Full Scope 3D Analysis of a VVER-1000 Containment Pressurization during a LB-LOCA by employing AutoCAD and GOTHIC code

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Abstract

One of the main goals of severe accident management strategies is to maintain containment integrity to prevent radioactive release into the environment. As a result, containment internal loads need to be investigated during a postulated accident. In the present study, short-term containment thermal-hydraulic (TH) parameters of a VVER-1000/V446 reactor are analysed during a LB-LOCA. To achieve this goal, in the first step as-built 3D structure of VVER-1000/V446 containment was modelled in detail by using AutoCAD. The AutoCAD model has been processed to be prepared for GOTHIC 3D input. Meanwhile, an equivalent GOTHIC lumped parameter (LP) model is also prepared to validate the modelling procedure and results against the FSAR. Finally, LP profiles and 3D TH contour results of GOTHIC code were presented and discussed. LP results show a close agreement with FSAR reference and can approve the accuracy of the simulation procedure. 3D contours present all-coordinate detailed TH parameters versus time inside the containment. Spatial distribution of TH parameters and minor short-term effects of spray as Engineering Safety Features (ESFs) to tackle the containment pressurization can be evaluated by employing these contours. 3D simulation results can provide advantages for the precise locating and installation of ESFs in design and operation to achieve the highest efficiency in case of containment accident.

Keywords: GOTHIC code, Containment, Thermal-Hydraulic simulation, LB-LOCA, Pressurization, VVER-1000

1. Introduction

Nuclear safety as a fundamental concept of the nuclear industry has the most important effects on the prospective and public engagement of future nuclear energy. A nuclear power plant operates normally during states like startup, power operation, shutting down, refuelling, etc. Some abnormal operations that have undergone at least once during the operational lifetime of a plant (e.g. valve stuck) are called "Anticipated Operational Occurrences" (AOOs) in accidents terminology. Accident conditions are usually more severe than AOOs, they largely deviate from normal operational states relative to AOOs. These accident conditions can be categorized as Design Basis Accident (DBA), Beyond Design Basis Accident (BDBA) and finally severe accidents in ascending order of safety risk respectively. DBAs are postulated events that are considered in the design stage of the plant. If an event develops into a DBA, damage to the fuel and radioactive material release are kept within authorized limits. The most fearsome of an accident in a nuclear power plant occurs if an initiating event progresses beyond

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the design criteria and turns into a BDBA and severe accident then. Severe accidents lead to core degradation and threaten containment integrity (IAEA, 2019). The containment is the final barrier in Defence in Depth (DiD) strategy, it is designed to mitigate radioactive release into the environment if the reactor vessel is breached. Therefore, preventing containment failure is the most important goal of severe accident management and DiD strategies.

The Loss Of Coolant Accident (LOCA) is one of the DBA types where coolant at high pressure and temperature inside the reactor coolant system leaks into the containment atmosphere through a pipe break. This accident leads to containment pressurization and a rapid temperature increase in the containment that might exceed its design values. Such an accident would result in loss of the containment integrity and radioactive leakage into the environment. Therefore, TH parameters of a containment atmosphere during a DBA need to be investigated as a safety assessment procedure. To implement this assessment various tools and methods can be employed; i) simulation through available nuclear codes with LP methodology such as CONTAIN (Williams et al., 1997) and MELCOR (L.L. Humphries, R.K. Cole, D.L. Louie, V.G. Figueroa, 2015), ii) using 3D/CFD codes/software such as GASFLOW (Nichols et al., 1998), ANSYS-CFX (Stubley, 2009) and GOTHIC (EPRI, 2012), or iii) developing thermal-hydraulics models through a programming language like MATLAB (The MathWorks Inc, 2018) or FORTRAN (Sun Microsystems, 2001) by usually imposing conservation equation on single-cell or multicell models to simulate the containment pressurization (Safarzadeh et al., 2021).

Šadek et al. analysed a two-loop pressurized water reactor containment behaviour after a station blackout scenario by using three different integral codes, namely ASTEC, MELCOR, and MAAP (Šadek et al., 2017). They compared the results based on methods applied in each code. MELCOR was used in a study to validate a containment input model for a CANDU-6 plant by comparing the results with integrated leakage rate tests (Kim et al., 2018). Noori-Kalkhoran et al. investigated the temperature and pressure profiles of a VVER-1000 containment during a LB-LOCA by using single and multi-cell models programmed in MATLAB and CONTAIN code simulation (Noori-Kalkhoran et al., 2016, 2014a, 2014b). Results were validated against FSAR and discrepancy source has been discussed.

In the nuclear industry, Lumped Parameter (LP) codes have been widely used for licensing purposes. They have a large validation base and are improved with the help of related experiments that modifies certain correlations. However, these codes simplify certain physical phenomena to reduce the computational cost of running a demanding simulation as complex as a severe accident progression in a very large and detailed containment. Recently 3D codes such as GOTHIC with higher spatial resolution and more accurate representation of physical phenomena have been utilized by more and more nuclear engineers in containment analysis with the advancement of computational power (IAEA, 2011). Although the nuclear codes used in the publications mentioned above provide reasonably good accuracy for the simulations concerned, the implementation of 3D codes might provide a better view of physical phenomena inside the containment in a severe accident scenario (like what happened in Fukushima Daiichi,2011) due to the intrinsic limitations of LP codes. In one of the recent 3D containment thermal-hydraulic analyses, Cosials et al. (Fernández-Cosials et al., 2017) studied the pressure and temperature response of AP1000 containment by using 3D features of GOTHIC code following LB-LOCA. They have also modelled a PWR-KWU containment by using both GOTHIC LP and 3D capabilities in another publication (Fernández-Cosials et al., 2019). Results of the models were compared and the effects of some modelling parameters were investigated in a sensitivity analysis. GOTHIC code was also used in a study to investigate equipment and instrumentation qualification criteria in a three-dimensional simulation of

PWR-W containment after a double-ended guillotine break LOCA (Jimenez et al., 2017). Employing other 3D software, (Kaltenbach and Laurien, 2018) simulated a containment spray cooling model of THAI prototype containment in ANSYS-CFX and validated the model by temperature and pressure data of an experiment conducted on the same facility. GASFLOW-MPI was used in containment thermal-hydraulic analysis by developing a dynamic film model to investigate the effect of a passive containment cooling system (Li et al., 2019).

In this research for the first time, GOTHIC 3D simulation features have been employed and evaluated for a VVER-1000 containment. A unique VVER-1000/V446 containment was modelled in detail by using AutoCAD and GOTHIC 3D capabilities during a LB-LOCA. Results of simulations present 3D contours of TH parameters inside containment and can cover whole coordinates of the structure. In addition, an equivalent LP model has been developed in GOTHIC to validate the methods and simulation procedure and even compare the accuracy of LP and 3D methodology. As final steps LP results have been validated against FSAR and 3D contours evaluated against containment design safety criteria.

2. Methodology

In this section, GOTHIC code and its capabilities will be introduced. After providing the basic information about VVER-1000/V446 containment structure, the development of the AutoCAD and GOTHIC 3D model will be presented step by step. Finally, accident conditions will be described before discussing the output of simulations.

2.1. GOTHIC code

GOTHIC (Generation of Thermal-Hydraulic Information for Containments (EPRI, 2012) is a thermal-hydraulic code that gives solutions for mass, momentum and energy conservation equations for multi-component and multi-phase flow. It is developed by Numerical Applications Inc. in the USA and is typically used in the design and severe accident simulations to model the reactor containment (NEA/CSNI, 2014).

GOTHIC is a hybrid code, which can perform as LP code and a CFD code simultaneously. It utilizes the advantages of both types of severe accident codes and provides great flexibility to model the containment since the user could adjust the balance between computational cost and accuracy by defining various regions as control volumes of either CFD or LP code. The user can classify the regions inside the containment in terms of importance and model the lower impact regions as LP control volumes to save the time and effort to build the geometry needed to simulate the accident. The 3D capabilities of a CFD code were recently integrated into the code, previously it was only a LP code (NEA/CSNI, 2014).

Unlike other generic CFD codes that implement body-fitting meshes on the geometry, GOTHIC utilizes a porous media approach to model complex geometries. A cell porosity factor is assigned to each cell in the 3D mesh to define whether the cell is open, partially open or closed. A porosity factor is a number between 0 and 1, If it is zero, it means the cell is completely blocked and GOTHIC removes the cell from the solution matrix and the assigned initial conditions for that cell remain the same through the transient. If it equals 1, the cell is considered completely open to the fluid (EPRI, 2012).

2.2. VVER-1000/V446 and its containment

VVER1000/V446 is a type of pressurized water reactor built by the Russian industry. The reactor coolant system includes four loops, each has a horizontal steam generator with a main coolant pump. The nominal heat power of the reactor is 3000 MWth. The containment was designed as a double anti-accident shell as it consists of two layers; the outer is a cylindrical reinforced concrete one with a semisphere end at the top and the inner spherical steel one (Fig. 1), both containment forms the annulus together. The gap between them is maintained at negative pressure to prevent any leakage in an emergency (AEOI, 2003). Table 1 provides details about containment specifications.

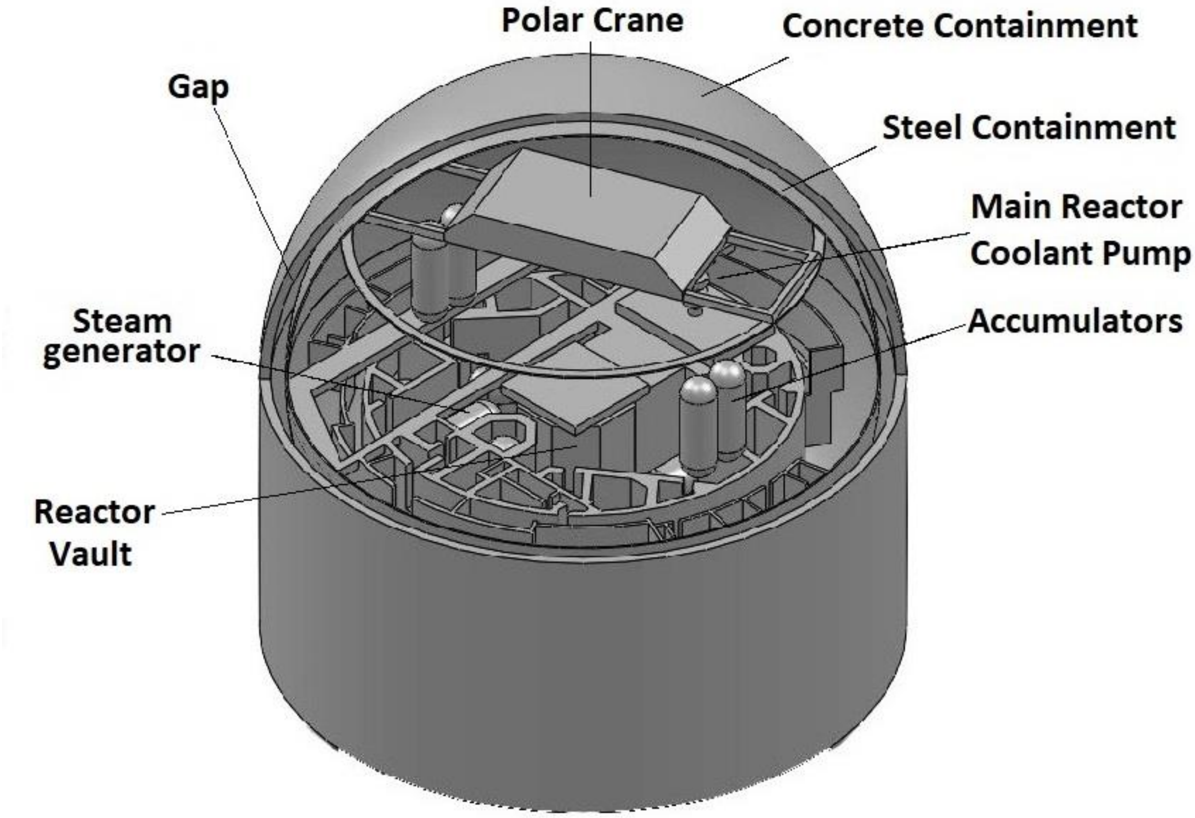

Fig. 1. The design of the VVER-1000/V446 containment.

