rule was that on average only 3 matches a week could be played on natural turfgrass.

1977 Statens Naturvardsverket reported that the artificial turf in the Valhalla Stadium, Gothenburg received 5761 hours of use over 2 years. He concluded that this Association Football field had a use factor 12.5 times greater than when the field was natural turfgrass.

1979 Leach compared the use of an artificial surface in Atwood Stadium, Flint, MI with natural surfaces. He concluded " that one synthetic field could handle the same amount of activity as 17 grass fields". Waddington, *et al* suggests that this statement does not seem to take into account the problems of scheduling.

9.3.2.6. A European Overview of Artificial Turfgrass.

The major display sports in Europe are the various games of Football and in particular Association Football; these games when played at the highest level must be played on natural turfgrass. For a number of reasons the maintenance of in situ turfgrass in large stadia is problematic. In recognition of this, towards the end of the 1980s three English Football Association clubs were given permission to use artificial playing surfaces in League matches. In 1988 this permission was withdrawn because the high bounce factors produced by the surface had a negative influence on the Game. In addition, players expressed doubts about the greater potential for immediate injury and the potential for long term wear on joints and limbs.

Without research aimed at matching the characteristics produced by in situ turfgrass, it is unlikely that the artificial grass will become the principal surface in European stadia where Association Football is played.

[12] Sunday Times Report on a lecture Richard Dodds gave to Medical Council.

However, a member of the UEFA playing pitch committee suggested in correspondence [1997] that, "ultimately they [UEFA] expected to see all games played on artificial surfaces".[13] Currently UEFA will allow Games to be played on artificial surfaces where there is limited opportunity to grow and maintain natural turfgrass, for example, above the Arctic Circle.

APPENDIX FOUR.

9.4.0. CASE STUDIES.

9.4.1. Harris County Dome, Houston Texas, USA, 1965.

9.4.1.1. Introduction.

The case study of this enclosed stadium is included even though its roof is not retractable. This is warranted on the grounds that the Harris County Domed Stadium, Houston, Texas, USA, was the world's first large purpose designed multi-use stadium. It had a maximum capacity of 66,000. The stadium was to be known as the Astrodome called that after the Houston Astros Baseball Team. This study describes the building and considers the influence the building had on the natural turfgrass playing surface and artificial playing surfaces.

The importance of this stadium was that it introduced a sea change in the way stadia were to be perceived. It set future standards for spectator comfort and for arena flexibility. The aim of this stadium was to display under cover American Baseball and Football on an in situ natural turfgrass: in those objectives it failed. The in situ natural turfgrass had to be replaced by an artificial playing surface to allow the stadium to function in respect of those two games.

However, in the USA the consequences of this development were threefold: firstly, stadia would become places that were safer and more comfortable; secondly, stadia would be perceived differently by both spectators and players; thirdly, future stadia would display a range of uses exceeding in number and variety the traditional displays of baseball and football.

These benefits were generally perceived to follow from the change to an artificial surface. There were the additional contributory factors such as comfort and amenity, unrelated to the playing surface. But the commercial contribution made by the artificial surface encouraged over the next 10-15 years a tendency to install artificial surfaces in North America whether stadia were open or closed. **(6.2.0.1.).**

John and Sheard Editions 1&2, record that thirteen large stadia were built in North America between 1964 and 1989. Large is defined as having spectator capacities for certain

---

[13] Correspondence between FIFA Pitch Committee Member and Phillips J

playing surfaces on a permanent basis in any enclosed stadia and the open stadia were generally provided with artificial playing surfaces. Nevertheless, despite this commercial movement there was an apparent growing dislike amongst the players for the artificial surface. It was in some of these open stadia that the return to natural turfgrass was made possible. Despite the move back towards natural turfgrass the Astrodome had provided the basic prototype for the advance in stadia development

Fig. 9.4.1.1.. Internal view of the Astrodome.

Fig. 9.4.1.2. Bird s Eye view of the Astrodome.

9.4.1.2 Case Study

Until the completion of the Louisiana Super Dome in 1975 the Astrodome was the world's largest domed stadium, with a diameter of 216 metres over the roof ring beam and a maximum ceiling height of 63 metres.

The domed roof was constructed of six continuous rings of fabricated steelwork. Each ring was connected by triangular steel supports formed into diamond units, each advancing up the curve of the roof to its zenith. Mario Salvadori points out that this roof weighed 30 pounds per square foot.[14] . This weight is economical for such a span and is made possible through the form of the dome. Salvadori however, limits his observation to the principal structure. The secondary structure supported over 4500 natural translucent panels which were glazed with cream plastic sheets. These units reduced further the light emission factor into the stadium.

> When the stadium finally opened in 1966, two years after the failure of the in situ turfgrass, it was equipped with an artificial playing surface. At that time the stadium provided 66,000 seats for concerts, 62,439 for American football and 52,314 seats for baseball. Most of the 45,000 fixed seats were distributed in three concentric galleries, each with differing capacities. The varying residual accommodation was provided by defining the areas required within the arena for football and baseball. The reconfigurations were formed by moving the removable or folding seating to the shapes required for the varying activities. The ease with which the stadium could be reconfigured was demonstrated by the statistic that "286 events were staged or scheduled to be staged during 1986."[15]

The events displayed at the Astrodome extend beyond the display of the conventional sport to include circuses, rodeos, and political and religious conventions.

There are over 50,000 upholstered seats with matching backs. These seats are equivalent to those installed in major theatres. The stadium pioneered the ideal of luxury Sky-Boxes, which included private dining facilities. There is also a number of public dining areas overlooking the arena.

---

[14] Salvadori M, Why Buildings Stand Up, WW Norton & Co, New York, London. 1990. Page 245.

[15] Discussion with stadium manager during a visit to the stadium. Phillips. August 1986,

The Astrodome is fully air-conditioned and has a cooling capacity of 6,600 tons during events. The system circulates 2.5 million cubic feet of air per minute during events. When the conditioning system is in operation 250,000 cubic feet of fresh air is drawn into the stadium every minute.

9.4.1.3. The Natural Turfgrass Playing Surface

Little is published of the detail of the original natural turfgrass surface except that it was seeded with Tifway 14, Bermuda grass. The details of the composition of the rootzone or the means of the rootzone drainage are not recorded. The assumption must be made that there was a sprinkler system included in the design.

What is recorded is that three days before the initial opening of the Stadium on the 12th of April,1965, an exhibition baseball game, between the Astros and the New York Yankees, demonstrated that the diamond-shaped openings formed by the roof construction were filled with acrylic transparent panels. "The bright light made it impossible for the baseball players to discern fly balls"[16]. Fly balls are those balls, in baseball, that are hit high and long and appear to hang in the air before descending.

To counter this problem the roof lights were painted a semi-opaque white, the consequence of which was that the turfgrass beneath it died. This necessitated vital and early action. Development work had been carried out on Artificial turf surfaces since the early 1950s but the Astrodome failure focused that development on material suitable for professional players. From this work evolved the plastic turfgrass which became known as Astroturf. The new surface was laid in the Dome for the opening day, 1966.

> A commentator suggests that it was the painting of the panels that caused the grass to die. Subsequent desk research experience for this thesis indicates that the grass would have failed in that environment even if the panels had not been painted, thus confirming the John and Sheard comment that "No transparent or translucent roof yet permitted the growth of natural turf suitable for playing ball sports".[17]

---

[16] Provoost, M Edt The Stadium, The Architecture of Mass Sport, NIA Publishers Rotterdam,2000. page148
[17] Stadia A Design and Development Guide Geraint John And Rod Sheard Butterworth Architecture, Oxford 1994.

After overcoming the initial problems the stadium moved forward for sometime without serious competition from other stadia and consequently achieved a measure of commercial success. But after 25 years the building began to look and feel run down. The artificial surface also began to lose its appeal to the players who wanted to play on natural turfgrass. A new name had to be sought for the Dome because the Houston Astros were about to leave the stadium. The stadium had changed its name initially from the Harris County Dome to the Astrodome and now it was to be called the Reliant Dome.

David Mancia sums up the disaffection with the Astrodome as follows:
"It held its own for many years, but in the mid 1980s and 1990s, with the advent of the stadium boom, the Dome certainly began to show its age. Still an awesome structure to behold, the stadium wasn't responding to the new needs in sports design. The concourses were too dark and grossly undersized by modern standards. The sightlines of the circular seating bowl were recognised as inadequate. The quality of the luxury suites could not compete with the new modern facilities. After years of playing on both artificial and natural turfs around the country, teams began to prefer the natural turf. There was a move to get back outside- under the sun or stars-'and enjoy the game as it was meant to be'. Eventually, Houston's football team left the city and the Houston Astros began constructing a new retractable roof baseball stadium downtown. The only fulltime tenant remaining in the Reliant Dome in the mid to late 90s was the Houston Livestock and Rodeo Show".

> "A major renovation programme completed in 1989 increased the seating capacities to 63,001 for football, 54,370 for baseball, 68,000 for conventions, and a maximum of 74,000 for boxing or other similar events..... A new Monsanto 'Magic Carpet' system provides separate turfs for football and baseball..... The new turfs are housed in storage pits in the centre field and are rolled out on a cushion of air..... Each turf is marked for its sport and the new system substantially reduces the time needed for conversion of the stadium". [18]

The thrust of content of the Manica article, is not untypical of remarks about many similar large stadia in North America and elsewhere.

Some academics record the failure of many large stadia to establish long term financial stability. The reasons for this are not the subject of this thesis. It is however essential to be aware that these confirm the burdensome cost of providing high standards for spectator and player comfort.

In addition the retractable roof which is now increasingly becoming a desirable objective is very costly. The implementation of these standards not only increases capital and running costs, these high standards for spectator and player comfort have an impact on the physical form of stadia which in turn may have a direct detrimental impact on its natural in situ turfgrass.

9.4.1.4. The Artificial Surface

The Astrodome would have failed in its original design purpose without the development of the artificial surface. It would have been a commercial failure. Some details relating to artificial surfaces are contained in **(6.2.0.1)**. As it was, the artificial surface provided the stadium with a prominence that the normality of natural turf may not have attracted. The ease with which the surface could be reconfigured had a significant commercial impact on the financial turnover within a short period of time.

In the course of time the fashion of the artificial surface with all its commercial attractions was unable to sustain the stadium against the competition of other stadia with natural turfgrass, better sight lines and facilities. It did however take 25 years to arrive at that position.

9.4.2. Parc Olympique Stadium Montreal, Quebec, Canada (1976-88).

9.4.2.1. Introduction

Montreal, Olympic Stadium Quebec, Canada was the site of the first retractable roof over any large stadium. The intention was to install it for the 1976 Olympic Games. For political, economic, design and constructional complexities the work on the roof did not begin until seven years after the Games ended and was not completed until 1988. When completed the roof failed to function and soon remained in the closed position, until replaced by a new fixed roof in 1998.

The original roof retracted into a tower the lower point of which integrates with one curved end of the long axis of the oval stadium. The tower base extends 150 metres beyond that point. The tower contains commercial accommodation in addition to space required to house the machinery to open and close the roof. This case study concentrates on the roof, its complexity and ultimate failure. The roof typifies a philosophy of extravagance exercised on these Games which the following passage emphasises.

---

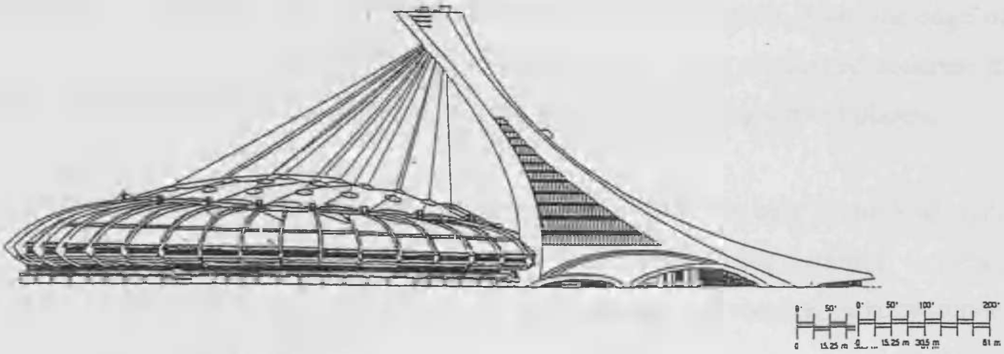
[18] David Manica Stadia Magazine, Feb2000.

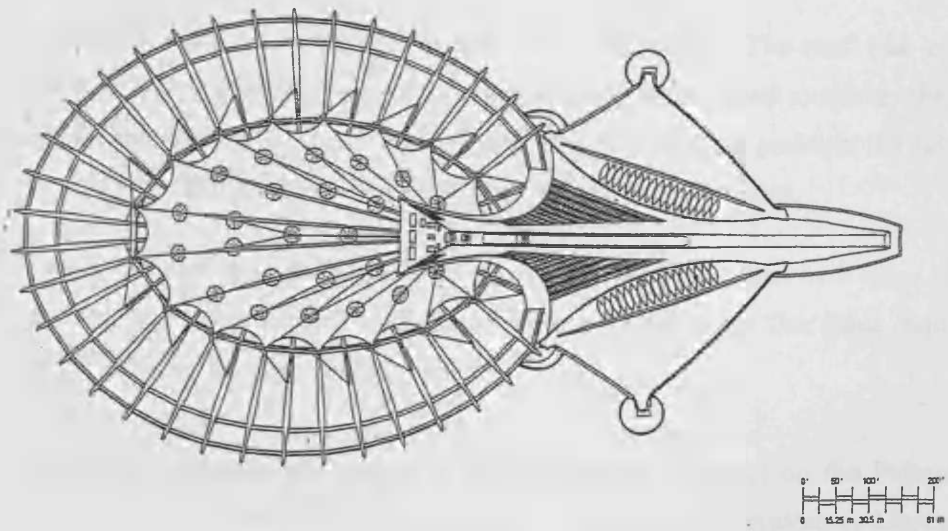
> It *(The Games)* will be remembered as a kaleidoscope of contradictory narratives and outcomes. Promised as 'modest' 'self-financing' Games, they ended up with such monumental facilities constructed with such little regard for their cost, that the Montreal Games became a byword for gargantuan extravaganzas. Yet the venues proved to be admirably suited for athletes and spectators, and the events were extremely well organised, enabling superb performances in virtually every sport.[19]

The retractable roof, which is the theme of this study, was formed of a fabric and was fitted between the outer edge of the grandstand roofs, which ran continuously around the stadium. The retractable roof was supported by twenty-six wires suspended from an arched reinforced concrete tower; the roof, when not required retracted into an opening on the underside of the tower.

Fig.9.4.2.1.

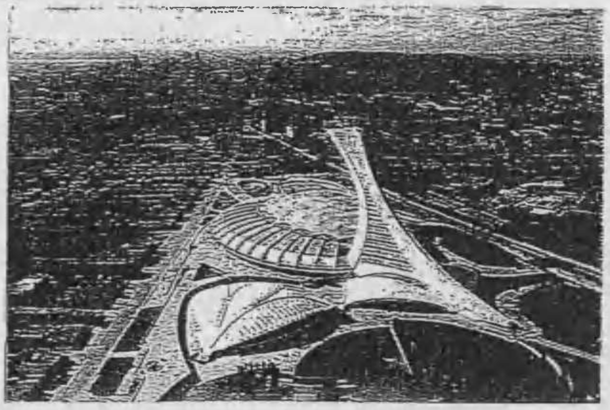
Illustrates the relationship between the Tower and the Stadium. It also shows the complexity of the plastic form of the Tower integrating with the form of the Stadium.





[19] Findling J & Pelle K. Edt Historical Dictionary of the modern Olympic Movement, Greenwood Press, Westport, Connecticut.& London. Page 153.

Fig. 9.4.2.2.
Illustrates the aerial view of the stadium with the retractable roof in the closed position. The Velodrome is sited below the Stadium.



9.4.2.2 The Case Study

The opening and closing concept for the roof was that it would be drawn into and extracted from an opening in the tower. The centre of the opening was 60 metres from one edge of the stadium's long axis, 120 metres above the surrounding ground. The reinforced concrete tower is an elegant complex arched form expressed as three gently converging curved planes.

The lower point of the tower integrates with one curved end of the long axis of the oval stadium; the base of the tower extends 150 metres beyond that point. The tower contains commercial accommodation and the space required to house the roof opening and closing machinery.

The retractable roof matched approximately the area of the arena. The roof was anchored by fixing points to the inner perimeter of the continuous cantilevered fixed roof over the stadium's grandstands surrounding the arena. When the roof was in its closed position the fabric arched between the anchor fixing points, allowing air movement at the perimeter.

However, when the roof was installed it proved too difficult to open and close. The fabric material used for the roof covering "was too stiff to accommodate the flex folds required in the operation of the retractable system employed".[20]

A Canadian stadium architect who was also the supervising architect on the Fukuoka Dome, Japan, provided further confirmation of the failure of the retraction system at Montreal. "The

[20] (Correspondence, Radcliffe Douglas C. Vice President Birdair Corp. USA 02.January 2001).

roof [he said] in practice proved too complex to move with facility and was abandoned as a retractable roof."[21]

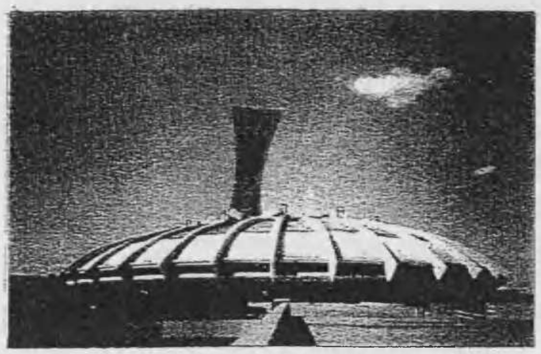


Fig.9.4.3.1.
Shows the opening in the tower designed to receive the fabric.

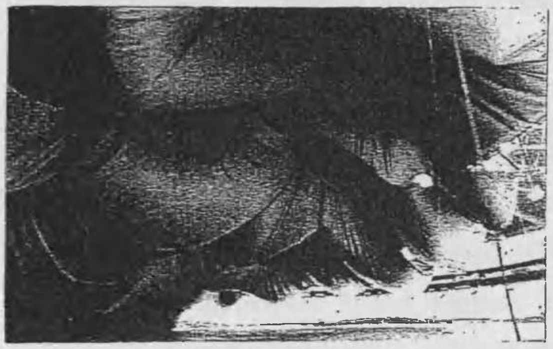


Fig.9.4.3.2.
The beginning of the process of withdrawing the fabric into the tower.

The fabric needed to be repaired regularly owing to a breakdown of the material from exposure to the elements and from the structural influences imposed by snow loads etc. The roof continued to attract abnormally high maintenance costs. In 1990, the roof had to be fixed in the closed position. It remained in this position until 1996 when the process of replacing the roof began; it was completed at the end of 1998 at a cost of 54, 000,000 $C.

The anecdotal evidence is that the maintenance costs attributed to the roof and the management facilities for the entire complex were estimated separately as 1,000,000,000 $C. These costs were in addition to the money required to fathom the issues related to the method of retractability for the roof fabric.

9.4.2.3 The Original roof. (Background information)

The Architect Taillibert provides the background to the generative ideas for the design of the roof of the Olympic Stadium and the other Olympic Buildings in 'Le Dossier' (Ce Tire a PART EST UN SUPPLEMENT DE GALERIE-DES ARTS NOI56 EDITE PAR REVUES ET PUBLICATIONS. 106 RUE DE RICHELIEU PARIS. 2e. GERANT: ANDRE PARINAUD. Undated).

This case study is based on the writings in 'Le Dossier', the comments of critics, a 1986 visit to the Stadium and The Historical Dictionary Of The Modern Olympic Movement Edited by

[21] (Source – telephone conversation with M Murray, Canadian Architect, September 1996).

Findling John E. And Pelle Kimberly D. Greenwood Press West- port, Connecticut. London 1996, (pages 153-160).

Taillibert describes his work at Montreal as "a masterpiece of textile architecture". This quotation, if true, must be limited to the form of the roof; the rest of the superstructure is mainly constructed in reinforced concrete. The external appearance of the building as a whole is one of plasticity, which is subjectively both unified and arresting.

During a visit in 1986 by the candidate, the retractable roof was not in place, but work was proceeding on the concrete tower designed to house the roof suspension system. The playing surface of the arena was natural turfgrass, as it was during the Games. The condition of the turfgrass was that it was kept long (50mm); it was green and without brown patches. The percentage turfgrass cover was not known but it appeared visually satisfactory. The stadium was at that time like any large compact club stadium with a centrally located open space above the playing surface, but with the advantage as far as the turfgrass was concerned of an athletics track surrounding the turfgrass playing surface. The track space contributes towards the open conditions, which allow higher levels of light over the playing surface.

Whilst there was no visual evidence of the retractable roof, there was however, much evidence of the deterioration in the construction details of the more complex buildings. These failings could be indicative of a number of factors: complexity of the detail design, poor workmanship, unrealistic programming and consequent over-manning of tasks leading to lack of financial control.

The retractable roof was developed in the post Olympic period in a climate of considerable financial embarrassment caused through a massive overspend on the capital overspend. The competitive element of the Games was highly successful and the quality of the facilities contributed to that success.

> The "total revenue of the 1976 Olympics was $C430 million, against operating expenses of $C207 million..... It is only when the capital cost of building the facilities is entered that the shortfall became $C1.2 billion".[22]

It is not the purpose of this thesis to trace the route through which these Games procured such monumental facilities, or how, as a consequence, these Games spiralled into a financial

[22] The Historical Dictionary of The Modern Olympic Movement Edited by Findling John E. and Pelle Kimberly D. Greenwood Press Westport, Connecticut. London 1996 (page 158).

shortfall of C$ 1.2 billion. A bibliography schedules the literature, which records this detail on pages 159-160 of The Historical Dictionary of The Modern Olympic Movement, Edited by Findling John E. and Pelle Kimberly D. Greenwood Press Westport, Connecticut. London 1996 (pages 153-160).

The completion of and the ultimate failure of the retractable roof not only changed the way the stadium could be used but also the playing characteristics of the playing surface. A roof over the stadium was deemed necessary because of the Montreal climate, which had a record of disrupting team games.

When the retraction system failed, the roof had to be fixed closed. As a consequence, the playing surface had to be changed from natural to artificial turfgrass.

The fact is that the two retractable roofs first developed, Pittsburgh, 1961 and Montreal, 1976-88 both failed to operate successfully. The first successful completed retractable roof was the "National Tennis Centre, Flinders Park, Melbourne, Victoria, Australia 1985-87"[23].

The cost of both Canadian stadia with retractable roofs exceeded their planned budgets: The Skydome, 1989 by 300%, the Olympic Stadium, it was suggested by 1000%. The reality is the whole project was out of strict financial control, with the consequence that it is difficult to apportion the degree of overspend attributable to the roof. What is surprising is that even after the availability of a twelve year period for refinement and contemplation the roof failed to fulfil its primary functions of being watertight and providing a failsafe retractable system.

The designers of the SkyDome Roof 1984-89 when they developed the retractable roof were aware that they had to maximise the extent of the free area over the stadium. This strategy allows as much light as possible to penetrate into the cavea, thereby increasing the possibility that natural turf grass will grow there.

The Architect of the SkyDome is critical of both Taillibert and other European stadium architects for persisting with the concept of the centrally located retractable roof. It is this strategy, he suggests, that adds to the difficulties of growing turfgrass in stadia.

Taillibert, if he was aware of the difficulties of growing turfgrass in stadia, did not discuss these issues in 'Le Dossier'. Sufficient written evidence existed, recording the failures of the natural

[23] Cox Architects. Selected and Current Works. Edited By Dobney S. The Images Publishing Group Pty Ltd 1994. (Pages 72-75)

turfgrass at the Astrodome, Houston, United States of America, 1964, for him to be aware of the issues.

The lessons drawn from this Case Study are that any innovative design especially where engineering dynamics are involved needs to be fully researched before being applied in any climate. The method of operating the roof was prone to failure, a failure made even more certain by the extremes of the Montreal climate. The 20,000 sq metres roof material was too stiff to fold into the shapes planned for it; the more it was folded the less integral became its water proofing qualities and these factors were exploited by the severe Montreal Climate.

9.4.2.4 The Replacement Roof

When the decision was taken to provide a new fixed roof it was taken to stem the maintenance costs on the membrane of the retractable roof. The installation of a permanent fixed roof implies that abandonment of reinstalling a natural turfgrass playing surface.

> " The actual roof membrane now being utilized is made up of two membranes, the outer is a PTFE coated woven fiberglass (Sheerfill by Chemfab), the inner membrane is a PVC coloured liner - Seaman's 8028 grade (28 ounce/sq.yard) material.
> The approximate distance between the outer and the inner liner is 7 meters from top to bottom, but there is a tapering as the design closes around the perimeter. Installed between the two membranes is a batt insulation, with forced heated air for snow melting requirements, as well. The liner has "boots" along the liner cables primarily used for venting pressure, but there are no vents in the membrane. Any ventilation for smoke would be at the perimeter beam, which was not part of our contract. Owing to the design requirements for insulation, the % light transmission through the roof is virtually zero".[24]
>
> "The stadium presently is host to the Montreal Expos of the Major League Baseball and the Montreal Alouettes of the Canadian football League. The purpose of installing the roof was that the then owners of the stadium "Regie des Installations Olympiques (RIO) wanted to add more revenue capabilities"[25].The current position is that the football club, "The Alouettes of Montreal, no longer play in the Olympic stadium. They now use a smaller but open stadium in the centre of Montreal".

---

[24] (Correspondence between Phillips J and Radcliffe Douglas C. Vice President Birdair Corp. USA 02.January 2001).
[25] Radcliffe, Douglas,C. Panstadia International Quarterly Report Volume 5/No 2 August, 1998 page 41..

Douglas Ratcliffe suggested in the above article that the initiators of the retractable roof were Regie des Installations Olympiques (RIO). They were not. The evidence is that the Mayor of Montreal, Jean Drapeau had encouraged French Architect Roger Taillibert of Paris, France to devise the main facilities in Olympic Park.

> " The Olympic Stadium was to include a fifty storey tower and a retractable roof. The engineering for the velodrome, 'a giant arc of a roof sweeping over glass walls, rising higher and higher with no visible means of support, then sloping back to earth,' was among the most complex in the world. Construction was frequently disrupted by Taillibert's penchant for last minute changes, the incompetence of contractors hired for political connections, and strikes and stoppages, in the context of continuing federalist-separatist and English-French tensions, and rapid inflation"[26].