Table 1

VVER-1000/V446 containment specifications

Parameter	Value
Structural Parameters:	
Inner steel diameter (mm)	28000
Inner steel thickness (mm)	30
outer cast-in-situ reinforced concrete thickness (mm)	1750
Containment free volume (m^3)	71040
Design parameters:	
Maximum internal pressure at 150 ^{o}C (MPa)	0.46
Maximum pneumatic test pressure at a temperature of up to 60 ^{o}C (MPa)	0.51

Peak temperature (in separate compartment) (^{o}C)	Up to 206 ^{o}C during up to 5 minutes
Maximum (averaged over the volume) temperature (^{o}C)	150
Thermal Conductors:	
The total area of all the concrete walls (m^2)	18860
The surface area of the steel containment, the effective area of the metal structures and the equipment without heat insulation (m^2)	17712

3. 3D simulation

3.1. Development of a detailed CAD model of the containment

A Computer-Aided Design (CAD) software provides a more user-friendly and easier-to-interact environment for 3D modelling in comparison to the GOTHIC graphical interface. Therefore, the full as-built geometry of the containment was developed in AutoCAD. VVER-1000/V446 containment structure has been designed/formed by 10 different horizontal cross-section sketches (10 different elevations). Each of these cross-sections makes one of the 10 vertical slices of the containment and keeps the same compartment design along with its height. These elevations are distributed along -6.00 m, -1.50 m, 2.00 m, 6.00 m, 9.00 m, 10.50 m, 12.00 m, 16.40m, 21.50 m and finally 26.80m. The containment rooms have been developed as 2D in the first step and then turned into 3D volumes by extruding their cross section along with their height according to their elevation in AutoCAD. Those vertical 3D sections from bottom to top are integrated to demonstrate the whole containment building as shown in Fig. 2. Control volumes, indeed, are made of one or multiple designation rooms in the reactor building that are connected by doors, corridors, staircases and sometimes flow paths. In other words, they are enclosing sets of various rooms of the containment plan. A unique colour was assigned to each control volume set to distinguish them in the model as shown in Fig. 2.

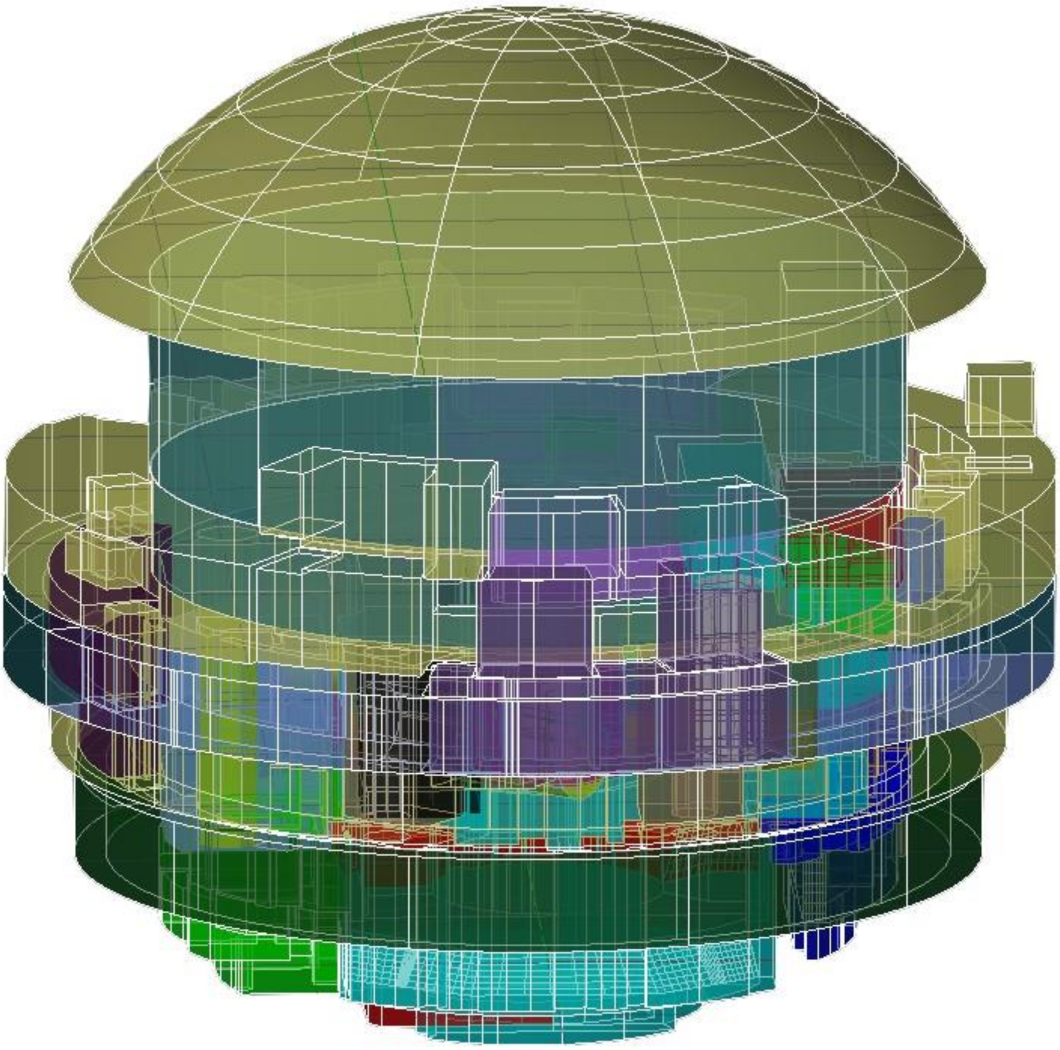

Fig. 2. Detailed 3D CAD drawing, showing designation rooms and associated control volumes.

3.2. Preparing a CAD simplified model and GOTHIC input

Geometrical information in the detailed model could not be transferred into the GOTHIC environment directly, since GOTHIC only uses simple geometrical forms like blocks, cylinders, cones, wedges and caps (allowed blockage geometry types). Therefore, an intermediate step should be taken here to 'translate' the geometrical 'language' of the detailed CAD geometry to the simplified GOTHIC geometrical 'language'. This approach gives a tool to investigate different sub-regions inside the containment in terms of thermal-hydraulic parameters.

The diameter of the VVER-1000/V446 containment is 56 meters and the whole containment is subdivided into 60×60×60 grid lines. Cell size is selected as 5×5×5 meters, based on a previous work that shows around 1700 cells in a GOTHIC 3D MZM model could simulate temperature and pressure evolution during an LB-LOCA reasonably well in comparison to another model with the same approach but having approximately 7 times higher cells (Bocanegra et al., 2016). An enclosing rectangular prism is built according to the mesh system for each control volume as could be seen in Fig. 3. The fitting of the geometry to the mesh as early as this stage is necessary due to the problems that might emerge in later phases in terms of maintaining thermal independence between two fluid regions (Bocanegra et al., 2016).

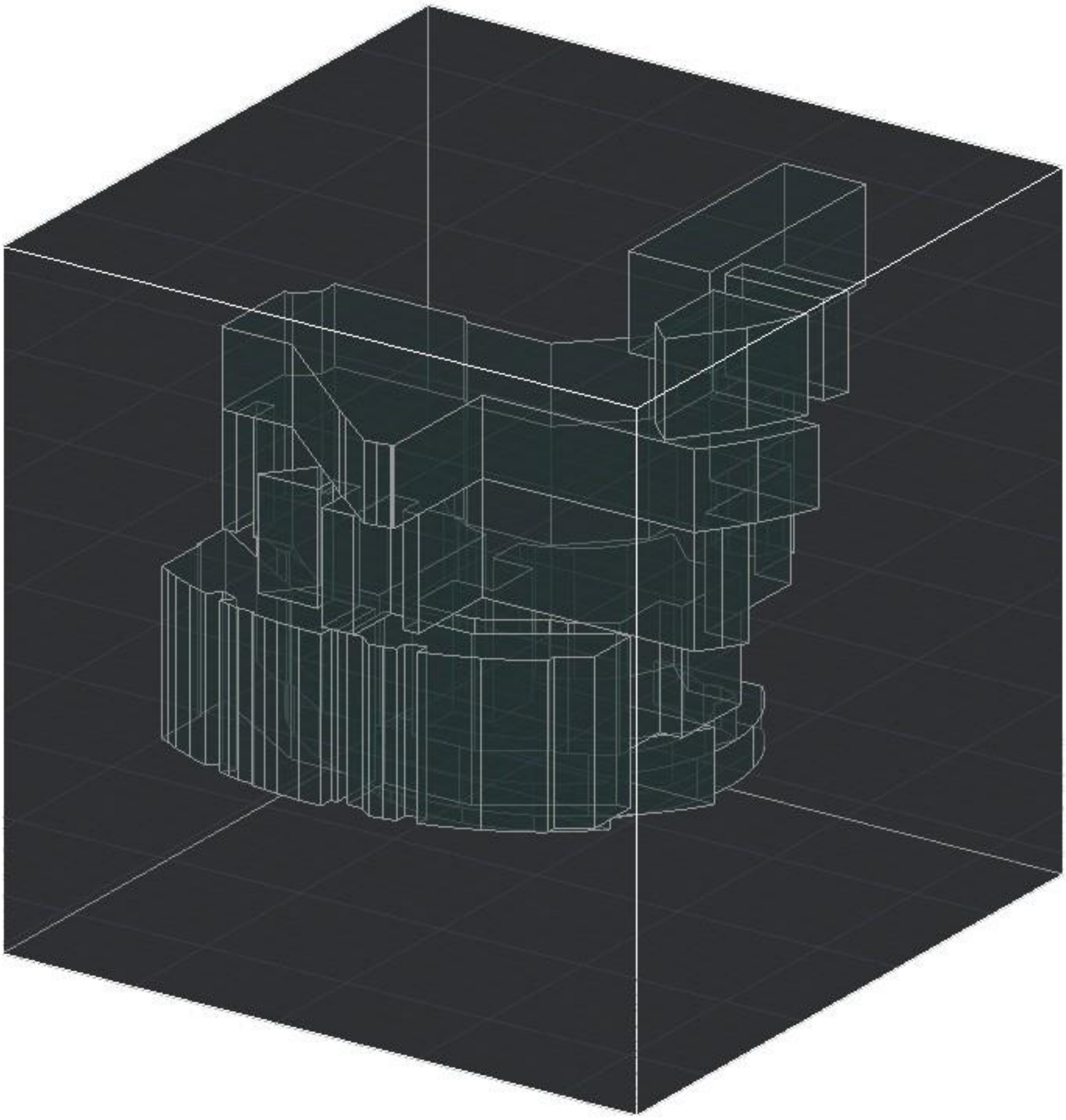

Fig. 3. Typical control volume (CV 2) in rectangular prism prepared for meshing.

Instead of defining the 3D free space in GOTHIC by using geometric blockages that displace fluid, it is possible to use another type of blockage, namely openings that displace solid in a control volume (EPRI, 2012). Wedge has been selected to use as the basic allowed geometrical shape to span the region needed since it provides the easiest and most consistent way to achieve the goal. The entire free volume inside each rectangular prism breaks into small wedges through triangulation of the surface and specifying the height. Each corner of a wedge is assigned to a unique number. Each number has its x, y, z coordinates with respect to the control volume origin. Thus, a user could extract all the data (x, y, z coordinates of three corners of the triangle and the height) necessary to transfer the position of each wedge to GOTHIC 3D format. First, the raw data was extracted from the CAD software (corner coordinates) and then grouped for each wedge for each control volume in MS EXCEL. Moreover, the GOTHIC interface demands a certain data arrangement to describe each wedge according to its position. A specific

Visual Basic Applications (VBA) macro was written for the task in MS Excel to transfer the data accordingly.

3.3. GOTHIC 3D modelling with the transferred geometry

Fig. 4 shows the GOTHIC 3D graphical user interface (GUI) after selecting the subdivided volumes option for the typical control volume no 6. Each cell in the figure has a dedicated porosity factor to define the free volume inside the cell. Average thermal-hydraulic parameters of the whole cell are stored in its centre which means each cell acts like a point that stores the information.

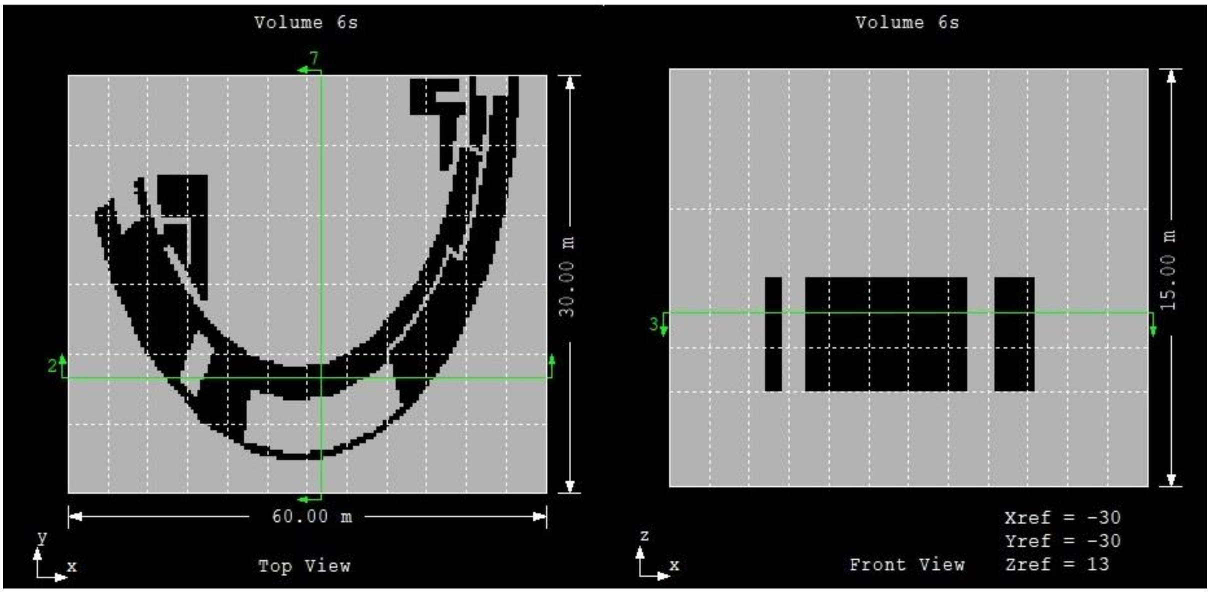

Fig. 4. 3D model of control volume no 6 in GOTHIC 3D GUI.

29 control volumes, 143 thermal conductors, 66 flow paths, 46 3D connectors, 6 boundary conditions, 24 valves, and 2 spray nozzles are defined within the containment in consideration of all 3D configurations of the modelling elements. Control volumes with their specifications could be seen in Table 2. In addition, the control volume layout of the containment is presented in Fig. 5. In the MZM approach, control volumes are connected hydraulically through flow paths, representing openings, pipes and doors in the containment. 3D connectors could also be used to transfer mass and energy between control volumes by connecting multiple cells at the common boundary. Thermal conductors are used to modeling the heat transfer between solid structures and fluid, solid structures between two control volumes, radiative heat transfer between solid structures and heat capacity of solid structures. There are two types of thermal conductors; internal and external. For internal thermal conductors, both surfaces of the solid structure are connected to the same control volume. Surfaces are assigned to different control volumes for external thermal conductors and used as modelling of walls separating two control volumes (EPRI, 2012). Multiple heat transfer models (based on different heat transfer coefficients' equations/correlations) are employed in nuclear codes to simulate the thermal conductors' behaviour (Chen et al., 2018; Wang et al., 2020). GOTHIC has several heat transfer coefficient options that can be used for containment analyses. These include the film, direct, Tagami, and user-specified heat transfer coefficient options. GOTHIC also has a number of

condensation options that can be used for containment analyses. These include the Uchida, Gido-Koestel, and DLM (diffusion layer model) options (Ofstun, 2004). In this study the direct heat transfer coefficient set is used, along with the DLM mass transfer correlation, for all of the heat sinks inside containment (Kindred, 2018; NRC, 2003). In addition, thermal conductors have been divided into different nodes for the numerical implementation of heat transfer models by using the auto-divide option of the GOTHIC code (Kindred, 2018). 24 flow path connections in the model are described as valves that are closed until the pressure gradient between two adjacent control volumes that are connected through the flow path reaches 0.01 MPa. The containment spray system is also considered in this model by employing two spray nozzles, each having a connection to a boundary condition. The spray system will actuate when the pressure reaches 130 kPa (AEOI, 2003) to reduce pressure and temperature inside the containment during accident progression.

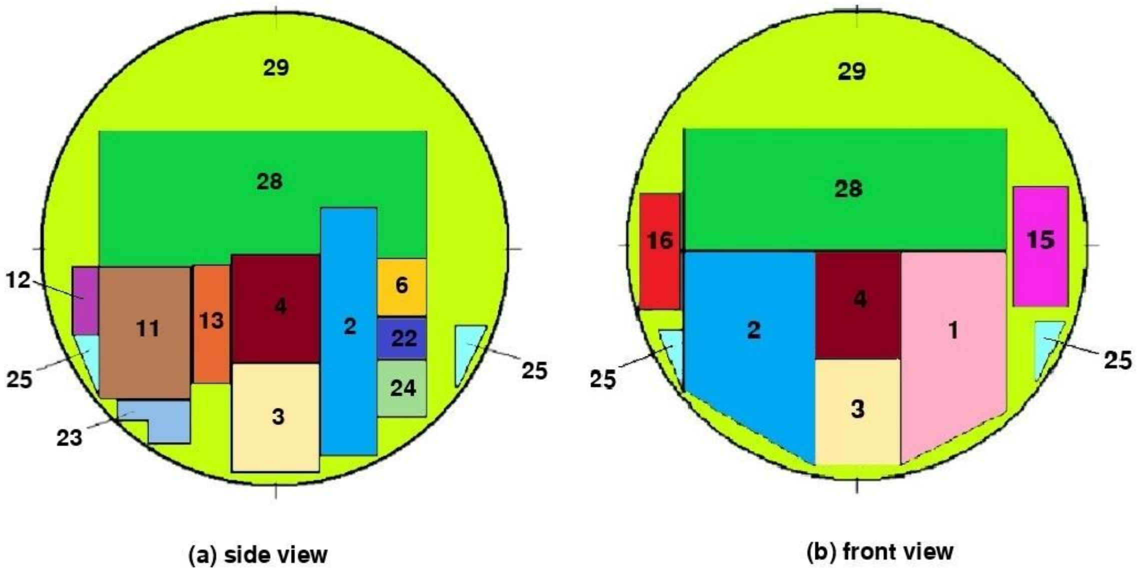

Fig. 5. Control volume layout of the containment, vertical cross-sections: a) side view b) front view

Table 2
Containment control volume parameters.

No	Description of the control volume	Volume (m^3)
1	Rooms of Steam Generator 1-2 and their loops	4870
2	Rooms of Steam Generator 3-4 and their loops	4830
3 and 4	Reactor Vault	458 and 1100
5	Annular corridor from 0 to 180 degrees, Shafts of steamlines of loops 1 and 2	699
6	Annular corridor from 180 to 360 degrees, measurement chamber, Shafts of steamlines of loops 3 and 4	787
7-10	Main coolant pump rooms	≈ 260 (each)
11	Fuel Pool	1380
12	New Fuel Storage	677
13	Reactor internals inspection pool	541
14	Cask pool	130
15 and 16	Ventilation system rooms	917 (each)

17-21	Active water treatment filter rooms and filter-container room	≈ 50 (each)
22	Valve chamber of nuclear component cooling system	278
23	I&C rooms, spare rooms and stairs	905
24	I&C rooms, spare rooms and stairs	847
25	Annular pipeline corridors from 0 to 360 degrees	784
26	Heat exchanger cooler rooms	135
27	Recuperative heat exchanger room	35
28	Central hall above the upper desk until 31.7 m	16949
29	Hall volume above the cylindrical wall (the dome) and between the cylindrical wall and containment (annular space)	26335

3.4. LB-LOCA and GOTHIC LP model

The simulated accident is a specific type of LB-LOCA, a Double-Ended Cold Leg (DECL) break. This guillotine type pipe rupture on the cold leg has an 850 mm break diameter and the location of the break is in loop 4 of the reactor (control volume 2) (AEOI, 2003). Table 3 lists the initial conditions of the reactor (applied by FSAR to calculate the break mass and energy source) and containment were used in this study.

Table 3
Initial condition of reactor and containment

Parameter	**Value**
Reactor	
Power (MW)	3120.00
Pressure in the primary loop (MPa)	16.00
Pressure in the secondary loop (MPa)	6.37
Number of ECCS accumulators (design)	3
Water temperature in accumulators (°C)	70.00
Number of high pressure injection coolant pumps (design)	1
Number of low pressure injection coolant pumps (design)	1
Water temperature in borated water storage tanks (°C)	60.00
Containment	
Containment temperature (°C) in:	
Lower cells	30.00
Central Cells	60.00
Upper Cells	30.00
Containment Pressure (bar/MPa)	1.00/0.10
Containment Relative Humidity-HR(%)	60.00
Spray Water Temperature (°C)	30.00
Spray cone angle (deg)	75.00
Flow rate per spray nozzle (kg/s)	83.30

In a LOCA scenario, the amount of water that is subcooled in the reactor coolant system discharges through the break into the containment atmosphere and increases the pressure and temperature in the containment. Russian TECH-M-97 code is used in the analysis of the mass and energy release for the postulated accident by FSAR (AEOI, 2003). The set of break mass and energy data released into the containment (Fig. 6) was extracted from FSAR. Two Breaks Sources (BSs) on the cold leg of loop 4 were modelled with 4 boundary conditions by separating steam and water discharges for each break. Two more boundary conditions were used in the process of representing of containment spray system, each boundary condition defining the mass flow rate and temperature of the fluid was assigned to a spray header in the dome (control volume 29).