This was the background to the incorporation of a roof with a complex and undeveloped system of retraction combined with a roof material which had not been previously used in similar situations.

These factors were combined with a stadium superstructure which in itself was complex in both its design and construction. Therefore, it was not surprising that such a roof was not in position for the Games.

Clearly the retractable roof was planned to be available for the Commencement of the Games in 1976. By the time RIO took over the stadium the failure of the roof was established.

RIO had since1990 the advantages of the ease of reconfiguration an artificial playing surface provides in a multi-purpose stadium. The only advantages the new fixed roof would provide were reduced running costs and an overwhelming advantage in spectator comfort. The disadvantage the stadium now has is that it lacks the environmental flexibility provided, for example, by the SkyDome.

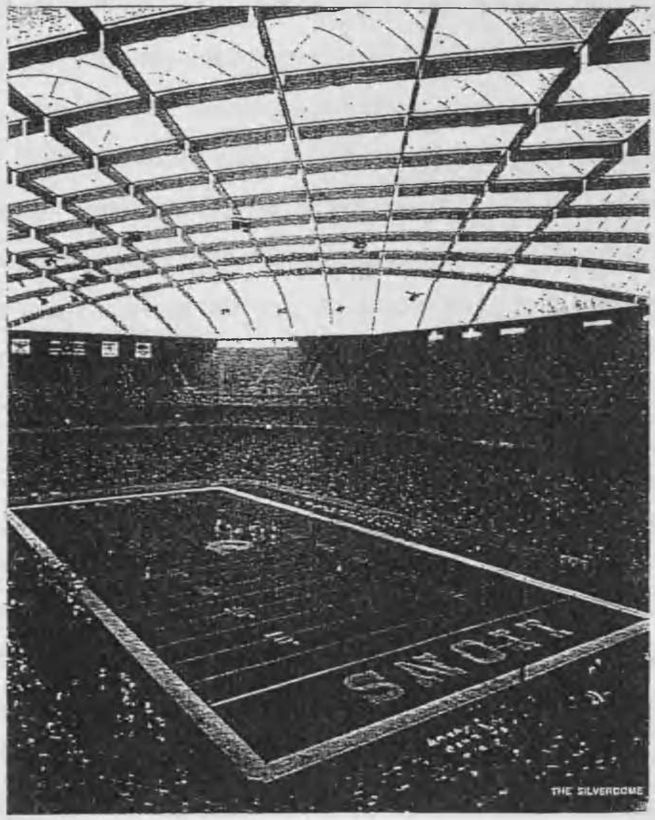
9.4.3 SILVERDOME STADIUM, PONTIAC, MICHIGAN, USA

9.4.3.1 Introduction

[26] The Historical Dictionary of The Modern Olympic Movement Edited by Findling John E. and Pelle Kimberly D. Greenwood Press Westport, Connecticut. London 1996 (page 154).

This is a covered stadium without a retractable roof. Its inclusion is warranted on the grounds that research associated with it established ways of providing in situ turfgrass playing surfaces in low levels of light. Problems in growing healthy turfgrass in an indoor stadium had been highlighted by the Harris County Dome Stadium, Houston, Texas, USA, **(9.4.1.)**. The Silverdome Stadium interior is shown in **Fig 9.4.3.1.**

Fig 9.4.3.1.
The interior of the Pontiac Silverdome Stadium, Pontiac, Michigan, USA. The artificial turfgrass playing area was changed for the FIFA 1994 World Cup



The research associated with the Silverdome carried out between 1991and 1994, demonstrated that if healthy turfgrass is introduced into large, enclosed spaces which provide environmental conditions equal to those encountered at the Silverdome, turfgrass can survive in the short term. Short term is defined as periods of up to 30 days.

Federation Internationale de Football Association (FIFA) in order to promote their game in north America wanted to stage their World Cup in 1994 in the USA, and in doing so use the Silverdome for some of its games and for the final match.

The normal playing surface of the Silverdome Stadium is artificial grass. Association Football at its highest level, can only be played on natural turfgrass. To meet this condition the Silverdome playing surface had to be changed to natural turfgrass. To maintain the economic viability of the stadium during the period of research, the research was carried out away from the stadium. This evidence allowed Association Football to be played at the Silverdome including the final match of the FIFA World Cup, USA, 1994.

> FIFA issued the following media release covering the condition of the playing surface.
> The natural turfgrass implanted in the Pontiac Silverdome has passed all the tests to which it was subjected in readiness for the World Cup final competition next year and can be reused for the tournament without any qualms. An inspection conducted by FIFA in the Detroit venue came to this conclusion after completion of a simulated World Cup fixture programme involving real matches and training sessions lasting eleven days. The turf planted on 8 June was still in good condition when it was dismantled on the 30 June that extra lighting will not be needed next year. During the tests it transpired that soft ultraviolet light will be adequate to maintain the quality of the turf. Ten per cent of the normal ultraviolet rays can penetrate the teflon roof canopy which is held aloft by indoor air pressure. The turf will be preserved in hexagonal containers close to the Silverdome ready for next year.[27]

Through the eventual work carried out by others the thrust of the Silverdome experiments took on further significance, resulting in the development of a playing surface system based on plastic pallets smaller in size than the metal pallets used at the Silverdome. A pallet was also formed in concrete was also developed. This pallet was large enough to contain the complete in situ turfgrass playing surface.

Both systems were used to move turfgrass to and from a stadium to facilitate multi-use displays and also aid the maintenance of turfgrass. The single pallet system was to prove more practical in its application, than the multi pallet system. **Case studies (9.4.7.and 9.4.8).**

9.4.3.2. Case Study

The Silverdome is one of a number of large stadia covered with a "Teflon coated fibreglass roof, supported entirely by internal air pressure and restrained by a diagonal network of steel cables. The roof membrane is 6% translucent".[28] These conditions produce insufficient levels of natural light to grow and maintain in situ natural turfgrass. Such low levels of light are of no relevance when playing surfaces are artificial.

FIFA, however, wanted to promote their Game in the USA, the Silverdome provided the opportunity to use a stadium with an 80,000 spectator capacity and was an indoor arena. Its drawback was the artificial surface.

Therefore the turfgrass scientists at the Hancock Research Centre, Michigan State University, Michigan, USA, were asked in 1991 by FIFA to consider the implications of installing and maintaining a natural turf playing pitch inside the Pontiac Silverdome Stadium.
"Preliminary research was conducted inside the stadium during June/July 1992. Grass types, Plant Growth Regulators (PGRs) and supplementary lighting were evaluated".

The solution proposed was to a provide a natural turfgrass playing area for the stadium by growing turfgrass away from the stadium, in open conditions and in multiple pallets. The pallets were then re-assembled in the stadium to form the playing pitch.

9.4.3.3 Outline Detail of the Experiment

The stadium's commercial schedule made it impossible to conduct the experimental work within the stadium and comply with the F.I.F.A schedule to prove the concept by June,1993. Therefore, during August1992 a research dome was built at the Hancock Research Centre. "The experimental dome was covered with the same fabric as that used on the Silverdome roof. The dome provided 6,600 sq. ft of research space, which approximates to one-tenth of the area of an average professional Association Football pitch."[29].

---

[27] FIFA Media Service, 1. July 1993.

[28] Stadia, A Design and Development Guide, 1st Edition. Geraint John and Rod Sheard, Butterworth Architecture, page 73, 1994.

[29] (Indoor Turf/World Cup '94 Project Update Michigan University).

"Lack of suitable light poses the greatest obstacle to maintaining turf grass inside the stadium as the fabric transmits less than 10% of total shade and filters out much of the blue light critical for plant growth. Diseases, heat, and moisture problems have also proved to be important factors in the management of turf grass."

The factor of translucency quoted by John and Sheard was 6%; the figure quoted in the experiment is 10%. The lower figure is the theoretical figure produced by the manufacturer. The higher figure probably takes into account the transmission losses through airborne pollution and also the influence of accumulated dirt on the external fabric of the stadium.

During January 1992 a prototype of a portable modular container for the turf grass was developed inside the research dome. The eventual playing surface was formed from 1838 steel hexagon modules, each covering 48·7 sq.ft., 88 triangles, each covering 12·2 sq. ft and 37 trapezoids, each covering 24·4 sq. ft. Each module was 6·75 inches deep, the top band of which was removable.

The steel units were placed side by side, remote from the stadium. A 3,300-ton mixture of sand, peat and loam to fill them had been mixed from 2-4 January, 1993 and stored for use. The sod which consists of a mixture of 85% Kentucky Blue Grass *(Boa pratensis)* ad 15% perennial rye grass *(lolium perenne)* was grown in California in the winter of 1992/93 and shipped to Michigan by refrigerated trucks.

Prior to sodding, which took place between the 12Th and 22ndof April, the hexagon modules had been levelled, filled with soil and compacted. Sodding (turfing) took place at the rate of 10,000 sq.ft. per day. At that work rate over that time period it produced a turf area required for the pitch and also a 6% margin for the failure of seed germination and additionally, a margin for excessive turf wear.

The field was constructed between 1st March and 22nd April. Between 10 and 30 people worked on the construction for a 10-12 hour day over that period. It is assumed the time factors for the manufacture of the hexagon pallets were excluded from those labour figures. Local golf courses, lawn care companies, M.S.U. students, staff and faculty supplied the labour.

Between the latter half of April and the beginning of June the field was mown and irrigated daily to encourage high-density plant growth and to prevent moisture stress. Six travelling sprinklers were used to irrigate the field. Reel mowers were used to provide a high quality cut at low moving heights (2" initially then decreasing to 1·5" prior to moving the turf indoors). Fertiliser was applied bi-weekly to maintain a consistent supply of nutrients. Between 7th June and 11th June, 30 people worked over a 44-hour period to move the turf inside the stadium on flat bed trailers. Forklift trucks were used to position the modules on the floor to form the field. Over the next few days the field was rolled and mown to prepare it for play. Seams between the individual modules were top-dressed and rolled to achieve a uniform, level playing surface. [30]

9.4.3.4. The FIFA Inspection

This technique which evolved from the experiments allows a pitch to be taken into and removed from a stadium as required. However, in this case the turfgrass was only brought into the stadium on two occasions. The first of these occasions was to demonstrate to the Board of FIFA that the experiment was a success. This they agreed as reported in their press statement.

"The turf planted on the 8th of June was still in such good condition when it was removed from the stadium on 30th June that extra light will not be needed next year. During the tests it transpired that soft ultraviolet light will be adequate to maintain the quality of the turf. Ten per cent of the normal ultraviolet rays can penetrate the Teflon roof canopy, which is held aloft by indoor air pressure. The turf will be held in its hexagonal containers close to the Silverdome ready for next year".[31]

The following events took place in the stadium during the inspection period:

18 June. 1993.
Germany played England in the first major football match played indoors on natural turf.

21 June.

U.S. National Women's Team played the Canadian Women's Team.

24-28 June

The Watch Tower Convention 1993.

29 June-8 July.

Two soccer matches were played.

'The field held up well, through all four games and team practice sessions. F.I.F.A. proclaimed the experiment a tremendous success'[32].

---

[30] (Indoor Turf - World Cup '94, Projects Update, Michigan University).

[31] FIFA Media Service 1.Juli 1993.

[32] (Indoor Turf – World Cup '94, Project Updates, Michigan University).

The field was removed and reassembled outside the Stadium over a period of 28 hours between 30 June and 2 July. No sections of the turf required reseeding or replacement. The field was maintained as a 'high quality athletic field' with daily mowing and irrigation. From mid-December to mid-March the field was covered to avoid desiccation.

From mid-March onwards (until the field was taken back into the Stadium over a working period of 30 hours), the field was mown daily and irrigated frequently by travelling sprinklers. To maintain a level surface, top dressings of sand were applied on several occasions.

Such was the quality of the turf assembly that no additional top dressing was required, as the seams between the hexagonal modules fitted tightly. The ball bounce and roll evaluations were deemed to be acceptable. 'Except for lining, the field was ready for play 24 hours after the last module was laid'.

The second occasion the turfgrass was taken into the stadium was for the World Cup Games. The pitch played well for the 30-days duration of the tournament.

During the installation, the field was rolled daily by using a combination of a single drum three-gang or mower type roller. Following rolling, the field was brushed to stand the turf upright for mowing. Occasionally, a turfgrass sweeper brush was used to remove turfgrass debris. The field was mown daily at a height of 2.4cm. Clippings were collected and discarded. Irrigation was unnecessary while the turfgrass was inside the Stadium.[33]

During the first week of installation the temperature and humidity were in the 90s. In order to promote drying and the prevention of turf disease, 12 industrial fans were moved constantly around the Stadium. To minimise turf grass stress, non-turf-related traffic, such as television cameras, advertisement signboards and visitors to the field were kept to a minimum.

---

[33] (Indoor Turf – World Cup '94 Projects Update Michigan University).

9.4.3..5. Schedule of Events for the FIFA World Cup

17 June. 1994.
Switzerland practised for 1.5 hours.

The U.S.A. followed with their practice session.

During the evening a video was shown and music entertainment was held.

18 June.
U.S.A. played Switzerland.
Despite the week of hot and humid weather, ideal neither for team nor spectators, the field condition after the game remained outstanding. No divots had torn through the turf grass mat layer to expose the soil, despite the use of steel cleats by many players. Divots were repaired the day following the game by lifting and pulling the sides of a worn area together, similar to fixing divots on golf greens.[34]

19 June.
Temperature dropped to 70/80^{0}F. and R.H. to between 60/80%.

21 June.
Rumanian Team practised for an unspecified time.

22 June.
Switzerland played Rumania.

23 June.
The Russian Team and the Swedish Team practised.

25/26 June.
Divots were repaired.

27 June.
The Brazilian Team practised.

28 June.
Brazil played Sweden. The final match.

After the finals on the 29/30 of June the sod was cut and sent to construct a new soccer field at Belle Isle, MI. The rootzone was sold to a golf course company to build nine putting greens. The steel modules were also sold.
The system was rated a success. Japanese developers considered using the system at the Fukuoka Dome (July 1994), but subsequently decided to use artificial turf as the playing surface.

---

[34] (Indoor Turf/World Cup '94, Project Update, Michigan University).

Research is reported to be continuing at Michigan to establish techniques to maintain turf grass indoors under low light conditions, in the long term, that is for periods of more than 60 days. Such duration could be suggested as representing a permanent basis. Whilst the arrangement was considered a success, this success must be considered in the light of the circumstances that the field was moved in and out twice and on the last of those occasions disposed of. There is no research for example, on the long-term maintenance and durability of the steel pans and the number of times the turf in those pans could have been used without total replacement.

During the time the field was lying fallow it was maintained to high standards and was protected from desiccation during the winter months. A similar field wintering in the UK would be subjected to playing seasons and recovery periods in less sympathetic conditions. It is reported that the cost of transporting the modules in and out of the stadium was £250,000. The authenticity of this figure is not available.

Whilst the arrangement was considered a success, this success must be considered in the light of the circumstances that the field was moved in and out twice and on the last of those occasions disposed of. There is no research for example, on the long-term maintenance and durability of the steel pans and the number of times the turf in those pans could have been used without total replacement.

During the time the field was lying fallow it was maintained to high standards and was protected from desiccation during the winter months. A similar field wintering in the UK would be subjected to playing seasons and recovery periods in less sympathetic conditions. It is reported that the cost of transporting the modules in and out of the stadium was £250,000. The authenticity of this figure is not available.

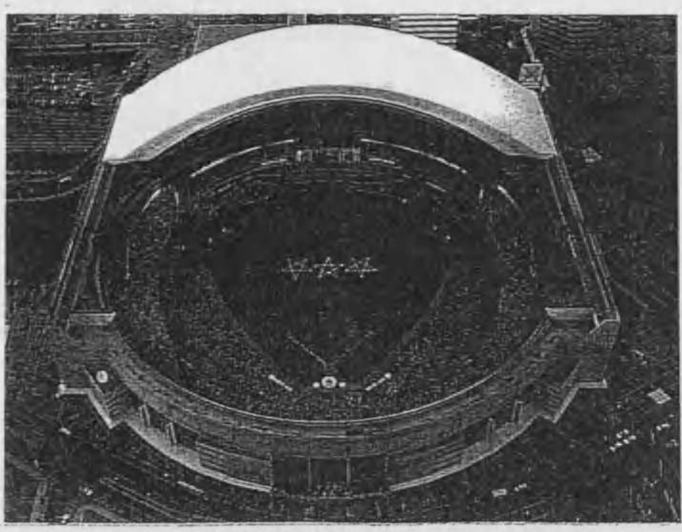
9.4.4. The Toronto Skydome, Toronto, Canada (1989).

9.4.4.1. Introduction.

The Skydome was the first large stadium with a successfully operating retractable roof. However, perhaps because of its complexity and high initial costs, there has been no other stadium built with identical methods of roof movement. There have been modified applications such as the roof of the Fukuoka Dome, Fukuoka City, Japan, opened April 1993. But this roof also has traces in its concept of the roof of the Pittsburgh Civic arena. The extent of the development time spent on the Skydome roof proved to be well founded, as this large innovative rotating overlapping panel roof has proved to be successful in the longer term.

Fig,.9.4.4.1. Skydome in Baseball Configuration.

Fig.9.4.4.2. The roof in the closed position.



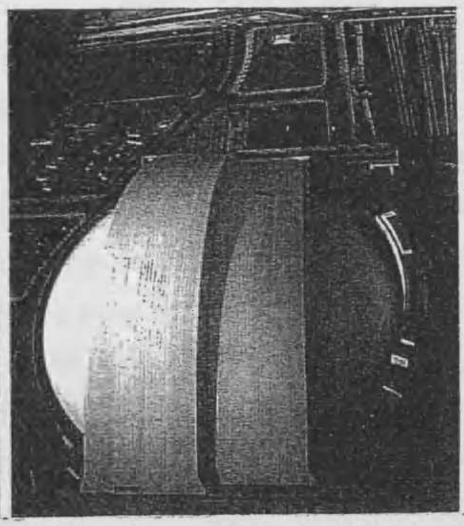


Fig.9.4.4.4. Cross Section with the roof closed.

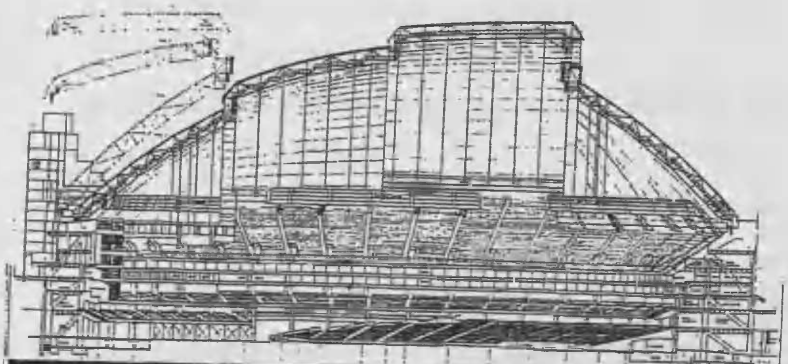


Fig. 9.4.4.3. Skydome In Football Configuration.

9.4.4.2. The Case Study

The Skydome is located on a downtown site adjacent to the Canadian National (CN) Tower, Toronto, Canada. The stadium spans 205m at its widest and has a maximum height of 86m. The spectator capacities vary with the reconfiguration of its cavea: 51,000 for baseball, 53,000 for Canadian football and up to 68,000 for concerts. A 'Skytent' can be introduced into the auditorium to allow for events which attract audiences of between "10,000 and 20,000" spectators, as such numbers would be inappropriate in the normal cavea.

Other facilities include 161 privately leased boxes, bars and restaurants, health club, retail outlets, Founders' club, Hard Rock Café and a Windows Stadium Restaurant. Besides the press and television facilities there is a media production studio. The stadium also includes a hotel with 348 bedrooms, 70 of which face the field. The hotel foyer has a drive-in plaza, which also provides a view of the playing arena, as does the hotel dining room and bar. However, the most conspicuous feature of the building is its arrangement for opening and closing the roof.

As a consequence of its downtown location the stadium has only 775 integral car parking spaces. Spectators using private transport use the existing 17,000 parking places in the centre of

As a consequence of its downtown location the stadium has only 775 integral car parking spaces. Spectators using private transport use the existing 17,000 parking places in the centre of downtownToronto. However, two underground stations, as well as the central overland railway station serve the stadium. The latter is linked to the SkyDome by a covered walkway.

The designers of the roof had taken into account the influence of the Toronto climate on both the dome surface finish and the mechanism responsible for moving the roof. The climate is one of extremes: in winter, there is heavy snowfall, cold winds and freezing rain; spring and summer provide pleasant weather; but these conditions are punctuated in summer by spells of hot humid weather, ending in thunder storms. Prior to the use of the Skydome stadium, sport in Toronto had suffered historically from the extremes of the weather.

In 1970 initial financial studies were undertaken to provide a stadium which would leave events independent of the climate.

In the summer, fans overwhelmingly wanted to be able to sit in the sun. Sitting in fixed roof stadia in good weather has proven to be unpopular with fans: sitting in open stadia in rain or snow is equally unpopular. However, it was not until the intervention of the Premier of Ontario in 1983 that it became clear that providing a roof over a stadium by itself was not enough. Consideration for the enjoyment of sport and concert fans, commercial needs of teams and the ideal conditions for players and performance led to the conclusion that the roof must be able to open in order to maximise the enjoyment of events, under open air or enclosed conditions, in response to the weather"[35].

On its completion the Skydome provided facilities for not only the two principal sporting uses, but also displayed Soccer, Gaelic football, Cricket, International Tennis, Hurling, Basketball, Figure Skating, Motor Cross and Demolition Derbys, Wrestlemania 6, Equestrian Events and a World Indoor Athletic Meet. Non-sporting events include Rock Concerts, Grand Opera and Musicals, Boat Shows, and also Religious Meetings.

Despite the failure of the roof over the Montreal Olympic Stadium, its influence on the roof of the Skydome should not be underestimated. Montreal lies just 320 miles N.N.E. of Toronto. There is an accepted strong Provincial political rivalry between these two cities, certainly

[35] (Toronto Skydome. Roderick (Rod) G. Robbie, Architect, Principal Robbie/Young & Wright Architects Inc. et al. Source and date unknown).

sufficiently strong to ensure the inevitability of the successful operation of the retractable roof over the Toronto Skydome. The designers of the Skydome were aware of the reasons for the failure of the Montreal retractable roof. They were also aware that the strategy at Montreal of locating the removable roof centrally over the area of the playing field is not the best position to allow light into a stadium.

9.4.4.3. Technical Details of the Skydome

The stadium has a multi-zone air conditioning system providing heating, cooling and fresh air ventilation which not only satisfies the requirements of the spectators but also blows air on to the playing surface. Air movement over the playing surface at controlled rates is a requirement that aids the growth and maintenance of turfgrass.

Because the Skydome is classified as a covered stadium, no one would certify that natural turfgrass could be maintained in the environment produced by the building. Therefore an artificial playing surface was included, with the option that management could substitute a remotely grown natural turfgrass playing surface when required.

In order to fulfil the requirement to substitute natural grass for artificial grass, a one-piece playing field was developed, which could be rolled in and out of the stadium. The known details of this are as follows:

The playing field is a concrete containment structure which holds the entire natural grass system including soil, turf, drainage and irrigation. The turf is crowned like normal football fields and the structure is supported on a series of steel wheel bogies, which run on steel plates cast into the main level concrete floor. When not in use, the field is rolled out, with the electrically driven bogies, to an outdoor location where the grass can grow and be maintained in the natural outdoors. [36]

9.4.4.4. Retractable Roof.

The roof panel at the north end is fixed in place and is shaped in the form of a quarter dome with a circular base. The two middle panels are parabolic barrel vaults, each individually supported on a track system on the west and east side of the stadium, allowing linear horizontal motion of each panel in a north south direction. In the open position, the northern barrel arch

[36] (Toronto SkyDome.Roderick (Rod) G. Robbie, Architect, Principal Robbie/Young & Wright Architects Inc. etal. Source and date unknown).

telescopes below the southern barrel arch with both panels directly over the fixed north quarter dome. The most southern panel is a quarter dome similar to the fixed northern panel except larger in size. This panel is supported on a circular track system allowing the panel to move in a circular horizontal motion, clockwise 100 degrees, resting immediately above the fixed quarter dome, but below the two telescopic barrel arch panels when the roof is fully open.[37]

The roof opening, which has several modes of operation is computer controlled and can be closed from the fully opened to the closed state in 20 minutes. There is an override, which forbids the operation of the roof at sustained wind speeds of 65km/h. The structural design of the roof is not dependent on 'single critical structural elements, which should they fail, would result in collapse of the roof.' The roof panels and structure are treated with acoustic insulation; the fabric has high standards of thermal insulation. Weather integrity between the moving panels is provided by a unique weather seal, which bridges a 500mm space between the panels. The rigidity of the roof design allows heavy loads to be hung from it, which enables the space to provide excellent acoustical standards for a range of musical events. This rigidity also enables the roof to close without audible noise or vibration. As a component the roof has been designed for "two hundred openings and closings each year, for a one hundred year fault free reliable operating life".

The Skydome makes recognition of the problem discussed in this dissertation of the appropriateness of large volume spaces for events, which attract capacities of 30,000 or fewer. This problem has been answered by the introduction of a 'Skytent'. This is a patented suspended canopy, which includes an acoustic ceiling. The ceiling system is supported on cables with winches, which facilitate the removal of the ceiling for half mode events. The 'Skytent' has revolutionised the ability to provide arena sized concerts in a large enclosed stadium. The space can also be used for sporting events, which do not attract spectator capacities required to fill the full size stadium.

The cost of the SkyDome increased by almost three times the original budget. The reasons for that scale of increase are not recorded. But in its defence its concept is not like any other stadium. It is located on a Downtown site and acknowledges the problems of scale and character that those locations impose. The Skydome has achieved such a dominance in the life

[37] (Toronto Skydome. Roderick (Rod) G. Robbie, Architect, Principal Robbie/Young & Wright Architects Inc. et al. Source and date unknown).

9.4.5. The Amsterdam ArenA, Amsterdam, Netherlands.

9.4.5.1. Introduction

The 51,000 capacity ArenA opened in August, 1996 at a reported cost of £106,000,000. It was the first multi-use stadium in Europe to incorporate an in situ natural turfgrass playing surface and a retractable roof.