Three different stages can be hypothetically considered for DECL scenario; i)fast pressure reduction in the primary loop ii)re-flooding of the reactor core and iii)long-term core cooling. Any of the stages enumerated is characterized by the features of mass and energy release from the primary system and can be tabulated in Figure 6, e.g. the sharp rise of water mass and energy around 80 s is related to re-flooding the reactor core where water from the emergency core cooling system accumulators (ECCS) comes to account.

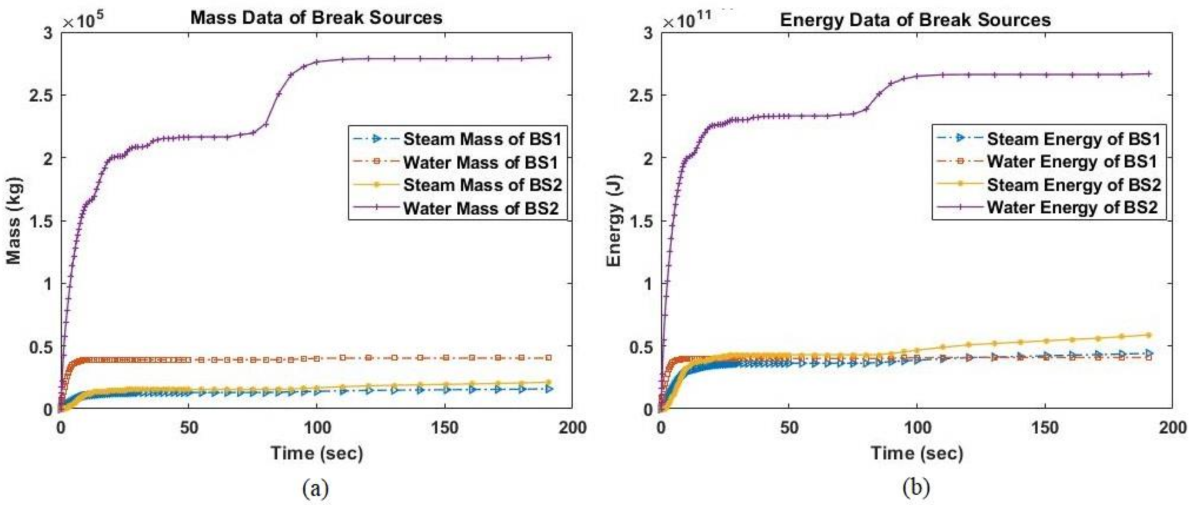

Fig. 6. Break Mass (a) and Energy (b) data during LB-LOCA

Russian ANGAR code has been used by FSAR to analyse thermal-hydraulic parameters in the containment. Since ANGAR is a LP code, a direct comparison of the simulation results with the GOTHIC 3D model is not appropriate due to the fundamentally different assumptions and calculation methods between the two codes. Therefore, an equivalent GOTHIC LP model was developed from the GOTHIC 3D one to validate the results by using the `revert to lumped' feature of the code. This conversion to LP model also adds the capability of investigating LP and 3D code strength by comparing the results. The conversion included several steps to match two different models such as remodelling of 3D connectors as flow paths, since the former is not allowed in GOTHIC LP mode or consideration of changes in the inertia length of flow paths. It should be noted the same layout of control volumes shown in Fig. 5 was considered in the GOTHIC LP simulation.

4. Results and Discussion

The temperature and pressure profiles of the containment prepared from the results of the GOTHIC LP simulation were compared to the FSAR for selected control volumes to validate the simulation procedures and inputs. After the first comparisons, numerous test runs were performed for sensitivity analysis and to increase the accuracy of the results. Inconsistency of models results were mainly about some undefined parameter values in FSAR such as initial pool water temperature, spray droplet diameter and temperature, and spray header configuration. Another source of discrepancies was a result of intrinsic GOTHIC features such as different heat transfer correlations between containment and environment and its effects on the results. GOTHIC LP and 3D (3D results have been averaged over the relevant volume) and FSAR results are shown in figures 7, 8 and 9 for ease of comparison.

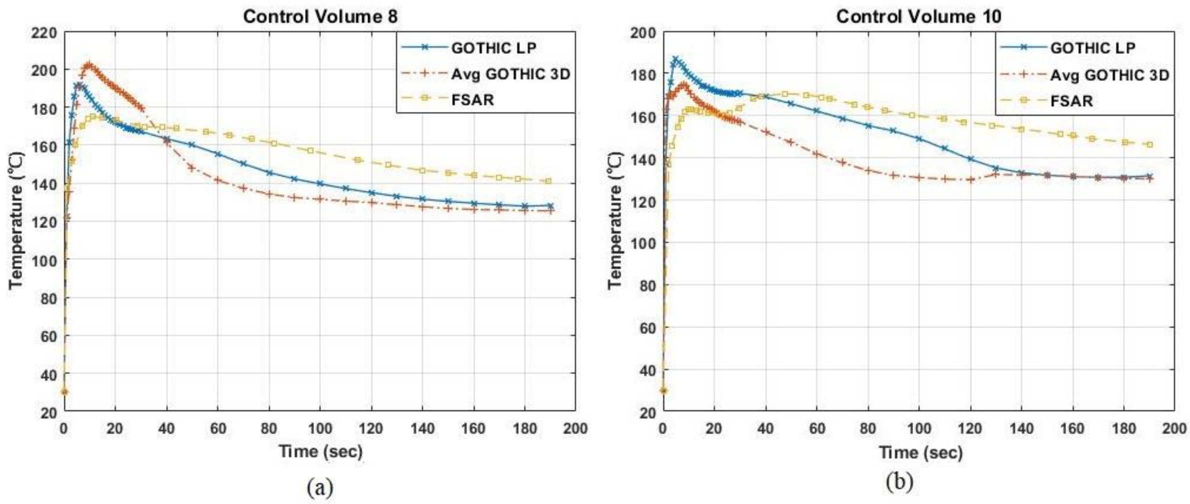

Fig. 7. Short-term temperature profile of control volumes 8 (a) and 10 (b) during the LB-LOCA.

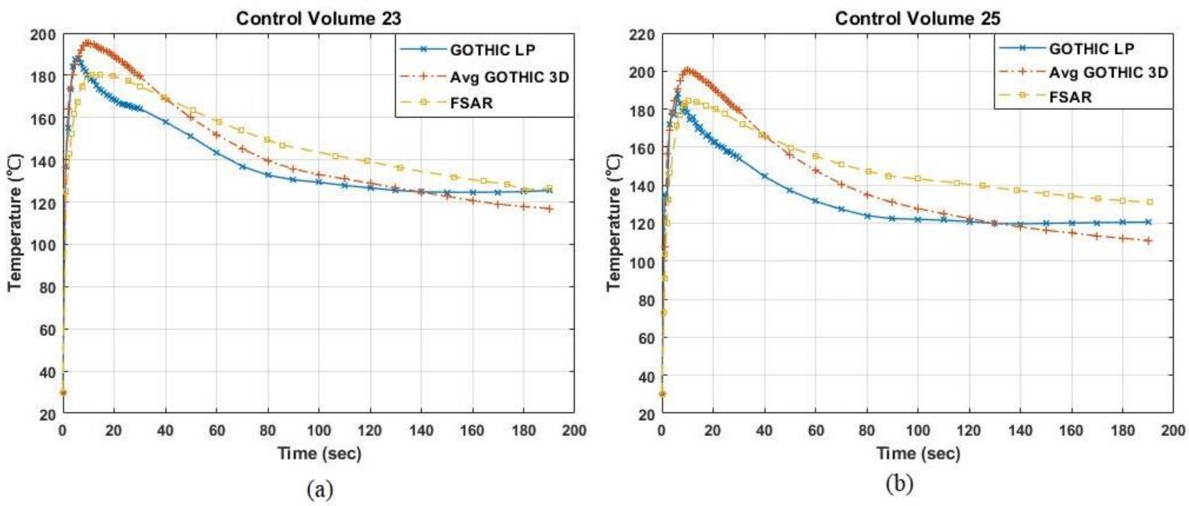

Fig. 8. Short-term temperature profile of control volumes 23 (a) and 25 (b) during the LB-LOCA.

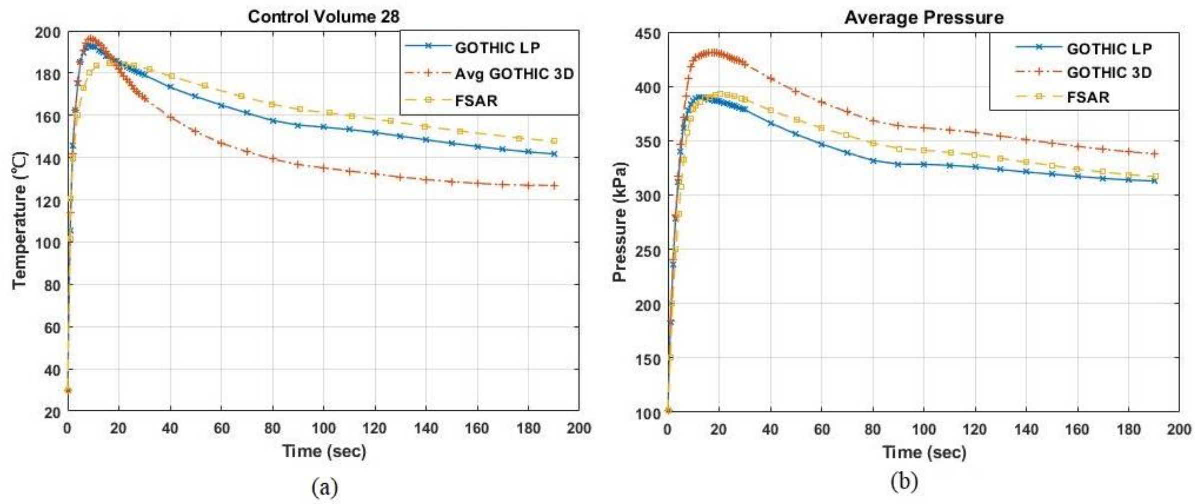

Fig. 9. Short-term temperature profile of control volume 28 (a) and average pressure of the containment (b) during the LB-LOCA.

Figs. 7, 8 and 9(a) show the short-term temperature profiles of control volumes 8, 10, 23, 25, and 28 respectively. This selection is based on considering the different parts of containment for results validation. Since control volumes 8 and 10 (two main coolant pump rooms) have small volumes-and therefore their thermal inertia is relatively low-and are near the break source, the larger discrepancies can be observed in their profiles. Even in the FSAR, the curve of control volume 10 does not fit the general tendency at earlier stages. Nonetheless, the temperature profiles of both GOTHIC simulations (LP and 3D mode) are in agreement with FSAR results for all control volumes; the deviation is within a reasonable limit. The temperature rises as the coolant discharge into the containment from the break. After a certain point, the heat transfer (cooling) effects of the containment spray system, thermal structures, and the heat transfer between the containment and the environment lead to a declining trend of the temperature profile. On the other hand, the GOTHIC 3D peak value is higher than the FSAR, but passing the first peak the heat loss of the containment is faster and as a result, the temperature drops below FSAR values. The main distinctive tendency of GOTHIC LP results is the slightly earlier peak time compared to FSAR and GOTHIC 3D results.

The change in the average pressure of the containment during the LOCA for the first 190 seconds is reported in Fig.9(b). The behaviour of the average pressure curves of both GOTHIC LP and 3D simulations is significantly similar to FSAR results. The maximum average pressure of the GOTHIC LP mode is 390 kPa, almost the same as the FSAR maximum average pressure, 392 kPa at 20 seconds although the pressure peak time value is slightly shorter for the GOTHIC LP mode. The GOTHIC 3D model has a higher maximum average pressure at 431 kPa at 18 seconds. The result is in the acceptable range with a relative error of 10% in comparison to the FSAR result and below the design maximum average pressure of 460 kPa.

Pressure distribution inside the containment is more homogenous due to the dispersion of pressure at sonic speed from the pipe break, whereas temperature distribution is less homogenous. Figures 10-16 show the 3D contours of the temperature profiles inside the containment for various elevations. The transient behaviour of contours has been presented at different times of 2, 5, 10, 15, 30 and 150 seconds. These time points were selected in a manner to cover all the alterations of temperature contours during short-term simulation. It is worth to be noted that all TH parameters inside containment are available at all points of the containment as a result of this simulation and these figures are just typical outcomes. These temperature contours are prepared in ParaView (Ahrens et al., 2005) data-visualization tool in the post-processing stage. The temperature rises through the first seconds rapidly and reaches its peak around 10 seconds after the break. Following its peak, it gradually decreases over time just as the temperature profiles demonstrated in Figs. 7-9. The same behaviour of GOTHIC LP and FSAR results versus time can be seen in these figures(3D results). The main advantages of these 3D contours regarding LP mode are; i) the capability of demonstrating the TH parameters in all coordinates of containment and ii) analyzing local hot spots inside the individual containment compartment for precise safety assessment. These figures can prove the contrast of temperature profile in individual volumes where this contrast has been omitted in LP mode because of its nature.

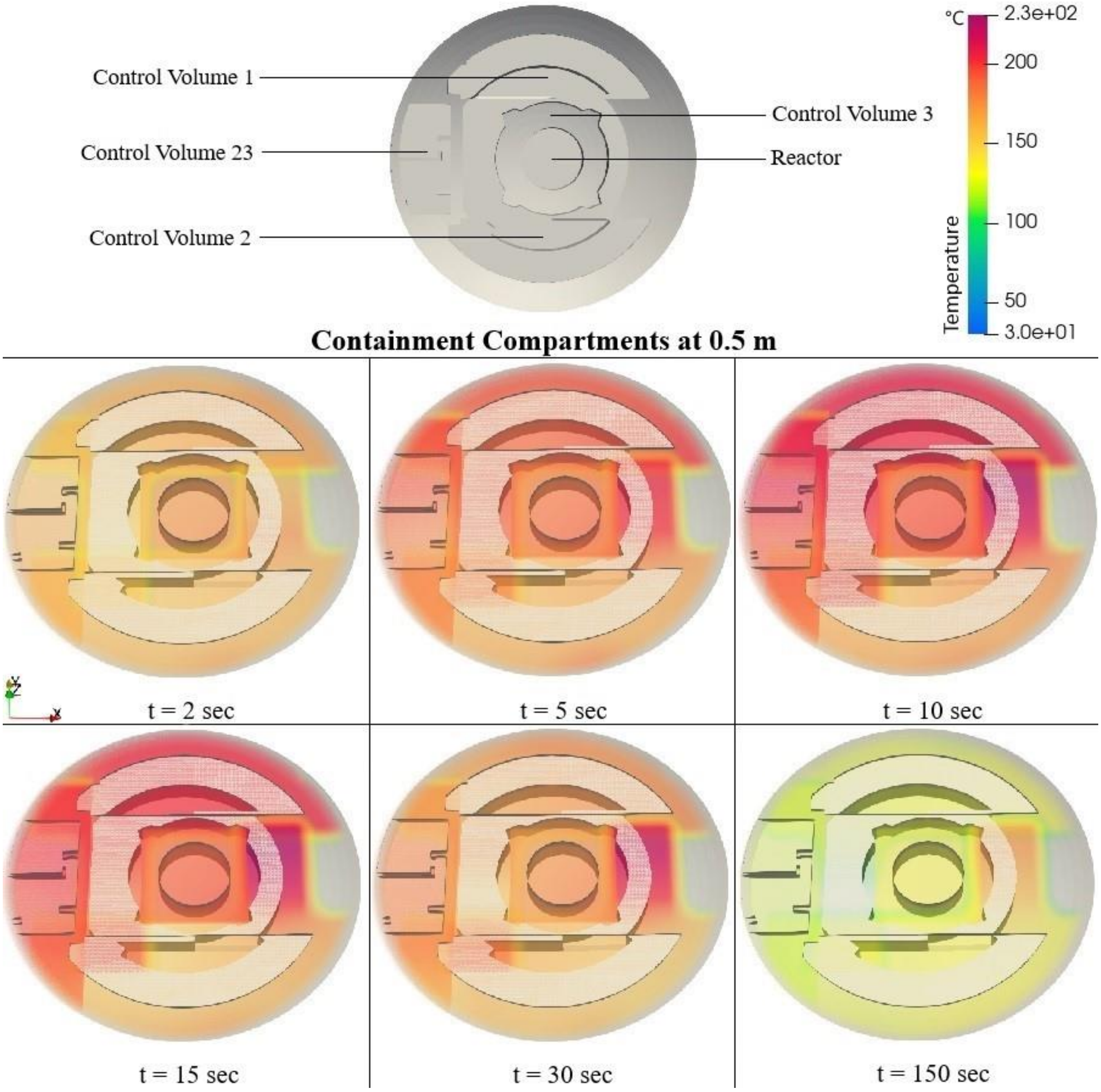

Fig. 10. 3D temperature contours inside the containment at elevation z=0.5 m.

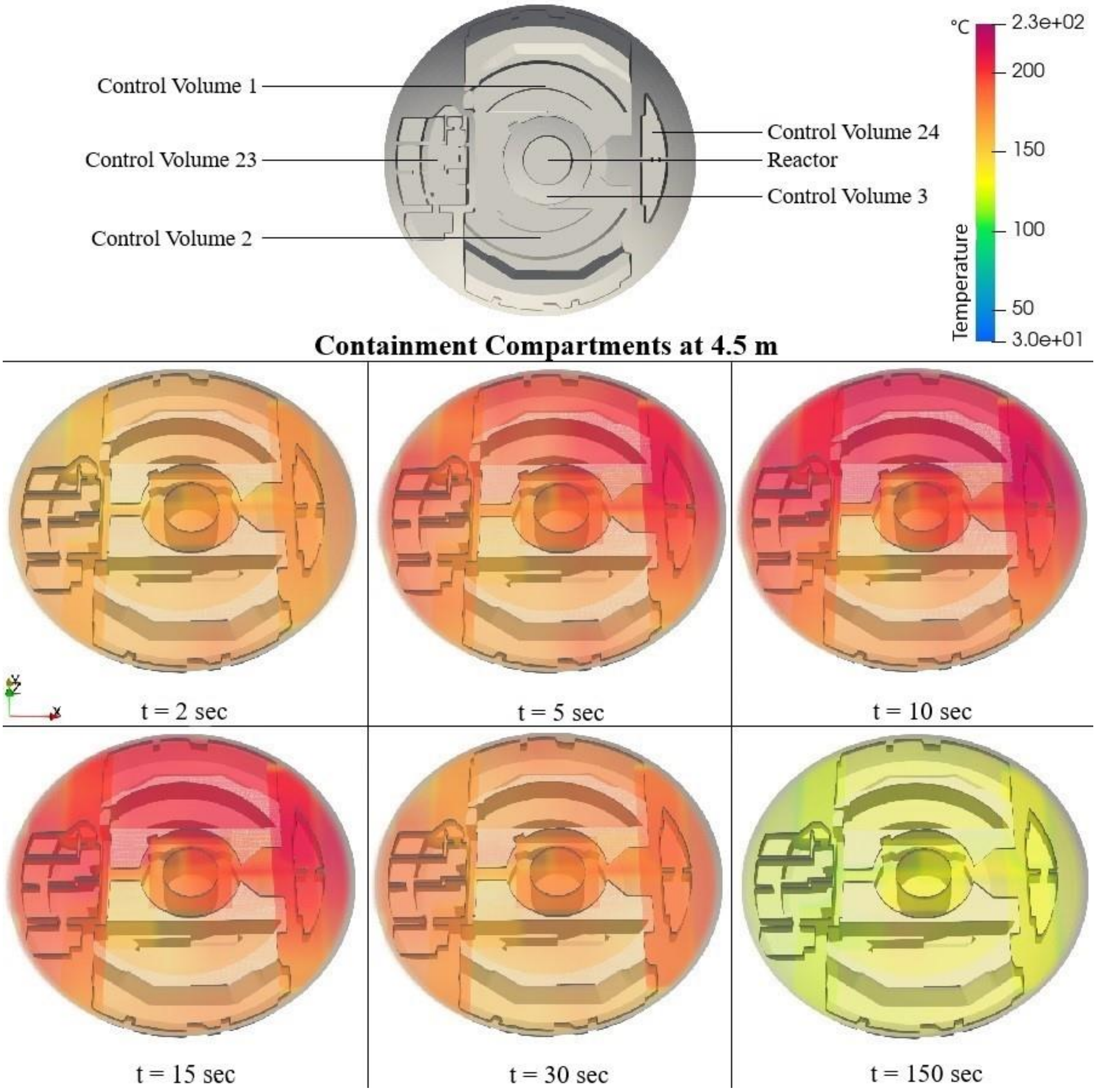

Fig. 11. 3D temperature contours inside the containment at elevation z=4.5 m.