The stadium's anchor tenant is the Ajax Association Football Club. They play in the stadium between 26 and 35 matches a year. The stadium has also become the base for the Amsterdam Admirals; additionally, it continually hosts a wide range of other events not associated with the games of football.

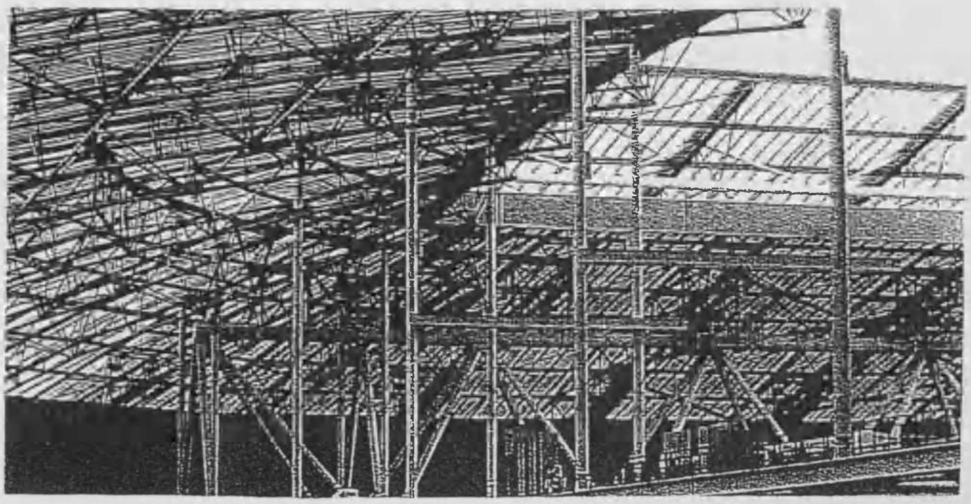
The centrally located bi-parting retractable roof offered the options of providing open or closed conditions in the cavea. The speculation was that a moving roof would allow turfgrass to grow and be maintained in this stadium in the way it could not do in the Astrodome or Silverdome. The reality was different: it has not been possible to maintain in situ turfgrass in an acceptable playing condition in the ArenA for long periods. The solution to this problem was to re-turf the playing area wholly or partly at frequent intervals, sometimes fives times a year.

Fig.9.4.5.1.
View of ArenA showing:
a) **the roadway passing under the stadium, which influences the need for a modified turfgrass rootzone.**
b) **the arched roof structure which accommodated the sideways retractable roof.**
c) **the clear visual expression of the upper part of the cavea.**
d) **the restrictive opening produced by the centrally located retractable roof.**

Fig.9,4.5.1.2 The playing surface, August 1996. The white dots on the right of the picture are fans used to dispel the dew. Examination of the centre of the picture reveals the grass dye used to disguise bare earth.

Fig.9.4.5.1.3. The playing surface used for a 'kick about' prior to a match August 1996. Wear can be seen along the touch line after only the third use of the playing surface for football.

Fig.9.4.5.1.4. The supporting steelwork for the fixed and retractable roof. The hanging steel supports maintenance walkways. The picture reveals the importance of carefully considering a support strategy in considering the contribution that strategy makes in aiding the light flux on the playing surface.



9.4.5.2. The Case Study

This study is confined to recording the issues surrounding the turfgrass failure and the adoption of the strategy for solving that problem.

A study of the processes of procurement indicates that the needs of the in situ turfgrass playing surface received little or no recognition at the initial design stage. At one stage it had been intended to surround the football playing area with an athletic track. The idea was abandoned on the grounds of increased capital costs. If the retractable roof had extended over the running track, the in situ turfgrass may have had a better chance of survival.

When consultants were eventually appointed they suggested the playing surface should be moved in and out of the stadium in pallets. There was space adjacent to lay out the pallets and thus provide horticultural treatment. Space was also available to establish a turfgrass nursery. This advice could not be followed for the following reasons:

- The level of the playing surface had been raised by two metres above the stadium's surrounding platform level. This made pallet transfer not impossible but uneconomic.

- Heidemij Realisatie now called Arcadis considered the technique of pallet transfer insufficiently developed to provide a long-term solution.

The proposal was to install Prescription Athletic Turf, P.A.T, a computer controlled horticultural system, which has the aim of leaving the turfgrass in a continuously healthy condition. This system was used in the refurbishment of the playing surface of the Joe Robbie Stadium, Miami, Florida, USA.

The principle of the Prescription Athletic Turf, PAT system is simply put by Bruce Smith:

> It is a closed system design and it incorporates a highly effective sub-irrigation and water conservation system, using the latest sensor technology linked to computers running custom software. These computers monitor and control the rootzone environment to ensure that moisture content remains at optimum levels for growth. The sub-surface includes a unique vacuum

chamber system connected to the drain matrix so that excess water can be forcibly displaced at a rate of nearly 100,000, (sic 90,000) gallons per hour[38].

At ArenA the turfgrass was laid on an impermeable layer, in this case a suspended concrete slab. The slab was not insulated. If it had been, the rootzone soil profile temperatures would have had less fluctuation on the underside of the rootzone The upper face of the concrete was covered with 2-mm plastic (PVM) sheets welded together and extended at their perimeters to form a continuous watertight up-stand 550-mm high.

The first 250mm of the rootzone consisted of a well-consolidated base layer of fine aggregate. This was then partly excavated to receive the PAT drainage pipes running in six equally spaced rows along the length of the playing pitch. The water grills were equally spaced at right angles to the drains at 820-mm centres. The composition of the upper 300mm layer was not revealed during discussions. Difficulties were generally encountered in obtaining information because of impending litigation proceedings concerning the turfgrass failure. But it is almost certain that the upper 300-mm of the rootzone would have been composed of a single layer of modified sand. The difficulty relates to determining the grade of sand; boring the surface for a sand sample was not allowed. A fuller explanation of the PAT system is set out under section **4.9.0.2.** The probability was that the polystand would have been 75% perennial ryegrass and meadow grass. This was a mixture favoured by the Dutch for playing surfaces around this period.

9.4.5.3. Work on Site

Heidemij Realisatie (HR) sub-contracted the work involved in constructing the playing area to Venue Revenue Services (VRS) whose Managing Director was Robert E, Else.

About 8 weeks before the opening date, Heidemij Realisatie lost confidence in the ability of (VRS) to produce a quality playing surface in time for the opening in early August, 1996. The grass was yellowing. Robert Else suggested in an interview that the main reason for the failure was the lack of air at the grass surface. But yellowing of turfgrass can be associated with a lack of nitrogen and a mineral deficiency.

Because of this loss of confidence H.R. appointed a new specialist grass sub-contractor.

---

38 . Panstadia International, Quarterly Report, Vol 3 No 2 January 1996 A Dream Come True. Bruce Smith).

The new specialist treated the grass for a disease, which Else claims was wrongly diagnosed. A decision was taken to re-turf the stadium. In doing so a total of between 75mm and 100m of the PAT base material was excavated and replaced by peat compost as a base layer for 50-mm of turfgrass. Else further claims the introduction of the peat interfered with the PAT drainage system and this layer also reduced the airflow through to any future rooting system. This theoretical argument can be correct but the degree of influence that the interference made could only be established by testing, to determine if the interference was critical to growth.
But a difficulty also arises in applying this argument as the PAT system has never been used in this stadium and therefore invalidates the discussion. Two separate sources confirm that the PAT system has not been used:

- Observation at the stadium.
- An extract from an Arbitral Interlocutory Order which states, "Consequently it cannot be postulated that the fact the PAT system in the end did not function, nor ever function, is attributable to a short coming of the Sub-Contractor".[39]

Despite changing Sub-contractors Heidemij Realisatie had during mid-August to re-turf the playing area, as the newly installed turfgrass surface had also turned yellow. That turf probably had not knitted with the base material, thus causing a shallow rooting system, the result of which was that the surface of the grass was moving under players' feet, making it difficult for them to turn.

Another suggestion for the yellowing of the original turf was that the roof had been closed 40 times since the first grass was laid. The roof had been designed to close only between 15 and 20 times per year. There is no substantive evidence for any of these suggestions.

However, it was felt that there were two main causes for the failure:

- The intensity of use had exceeded the recovery capacity of the turf.
- There was insufficient air movement on the surface of the grass.

Both these arguments can be substantiated. The stadium was certainly overused between the 3rd and the 26th of August, 1996 as the records show. However, overuse does not account for the fact that the turfgrass failed before the stadium opened. Insufficient air movement over the playing surface was substantiated by a sample of uncontrolled measurements.

---

[39] Extracts from the Arbitral Interlocutory Order By The Arbitration Board of the Building Industry in the Netherlands No 19322, October 1997.

An alternative view for the failure was provided in an interview with Robert Else, Director of VRS who installed the PAT system which is recorded as follows :
"Work commenced on the sub-base and surface preparation in March, 1996. Seeding took place in May 1996. The main contractor then carried out assembly work at both ends of the pitch at a time before the grass was established. This had a deleterious influence on these areas".

Any load on turfgrass at whatever stage of growth, will inevitably cause problems. This is especially so when loads exceed that which can be prescribed as normal. The consequence of such loading is compaction and deprivation of light. The latter was caused by directly stacking the materials on the turfgrass which is the cause of the compaction. Once an area has been seeded it should remain free of traffic except that needed for horticultural care for 10 to14 weeks.

There were two issues that received little discussion in connection with the turfgrass failure. The first of these was the degree of efficiency of the rootzone drainage. The now defunct PAT system was laid without falls and therefore in its present condition is dependent on gravity to move excess water. The supposition must be that the drainage system, if it works at all, can best be described as very slow.

There is some implied evidence for the poor drainage at the ArenA. An Amsterdam paper Algemeen Dagblad, dated the 29th of August,1996 reported as follows:

> This phenomenon of a closed roof over a stadium was first seen at the preliminary events of the 1994 –Football World Cup competition in the USA. It was raining cats and dogs yesterday in Amsterdam. By closing the sliding roof which consists of two moving, transparent panels measuring 40x118 metres, the arena management protected the valued grass which is already in a bad condition. Continuing the match in wet conditions could have caused such a bad situation for the grass that the international match between Holland and Brazil next Saturday [3 days later] would have to be cancelled or played at the Rotterdam Feyenoord Stadium. (Translation F, Cadee).

The second issue that received little discussion in connection with the turfgrass failure was the reduction of lighting levels within the stadium. It was left to the press to report the comments of turfgrass experts such as Dr Jeroen van Arendonk who had conducted lighting tests in the stadium. These tests were not controlled but he was sufficiently confident with his results to declare that the levels in some parts of the stadium were too low to sustain turfgrass.

ArenA has at ground level in each corner a free opening of an approximate area of 40 square metres. Running around the stadium at the lowest point of the roof is a continuous open slot. The assumption was that the combination of these openings would provide for the movement of air over the turfgrass. Subsequent wind tunnel testing at the Welsh School of Architecture on a theoretical stadium indicated that the positions of these openings could never have satisfied the requirements for air movement over the turfgrass surface.

To aid the process of drying out the turfgrass H.R. utilised 6 industrial air blowers along each touch line.

Green dye was also applied to 30-40 small bare areas to camouflage failures. It was the view of HR. at that stage that lack of light was not a problem; provided there was 70% light the grass would flourish. The question was 70% of which particular level. Around this time the Dutch Press were printing the views of independent experts indicating that light reduction in the stadium was a problem.

There is no doubt that thus far the grass has failed at Arena A. Aesthetically it looked acceptable except where the green dye had been applied but the dye was not evident under artificial lighting. The footballers are not happy with the surface. The Ajax manager is reported as saying 'I must have the grass shorter and the surface harder' [Reported by Heidemij Realisatie August, 1996]. The owners of the stadium are unhappy because the turf needed periods of recovery. There was a conflict between the need to maximise the use of the stadium and the requirement to satisfy the playing criteria of the principal tenant, the Ajax Football Club.

H.R. were unable to pinpoint the failure in any one direction. It is however, reasonable to indicate the following:

The contractor's programme for completing the works did not allow a sufficient time for the grass to develop an established rooting system.

When PAT was invented in the early 1970s the intention was to install it in open conditions. The system provides a stable rootzone through drainage control, irrigation or liquid feeding and aeration. These functions are an essential requirement of the photosynthetic processes but without the necessary levels of light energy and the required air movement over the turfgrass leaves to control the stomata, the chain of activities is incomplete.

The ability of the system to provide these requirements in the case of ArenA takes the form of a theoretical discussion because its PAT system is defunct. The requirement of feeding and aeration is now provided by other means. The requirements for drainage can now only be provided by the installation of one of the traditional drainage systems. This work has not been carried out. The levels of natural lighting are lower in sections of the arena than those required for turfgrass growth and maintenance. The lighting level values will decrease in time as the plastic will lose some of its transparency through surface discoloration and the accumulation of atmospheric dirt.

The solution to the turfgrass problem at Ajax has been to adopt a policy of re-turfing the playing area on a regular basis, sometimes five times a year. The cost of each returfing operation depends on whether the new turf is limited to a part of or the whole playing surface. The costs at 1998 levels range between £60,000 and £100,000. The surface therefore is treated as temporary. This may well be one of the options in maintaining turfgrass in such stadia. These issues are discussed in sections **(6.1.0.1 to 6.1.0.5.)** and **(8.1.0.1.)**

9.4.6. Millennium Stadium, Cardiff, Wales, UK, Europe.

9.4.6.1. Introduction.

The Millennium Stadium was built for the Rugby World Cup, held in Wales in1998. The Arms Park, Cardiff, the previous stadium was demolished to form part of the site for the new stadium. This over-tight complex urban site is best understood from the illustrations, which form Figs 9.4.6.1 & Fig 9.4.6.2. It is a site, which has a tradition since the turn of the 19th Century of being used for sporting activities. It has been variously used simultaneously for Club Rugby, County Cricket and as a Tennis and Outdoor Bowling Club. The site eventually evolved to house just two stadia, one dedicated to International Rugby Football, the other to Club Rugby Football.

Fig 9.4.6.1. The Wales National Stadium (Arms Park) Prior to Demolition 1996.

The Cardiff Rugby Club Stadium on the Northern Side of the National Stadium. The River Taff is on its Western side and the Empire Pool is on the South Western corner of the site. The Eastern side of the Stadium provided open accommodation.

Fig 9.4.6.2. The Millennium Stadium 1998.

The long axis of the playing surface now has a North-South Orientation. The Empire Pool has been replaced by an entertainment centre. The Cardiff Rugby Club has been even more overshadowed by the bulk of the National Stadium Superstructure than was previously the case.

The long axis of the playing surface now has a North-South Orientation. The Empire Pool has been replaced by an entertainment centre. The Cardiff Rugby Club has been even more overshadowed by the bulk of theNational Stadium Superstructure than was previously the case.

The capacity of the Arms Park, Cardiff, was reported as 57,000[40]. That capacity had to be reduced to 53,000 to meet the requirements of the Guide to Safety at Sports Grounds.[41] Eleven thousand of those spectators had to stand; the idea of this was that tickets at the east end would be affordable for less affluent spectators. The requirement for all seating accommodation would have further reduced the capacity of the Arms Park to approximately 48,000. This capacity did not match the capacities of the National Stadia of England, Scotland or France.

It was against this background that the decision was taken to build a new stadium on the site of the Wales National Stadium. A new stadium was required in order that Wales could hold the Rugby World Cup in Wales in 1998. The brief was to commission a stadium, with a retractable roof and with an 80,000-spectator capacity. The problem the designers of the new stadium were faced with was how to include an additional all seating capacity for 32,000 spectators within an already confined site. The spectator capacity figures were later reduced from 80,000 to 75,000 and then finally to 72,500. This Stadium was the first stadium in the UK to have a retractable roof and an in situ playing surface set in a multi-pallet system. The decision to include turfgrass pallets did not form part of the original design brief.

Two strategies enabled the designers to achieve an increase in spectator capacity: 1) turning the long axis of the Arms Park playing surface through 90° so that it ran broadly South to North; 2) the acquisition of properties on the eastern side of the site. The land acquisition was later to have repercussions, which remain unresolved. These details do not form part of this study.

The purpose of this study is to consider details relating to the turfgrass playing area. In terms of fulfilling the requirement of the original brief the turfgrass playing surface in its present condition must be considered a failure. The reason for this failure cannot be considered in isolation. This stadium is worthy of a separate study taking into account the considerations listed:

- The procurement of the Stadium.
- The siting of the Stadium in its relationship to the City's central area.
- The capacity of the City's infrastructure to absorb the influence of the Stadium.

---

[40] John, G, & Sheard, R, STADIA, A Design and Development Guide. Architectural Press, 2nd Etd, 1997. Page 113.

[41] House of Commons-Culture, Media and Sport- Appendices to Minutes of Evidence. 18th April 2000. Memorandum submitted by the Millennium Stadium. Page,1 of 3.

- The real costs as opposed to the contractual costs of the erection of the Stadium.

It is the purpose of this study to consider these issues only where they may have had an impact on turfgrass strategy.

9.4.6.2. The Case Study.

9.4.6. 2.1. The Condition of the Arms Park Turfgrass.

Historically the Arms Park had produced playing surfaces of poor quality. They were prone to waterlogging, probably due to the tidal influence of the River Taff which flows on the western side of the site. Playing surface conditions were improved in parallel with the upgrading of the seating arrangements. The stadium was gradually being transformed into an embryonic compact stadium with the east end left open to provide cheaper standing accommodation.

The playing surface continued to cause problems which were concentrated at the River Taff end. To alleviate this difficulty a cultivar called Aberelf bred at IGER at Aberystwyth, Wales was introduced into the turfgrass mix. Aberelf was certified as a new cultivar in 1995 by the Plant Breeders Association. It was bred for its characteristic of wear tolerance, but not specifically for stadia locations. It would have formed part of a mix consisting of Perennial Rye Grasses with Red Fescue used to bind the turfgrass surface. The surface persisted in providing problems probably owing to the back wash of tidal water from the River Taff.

9.4.6.2.2. The Millennium Stadium Turfgrass.

After the Building Contract for the stadium had been let a Report was commissioned from The Institute of Grassland and Environmental Research (IGER). The purpose of the report was to provide a "Review of the Impact of the Stadium Environment on the Pitch." The report is not in the public domain but it has been read by the writer. It makes fourteen preliminary recommendations and a further five recommendations to be implemented after the stadium was in use.

The theoretical studies carried out for this Thesis are in line with those recommendations of the IGER Report. concerning daily total photosynthetically active irradiance, the maintenance of grass blade length and air movement across the playing surface. One exception to the concurrence between the studies relates to the use of artificial light as a means of supplementing reduced daylight standards. The disagreement does not relate to issues of theory but to issues of practicality in applying that theory. These points will be considered in the Discussion.

stadium. The reasons for this are easily discernible by comparing the roof openings and the superstructure bulk of **Figs 9.4.6.1. & 9.4.6.2.**

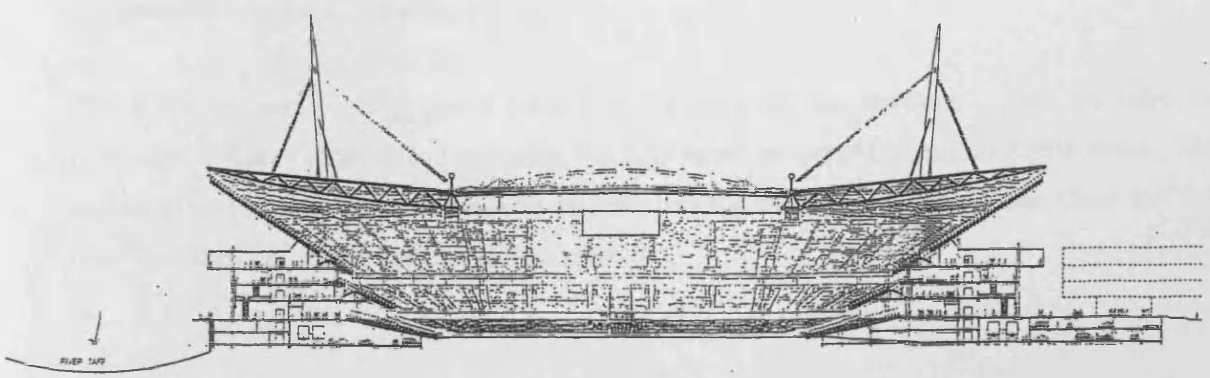
The Report sets out scientifically established criteria for the preservation of natural in situ turfgrass in stadia. Nevertheless, the basic lessons from this Report are not the turfgrass principles but that there is little value in commissioning any report if the commissioning date does not allow the report's recommendations to be considered either as research objectives or does not allow the results of such recommendations to be absorbed within a design process and a contractual building programme.

That is not to suggest that the Report's recommendations were sufficiently broad. There are two factors that appear to militate against a broader approach: the site was cramped and the fixed price contract sum for the stadium was agreed, implying only minor changes were possible.

In respect of the in situ natural turfgrass it appeared not to be a prime consideration in the design process nor was the way the turfgrass was to be used. The procurement of this stadium in this respect was no different from the procurement of others at that time.

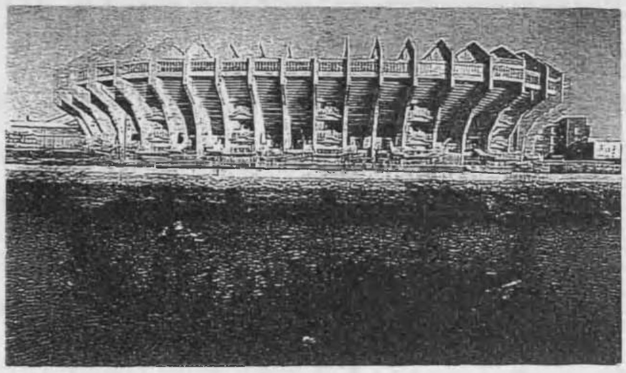
The report calls for air movement across the playing surface. The cross section through the stadium had been developed and its steelwork was in the process of being manufactured. The decision had been taken regarding the type of retractable roof to be used. The stadium's cross section is shown below.

Fig 9.4.6.2.2. **The cross section shows the amenity and access areas attached to the underside of the cavea. This design strategy prevents the introduction of passive air movement over the playing surface by not allowing that movement through the superstructure. The cross section visually confirms that there is only a marginal difference in the impact a centrally located retractable roof has on shadow and light falling on a playing surface, compared with a conventional roof providing an opening of equal area. The marginal advantage the conventional roof has is that it will permit a shallower structure.**



It is interesting to compare the photographs between the external appearance of the old stadium demolished and that of the new stadium. The functional expression of the old stadium provides an unmistakable impression of a cavea being cradled within the its structure. Its appearance also provides the opportunity to facilitate openings through the superstructure that would allow air to reach the playing surface.

Fig 9.4.6.2.3. **The Old Stadium seen from the River Taff.**



9.4.6.2.3. The Removable Pallets

The playing surface in the stadium is formed approximately of 7800 removable fibreglass pallets each 900 mm square 280 mm deep. The pallet bases are indented in two directions, for two reasons, to promote pallet rigidity and to facilitate the use of the fork lift trucks to move the pallets.

These pallets were not a part of the IGER proposals. They were introduced as the result of a visit to the Giants Stadium, New York where they are also in situ. Their primary purpose was to allow the surface to be changed from a soft surface to a hard surface by removing the pallets away from the stadium. Therefore the time to discuss their use is at a time when consideration can be given to their storage, when they are taken away from a stadium. The closer they are stored to the stadium the lower will be the costs of their removal. The pallets should be laid out horizontally to receive horticultural treatment.

The IGER proposal was to use a traditional rootzone in the stadium. They included the provision of spare turfgrass and rootzone, the equivalent of two Millennium Arena areas. This turf would have been used to replace a complete playing surface or a part of one. Once turf was used from the nursery the areas would be reseeded.

A beneficial incidental consequence of the use of pallets was that the Contractor's Construction programme was relieved of site congestion towards the end of the contract period. Had the traditional rootzone method been adopted, the probability was that the stadium may not have opened on time as the area occupied by the playing surface could not have been used for the processes of construction for about 14 weeks before the opening date. The pallets also allowed the stadium playing surface to be used at predetermined points during the contractor's programme. This arrangement could only have been facilitated through the use of pallets.

The difficulty with the latter part of this Case Study is that the candidate was not allowed access to the stadium management until towards the end of this study. Therefore since the pallets had been in use it has been necessary to rely on newspaper articles and the experience of the Giants Stadium, New York. The pallets there are now used only to replace worn turfgrass pallets and are no longer moved from the arena. This appears also to be the case in the Millennium Stadium. Nevertheless, the option that they can be moved remains a benefit.

When one pallet was recently examined by the candidate a piece of turfgrass was removed from its surface. The rootzone was totally compacted. A sour smell was detected, that smell that denoted a lack of oxygen in the rootzone. The probability is that all the pallets are suffering in the same way, the consequence being that all the rootzones will have to be replaced. Compaction will return with overuse, necessitating a programme of continuous aeration, Aeration will help the process of returfing which has to take place on a regular basis to provide an acceptable playing surface. It would also be helpful to investigate the possibility of inefficient draining within the pallets. There is no doubt installing the pallets was the correct decision in respect of aiding the contractor's building programme but it may be judged a poor one in terms of longer term turfgrass maintenance and also in providing flexibility in use.

The long-term prognosis for the turfgrass playing surface should be the result of a cost benefit analysis. This analysis should consider the following:

1) Keeping the present pallet arrangement.
2) Reverting to a traditional rootzone.
3) Providing an artificial surface when feasible.

This analysis should extend beyond the technical considerations of the turfgrass but set the study in the context of the growing from other stadia such as the new Wembley Stadium. This competition might force the Stadium Management to consider more exactly the costs of refurbishing the turfgrass several times a year. This argument is predicated on the assumption that Wembley Stadium will be free of turfgrass problems.

9.4.7. The Gelredome, Arnhem, Netherlands Europe.

9.4.7.1. Introduction.

Arnhem, 80km South East of Amsterdam has a population of 150,000. The latitude of Arnhem is 51°-59 N and 5°-55 E. The climate at times can be relatively severe with an average winter temperature of 4°C; the summer average is 20°C. The winter extreme is -12° C, that of summer 30°C. The summer Relative Humidity is between 70% and 75%; the winter levels are 85% to 90%.