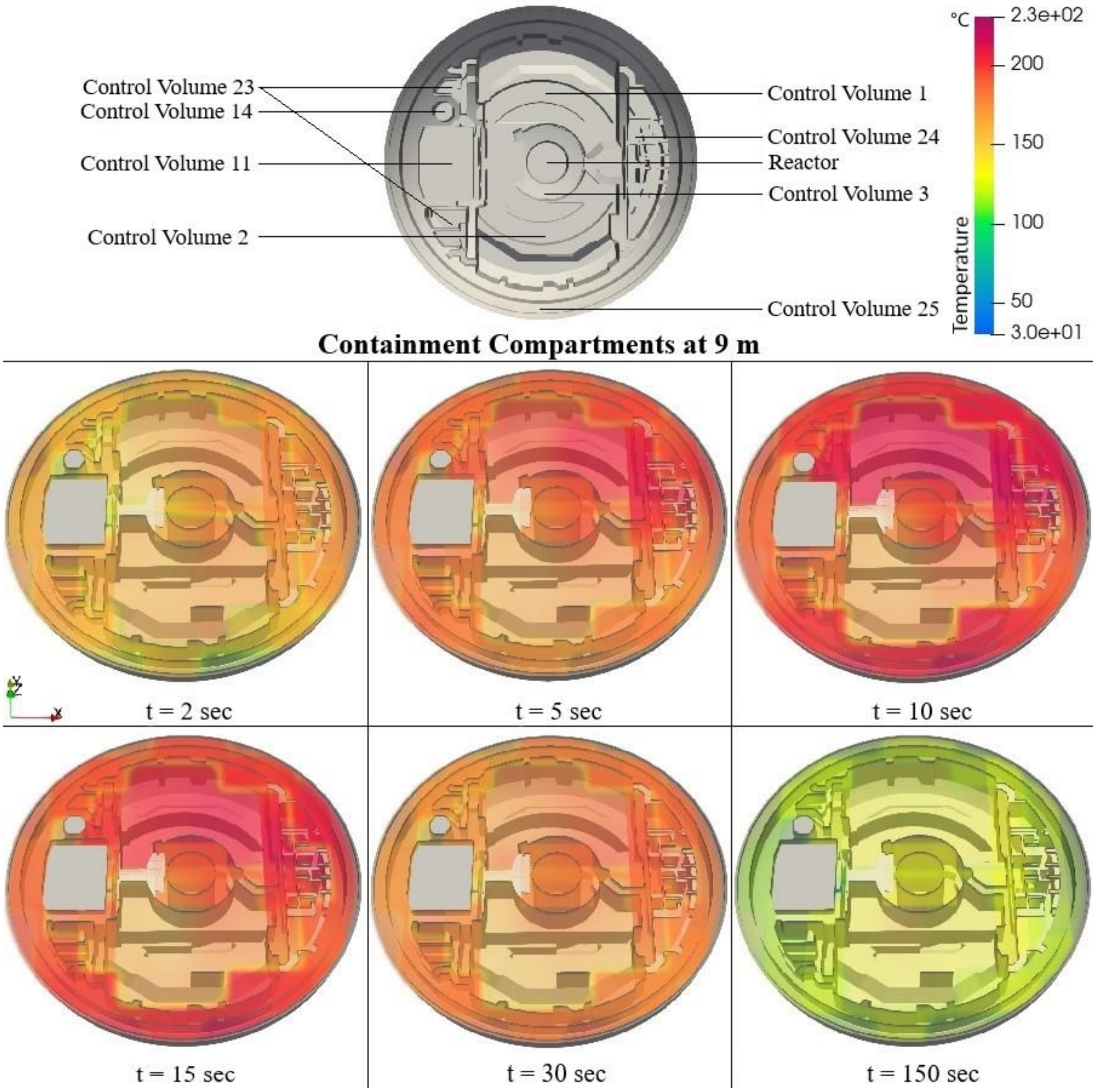

Fig. 12. 3D temperature contours inside the containment at elevation z=9 m.

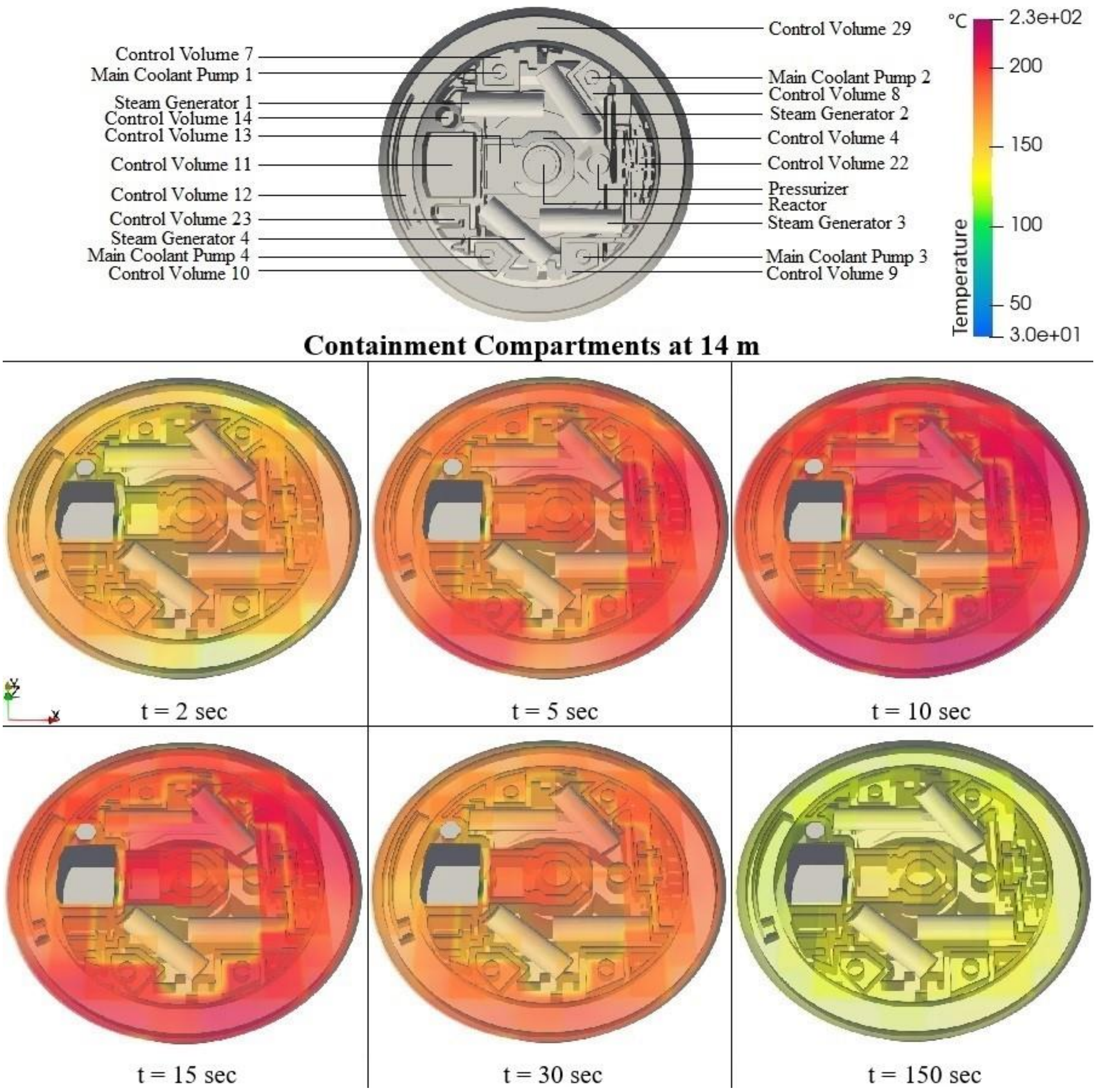

Fig. 13. 3D temperature contours inside the containment at elevation z=14 m.

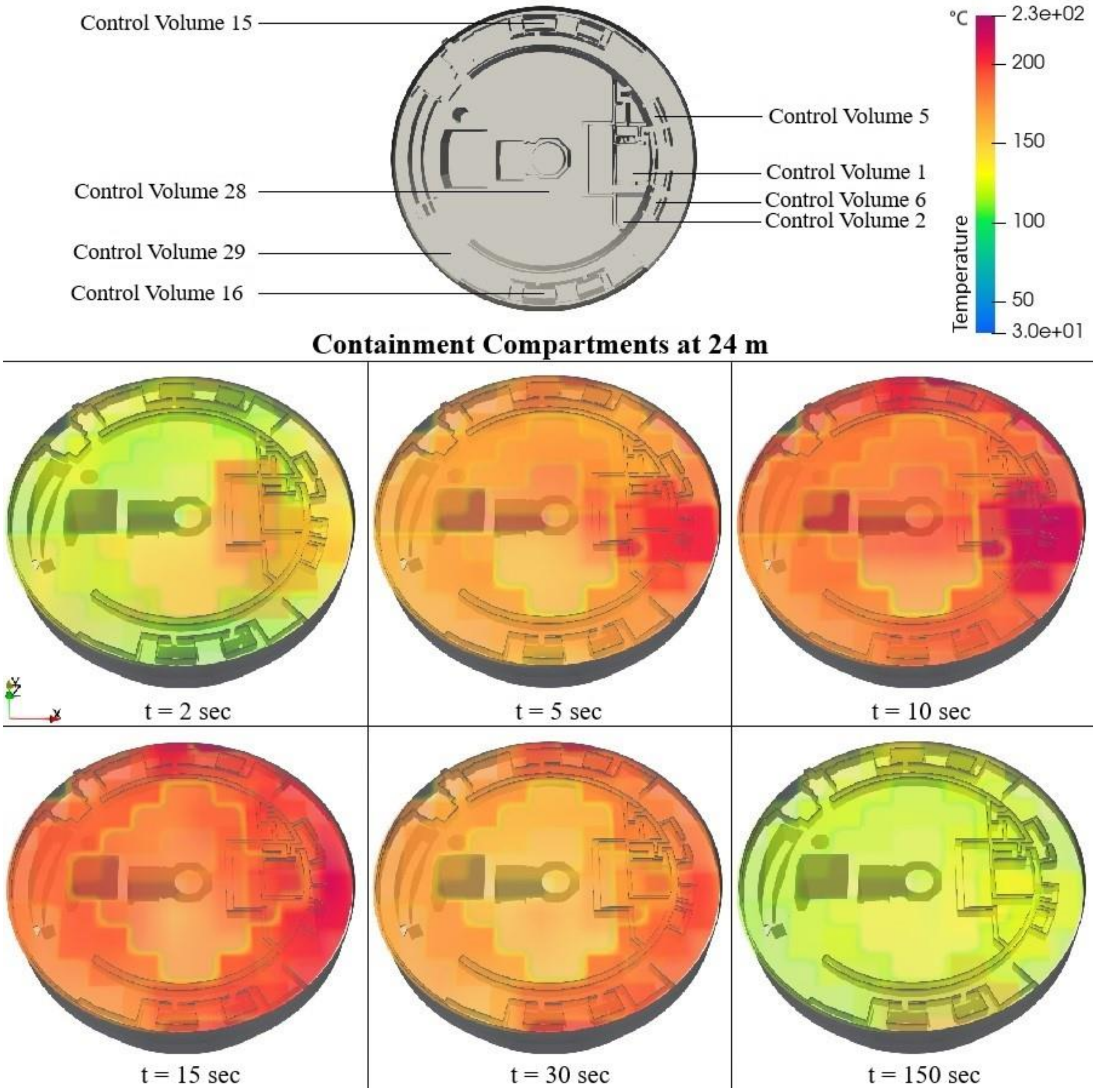

Fig. 14. 3D temperature contours inside the containment at elevation z=24 m.