This small stadium (capacity 30,000) opened in March, 1998 and was the first stadium to have a centrally located retractable roof and an in situ turfgrass playing surface which could be withdrawn from the stadium in a single turfgrass pallet. When not in use the pitch is 'parked' adjacent to the stadium on its long axis. A similar stadium opened in 2001 at Gelsenkirchen, Germany but with a capacity of 53,000 spectators.

The decision to use a sliding pitch primarily stemmed from the failure of the playing surface at the ArenA Amsterdam. The retractable roof was installed for the first time in the interests of spectators and players not in the interests of turfgrass. Since the stadium opened it has established itself as a multi-use stadium and provided the base for its anchor tenant, the Vitesse Football Club.

Fig. 9.4.7.1
External view of stadium showing:
a) the propped opening through which the single concrete pallet passes.
b) the playing pitch in its outside location, the upper surface is approximately 2m above the general level.
c) the elevation also indicates the two arched bifurcating sections of the retractable roof.

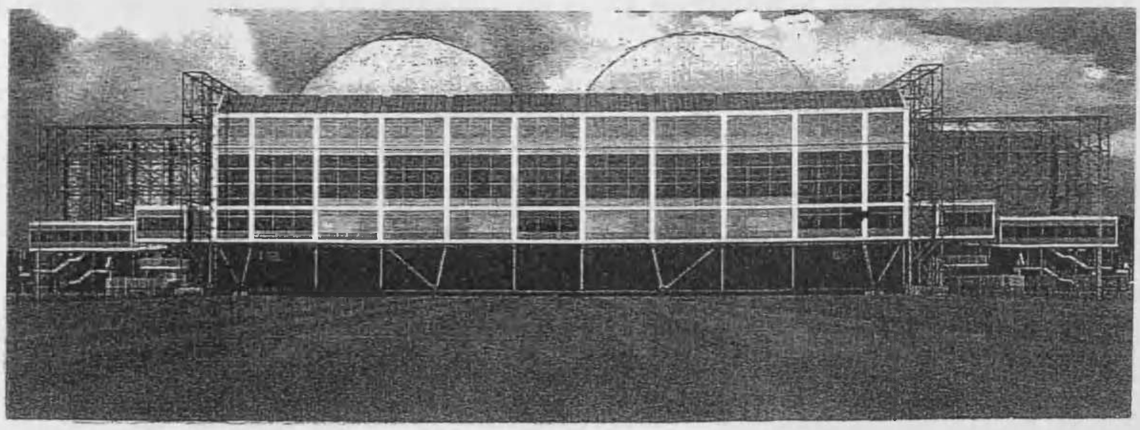


Fig.9.4.7.1.2.
Internal view of stadium during the construction period showing:
a) the pitch in the process of moving through the stadium
b) one of the roof sections not yet constructed.
c) one corner reaction point for the grandstand over the letter box.

9.4.7.2. The Case Study.

The concrete pallet which contains the pitch measures 115·2m x 72·4m x 65cm. The rootzone is 40·5 cm deep, consists of 90% sand and 10% loam. The sward is a polystand of "30% Barcampsia tufted hair-grass *(Deschampsia caespitosa);* 25% Barrage perennial ryegrass, *(Lolium perenne);* 20% Bardessa perennial ryegrass, 20% Barcelona smooth stalked-meadow grass. *(Poa pratensis);* 5% Barenbrug rough-stalked meadow grass, *(Poa trivialis)".* [42] The initial sowing produced a dense sward. But at the southern end the grass was beginning to yellow. Heidemji, the Horticultural specialist now renamed Arcadis, suggested in correspondence that the reason for this was the need to adjust the nitrogen supply.

The surrounds and base of the pallet comprise 200-mm thick reinforced concrete. The inside faces are bitumen coated; there is no slab insulation. This omission will influence the soil temperature profile of the rootzone. "In the summer the soil temperature would be high and in

[42] Turf Management September 1997 page 19.

the winter the soil would be cold and humid."[43] On balance the preference may be to add insulation to the pallet as this would tend to stabilise the soil temperature in the winter period. The insulation would help to reduce the costs of undersoil heating but increase the costs of irrigation in summer. The pallet contains besides the rootzone drainage, irrigation systems and undersoil heating.

The pallet is supported on 384 concrete downstand nibs, each capped with Teflon pads on which the pallet slides. The nibs also reduce the weight of the pallet by acting as base supports. The weight of the integrated pitch construction is reported as 11,000 tonnes. The mechanism for the pitch is designed to allow the pitch to be taken in and out of the stadium 26 times per year. A completed pitch movement can take up to six hours. But in practice the pitch is moved the day before it is required to allow for the possibility of movement failure.

The pallet is moved in and out of the Stadium through an opening at the base of the grandstand. The clear span of the opening equals the width of the field plus a tolerance; its height is approximately 1500 mm. The opening has been likened to the opening and closing principles of a 'letterbox'. The consequences of this large free span results in a complex triangular construction to support the grandstand, the end reactions of which are taken on steel lattice towers in each of the affected corners. The towers also maximise the distribution of the loads over ground which has low bearing capacities. But the towers also sterilise the corners for spectator viewing. The designers recognised the inevitability of high beam deflection values; nevertheless it became necessary to dampen the dynamic loads by propping when the grandstand is occupied during a football match.

The pallet is pulled or pushed through the 'letterbox' by 4 hydraulic gripper jacks, placed at the end perimeter of the docking area. Control guides are set in a concrete trough linked to each 'jack'. During the initial life of the building there have been movement problems owing to more than anticipated friction. The increased friction was the result of dirt embedded in the grease acting as the lubricating agent between the steel runners and the Teflon pads. To counter these problems the working forces on the 4 hydraulic gripper jacks were recalibrated and a different lubricating agent applied. Since the initial problems the pallet has moved freely as the pads have been replaced when required and the steel surfaces are kept clean.

> Simon Inglis reports "the final choice of near silent Teflon pads came about after seeing them in use by the German company Schiessdefries in the Bremen Shipyards. This method was then verified by the DNO, a research institution in the Netherlands".

[43] Turf Management September 1997 page 19.

Jasper Amstel, the Stadium Manager reports by correspondence that the movement system has been so reliable that the Terraplas Floor Panel system has never been used.

> "For us the system is a backup in case of technical problems with moving the pitch. From the stadium opening in March 1998 until July 2000 we have had nearly two million visitors. There have been 62 soccer games, 18 big concerts, 12 big private presentations of companies' products etc.....600 small conferences and over 3,000 tours. For our fiscal year starting 1st July, 2000 we expect 850,000 visitors and 39 large events including soccer, concerts and private presentations."

This stadium represents a way forward by combining in one multi-use stadium a centrally located retractable roof with a dual choice of surfaces, natural or artificial. The success of this stadium reinforces the view that a turfgrass strategy must be developed at the procurement stage of stadia development. Arguments can be mounted as to whether there was a need to include a retractable roof; these issues are discussed in **6.1.0.2.**

9.4.8. The Sapporo Dome, Sapporo, Hokkaido, Japan.

9.4.8.1. Introduction.

Despite the fact that the stadium has a fixed roof, a case study is included because it presents alternative structural and mechanical solutions to withdrawing a single pallet through the stadium from those adopted at the Gelredome, Arnhem. The solution used in the Sapporo dome obviates the problems of dynamic deflections, heavy foundations and restrictive planning where the pitch passes under the grandstand at Arnhem. The method of moving the pallets at the Sapporo Dome is based on the 'hover' principles rather than push or push hydraulic system at Arnhem.

Fig. 9.4.8.1.
Illustrates planning of both arenas and sets them within the context of the site. It should be noted that the long axis is the football pitch has to swivel through 90° to pass to the outer arena. The size of the complex can be assessed by the two additional football pitches adjacent to the outside arena.

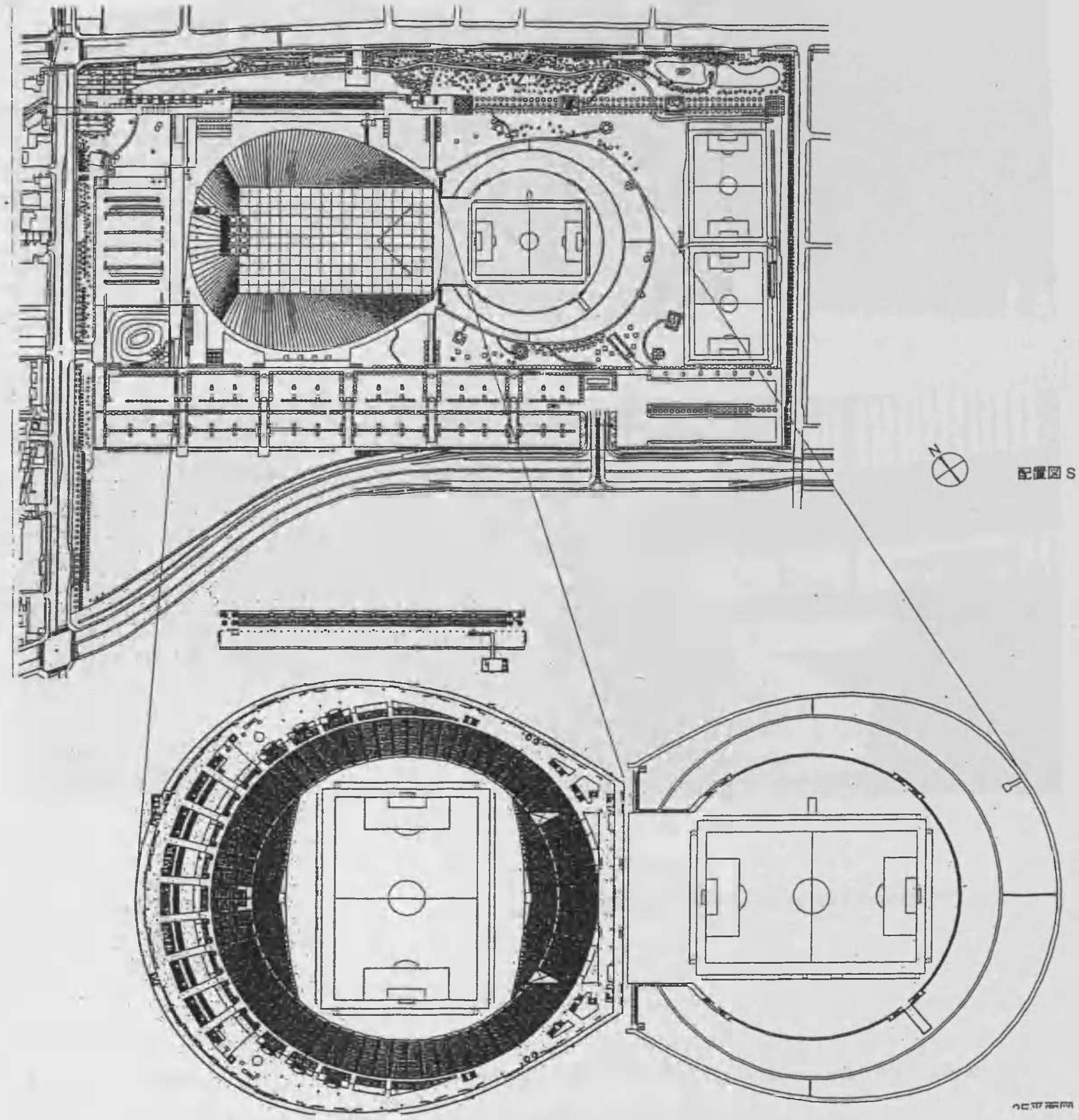


Fig.9.4.8.1.2
The playing field passing through the 'letter box'.

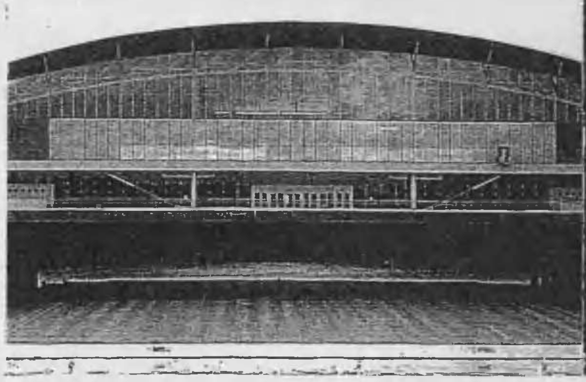


Fig. 9.4.8.1.3.
The stands being moved to prepare letter box opening.

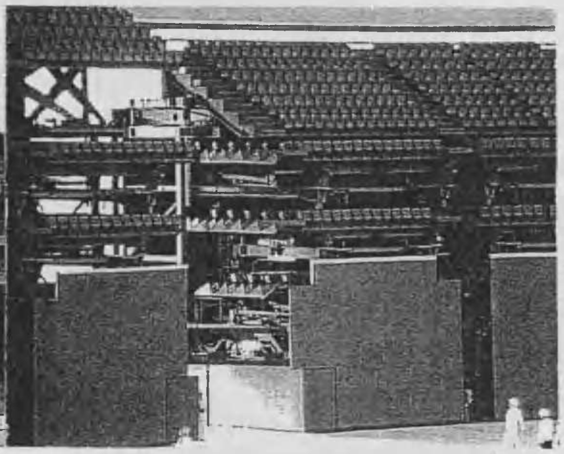


Fig.9.4.8.1.4.
Installing the artificial surface.

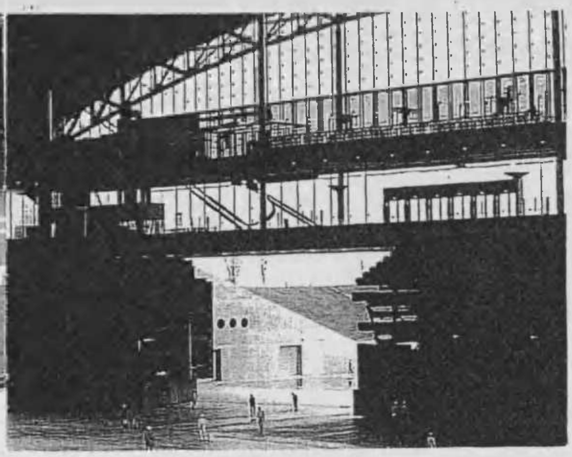


Fig. 9.4.8.1.5.
Preparing to swivel playing pitch through 90°.

9.4.8.2. Case Study

Besides reviewing the 'letter box' construction **(10.4.7.)** the study also considers some other factors setting the Sapporo Dome apart from other stadia in the following ways:

1. Context.
2. Fixed roof.
3. Means of moving the pallet.

9.4.8.2.1 Context.

The Sapporo Dome forms one part of a two-part complex, the other part being an outdoor arena. The outdoor arena forms a horseshoe shape. When the playing surface in the Dome is transferred from the Dome it becomes the playing surface of the outdoor arena. The form of the outdoor arena is emphasised by grass banks, reminiscent of Olympia, Ancient Greece.

The use of the outdoor stadium is restricted to the summer season because of the winter climate. The conditions of the winter climate are highlighted by the fact that the1972 Winter Olympic Games were hosted at Sapporo, the Northernmost City in Japan. Sapporo is located on Latitude 43°10'N and 141°15'E. This location produces winters that are long and cold. " ..... According to statistical records of 1997, the maximum snow cover of any given day up to that year, was 1.69 metres ((February 13,1939) ". The estimates of the total winter snowfall in the Sapporo region range between seven and twelve metres.

Dr Hiroshi Hara, the architect of the Dome, describes the planning context of the dome as a "Sports Garden". He explains that the site is divided into five botanical strips, parallel with the boulevard. Each strip will have its own unique nature. Further, a compound of trees surrounds the entire site, with walkways provided through the greenery. These will be ever-changing and ever-growing components of the sports garden, and will provide a variety of scenery around the dome. This nature friendly method also allows for a major dome to be built with minor environmental effects on the present residential areas and the Hitsujigaoka District 2.

9.4.8.2.2. Fixed Roof.

The Sapporo Dome has a recognisable architectural significance, which results from the vision of both Client and Architect. The building's dominant element is its roof, but that dominance is subdued on three sides by its integration into a reformed and moulded landscape.

Dr Hiroshi Hara will have concluded from stadia studies that where in situ turfgrass is planted in such enclosed environments without supplementary lighting, it fails; the solution to this is to withdraw the turfgrass from a stadium. The Architect may have rejected the use of a retractable roof because of the regional climate but the incorporation of a retractable roof may have diminished the stadium's visual integrity.

However, the reality is that a retractable roof may have had to remain closed during the winter period. There also may have been problems in activating the roof moving mechanism in freezing conditions, but that would be a matter for both awareness and essential studies.

The issue is whether this architectural concept will in the long-term compromise the original management intention of this stadium, in the same way that the architectural concept presided over the failure of the Montreal Olympic Stadium. The advantage this stadium has is that the maintenance of the turfgrass was considered at the design stage. The outstanding question is whether or not it will be physically possible to move the pallet out of the stadium frequently in the winter months. If that is not possible the turfgrass will inevitably die. The prediction is that this stadium will become a stadium which exploits the artificial surface during the winter months and both surfaces during the summer months. Only a long-term observation of the Sapporo Dome will verify that statement.

The claim is that the shape of the roof does not allow snow to accumulate on it but causes it to slide off the stainless steel surfaces and/or lets the prevailing wind blow it off. The underside of the roof also provides support for the even distribution of artificial lighting, acoustical aids and air conditioning outlets. Such even distributions are not easily incorporated in retractable roofs.

9.4.8.2.3. 'Letter Box' Construction.

The transfer strategy for moving the playing surface outside the stadium is fundamentally different from the Arnhem arrangement. In this case the end grandstand, adjacent to the opening in the wall through which the pitch passes is divided to isolated structures. These are rolled away to allow the pitch to pass through the openable doors in the end wall of the stadium.

The free opening is 95 metres x 20 metres and when closed is masked by spectator seating. The method of dividing and moving the grandstand leaves only the simpler problem of the self-support of the outer high wall in its open and closed situations. This solution may offer the possibility of using the single pallet method on sites with difficult ground conditions and also in situations where capacities above 50,000 have to be considered.

9.4.8.3. Moving the Pallet.

Professor Botond Bognar records in correspondence that,

> "The movable soccer field ((hovering stage) is a steel structure, 120 metres long, and 85 metres wide, 1·38 metres high and carries on its top the natural turf. This stage hovers with a pneumatic force of 1·09 atmosphere and can also rotate on 34 wheels. Its total weight is 8,300 tonnes, but this weight decreases to one tenth when the stage hovers. Its moving speed is about four metres per minute and it takes 25 minutes to rotate 90°. The rotation is necessary so that the field can face the main stand. During winters too the stage usually stays outside. During this time of year grass is hibernating under the snow, but in spring grass can freeze in the thawing season. Therefore the stage has electric heating devices under the turf to prevent freezing. The steel frame structure is outfitted

with air sealing, air blowers for hovering, a layer of [Pre-cast planks] concrete, drain pipes, heating elements, a layer of soil and sand, and natural lawn, in addition to two movable water sprinklers, and devices for power supply, turning and sliding"[44].

"The turf is 90% Kentucky blue grass and 10% perennial grass." [45]

9.4.8.4. The function of the Building

The indoor stadium has the purpose of displaying American Baseball, Soccer and Concerts all year round. The outside stadium is for summer use only.

"Reconfiguration for these events can take place within five hours". This rate of reconfiguration is achieved marginally more quickly than with the existing European one pallet systems.

The architect suggests that the Sapporo Dome has two major characteristics: "the first stems from the need to have a natural grass playing field within the dome for the World Cup; the second, the garden concept"[46].

Whether or not the functioning of the turfgrass can be assured in the climatic conditions of Sapporo will be a matter of controlled observation over a number of seasons. This stadium has provided however, in two of its systems a) the means of moving the pallets, a system first proposed in the theoretical exercise for the KholerDome Luton UK 1994-1995;[47] and b) an alternative arrangement for passing the turfgrass pallet through a stadium.

---

[44] Professor Botond Bognar. Professor of Architecture; Associate Center for Advanced Study, University of Illinois at Urbana-Champaign. USA. Correspondence 10th February, 2002.

[45] *Ibid*

[46] Hiroshi Hara the Floating World of his Architecture, Botand Bognar Wiley-Academy, Chichester, UK (page 254).

[47] Andy Cook. Building 30th August 1996.

APPENDIX FIVE.

9.5.0. AN OUTLINE OF THE PHOTOSYNTHETIC PROCESS.

Turfgrass plants sustain themselves without eating organisms or organic molecules; they are fed by the complex reactions and interactions that make up the photosynthetic process. The process is carried out in two complex stages. In the first of two stages plants use the light energy from the sun, thereby enabling them to make food molecules from carbon dioxide and water. The second stage, the Calvin Cycle is driven by CO_2 taken from the air. Nearly all organisms depend ultimately for sustenance on the photosynthetic process.

Fig 9.5.0.1.

The equation summarising the photosynthetic process is illustrated within the context of a leaf.

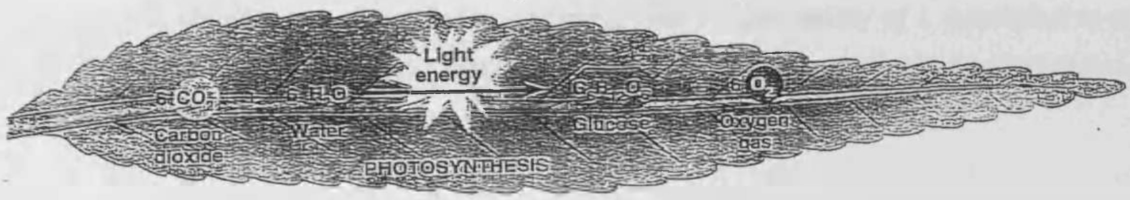
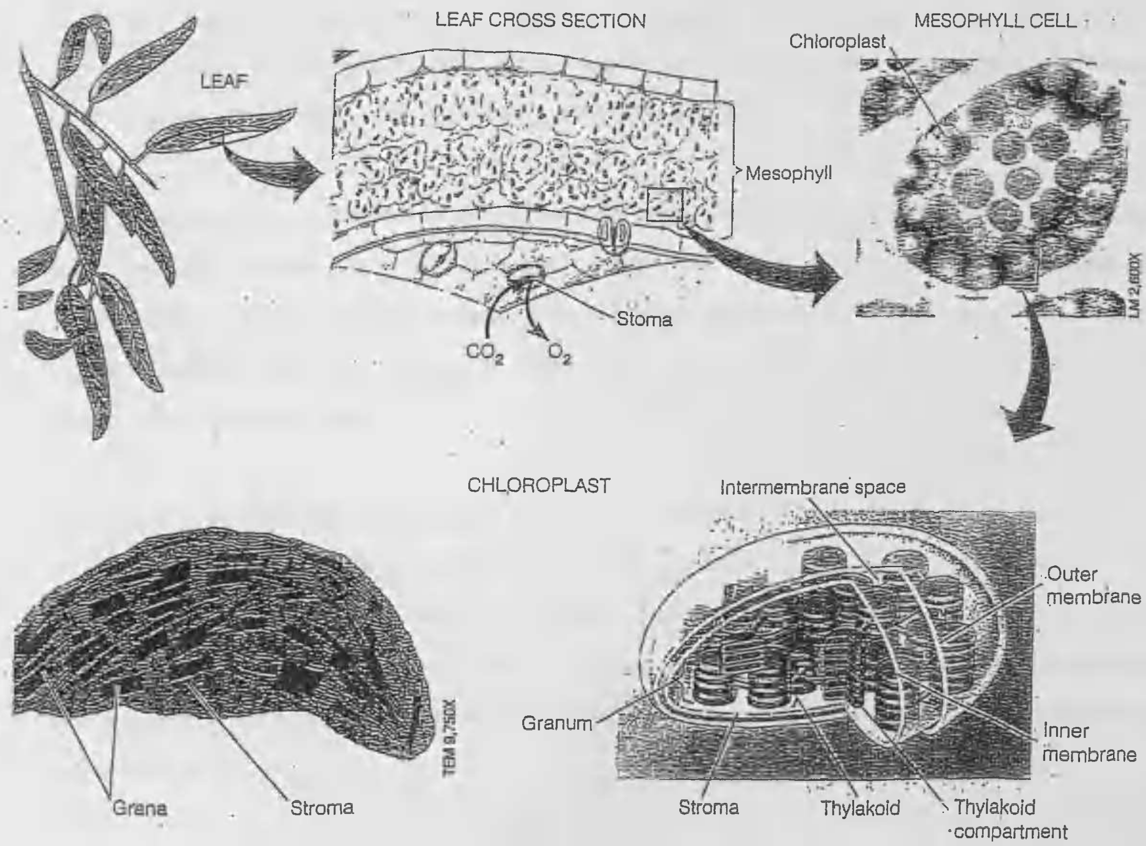


Fig 9.5.0.2.

The cross section of a leaf showing the parts making up its structure and naming its parts.



Chlorophyll located within the chloroplasts performs the first step of the first phase of the photosynthetic process. Chloroplasts and other structures that perform specific functions within cells are collectively termed organelles. The different cells within organelles function as living units because of the co-operation between these cells and the chloroplasts.

The green colour in turfgrass plants is derived from the chlorophyll pigment set within the chloroplasts.

> Chlorophyll, made up of atoms of Carbon, Hydrogen, Oxygen, Nitrogen and Magnesium, by itself performs only the first step in photosynthesis. The whole process requires an array of many molecules working together with chlorophyll. These molecules are housed in chloroplasts, tiny structures in plant cells..... The ability of a chloroplast to carry out photosynthesis results from the specific arrangement of all the molecules in the chloroplast.[48]

The photosynthetic process begins with the chlorophyll pigment capturing light energy from the sun. That energy is then put to work by the chloroplasts set in the cells of turfgrass plants: most of these cells are predominantly located in the leaves of turfgrass plants. That harnessed physical energy is converted into chemical energy and stored in the chloroplasts as glucose and other organic molecules made from carbon dioxide and water.

Chloroplasts are concentrated in the cells of the mesophyll, which is the internal green tissue of the plant leaf. There are many mesophyll cells in a leaf and each mesophyll contains many chloroplasts. Carbon dioxide enters the leaf, and oxygen exits via the stomata. Membranes in the chloroplasts form the structural framework where many of the photosynthetic reactions occur. The chloroplast has an inner and outer membrane with space between them.

The chloroplast's inner membrane encloses a second compartment called stroma. This compartment is filled with a thick fluid in which sugars are made from carbon dioxide. Within the stroma is suspended an elaborate system of disc-like membranous sacs called thylakoid. Built into the thylakoid membranes are the chlorophyll molecules that capture light energy that convert light energy to chemical energy. When thylakoid membranes occur in stacks they are referred to as grana.

---

[48] Campbell, N, A, Mitchell, L,G, Reece, J,B. Biology Concepts and Connections. The Benjamin/ Cummings P.C.Inc. 1994. Page 18.

The photosynthetic process occurs in two interdependent stages: each stage requires multiple steps to complete the process.

- The steps in the first stage convert light energy into chemical energy, O_2 gas is produced as a waste product.

- The steps of the second stage are processes involved in the Calvin Cycle. In this cyclic series of reactions, sugar molecules are formed using CO_2 and the energy containing the products of the light reactions of the first stage.

The reactions of the first stage occur in the thylakoid membranes of the chloroplast's grana. Light absorbed by the chlorophyll furnishes the energy that eventually powers the food-making machinery of photosynthesis. Light energy is used to make Adenosine tri-phosphate (ATP) from Adenosine di-phosphate (ADP) and phosphate. Light energy is also used to drive a transfer of electrons from water to NADP+ to NADPH by adding a pair of light-excited electrons along with an H+.

This reaction temporarily stores the energised electrons. As nicotinamide adenine dinucleotide, phosphate, co-enzyme II (NADP+) is reduced to NADPH; water is oxidised, giving off O_2.

The light reactions are the steps that absorb solar energy and convert it into chemical energy stored in the ATP and NADPH. Sugars are not made until the Calvin cycle, the second stage of the photosynthetic process.

The Calvin cycle occurs in stroma of the Chloroplast. The incorporation of carbon from CO_2 into organic compounds at this stage fixes the carbon. After carbon fixation, enzymes of the cycle make sugars by further reducing the fixed carbon by adding high-energy electrons to it along with H+.

NADPH is produced by the light reactions providing the high-energy electrons for reduction in the Calvin cycle. ATP from the light reactions provides chemical energy that powers several of the steps of the Calvin cycle. The Calvin cycle does not require direct light. However, in most plants, the Calvin cycle runs during daytime, when light reactions power the cycle's sugar assembly line by supplying it with NADPH and ADP.

Electromagnetic energy occurs in rhythmic wavelengths, measured in nanometers. The wavelengths of the overall spectrum range from 10^{-5} nm to $10,^{3}$m. But that part of the solar spectrum visible to the human eye, occurs only between wavelengths 380nm and.750nm. Within these wavelengths colours from violet at the lower end to red at the higher end can be detected by the human eye.

As sunlight shines on a plant leaf, the light at some wavelengths is absorbed and used in the first stage of photosynthesis. Energy at other wavelengths in the visible spectrum is reflected back or passes through the leaf. Light absorbing pigments in the grana absorb mainly blue-violet and red-orange wavelengths. Amongst the organelles are Chlorophyll *a* which participates directly in the light reactions. A very similar molecule, chlorophyll *b* absorbs mainly blue and orange light and reflects yellow/green pigments.

Chloroplasts also contain a family of yellow-orange pigments called carotenoids, that absorb mainly blue/green light. Chlorophyll *b* and carotenoids do not participate directly in the light reactions but serve to broaden the range of usable light; these pigments convey the light energy they absorb to chlorophyll *a* which then puts that energy to work in light reactions.

The theory of light in the visible wavelengths explains most of light's action relative to the photosynthesis process. However, light provides in addition, discrete fixed quantity packets of light energy. These packages are termed photons: the energy they provide is more powerful at the shorter end of the visible wavelength. For example a photon of violet light contains nearly twice the energy of a photon of red light.

When chlorophyll and the other pigments in a chloroplast absorb photons one, of the pigment's electrons gains potential energy and is raised from a ground state to an excited state. The excited state is very unstable and generally the electron falls back to its ground state almost immediately, releasing its excess energy as heat. Some pigments emit light as well as heat after absorbing photons. In this case the excited electron gives off a photon, in addition to heat as it reverts to its ground state. When illuminated, the chlorophyll will emit heat and photons of light that produce a reddish afterglow, as the electrons fall from the excited state to the ground state. In contrast to pure chlorophyll in solution, illuminated chlorophyll in an intact chloroplast passes its excited electron to a neighbouring molecule. The neighbouring molecule, called the primary acceptor, is reduced as chlorophyll is oxidised.

The solar-powered electron transfer from chlorophyll to the primary electron acceptor is the first step in the light reactions and the first of many oxidation reduction (redox) reactions in photosynthesis.

Chlorophyll *a* & *b* and the carotenoid pigments are clustered in the thylakoid membrane of each chloroplast in assemblies of 200-300 pigment molecules. Evidence suggests that only a single pair of the many chlorophyll *a* molecules in each assembly denotes excited electrons to the primary electron acceptor, thus triggering the light reactions.

This pair of Chlorophyll *a* molecules is the reaction centre of the pigment assembly. The other pigment molecules function collectively as a light gathering antenna that absorbs photons and passes the energy from molecule to molecule until it reaches the reaction centre. The combination of the antenna molecules, the reaction centre and the primary electron acceptor is the photosystem. This is the light-harvesting unit of the chloroplast's thylakoid membrane.

Two types of photosystems have been identified: they are referred to as photosystem 1 and photosystem 2. These numbers relate to the order of their discovery. In photosystem 1, the chlorophyll (a) molecule is called P700 because the light it absorbs best is red light with a wavelength of 700nm. The reaction centre of chlorophyll 2, is called P680 because the wavelength it absorbs best is 680nm. These two reaction-centre pigments are actually identical chlorophyll *a* modules, but their association with different proteins in the thylakoid membrane accounts for the slight difference in their light absorption.

There are two possible routes for electron flow during the light reactions: the cyclic flow and the noncyclic flow. Cyclic electron flow is the simpler of the two: it involves only one photosystem and generates only APT, no NADPH or O_2. It is cyclic because the high-energy electrons that leave the chlorophyll reaction centre return to it after passing through an electron transport chain.
The transport chain is similar to the one that functions in cellular respiration. It consists of a series of electron carrier molecules arranged in a membrane. In cellular respiration, the chain is situated in the inner membrane of the mitochondrion. In photosynthesis, it is in the thylakoid membrane of the chloroplast. After the antenna assembly is energised by a photon of light, the first step of the cycle is to transfer the high-energy electron from the reaction centre chlorophyll to the primary electron acceptor. The primary electron acceptor is then oxidised as it donates the excited electron to the first electron carrier of the electron transport chain. The electron is then shuttled from one electron carrier molecule to the next by additional redox reactions. At

each link in the chain, the electron loses energy, finally returning to the reaction centre at its low energy ground state. Some of the energy given up by the electron during the redox reactions is used to generate APT by chemiosmosis.

Cyclic electron flow operates along with certain non-cyclic electron flow in plants. Noncyclic flow, produces roughly equal quantities of ATP and ANDPH. However the Calvin cycle uses more ATP than ANDPH. The ATP made by the cyclic electron flow may make up the difference.

Noncyclic electron flow occurs in all plants. In contrast to cyclic electronic flow, noncyclic flow uses both photosystems 1 & 2. The electrons pass from the water into photosystem 2, from there by way of an electron transport chain to photosystem 1 and then from photosystem 1 via another electronic transport chain to NADP+. The process is noncyclic because electrons do not cycle back to the starting point. Since it takes two electrons to reduce NADP+ to NADPH, we track two electrons through the diagram.

The noncyclic electron flow starts with photosystem 1. Photons energise the antenna assembly, and high-energy electrons pass from the reaction centre chlorophyll to the primary electron acceptor. From here, the two electrons pass through a short electron transport chain and are temporary stored in high-energy electrons in NADPH. This leaves P700 with two missing electrons that must be replaced.

It is this photosystem 2 that replaces the electrons lost by P700. Absorption drives the transfer of two electrons from P680 to the primary electron acceptor of photosystem 2. The electrons then pass along an electron transport chain. During the cascade, the electrons lose energy, some of which is used to make ATP. At the end of the cascade, the electrons reach P700, filling its electron vacancies.

When photosystem 2 loses the two electrons that go to P700, P680 develops a strong attraction for electrons. P680 replaces its lost electrons by (splitting) oxidising a water molecule. When two electrons are removed from H2O two hydrogen ions H+ and 1/2 □O_2 remain. The H+ions remain in the chloroplast. The oxygen atom immediately combines with a second oxygen atom from another water molecule to form a molecule of O_2, which diffuses out of the plant cells and leaves the leaf through a stoma. The formation of NADPH, ATP, and O_2 by noncyclic electron flow marks the end of the light reactions. The high energy molecule NADPH and the waste product O_2 both result directly from the redox reactions. The synthesis of ATP is different. In both noncyclic and cyclic electron flow ATP synthesis is driven by chemiosmosis-the same mechanism that generates ATP in cellular respiration. Chemiosmosis. The production of ATP using the energy of hydrogen-ions gradients across membranes to phosphorylate ADP powers most ATP synthesis in cells.

The relationship between chloroplast structure and its function in photosynthesis shows the two photosystems and electron transport chains of noncyclic electron flow, located within the thylakoid membrane of a chloroplast. The photosystems are arranged in such a way that energy released during electron flow drives the transport of hydrogen ions H+ across the thylakoid membrane. The arrangement is very much like the one in our model for the electron transport of cellular respiration in the mitochondria.

In both cases, excited electrons pass along a series of electron carriers within a membrane, as redox reactions occur. The electrons give up energy on the way, and some of the energy is used to make up ATP by chemiosmosis. Although photosynthesis is a food-making process and cellular respiration is an energy harvesting process, electron transport in the chloroplast drives chemiosmosis the same way it does in the mitochondrion. Specifically, some of the electron carriers use energy released from the electrons to actively transport H+ from one side of the membrane to the other. In the chloroplast, the carriers move H+ across the thylakoid membrane from the stroma into the thylakoid compartment. This generates a concentration gradient of H+ across the membrane. Energy stored in this concentration gradient is used is used to drive ATP synthesis.

The protein complex ATP synthase, which provides a port through which H+ can defuse back into the stroma from the thylakoid compartment. The energy of the H+gradient drives H+back across and energy is released in the process. ATP synthase uses some of this energy phosphorylate ADP, to make ATP. In photosynthesis the chemiosmotic production of ATP is called photophosphorylation because its initial energy input is light energy. Notice the final electron acceptor is NADP+ not O_2 as in cellular respiration. Rather than being consumed, O_2 is produced when water is split to provide replacement electrons for photosystem (2). We have now examined the major events of the light reactions. The ATP and NADPH that are produced during these reactions are used in the next stage of photosynthesis.

The Calvin cycle functions within the chloroplast. The inputs into this sugar-making process are CO_2, from the air, and ATP and NADPH both generated from light reactions. Using carbon from CO_2, energy from ATP and high-energy electrons from NADPH, the Calvin cycle constructs an energy rich sugar molecule glyceraldelhyde 3-phosphate, G3P. The plant cell can use G3P to make glucose or other organic molecules as needed. To make a molecule of G3P the cycle must incorporate the carbon atoms from three molecules of CO_2. The cycle actually incorporates one carbon at a time, with three CO_2 molecules making a complete G3P molecule. The completion of the Calvin cycle is the final phase of the photosynthesis.

Plants in which the Calvin Cycle uses CO_2 directly from the air are called C_3 plants because the first organic compound produced is the three-carbon compound 3-PGA. C_3 plants are common and widely distributed. In dry weather C_3 plants can reduce the rate of photosynthesis and decrease crop productivity. On a hot day a C_3 plant closes its stomata.

Closing stomata is an adaptation that reduces water loss, but it also prevents $CO_2$from entering and O_2 from leaving. As a result CO_2 levels can get very low in the leaf, while O_2 from the light reactions builds up. When this happens, the first enzyme of the Calvin cycle (called rubisco) incorporates O_2 instead of CO_2. And the Calvin cycle produces (2-Carbon) compound instead of its usual 3 carbon product. The plant cell then breaks the two-carbon compound down to CO_2 and H_2O. The entire process, starting, with the fixation of O_2 is called photorespiration. Unlike photosynthesis, photorespiration yields no sugar molecules. Unlike cellular respiration, it produces no ATP.

This limited study of the photosynthetic process is dependant on pages 109 to 124 of Biology Concepts and Connections. Campbell Mitchell and Reece. The Benjamin/Cummings PC INC, 1994.

APPENDIX SIX

9.6.0. THE SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY.

The following pages show the photographs recording the shadow free areas produced by each of the different roof configurations. The months used as a base for collecting the data were January to June and December. The detailed arrangements for recording the photographs, including the chosen months, the specific day and the times of that day are set out in Part Seven.

The images serve only as a simplified record of the extent and scope of the A4 size photographs used to provide the data from which Tables 7.4.1.1.to 7.4.1.7. are compiled. These tables were in turn used to construct the Graphs designated Figs 7.4.1.1.to 7.4.1.7.

The photographic images were also used as a checklist to ensure that the research was covered as planned. It was during the checking stage that it was discovered, that contrary to expectations that the Asymmetrical Roofs N W & NE would be quite different in the positioning and extent of the shadow free area . Because this fact had not been anticipated only the one aspect was included in the photographic checklist. As the photographic compilation was not intended for publication it seemed of little relevance that the eastern aspect was missing in photographic form. The final advice at a later stage was to publish the extent of the research. At that stage there was no possibility to recast the layout of the photographs to include the additional roof.

The coding on the photographs is deciphered as follows:

Roof Configurations.

NR	No Roof.	JA	January.
CL	Centrally Located.	FE	February.
BL	Bi Parting Lattice.	MA	March.
BP	Bi Parting.	AR	April.
AS	Asymmetrical West.	MY	May.
		JU	June.
		DE	Dec.

Fig 9.6.1. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (JANUARY)

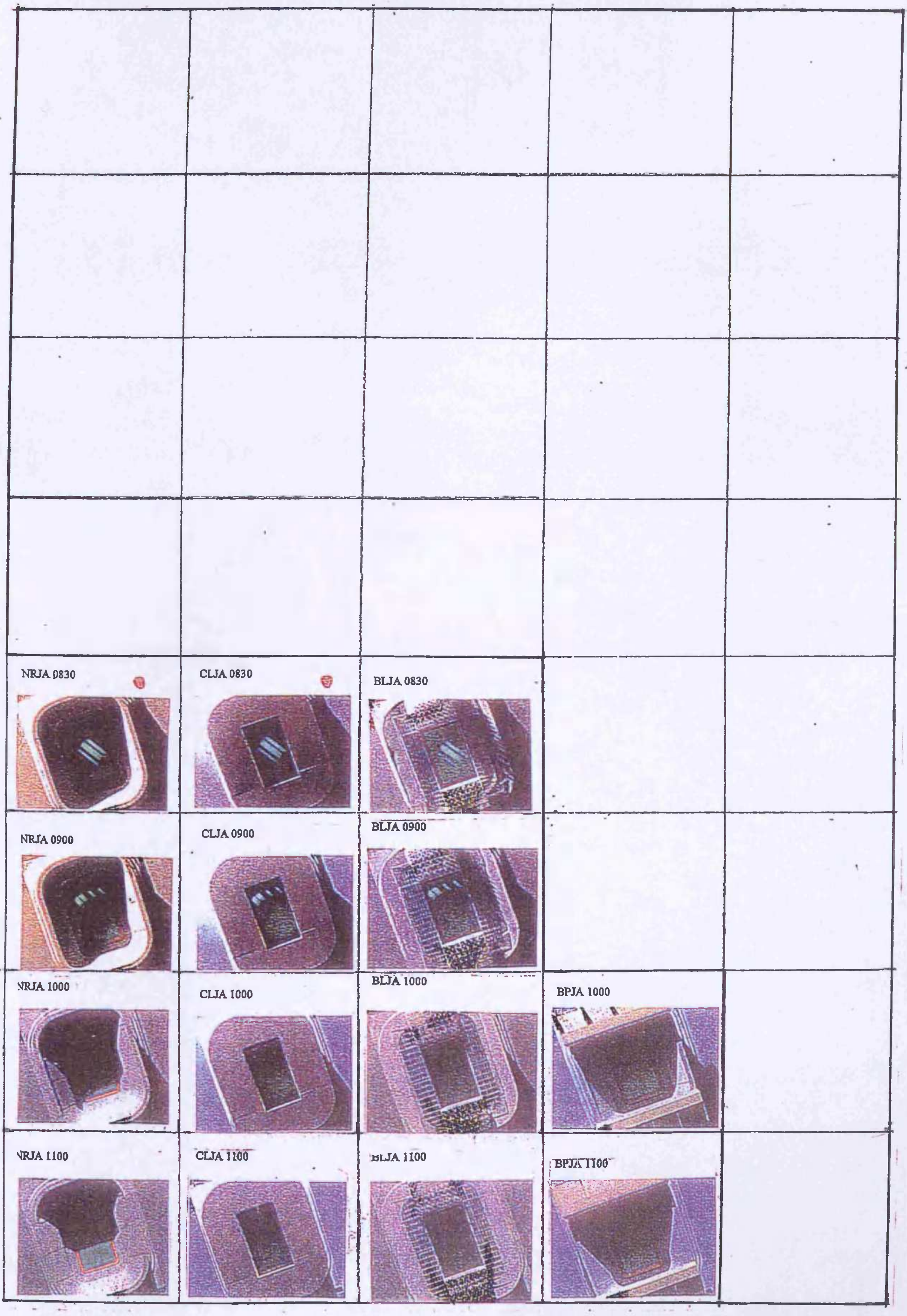


Fig 9.6.1. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (JANUARY)

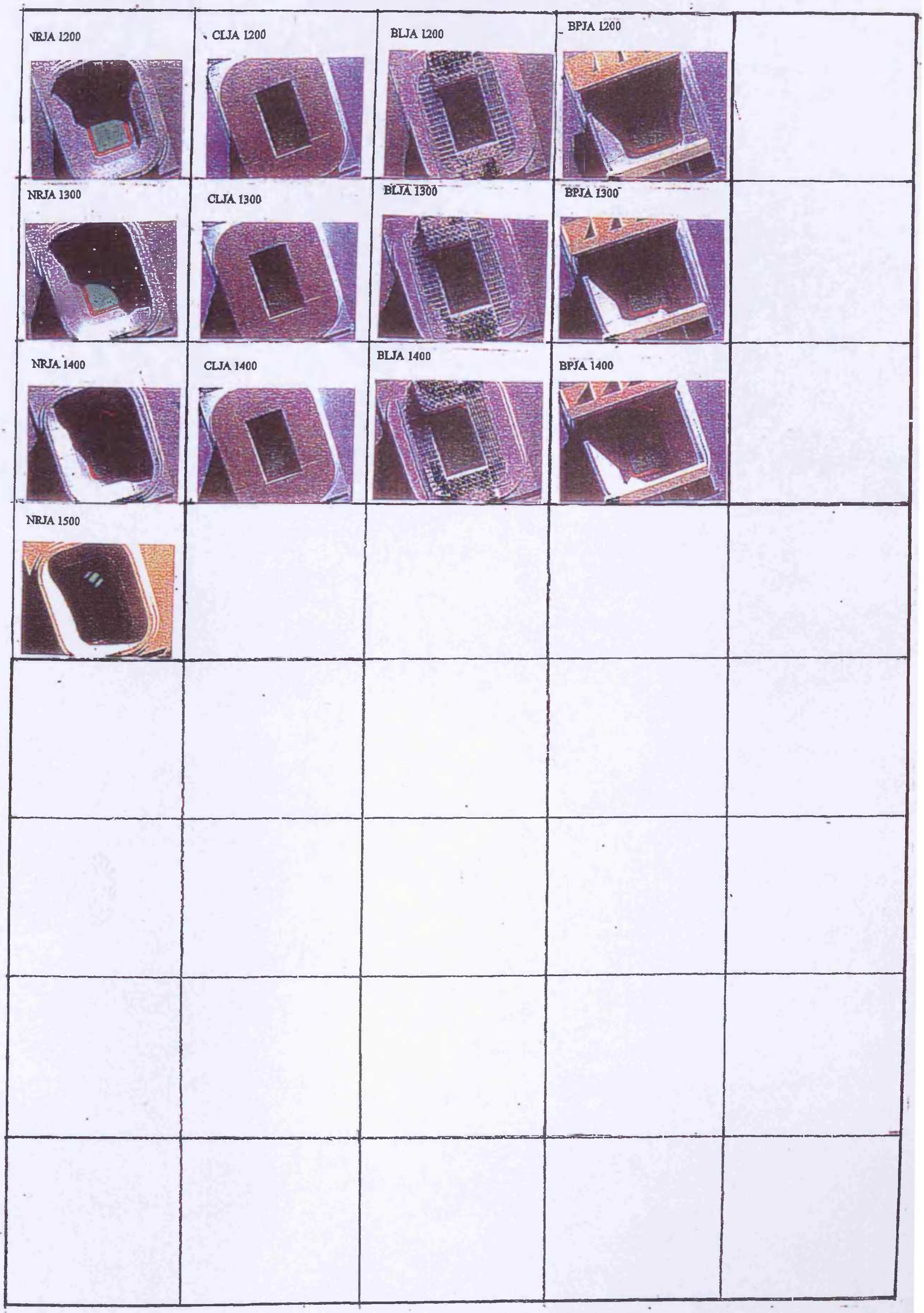


Fig 9.6.2. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (FEBRUARY)

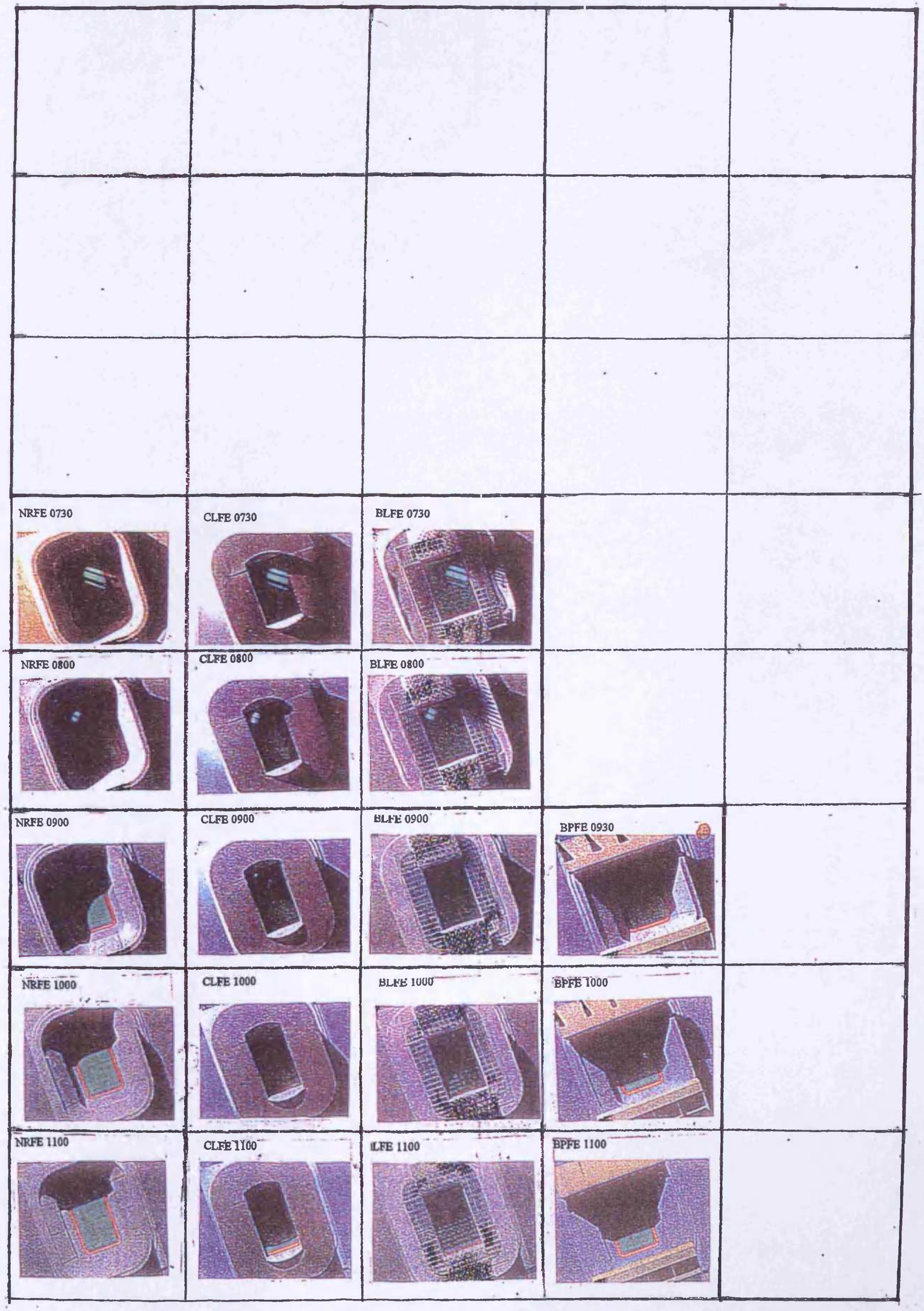


Fig 9.6.2. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY ; (FEBRUARY)