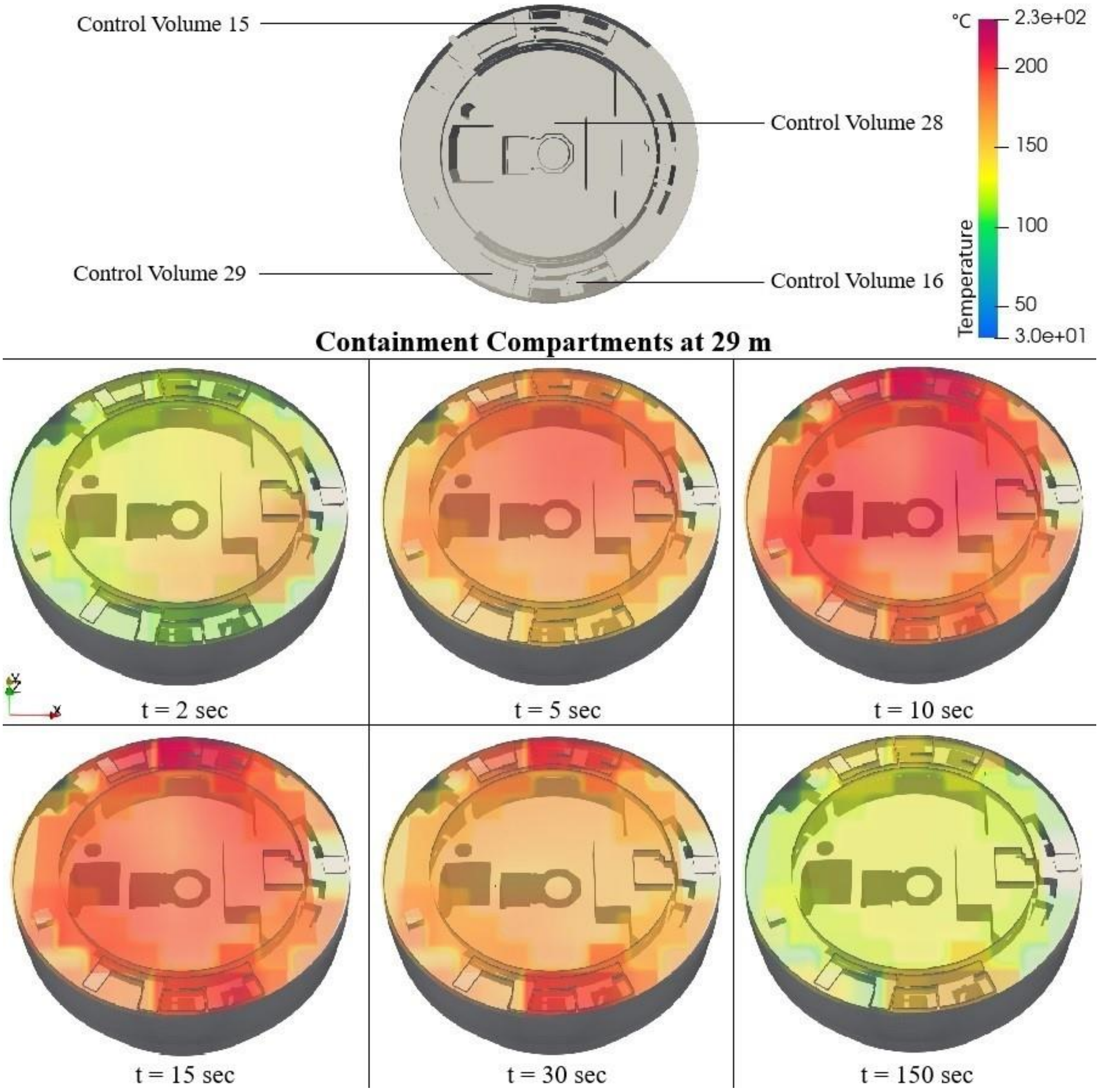

Fig. 15. 3D temperature contours inside the containment at elevation z=29 m.

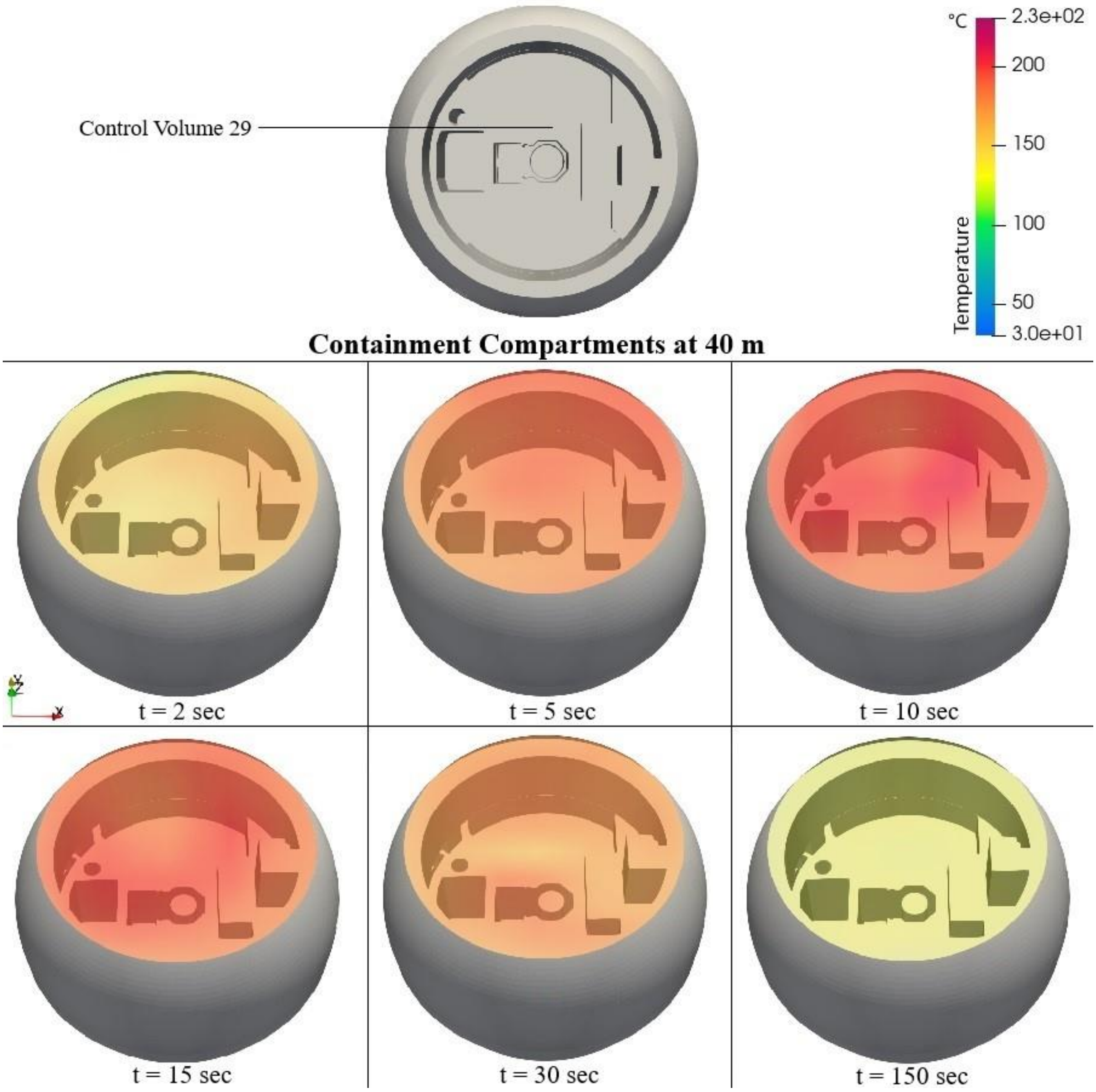

Fig. 16. 3D temperature contours inside the containment at elevation z=40 m.

In addition to 3D temperature contours at different elevations, the 3D vertical temperature contours through the containment at x and y normal planes are shown in Figs. 17 and 18 respectively. These plots depict the blowdown of mass and energy released through the break source and its movement inside the containment. It is noted that in these figures temperature of the control volumes adjacent to the break source increases rapidly at the initial stages after the accident in comparison to others. With progressing in accident time, as different factors of mass and energy transfer between control volumes, size of CVs, flow path, turbulent regimes, etc. come into play, it can clearly affect the contours and as can be seen the CVs under containment dome can get more intensive profiles. In addition, the major effects of spray system as ESFs in NPPs can be obviously monitored in long-term analysis (as it has exactly dedicated for this purpose). Although in DECL accident cause of enormous blowdown to the containment, the spray system actuates almost from the initial seconds of the accident (spray set point is 130 kPa in this study). So the temperature reduction inside the containment passing the maximum point (around 10-15 seconds) that can be seen in Fig 17 and 18 results from two factors, a)minor effect of spray actuation in short term and b)major effects of break mass and energy profile behaviour. It should be noted that in long-term analysis, the effects of spray in depressurization will be the dominant factor.

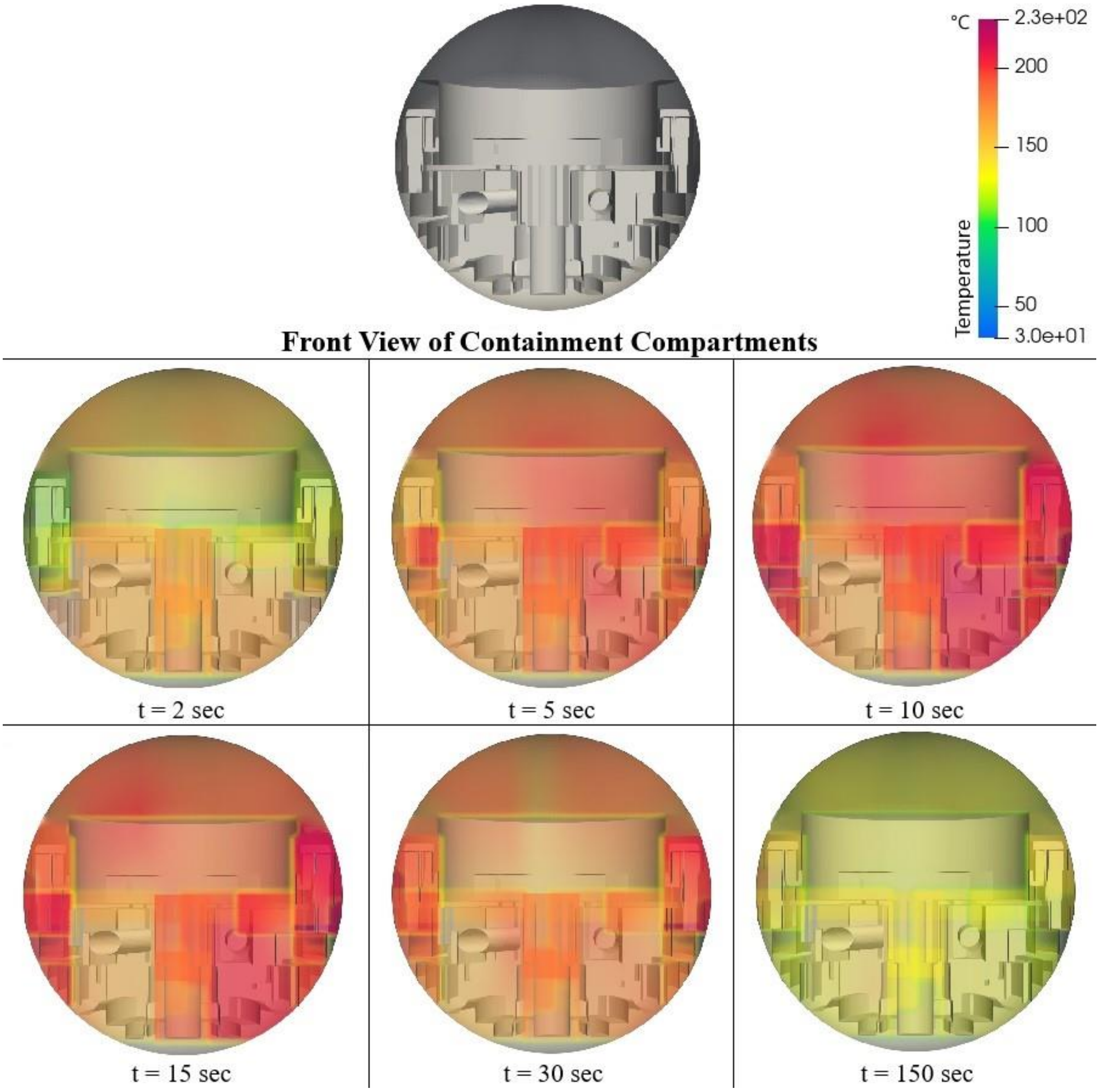

Fig. 17. 3D temperature contours inside containment on the xz-plane cutting through the centre.