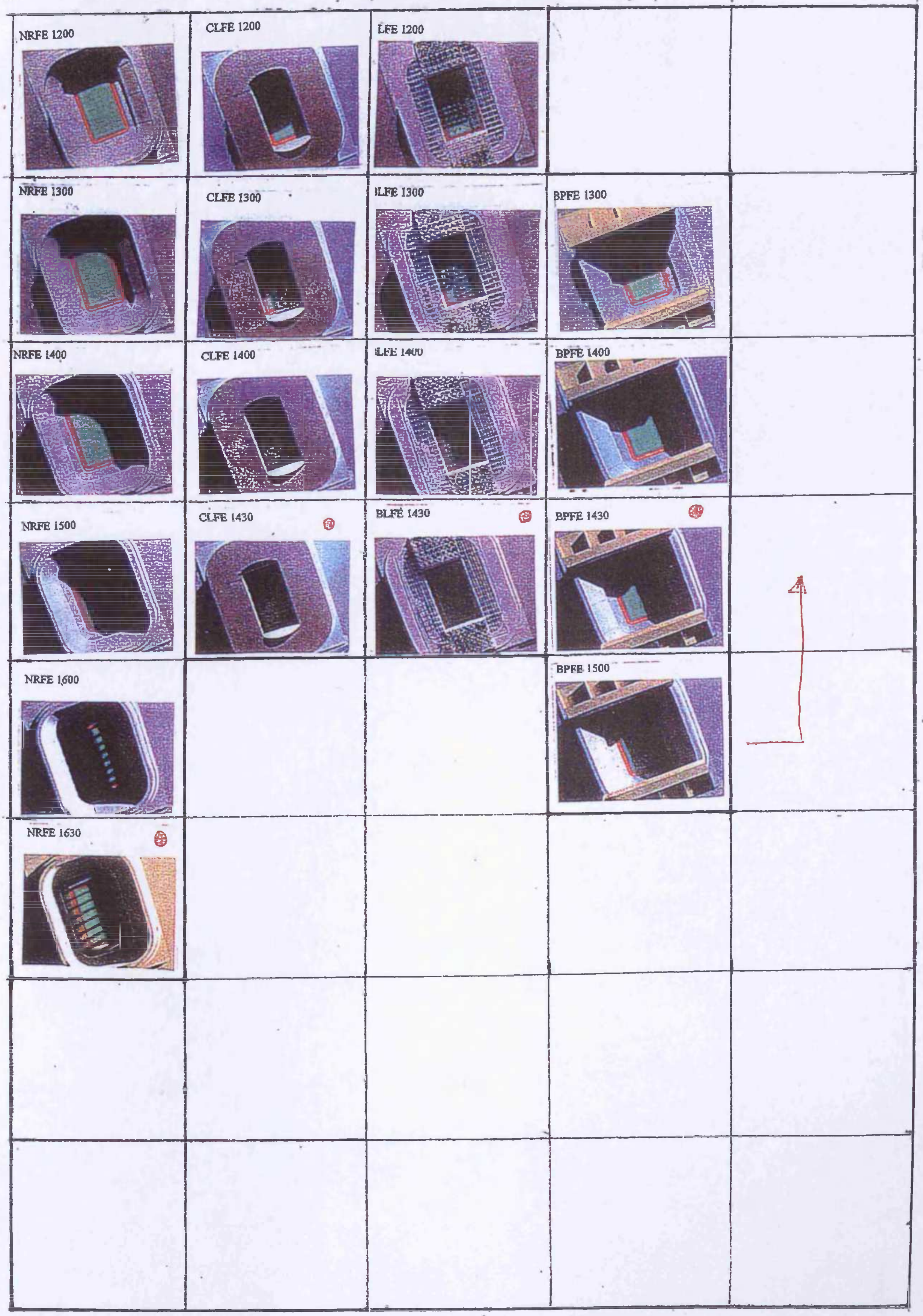


Fig 9.6.3. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (MARCH)

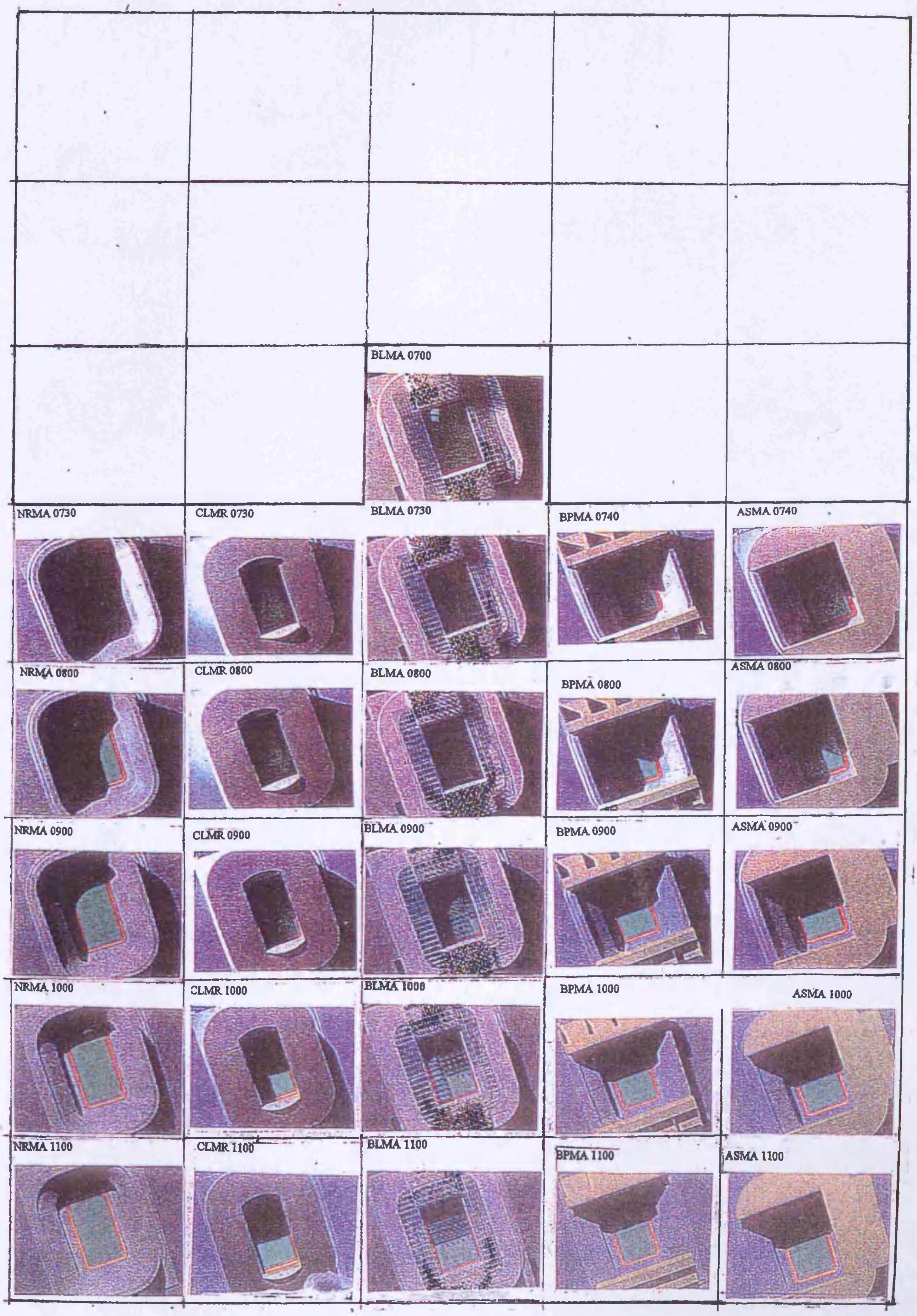
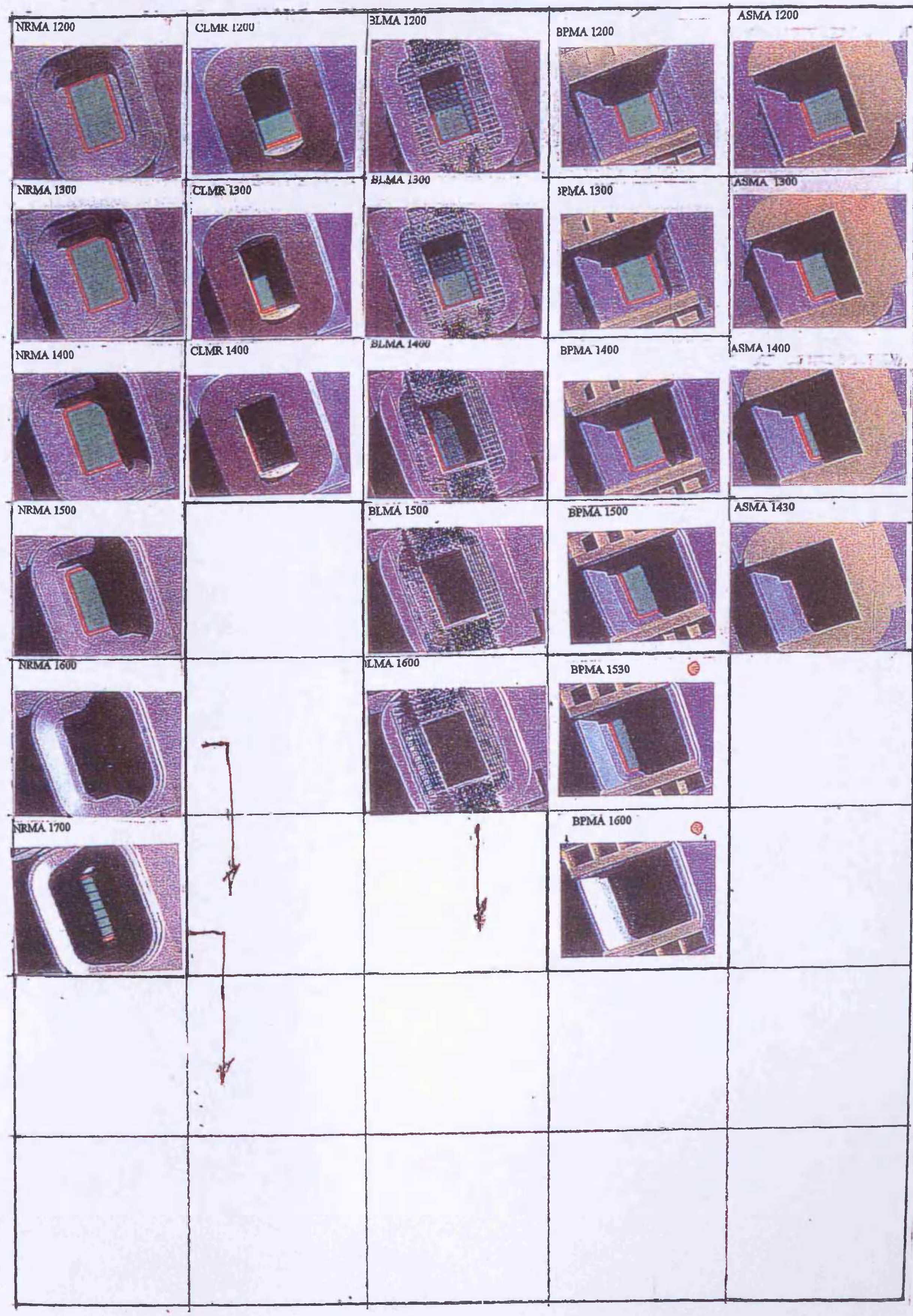


Fig 9.6.3. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (MARCH)



Fig, 9.6.4. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (APRIL)

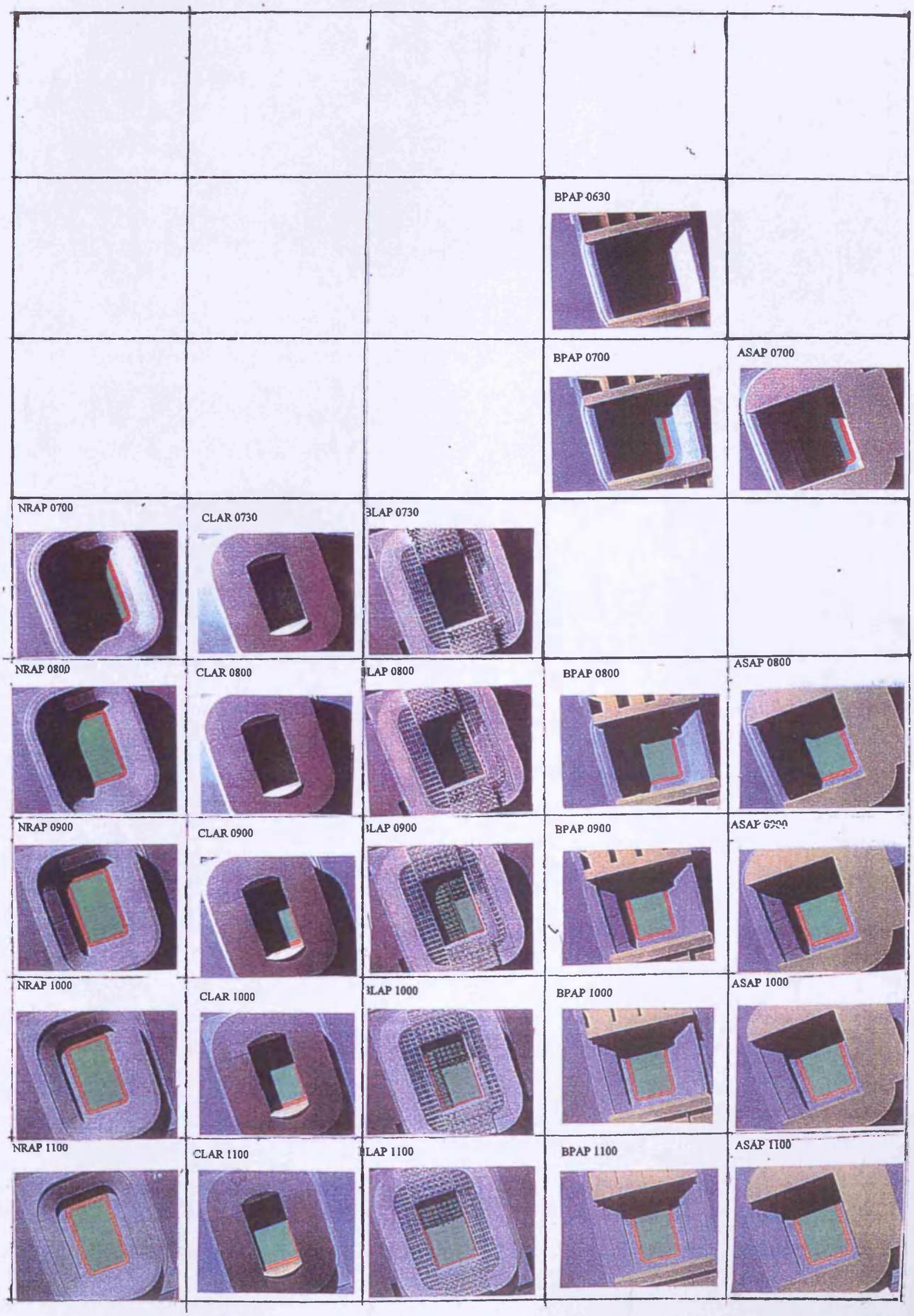


Fig 9.6.4. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (APRIL)

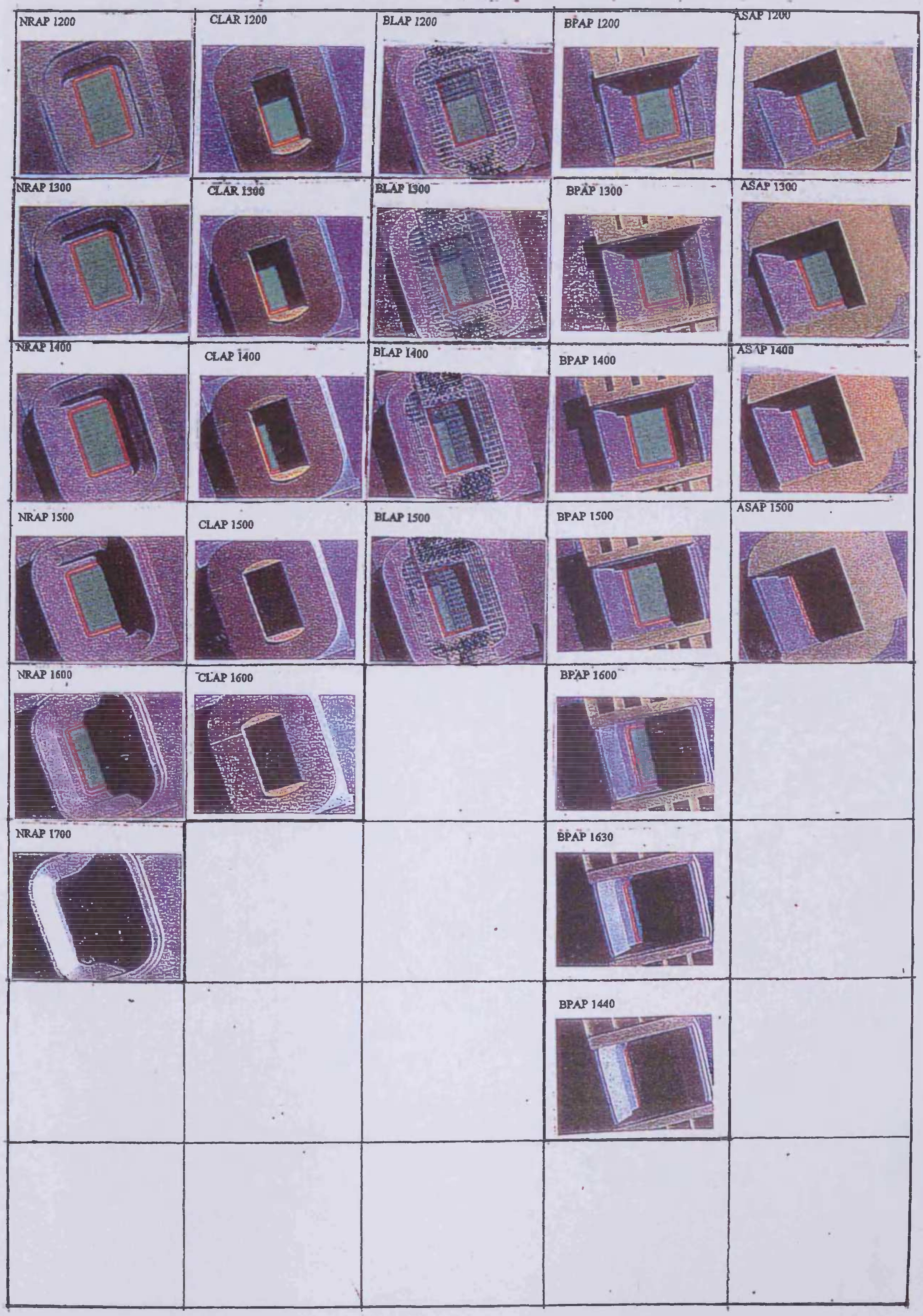


Fig 9.6.5. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (MAY)

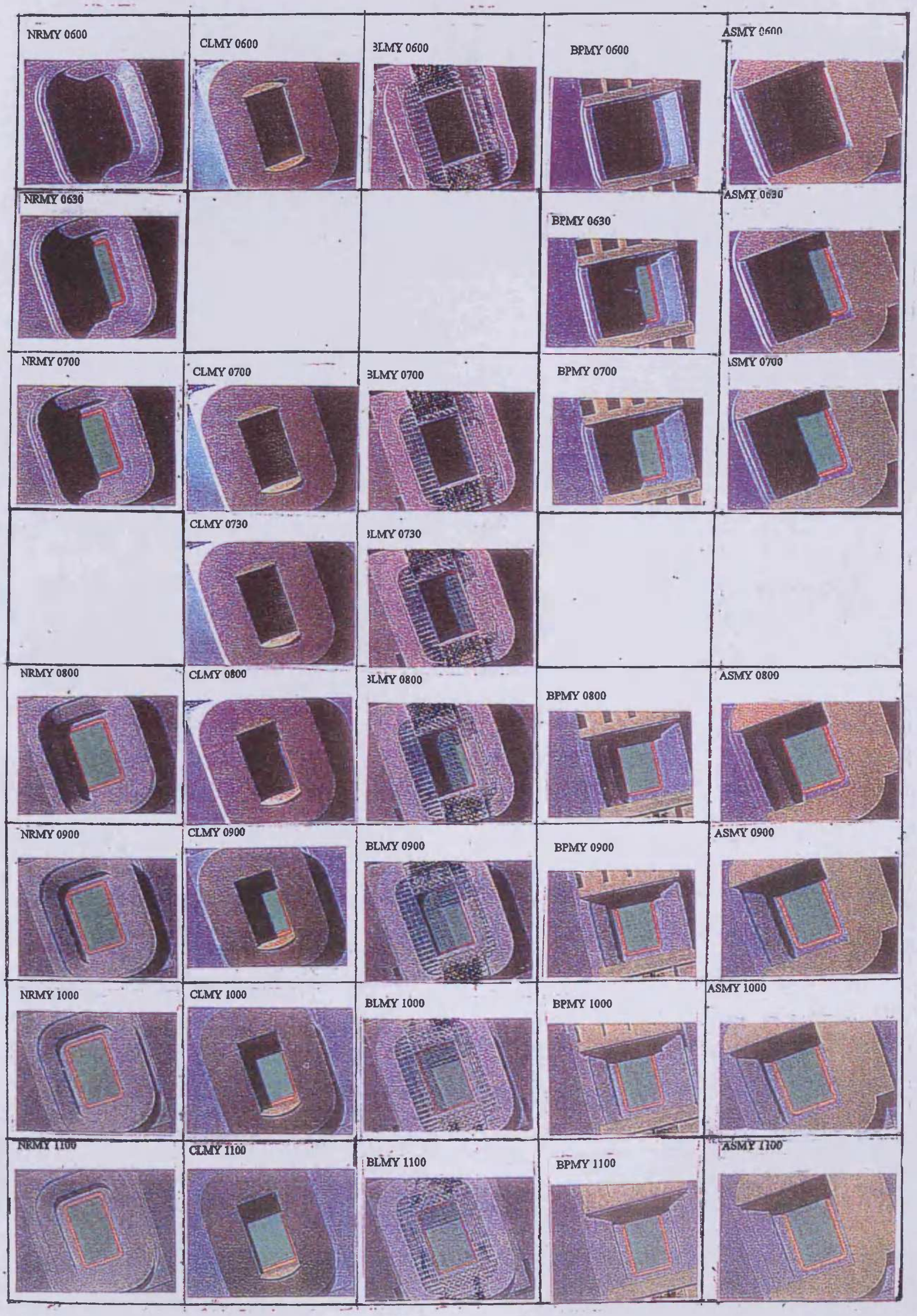


Fig 9.6.5.: SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (MAY)

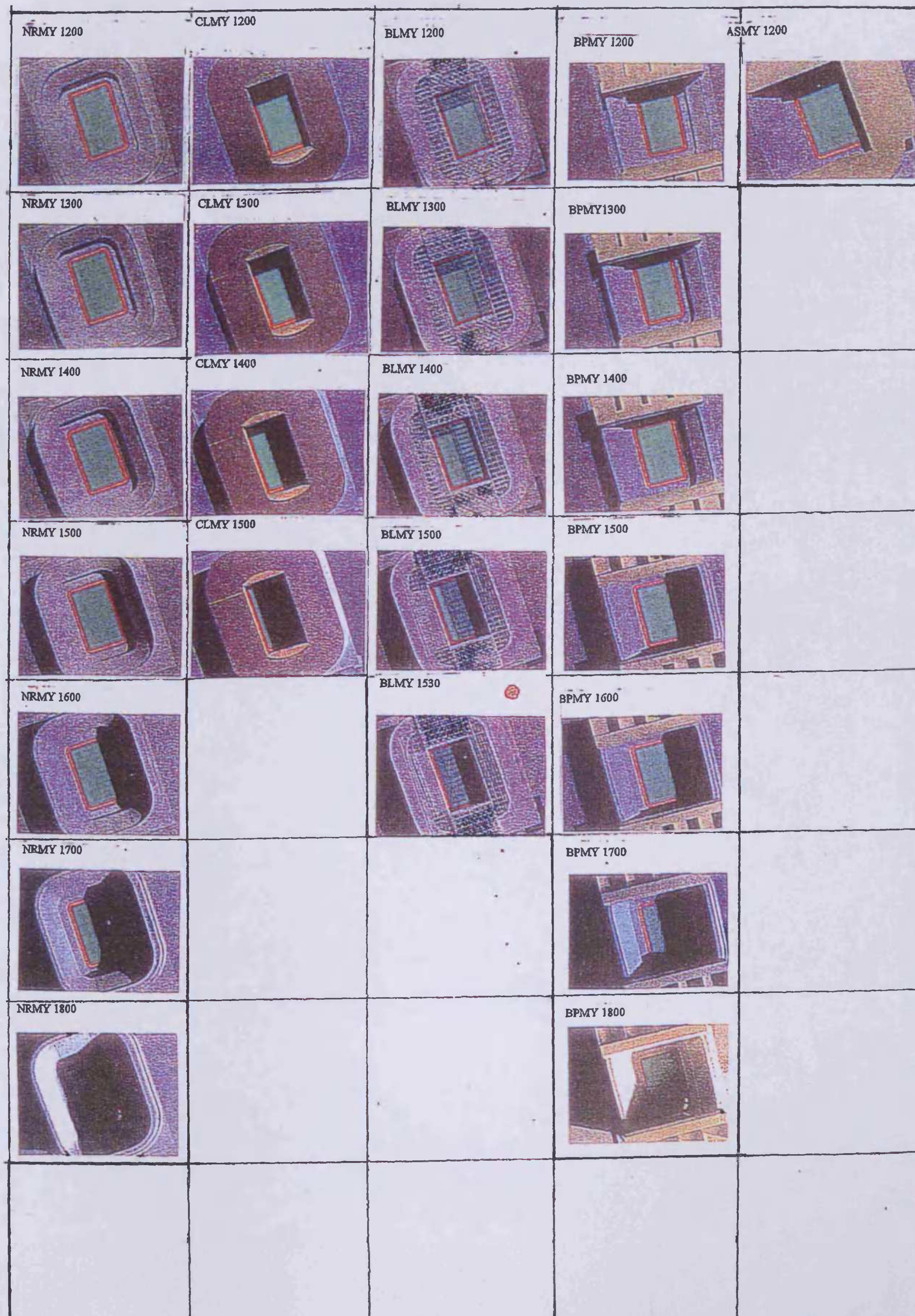


Fig 9.6.6. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (JUNE)

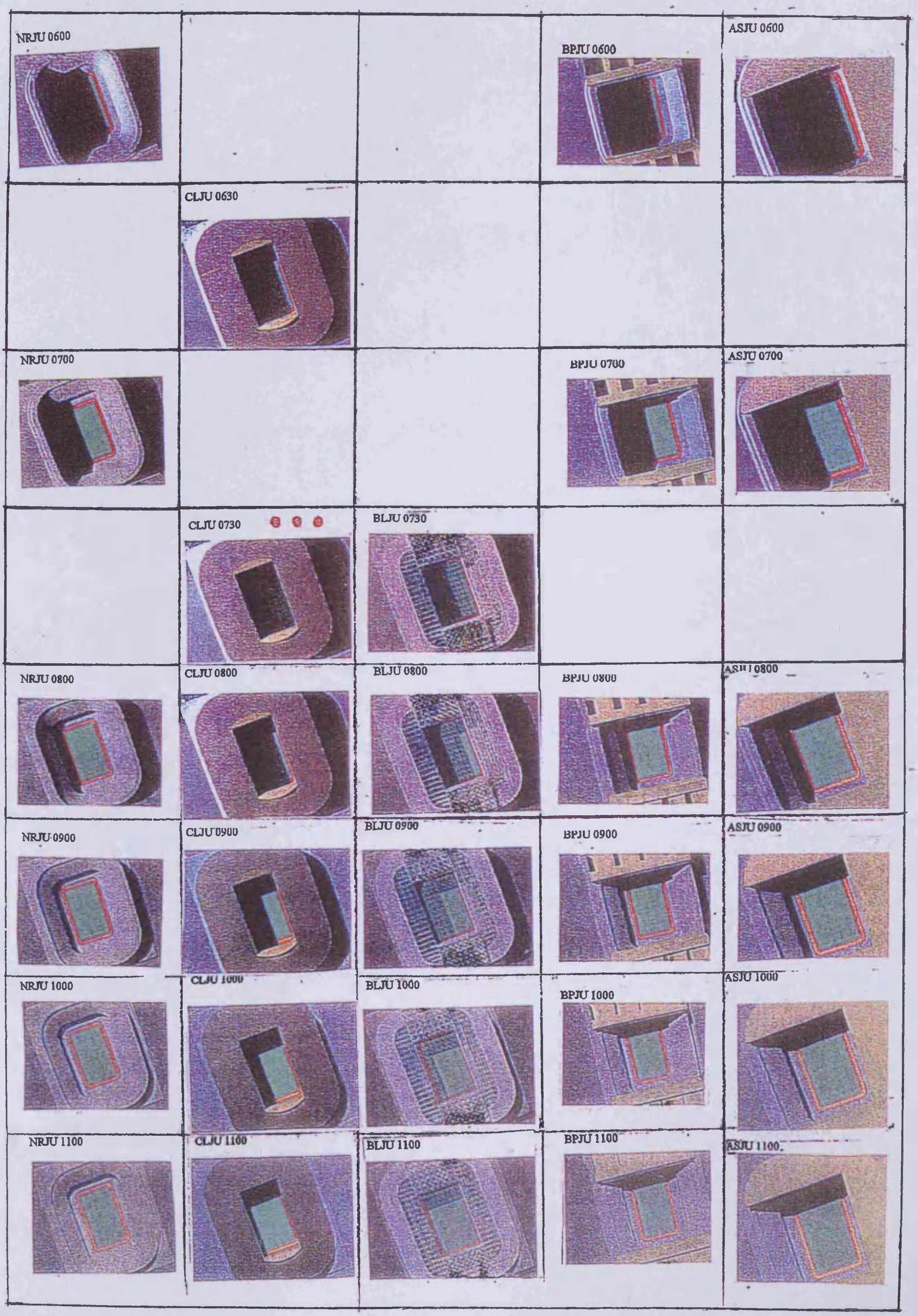


Fig 9.6.6. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (JUNE)

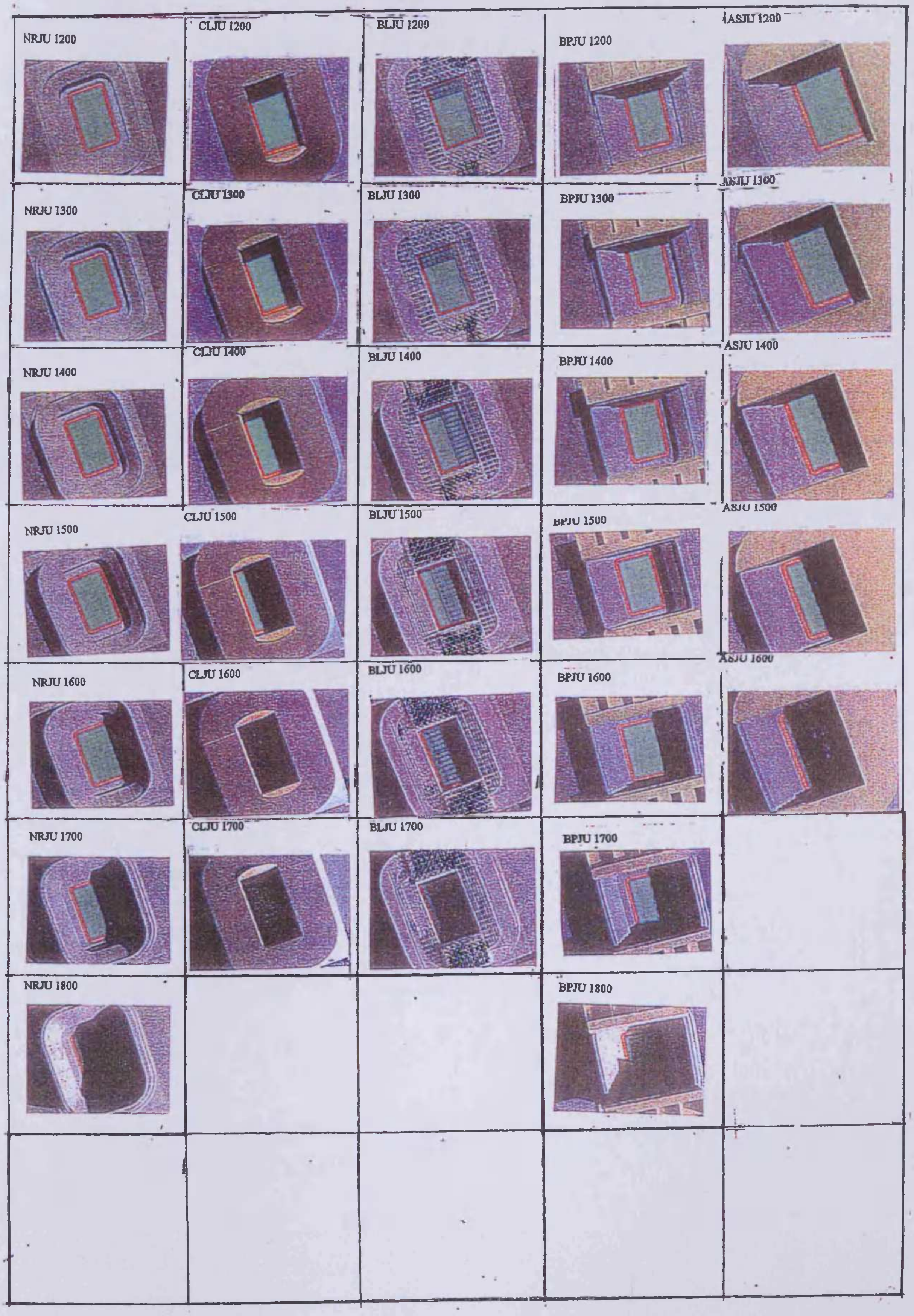


Fig 9.6.7. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY; (DECEMBER)

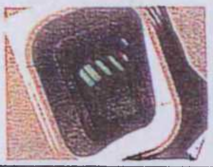
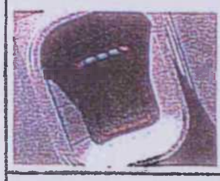
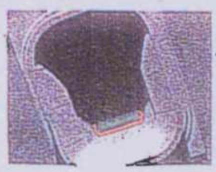
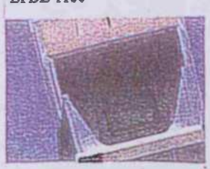
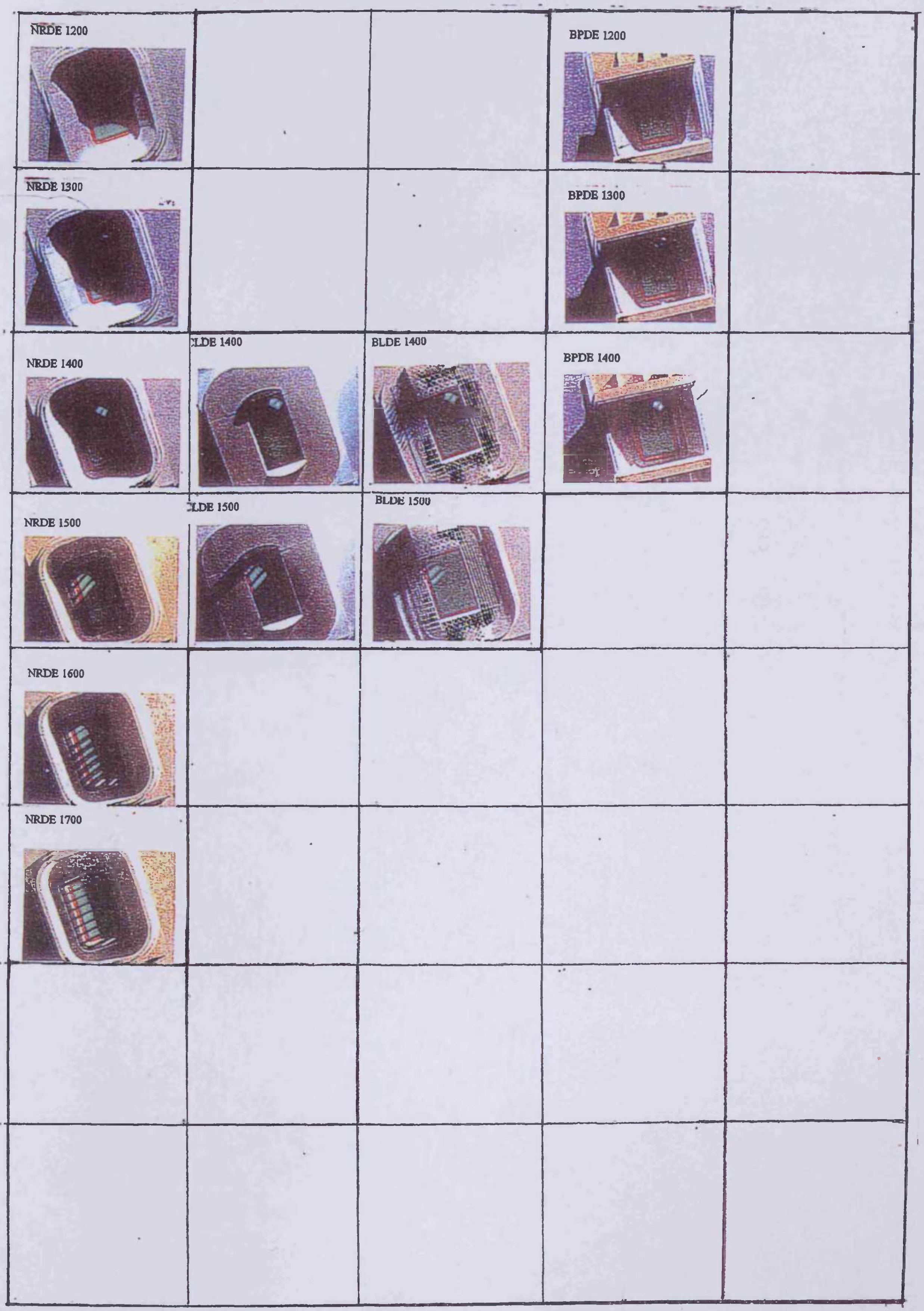
NRDE 0800 				
NRDE 0900 				
NRDE 1000 	:LDE 1000 	BLDE 1000 	BPDE 1000 	
NRDE 1100 			BPDE 1100 	

Fig 9.6.7. SHADOW PHOTOGRAPHS RECORDED IN THE ARTIFICIAL SKY (DECEMBER)



APPENDIX SEVEN

9.7.0. VISITS TO STADIA

The following stadia have been visited during the course of the study or prior to it.

Amsterdam ArenA, Amsterdam, Netherlands, Europe.
Arena Amphitheatre, Verona, Italy, Europe.

Colosseum Amphitheatre, Rome, Italy. Europe.

Gelredome Stadium, Arnhem, Netherlands, Europe.

Harris County Dome, Houston, Texas, USA.

Ibrox Park, Glasgow, Scotland, UK. Europe.

Nue Camp, Barcelona, Spain, Europe.

Mc Alpine Stadium, Huddersfield, England, UK. Europe.

Millennium Stadium, Cardiff, Wales UK. Europe.

Montreal Olympic Stadium, Montreal, Quebec. Canada, North America.

Murrayfield Stadium, Edinburgh, Scotland, UK. Europe.

Old Trafford Stadium, Manchester, England, UK. Europe.

Olympic Stadium, Barcelona, Spain, Europe.

Olympic Stadium., Rome, Italy, Europe.

Raebock Stadium, Bolton, UK. Europe.

San Siro, Milan, Italy, Europe.

San Nicoló, Bari, Italy, Europe.

Stade de France, St Denis, Paris, France, Europe.

Stadium of the Alps, Turin, Italy, Europe.

Stamford Bridge, Chelsea, London, UK Europe.

St James' Park, Newcastle on Tyne, England, UK. Europe.

10.7.0 REFERENCES

10.7.0.1. Bibliography.

65th Annual Michigan Turfgrass Conference Proceedings Vol 24 (Jan 17-19.1995.) Top dressing with Crumb Rubber from used Tires *Sic* Tyres in Turfgrass Areas. Michigan State University East Lansing MI, 1995, 3 pages.

66th Annual Michigan Turfgrass Conference Proceedings Vol 24 (Jan 17-19.1996).

Adams, W.A. Football Grounds in Great Britain. Soil and Turf. A Conference Paper delivered in Japan 1996. University of Wales, Aberystwyth, U.K.

Adams, W.A. *et el Making the most of Natural Turf Pitches. A National Survey of Winter Games Pitches with high Quality Drainage Designs.* Sports Council Natural Turfgrass Advisory Report No 10, The Sports Council, London, UK. 1993 20 pages.

Adams, W.A. and Gibbs, R.J. *Natural Turf for Sport and Amenity Science And Practice.* CAB International 1994.

Association of County Councils, Joint Working Party on Ground Safety And Public Order. *Ground Safety and Public Order, Hillsborough Stadium Disaster.* London Association of County Council Publications. 1991.

Availability of daylight, B.R.E Department of the Environment, Watford, UK, 1979.

Baker, A. *The Gladiator the Secret History of Rome's Warrior Slaves.* Ebury Press London. 2000.

Baker, S. W. The Effects of Shade and Changes In Microclimate on the Quality of Turf at Professional Football Clubs. *Journal Sports Research Institute* Vol 71 Bingley, Yorkshire, UK, pages 66-83.

Baker, S. W. *Sands for Sports Turf Construction and Maintenance.* 1990.

Bannister, Sir. F. *History of Architecture on the Comparative Method.* 15th Edition, Batsford London . 1950.

Barnes, M. *et al. Secrets of Lost Empires Reconstructing the Glories of Ages Past.* BBC Books, 1996 pages 137-179.

Beard, J. B. TURFGRASS SCIENCE AND CULTURE. Prentice-Hall International (UK) Limited, London. 1973.

Bognar, B. *Hiroshi Hara: The Floating World of His Architecture.* Wiley-Academy, Chichester, UK. 2000 P 254-71.

Bomgardner, D.L. History of the Roman Ampitheatre. Routledge, London 2000.

Blackwell, L. *Astrodome for Birmingham.* Building Design, 10t February, 5. 1984.

BS Recommendations for Artificial Sports Surfaces – Classification and general introduction. London. 1990.

BS Recommendations for Irrigation Techniques – Automatic turf irrigation systems. Part 1: Definitions of the programme of equipment by the owner. London. 1999.

The Building Research Station, Video Library Album, *The Fire Valley Parade*, Bradford UK

Canaway, M. Grass Mixes for Football and Rugby Pitches. *The Groundsman* 1992.

Canetti, E. 1973. *Crowds and Power.* Penguin Books, Middlesex, England, 1973 pages 30-105,

Carrow, R. N. and Duncan, R. R. 1999. *Salt-Affected Turfgrass Sites Assessment and Management.* 1999.

Cartwright, B. *Pitch Battles Galore.*1999.

Chapman, G. P. *The Biology of Grasses.* 1999.

Climate in the United Kingdom.. *A handbook of solar radiation, temperatures and other data for thirteen principal cities and towns.* Edited by Prof John Page Ralph Lebens H.M.S.O. London. 1986.

Collins, P. Playing Safe: Rod Sheard and Geraint John talk about the changing design of stadia. *Atrium*, April. 1990.

Connolly, P. *Colosseum, Rome's Arena of Death.* B.B.C. Books, London 2003.

Cook, A. and Baker, S. *Effects of Shade and Simulated Wear On The Growth And Performance of Eighteen Cultivars Of Perennial Ryegrass for Football Pitches.* Turfgrass Research Institute. Bingley, Yorkshire UK. 3 pages, undated.

Coote, J. *History of the Olympics In Pictures.* Tom Stacey Ltd London. 1972.

Cox Architects. *Selected and Current Works.* Images Publishing Group Ltd. Victoria, Australia 1994 Pages 66-77

Croker, T. The Secretary's column: Ted Croker looks at the possibility of a covered stadia in England. *FA Today.* 1, October 1979 pages 8-9.

Duble, R.L. *Water Management on Turfgrasses, Texas Agricultural Extension Services.* Texas July 2003.
http://aggiehorticulture.tamu.edu/plantanswers/turf/publications/water.html

Emmons, R. *Turfgrass Science and Management, Third Edition.* Delmar Thomson Learning, UK, USA, Australia.2000.

Football Pitches. Turfgrass Research Institute Bingley, Yorkshire, UK, 3 pages, undated.

Football Stadia Advisory Design Council.. *Football Stadia Bibliography* 1980-1990. London, Football Stadia Advisory Design Council. 1991

Football Stadia Advisory Design Council. *Designing for Spectators with Disabilities*. London, Football Stadia Advisory Design Council. 1992

Football Stadia Advisory Design Council. *Digest of Stadia Criteria.* London, Football Stadia Advisory Design Council. 1992

Football Stadia Advisory Design Council. *On the Sidelines, Football and Disabled Spectators*. London, Football Stadia Advisory Design Council. 1992.

Football Stadia Advisory Design Council. *Seating: Sightlines, Conversion of Terracing, Seat Types*. London, Football Stadia Advisory Design Council. 1991.

Football Stadia Advisory Design Council. *Stadium Public Address Systems*. London, Football Stadia Advisory Design Council. 1991

Football Stadia Advisory Design Council. *Stadium Public Address Systems*. London, Football Stadia Advisory Design Council. 1991.

Football Stadia Advisory Design Council. *Stadium Roofs*. London, Football Stadia Advisory Design Council. 1992.

Football Stadia Advisory Design Council. *Terraces Designing for Safe Standing at Football Stadia*. London, Football Stadia Advisory Design Council. 1993.

Football Stadia Advisory Design Council. *Design-Build. A Good Practice Guide Where Design-Build is Used for Stadia Construction* . London, Sports Council. 1994.

Football Stadia Advisory Design Council. *Stadium Control Rooms*. London, Sports Council. 1994.

Football Stadia Advisory Design Council. *Toilet Facilities at Stadia.* London, Sports Council. 1994.

Football Spectators Act 1989. London HMSO.

Ford, A. J. *Guidance notes for the procurement of CCTV for public safety at football grounds*. Home Office Science and Technology Group: Police Science Development Branch Publication no. 4/90. St. Albans, Home Office. 1990.

Gabucci, A. The Colosseum. J Paul Getty Museum 2001.

Gardiner, E. N. *Athletics of the Ancient World.* Oxford at the Clarendon Press. 1930.

Gardiner, E. N. *Athletics of the Ancient World.* Oxford at the Clarendon Press 1930. Reprinted by Arles Publishers Inc Chicago, IL. MCMLXXX, 1930.

Gardiner, E. N. Handbook of Archaeology and Antiquities. Macmillian & Co London. 1910.

Golesworthy, M. *The Encyclopaedia of Association Football.* Robert Hale Ltd London. 1958.

Gratton, C. and Taylor, P. Indoor arenas. The Missing Market. *Leisure Management*, 7 October, 1987. pages 32-34.

Guide to Safety at Sports Grounds, 4th Edition. London, The Stationary Office. 1997.

Handreck, K. and Black, N. *Growing Media for Ornamental Plants and Turf.* New South Wales University Press Kensington, Australia. 1994.

Hardy W. *et al*, Football (Sports) Pitch Conservation. A Thesis. Wye College 1996.

Harris, H. A. *Greek Athletes and Athletics.* Hutchinson of London. 1964.

Hisorical Dictionary of the Modern Olympic Movement. 1996. Edited by Findling, J.E. and Pelle, K. E. Greenwood Press Westpoint, Connecticut, London. 1996.

Home Office,. *Committee of inquiry into crowd safety and control at sports grounds.* Chairman: Mr. Justice Popperwell. Interim Report, London HMSO, 1985, CMND 9595.

Home Office, *Committee of inquiry into crowd safety and control at sports grounds.* Chairman: Mr. Justice Popperwell. Final Report, London HMSO, 1986. CMND 9710.

Home Office, *The Hillsborough stadium disaster*, Inquiry by Rt. Hon. Lord Justice Taylor. London HMSO. 15 April 1989.

Inglis, S. August 1998, *Rolling Gesture*, Panstadia International, Panstadia Publishing Co Ltd, Volume 5/No2. 1998 Pages 42-48,

Inglis, S.. *Football Grounds of Britain.* Collins Willows, London. 1996.

Inglis, S. *The Football Grounds of Europe.* Collins Willow. 1990 [Out of Print]

Inglis, S. *Sightlines, No Place Dome.* Yellow Jersey Press London, 2000 pages 263-283.

John, G. and Sheard, R. *Stadia, A Design and Development Guide.* Butterworth – Architecture. 1994

John, G. and Sheard, R. *Stadia, A Design and Development Guide.* Second Edition. Architectural Press. 1997

John, G. and Spring, M. 1987.Where are our big arenas going? *Baths Service and Recreation Management*, 1987 pages 46, 128-129.

Kelly, S.F. 1996. *Back Page Football, A Century of Newspaper Coverage*. Aurora Publishing. 1996

Langer, R.H.M. *How Grasses Grow*. Edward Arnold London. 1979

Leinauer, H. *et al* Poa Supina Schrad: A New Species for Turf. International Turfgrass Society Research Jouranal. Vol 8 1997

Lawson, D. M. *Fertiliser for Turf*. 1996.

Less, A. Biomechanical Aspects of Soccer Equipment. John Moores University, Liverpool 1996.

Levy, M. The Engineering of Architecture. *Panstadia International*.
Panstadia Publishing Co Ltd, Volume 4/No2 April 1997 Pages 42-43.

Lewis, K. G. & N. Branton.. *The Rise of British Commerce, 'Bedrock Series'* Pitman , 1930 pages 88-100.

Llewelyn, C.. *Learning lessons from Disasters*. A Welsh Consumer Council Report, Cardiff, 1998 Page 43..

Luder, O. *Sports Stadia After Hillsborough*. Papers presented at the Sports Council/ Royal Institute of British Architects Seminar, RIBA, 29 March 1990. London RIBA/Sports Council in association with the Football Trust.

Makowski, Z..S. *Number One, Pittsburgh, USA*. Steel Space Structures. Michael Joseph. London. 1965 (Pages 137-138).

Martialis, M.V. Liber de Spectaculis, Loeb Classical Library, Martial Vol. 1, Harvard University Press 1993.

McIntyre, K. and Jakobsen, B. *Drainage for Sports turf and Horticulture*. Horticultural Engineering Consultancy Australia. 1998

Millbank, P. Football Clubs: Time to Open Their Gates to All Sports. *Surveyor*, 16 May, 1975 pages 12-13. Olympic Stadia. Mexico City. Building for the XIXth Olympic Games 1968 *Building*, 6 September, 1975 pages 87-90.

Ne'eman, E. & Light, W. Availability of Sunshine. B.R.E. C.P. 75/75 Department of the Environment. Watford, UK.

Perrin, G. Seating for sport and leisure. *Leisure Management*, 1, January, 1985, pages 14 and 16.

Piano, R. *The Renzo Piano, Logbook*. Thames and Hudson 1997, pages 122-129, Pickering, D. *The Cassell Soccer Companion.* Cassell London. 1998.

Planning. *The Architect's Handbook.* "E and O.E" 6th Edition, Iliffe & Sons Ltd. London. 1950.

Popplewell, Mr Justice. *Committee of Enquiry into Crowd Safety and Control at Sports Grounds*, Final Report, LONDON, HMSO, 1986.

The Princely Courts of Europe 1500-1750. Editor Adamson, J. Weidenfeld & Nicolson, London, 1999, page 58.

Provoost, M. et- al, *The Stadium the Architecture of Mass Sport.* Michelle Colophon, Netherlands. 2000.

Puhalla, J., Krans, J. and Goatley, M. *Sports Fields: A Manual for Design, Construction and Maintenance.* 1999.

Radcliffe, D. C. *Montreal Olympic Stadium.* Panstadia International, Panstadia Publishing Co Ltd, Volume 5/No2 August 1998, Pages 41.

Retractable Dome For Pittsburgh Auditorium. *Civil Engineering*, June 1961 pages, 52-57.

Rhodes, D. *The Maintenance of Artificial Sand-filled Turf Used for Sport.* 1996.

Rogers III, J. N. *Sports Turf Research: A Futuristic and Realistic Look..* Michigan State University, East Lansing MI 488224-1325

Rogers III, J.N. *et al The Sports Turf Management Research Program at Michigan State University.* Standard Testing Publication 1305, American Society for Testing Materials , West Conshohocken PA 19428-2959. 1997 pages 132-144.

Rogers III, J.N. *The Sod That Came in from the Cold.* Natural Science At The Edge, December 1994, pages 192-198.

R.W.D.I. Technotes Issue 12. Turfgrass, Micro Climate Issues. R.W.D.E.J. Inc. Gualph Ontario. Canada NIK 188 undated.

Salvadori, M. 1990. *Why Buildings Stand Up.* W,W, Norton & Co, NewYork & London, 1990, pages 244-245.

SAN SIRO, I. *A Cura di:* Giuseppe Maria Jonghi-Lavarini, et al Di Baio Editore S.p.A. 1990.

SAN-SIRO, I. *A Cura di Silvana Sermisoni.* Electra, Milano. 1989.

Schroeder, C. B. and Sprague, H. B.. *Turfgrass Management: Good Turf for Lawn, Playing Fields and Parks – 5th Edition.* 1996.

Seren, G. L. *C'mon City*! Grahame Lloyd, Bridgend, Wales, 1999, pages 76-78.