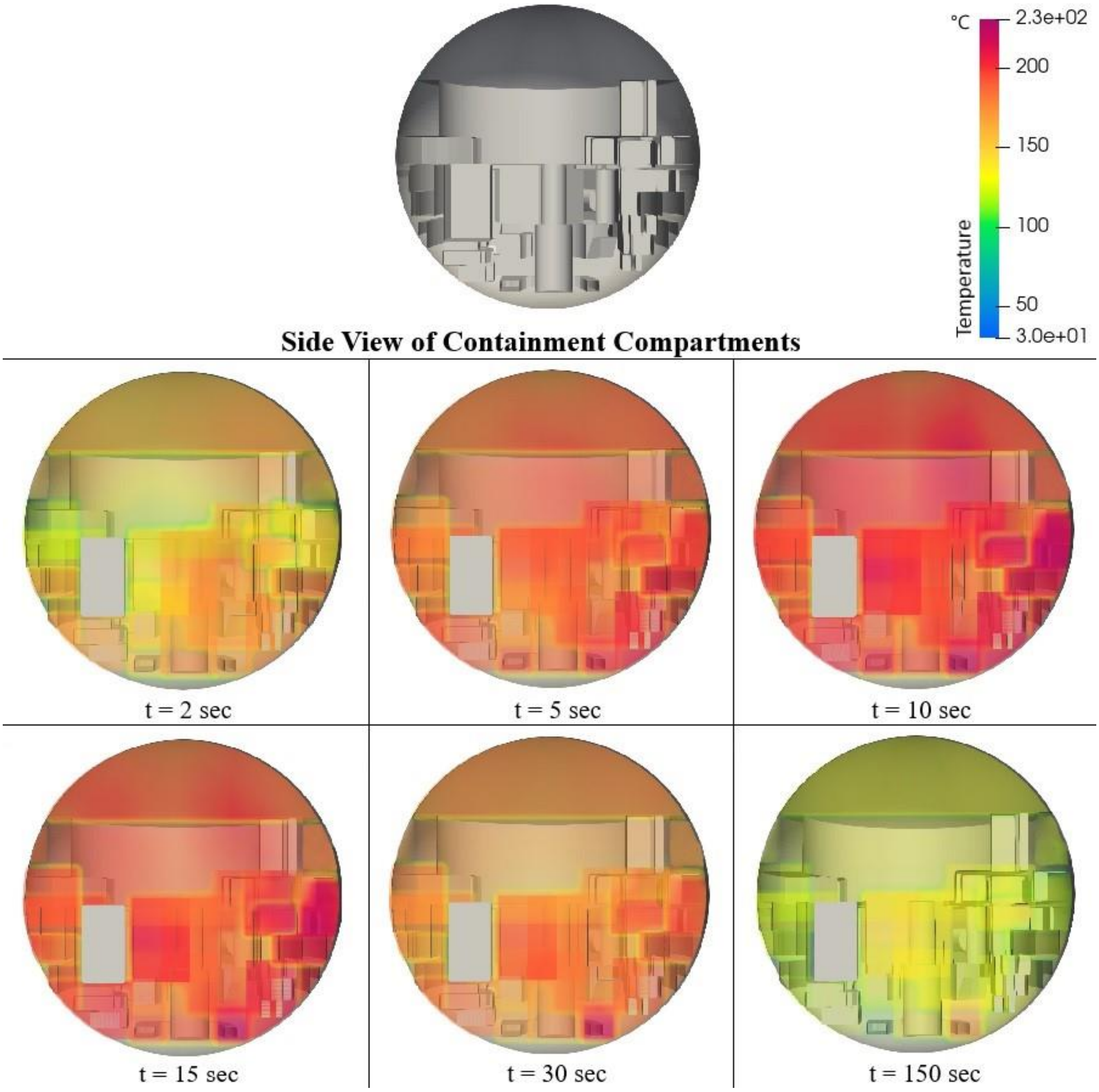

Fig. 18. 3D temperature contours inside containment on the yz-plane cutting through the centre.

Demonstrating the water and steam flow path and velocity vectors through containment structure can clarify the pressurization procedure of different containment control volumes. Figs 19 and 20 show the velocity vector resulting from the blowdown source and their flow directions at xz and yz plane respectively through the containment centre at the initial seconds of the accident (t=2 second). As it can be found in these pictures and could be expected, the highest velocity and flows of water and steam can be seen at the break source (CV 2)and its surrounded control volumes (large red arrows). The further we get from the break source, the velocity vectors size decreases due to smaller water and steam momentum and flows(smaller blue arrows). The high density of small blue vectors under the containment dome in comparison to other coordinates can justify the higher temperature and pressure profiles for control volumes 28 and 29.

Since GOTHIC LP and 3D mode and ANGAR (FSAR results) use their dedicated methods, correlation, algorithms, etc. discrepancies in the simulation results were expected within a reasonable limit. LP codes assume when fluid enters a control volume it is immediately mixed and interacts with all thermal structures instantaneously. Moreover, 3D flow patterns are not considered in LP codes (Fernández-Cosials et al., 2017). Even between two LP codes, the difference in code structures might cause discrepancies in the results.

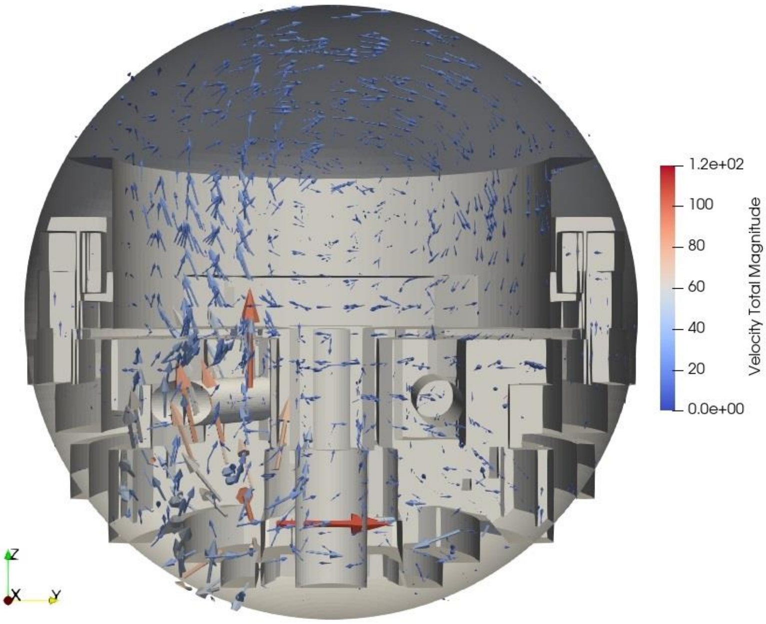

Fig. 19. Velocity vectors inside containment on the xz plan (t=2 second)

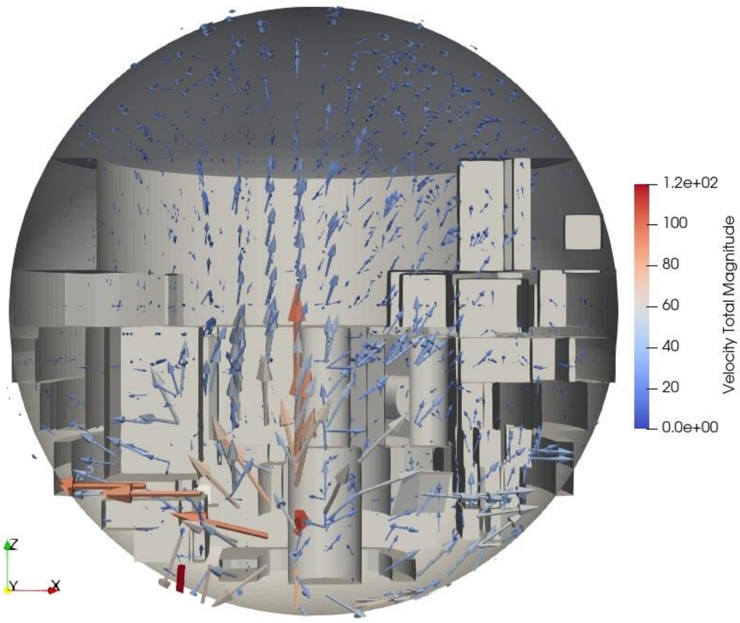

Fig. 20. Velocity vectors inside containment on the yz plan (t=2 second)

5. Conclusion

Defence in depth strategy defines the NPPs containment as the last barrier against the release of radioactive materials and developing the nuclear accident to be a global disaster. In a LOCA, the coolant discharges from the pipe break and increases the temperature and pressure inside the containment atmosphere. It poses a risk of containment failure and therefore investigation of containment thermal-hydraulic parameters is a necessity during LOCA. In this work, a detailed 3D simulation of a unique VVER-1000/V446 containment structure and its pressurization during LB-LOCA have been conducted by using AutoCAD and GOTHIC code. Results have been reported as LP 2D profiles for GOTHIC and ANGAR (FSAR results) and 3D contours for GOTHIC 3D mode. The following highlighted points can be concluded as a result of this study:

- Although 2D temperature and pressure profiles have the same trend for all three methods (GOTHIC LP, average GOTHIC 3D and ANGAR for FSAR) reported in Figs 7, 8 and 9(a) respectively, different equations, correlations, turbulent regime, numerical methods etc. employed in these methods/codes can make some minor different results.

- As expected, the results of 2D profiles for GOTHIC LP mode and ANGAR code are almost the same while the average GOTHIC 3D mode has agreed less w.r.t. the previous one (Figs 7-9). The main reason relates to the nature of GOTHIC 3D mode which uses a completely different methodology compared to the LP one. Even volume averaging of 3D calculated parameters in each control volume to make it as a 2D profile point can introduce some errors in the calculated outputs.

- 3D vertical temperature contours presented in Figs 17 and 18 can give an overall view of containment parameters and how their location regarding the break source can affect their profile behaviour from both time and value points.

- This study can give a complete understanding of the importance of using 3D simulation for containment parameters because of the occurrence of some hot spots in individual control volumes - that can be seen in 3D contours (and hidden in 2D ones). As 3D contours give a detailed map of containment parameters in all coordinates, it can be used to upgrade the safety assessment, in addition, to improving the ESFs siting in the NPPs design and operation stage.

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