Schmidt, T. *Building a Stadium which reflects the Games Architectural History of the Seoul Olympic Stadium*. Olympic Review, 239, September 1988, pages 441-4.

Sheard, R. *Sports Architecture*. Spon Press London and New York. 2001.

Smiley, R. *Compendium of Turfgrass diseases*. 1992.

Snake, Lawrence D.H. *Modern Verse in English 1900-1950* Cecil & Tate Eyre & Spottiswoode London .1958 .

Soprintendenza Archeologica Di Roma, *The Valley of The Colosseum*. Electra Milan, 1997, pages 3-25.

Sources of Colour 1970 Science Mac Adam D,L Editor MIT Press Cambridge Mass.

SPACE STRUCTURES FOR SPORTS BUILDINGS, 1987. Proceedings of the International Colloquium on Space Structures for Sports Buildings. Oct 27-30, 1987, Beijing China.. Science Press, Beijing, China. Elsevier Applied Science, London. 1987, Pages 36 -37

Sport England, *Natural Turf for Sport*. 2000.

Sports Council Technical Unit for Sport: John, G. and Campbell, K. *Handbook for Sports and Recreational Building Design*. Vol.1.Outdoor Sports, 2nd Edition. Butterworth-Heinemann. 1993.

Stadia, Arenas and Grandstands. Design Construction and Operation. 1998. Edited by Thompson *et al.*, Concrete Society Stadia 2000 Conference Proceedings, E &FN Spon, London & New York, April 1998.

Stadia and Arenas – Development, Design and Management. Editors Tolloczko, J. J. A., and Clarke, J. N.

The Stadium and the City. Edited by John Bale and Olof Moen, Keele University Press. 1995.

Stewart, V. I. *Sports Turf Science, Construction and Maintenance*. 1994.

Structural Design of Retractable Roof Structures. Editor Kazuo, I. WIT PRESS, Southampton, Boston USA. 2000.

STRI. *Turfgrass Seed.*

Taylor R et al. *The Day of the Hillsborough Disaster, A Narrative Account*. Liverpool University Press, Liverpool, England. 1995.

Tennant, J. *Football the Golden Age*. John Cassell & Co, London. 2001.

Turfgrass. Waddington, D. Carrow, R. amd Shearman, R. Editors, Agronomy No 32.Madison, Winconsin, USA.1992.

Weston, R. *Utzon*, Edition. Blondal, 2002, pages 270-5.

Wild, A, *Soils and the Environment (an introduction).* Cambridge University Press . 1993.

Williams Davis, R. and Geulph, I. *'Technotes', Turf Microclimate Issues.* No 12, Ontario, Canada N1K 1B8. 4 Page pamphlet.

York, C. A.. *Turfgrass Diseases and Associated Disorders*. 1998.

10.7.2. Dictionaries Used

An A. B. C. of English Usage, Treble, H. A. and Vallins, G. H., Oxford at the Clarendon Press, 1937.

Collins English Dictionary, Third Updated Edition, Harper Collins, 1994.

Collins English Dictionary, Fifth Updated Edition, Harper Collins, 2000.

Collins Dictionary of Environmental Science, Jones Et al Harper Collins, 1990.

The Chambers Dictionary, Harrap Publishers, 1998.

Dictionary of Science and Technology Editor Walker, M, Larousse Edinburgh & New York, 1995.

Oxford Reference ,Dictionary of Computing, New Edition. Illingworth V, Oxford University Press, 1991.

The Shorter Oxford Dictionary, Two Volumes, Rivised & Edited by C.T.Onions. Oxford at the Clarendon Press, 1933.

The New Oxford Dictionary of English, Edited by Judy Pearsall, Clarendon Press.Oxford, 1998.

French Dictionary: French Shorter Dictionary Sixth Edition, Chambers, 2000.

Italian Dictionary: Cassell's Italian Dictionary Seventh Edition, Cassell and Company Ltd. 1972.

Latin Dictionary: Cassell's Latin Dictionary Fifth Edition, Cassell and Company Ltd. 1984.

Modern English Usage Second Edition. Fowler, H. W., Oxford at the Clarendon Press, 1965.

Optima Green Dictionary, Johnson, C, Macdonald & Co London, 1991.

The Penguin Dictionary of Biology, Thain & Hickman, Ninth Edition, London, 1994.

The Penguin Dictionary of Chemistry, Edited, Sharp, D, Second Edition, London, 1990.

The Penguin Dictionary of Civil Engineering, Scott. J, Fourth Edition, London, 1991.

The Penguin Dictionary of Human Geography, Goodall, B, London, 1987.

The Penguin Dictionary of Physics, Edited,, 1991 Illingworth V, London, 1990.

10.7.3 Glossary

A

Abscisic acid (ABA) (ab-SIS-ik) A plant hormone that inhibits cell division and promotes dormancy, interacts with gibberellins in regulating seed germination.

Absorption The process in which incident radiant energy is retained by a substance

Acid A substance that increases the hydrogen ion concentration in a solution.

Acid precipitation Rain, snow, sleet, hail, drizzle etc. with a pH below 5.6 can damage or destroy organisms by acidifying lakes, streams and possibly land habitats.

Adiabatic process A thermodynamic change of state of a system in which there is no transfer of heat or mass across the boundaries of the system. Compression always results in warming, expansion in cooling.

Aerobic (air-OH-bik) Containing oxygen; an organism, environment or cellular process that requires oxygen.

Albedo The ratio of the amount of solar radiation reflected by a body to the amount incident upon it.

Alga (AL-guh) (plural algae) One of a great variety of protists, most of which are unicellular or colonial photosynthetic autotrophs with chloroplasts containing the pigment chlorophyll a; heterotrophic and multicellular protists closely related to unicellular autotrophs are also regarded as algae.

Ambient air The air of the surrounding environment.

Anabatic wind An upslope wind due to local surface heating.

Anaerobic (an-air-OH-bik) Lacking oxygen; an organism, environment, or cellular process that lacks oxygen and may be poisoned by it.

Anemometer An instrument for measuring wind speed.

Angiosperm (AN-jee-oh-spurm) A flowering plant, which forms seeds inside a protective chamber called an ovary.

Annual A plant that completes its life cycle in a single year or growing season.

Apical meristem (APP-ih-kul MAIR-ib-stem) A meristem at the tip of a plant root, or in the terminal and axillary bud of a shoot.

Assimilate To absorb (food) and to incorporate it into body tissue.

ATP synthase A cluster of several different enzymes (membrane proteins) in the mitochondrial cristae. ATP synthases function in chemiosmosis with adjacent electronic transport chains, using the energy of a hydrogen-ion concentration gradient to make ATP. ATP synthases also provide a port through which hydrogen ions can diffuse into a matrix of mitochondrion.

Attenuation Any process in which the flux density of a 'parallel beam' of energy decreases with increasing distance from the energy source.

Auricle Outgrowths of the edge of the leaf occurring in some grasses from either side of the collar at the junction of the leaf; present in varying sizes and shapes or may be absent.

Autotroph (AW-tuh-trofe) An organism that makes its own food, thereby sustaining itself without eating other organisms or their molecules. Plants, algae, and photosynthetic bacteria are autotrophs.

Auxin (AWK-sin) One of a family of plant hormones having a variety of effects; chiefly promotes the growth and development of shoots.

Awn Slender hairlike projection(s) arising from small flowers of grasses; variable in length and texture.

Axil The upper angle between a leaf or petiole and the stem from which it springs: also that between a branch and trunk.

Axillary bud (AK-she-LAIR-ee) An embryonic shoot present in the angle formed by a leaf and stem.

B

Biennial (by-EN-ee-ul) A plant that completes its life cycle in two years.

Biology Life science, or the scientific study of life.

Biomass The amount, or mass of organic material in an ecosystem.

Blade The extended upper portion of the leaf beyond the sheath; present in cross-section as flat, v-shape, thread like; blade tip as sharply pointed, boat or canoe shape; leaf surface and margin, as hairy, saw-like; and leaf colour as light to dark green.

Black Body An hypothetical body which absorbs all of the radiation striking it, i.e. allowing no reflection or transmission.

C

C_3 plant A plant that fixes carbon from CO_2 directly into the three-carbon compound 3-PGA in the Calvin cycle.

C_4 plant A plant that can fix carbon from CO_2 directly into the four-carbon compound. The enzyme involved has a very high attraction for CO_2 and can fix carbon when CO_2 levels are low in the leaf. The four carbon compound passes the fixed carbon to the Calvin cycle, maintaining sugar production and preventing photorespiration when leaf stomata are closed. Keeping stomata closed during the day is an adaptation for conserving water.

Calvin cycle The second of two stages of photosynthesis, the calvin cycle is a cyclic series of chemical reactions that occur in the stroma of the chloroplast, using the carbon in CO_2 and the ATP and NADPH produced by the light reactions to make the energy-rich sugar molecule, G3P.

CAM Plant A plant whose stomata are open and that fixes carbon only at night. Carbon is fixed into a four-carbon compound , and the carbon is passed to the Calvin cycle during the day. Keeping stomata open only at night is an adaptation for conserving water.

Carbohydrate (KAR-bo-HI-drate) A class of biological molecules consisting of simple single-monomer sugars (monosaccharides), disaccharides, or other multi-unit sugars (polysaccharides).

Carbon fixation The incorporation of carbon from atmospheric CO_2 into the carbon in organic compounds. During photosynthesis in a C_3 plant, carbon is fixed into a three-carbon sugar, as it enters the Calvin cycle. In C_4 and CAM plants, carbon is fixed into a four carbon sugar.

Cell A basic unit of living matter separated from its environment by a membrane; the fundamental structural unit of life.
Cell Body The part of the cell, such as the neuron, that houses the nucleus.

Chemisosmosis (KEM-ee-oz-MOH-sis) The production of ATP using the energy of hydrogen-ion gradients across the membranes to phosphorylate ADP; powers most ATP synthesis in cells.

Chloroplast (KLOR-uh-plast) An organelle found in plants and photosynthetic protists. Enclosed by two concentric membranes, a chloroplast absorbs sunlight and uses it to power the synthesis of organic food molecules (sugars).

Collar Strengthening tissue at the back of the ligule, immediately above the leaf sheath, often a different colour from the rest of the leaf blade; present as a broad, narrow or divided band.

Controlled experiment A component of the scientific method whereby a scientist carries out two parallel tests, an experimental test and a control test. The experimental test differs from the control by one factor, the variable.

Cortex (1) In plants, the ground tissue system of a root made up mostly of parenchyma cells, which store food and absorb minerals that have passed through the epidermis.
(2) In vertebrates, the outer portion of the kidney and of the adrenal gland

Cotyledon (KOT-ih-LEED-un) The first leaf that appears on an embryo of a flowering plant; a seed leaf. Monocot embryos have one cotyledon; dicot embryos have two.

Crown Refers to the junction of the root and stem usually at ground level.

Culm The stem of grasses and sedges.

Cuticle (KYOO-tih-kul) (1) In plants, a waxy coating on the surface of stems and leaves that helps retain water. (2) In animals, a tough, nonliving outer layer of skin.

Cyanobacteria (sy-AN-oh-bak-TEER-ee-uh) Photosynthetic, oxygen-producing bacteria, formerly called blue green algae.

Cytokinin (SY-toh-KINE-in) One of a family of plant hormones that promotes cell division, retards aging of flowers and fruits, and may interact antagonistically with auxins in regulating plant growth and development.

Cytoplasm (SY-toh-PLAZ-em) Everything inside a cell between the plasma membrane and the nucleus; consists of a semifluid medium of organelles.

D

Dewfall Condensation of water from the lower atmosphere onto objects near the ground.

Dew – Point The temperature to which a given parcel of air must be cooled (at constant pressure and constant water vapour content) in order for the situation to occur.

Dicot (DY-kot) A flowering plant whose embryo has two seed leaves or cotyledons.

Diffuse short-wave radiation Short-wave radiation reaching the Earth's surface after having been scattered from the Direct-Beam by molecules or other agents in the atmosphere.

Direct – beam short-wave radiation That portion of short-wave radiation received in a parallel beam 'directly' from the Sun.

E

Emissivity The ratio of the total radiant energy emitted per unit time per unit area of a surface at a specified wavelength and temperature to that of a Black Body under the same conditions.

Energy The capacity to perform work or to move matter in a direction it would not move if left alone.

Epidermis (EP-ih-DER-mis) (1) In plants the tissue system forming the protective outer covering of leaves, young stems, and young roots. (2) In animals, the living layer or layers of cells forming the protective covering, or outer skin.

Eukaryotic cell (yoo-KAIR-ee-OT-ik) A type of cell that has a membrane- enclosed nucleus and other membrane-enclosed organelles. All organisms except bacteria are composed of eukaryotic cells.

Evaporation (or vaporization) the process by which a liquid is transformed into a gas, in the atmosphere usually water changing to water vapour.

F

Family In classification, the taxonomic category above the genus and below the order.

Fertilisation Any substance added such as manure or a mixture of nitrates added to soil or water to increase productivity.

Fibrous (or bunch root system) A root system in which the roots are finely divided, usually in a clump.

Flower In an angiosperm, a short stem with four sets of modified leaves, bearing structures that function in sexual reproduction.

Flux Rate of flow of some quantity.

G

Ground tissue system A tissue of mostly parenchyma cells that makes up the bulk of a young plant and is continuous throughout its body. The ground tissue system fills the space between the epidermis and the vascular tissue system.

Guard cell A specialised epidermal cell in plants that regulates the size of a stoma, allowing gas exchange between the surrounding air and the photosynthetic cells in the leaf.

Gymnosperm (JIM-noh-spurm) A naked seed plant; its seed is said to be naked because it is not enclosed in a fruit.

H

Habitat A place where an organism lives.

Heat The amount of energy resulting from the movement of molecules in a body of matter. Heat is energy in its most random form.

Herbage The edible parts of plants which are removed by grazing, or that part of the plant which is removed by defoliation.

High-density-lipoprotein (HDL) A cholesterol carrier in the blood, made up of cholesterol and other lipids surrounded by a single layer of phospholipids in which proteins are embedded. An HDL carries less cholesterol than a related lipoprotein, LDL , and may be correlated with a decreased risk of blood vessel blockage.

Humus (HYOO-mus) Decomposing organic material found in topsoil.

Hydrocarbon A chemical compound composed only of the elements carbon and hydrogen.

I

Inflorescence Refers to the part of the turfgrass that consists of a flower bearing stalk.

Internode The portion of a plant stem between two nodes.

Irradiance The radiant flux on a unit area of a surface.

Irradiation Total radiant flux received by unit area of a given surface .

K

Keel Leaf shape of lower surface of the leaf; protrudes like the keel of a boat or canoe.

Kingdom Monera (moh-NAIR-uh) The taxonomic group that contains the bacteria or prokaryotes.

Kingdom Plantae (PLANT-ay) The taxonomic group that contains the plants.

L

Laminar Flow A flow in which the fluid moves smoothly in parallel stream lines; non-turbulent.

Lateral shoot Shoots originating from vegetative buds in the axis of leaves or from the nodes of stems, rhizomes or stolons.

Leaf The main site of photosynthesis in a plant; consists of a flattened blade and a stalk (petiole) that joins the leaf to a stem.

Lichen (LY-ken) A mutualistic association between a fungus and an alga or between a fungus and a cyanobacterium.

Light reactions The first of two stages in photosynthesis, the light reactions are the steps that absorb solar energy and convert it into chemical energy in the form of ATP and NADPH . The light reactions power the sugar-producing Calvin cycle, but produce no sugar themselves.

Ligule The small membrane or ring of hairs that occurs on the upper side of leaves, just at the junction of the leaf blade and the sheath and wraps around the stem; reduced or absent in some species; present as a fringe of hairs, acute, truncate or ciliate.

Long-day plant A plant that flowers in late spring or early summer when day length is increasing.

M

Margin Refers to the outside edges of the leaf blade.

Meristem (MAIR-eh-STEM) Plant tissue consisting of undifferentiated cells that divide and generate new cells and tissues.

Mesophyll (MEZ-oh-fil) The ground tissue of a leaf; the main site of photosynthesis.

Midrib Central vein of the blade of the leaf, often forming a pronounced ridge on the upper surface and a keel below.

Mitochondrion (MY-toh-KON-dree-on) (plural *mitochondria*) An organelle in the eukaryotic cell where cellular respiration occurs. Enclosed by two concentric membranes, it is where ATP is made.

Mitosis (MY-toh-sis) The division of a single nucleus into two genetically identical daughter nuclei. Mitosis and cytokinesis make up the mitotic (M) phase of the cell cycle.

Molecule Two or more atoms held together by chemical bonds.

Monoculture The cultivation of a single plant variety in a large land area.

Mycorrhiza (MY-ko-RY-za) (plural mycorrhizae) A mutualistic association of plant roots and fungi.

N

Nitrogen fixation The conversion of atmospheric nitrogen (N_2) into nitrogen compounds (NH_4^+, NO_3) that plants can absorb and use.

Nitrogenous base (nigh-TRAH-jen-us) An organic base that contains the element nitrogen.

Node The point of attachment of a leaf on a stem.

Nucleus (plural *nuclei*) (1) An atom's central core, containing protons and neutrons. (2) The genetic control centre of a eukaryotic cell.

O

Organelle (or-gan-EL) A structure with a specialised function within a cell.

Osmosis (oz-MOH-sis) The movement of water across a selectively permanent membrane.

Oxidation The loss of electrons from a substance involved in a redox reaction; always accompanies reduction.

P

Panicle An open, often branched and spreading flowering structure; one type of common inflorescence.

Papery bracts A series of small dry structures that surround or enclose the seed of almost all grasses.

Pathogen A disease-causing organism.

Perennial (peh-REN-ee-ul) A plant that can live for many years.

Petiole The stalk by which a leaf is attached to the rest of the plant.

Phosphorylation (fos-for-uh-LAW-shun) The transfer of a phosphate group, usually from ATP, to a molecule. Nearly all cellular work depends on ATP energizing other molecules by phosphorylation.

Photon (FOE-than) The elemental quality of radiant energy. The shorter the wavelength of light, the greater the energy of a photon.

Photoperiod The length of a day relative to the length of a night.

Photorespiration In a plant cell, the breakdown of a two carbon-compound produced by the Calvin cycle. The Calvin cycle produces the two-carbon compound, instead of its usual three-carbon product G3P, when leaf cells fix O_2, instead of CO_2. Photorespiration produces no sugar molecules or ATP.

Photosynthesis (FOE-toe-SIN-thuh-sis) The process by which plants, autotrophic protists, and some bacteria use light energy to make sugars and other organic food molecules from carbon dioxide and water. Photosynthesis is the food-making process upon which most organisms depend.

Photosynthetic autotroph (FOE-toe-sin-THET-ik-AW-toe-trofe) An organism that uses light energy to make food molecules.

Photosystem A light-harvesting "antenna" unit of the chloroplast's thylakoid membrane.

Phototropism (foh-TOT-treh-PIZ-em) Growth of a plant shoot toward or away from light.

pH scale A measure of the relative acidity of a solution ranging from 0 (most acidic) to 14 (most basic); pH stands for potential hydrogen and refers to the concentration of hydrogen ions (H^+).

Phytochrome (FYE-the-krome) A coloured protein in plants that contains a special set of atoms that absorbs light.

Primary Xylem (ZY-lum) Xylem tissue formed by cells of the vascular cylinder in a young plant.

Prokaryotic cell (pro-KAIR-ee-OT-ik) A type of cell lacking a membrane-enclosed nucleus and other membrane-enclosed organelles; found only in the kingdom Monera; a bacterial cell.

Prophase The first stage of mitosis. During prophase, duplicated chromosomes condense from chromatin, and the mitotic spindle forms and begins moving the chromosomes toward the centre of the cell.

R

Rachis The axis of the inflorescence.

Radiant energy The energy of any type of electromagnetic radiation.

Radiation The process by which electromagnetic radiation is propagated through free space by virtue of joint undulatory variations in the electric and magnetic fields in space.

Reaction centre In a photosystem in a chloroplast, the pair of chlorophyll *a* molecules that trigger the light reactions of photosynthesis. The reaction centre donates an electron excited by light energy to the primary electron acceptor molecule of the photosystem.

Redox (REE-doks) Short for oxidation-reduction; chemical reactions in which electrons are lost from one substance (oxidation) and added to another (reduction). Oxidation and reduction always occur together.

Rhizome (RY-zoam) A horizontal stem that grows below the ground.

Root pressure The upward push of xylem sap in a vascular plant, caused by active pumping of minerals into the xylem by the root cells.

Root system All of a plant's roots that anchor it in the soil, absorb and transport minerals and water, and store food.

S

Savanna A biome dominated by grasses and scattered trees.

Scabrous Rough and harsh to the touch; often show short stiff bristles or saw-like teeth on the part concerned.

Scattering The process by which small particles suspended in a medium of a different index of refraction diffuse a portion of the incident radiation in all directions.

Scientific method The logical process used by scientists to answer questions about nature. The method's key elements are observations, questions, hypotheses, predictions and tests.

Sclereid (SKLER-id) In plants, a very hard dead sclerenchyma cell found in nutshells and seed coats; a stone cell.

Sclerenchyma cell (skler-EN-kim-uh) In plants, a supportive cell with rigid secondary walls hardened with lignin.

Secondary phloem (FLO-um) Phloem tissue produced by the vascular cambium during secondary growth of a plant.

Seed A plant embryo packaged with a food supply within a protective covering.

Sensible heat That heat energy able to be sensed (e.g. with a thermometer). Used in contrast to Latent Heat.

Seed coat A tough outer covering of a seed, formed from the outer coat of an ovule; in a flowering plant, it encloses and protects the embryo and endosperm.

Seed dormancy Temporary suspension of growth and development of a seed.

Sheath Refers to that part of the leaf originating from the node, and surrounds part of the stem. It can be cylindrical or compressed with overlapping, open or closed margins. The leaf sheath may be split, split to near base with margins overlapping or closed.

Shoot system All of the plants stems, leaves, and reproductive structures.

Short-day plant A plant that flowers in the late summer, fall or winter, when daylight is shortening.

Solar altitude Vertical direction of the Sun above the horizon expressed in degrees.

Solar azimuth Horizontal direction of the Sun relative to a reference direction (usually true north) expressed in degrees.

Solar Time Measure of time based on the rotation of the Earth. Mean solar time is fixed and based on the average rotation, whereas apparent solar time is non-uniform, varying through the year according to the Equation of Time.

Solar Zenith Angle Vertical direction of the Sun relative to the zenith expressed in degrees. The reciprocal of Solar Altitude.

Somatic cell (so-MAT-ik) Any cell in a multicellular organism except a sperm or egg cell.

Somite (SO-mite) A block of mesoderm in a chordate embryo. Somites give rise to vertebrae and other segmental structures.

Spike A narrow and usually longer than wide inflorescence, the flowers borne along one stem.

Spikelet The small flowering unit of grasses, consisting of a series of bracts placed one inside another, attached to a branch of the main flowering stem. There are many spikelets in one inflorescence.

Sporangium (spuh-RANJ-ee-um) (plural *sporangia*) A bulbous structure at the tips of some branches.

Stamen (STAY-men) A pollen-producing male reproductive part of a flower, consisting of a stalk, and bearing an anther.

Stolon Refers to the horizontal stem, usually prostrate or trailing at ground level, always above the ground, often rooting at the nodes. Turf plants, bearing them exhibit a stoloniferous habit of growth.

Stoma (STO-muh) (plural, *stomata*) A pore surrounded by guard cells in the epidermis of a leaf. When stomata are open CO_2 enters a leaf, and water and O_2 exit. A plant conserves water when its stomata are closed.

Stroma (STRO-muh) A thick fluid enclosed by the inner membrane of a chloroplast. Sugars are made in the stroma by the enzymes of the Calvin cycle.

Stubble That part of the plant which remains after grazing or defoliation.

Surface tension A measure of how difficult it is to stretch or break a surface liquid.

Sward Turf or grass or a stretch of turf or grass.

T

Taxonomy (tak-SAHN-eh-mee) The branch of biology concerned with identifying, naming and classification of species.

Temperate grassland A treeless, temperate-zone biome dominated by various species of grasses.

Temperate zones Latitudes between the tropics and the Arctic Circle in the north and the Antarctic Circle in the south; regions with milder climates than the tropics or polar regions.

Temperature A measure of the intensity of heat, reflecting the average kinetic energy or speed of molecules.

Thylakoid (THY-luh-koid) A disklike sac formed by the inner membrane of the chloroplast. Thylakoid membranes contain chlorophyll and the enzymes of the light reactions of photosynthesis. A stack of thylakoids is called a granum.

Tiller A shoot or stem that arises from the base in grasses. Termed vegetative tiller if it produces leaves only, and a flowering tiller if it bears inflorescence.

Topsoil The uppermost layer (horizon) of soil, subject to extensive weathering.

Trace element An element that is essential for the survival of an organism but only in minute quantities.

Transpiration The process by which water in plants is transferred as water vapour to the atmosphere.

Tropical forest A biome located near the equator where temperatures are warm, days are 11-12 hours long year round, and where rainfall determines the dominant vegetation.

Tropism (TRO-piz-em) A growth response that changes a plant's shape or makes it grow toward or away from a stimulus.

Tuber An enlargement at the end of a rhizome, in which food is stored.

Tundra A biome at the northernmost limits of plant growth and at high altitudes, characterized by dwarf woody shrubs, grasses, mosses and lichens.

V

Vacuole (VAK-yoo-ohl) A membrane-enclosed sac that is part of the endomembrane system of a eukaryotic cell; has diverse functions.

Vegetative reproduction Asexual reproduction by a plant.

Vein Refers to the specialised organs which conduct plant foods to the sheath and leaf, and which removes from these organs, substances synthesised under the action of photosynthesis. Often prominent on the upper surface of a leaf blade.

Venation Refers to the veins running parallel to the apex of the blade. Some species have distinct mid-veins, while others have veins uniformly distributed across the leaf. The prominence of venation, on the upper and lower leaf surface, is useful in identification.

Vernation Refers to the arrangement of the youngest leaf in the bud shoot; either folded (conduplicate) or rolled (convolute) in the bud-shoot.

W

Wavelength The distance between crests of waves, such as those of the electromagnetic spectrum.

X

Xylem (ZY-lum) The nonliving portion of a plant's vascular system that provides support and conveys xylem sap from the roots to the rest of the plant. Xylem is made up of vessel elements and /or tracheids.

Xylem sap The solution of inorganic ions conveyed in xylem from a plant's roots to its shoots.