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Ammonia: its pivotal role in World War I and its significant continuing contribution to the development of the USA as a 20th century superpower

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Abstract

Necessity is the mother of invention; the bigger the challenge, the greater the necessity. This is nowhere more a truism than when adversaries face one another in war. Throughout history, wars have been the catalysts for invention, innovation and implementation. World War II is a prime example which not only led to the development and deployment of the atomic bomb but also to numerous technologies that successfully tackled the enormous variety of tactical, logistical and battlefield challenges. Through their technological leadership, a further outcome of WWII was that the United States of America emerged as the global superpower. This emergence, however, began three decades earlier in the years of World War I. Ordnance again was central to the most important technological developments; the WWI equivalent of the atomic bomb was ammonia. The USA, with its dependence on Chilean nitrates for both fertilizer and munitions during World War I, was directly at risk both from U-boats and from higher fertilizer prices resulting from the impact of increased global demand. Here we discuss how the US Federal Government and US scientists restructured to combat these challenges and the US National Defense Act provided funding for new nitrate plants. We will also touch on some of the classified research that was performed.

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Introduction

At the end of the 19th century, the USA was on the cusp of emerging as a technological giant unaware that many pivotal moments yet to unfold in the early decades of the 20th century. The USA was not without its critics as it developed from a set of eastern colonies to the continent spanning federation that it is today. Alexis de Tocqueville, for example, criticized the USA for its neglect of the sciences [1] arguing that its concern for material progress hampered its ability to provide leadership in the sciences and cultural arts. Many US citizens turning towards European inspiration; at the turn of the 20th century the American National Academy of Sciences (NAS) was only a fraction of the size of the British Royal Society or the German Leopoldina.

The early beginnings of the 20th century were marked with arguably the most impactful chemical achievement of the century, the ability to make "bread from air" [2]. The efforts of Haber, Bosch, and Mittasch to synthesis ammonia at industrial scales remains one of the most important chemical processes to this day with over 150 million metric tons synthesized annually [3,4]. This technology was invented by German scientists and Germany kept control of both catalyst and procedure. Thus, to support their populations, most of the world was still required to import mined nitrates for their fertilizers. The Haber-Bosch process, however, was not the only available technology for producing ammonia. The Frank-Caro process involves the reaction of CaC2 with N2 to form calcium carbamide which can then be hydrolyzed to NH₃ and CaCO₃ [5]. This process would be the principal synthetic method for ammonia production until the world-wide adoption of the Haber-Bosch process. The Birklean-Eyde process forms nitrates via the direct oxidation of N₂ in arc reactors provided an alternative, but energy intensive, route for nitrification [6], whilst The Buchner process produced NaCN-enabled generation of NH₃ via hydrolysis [7], although it was less well utilized. The dominance of Europe in the synthesis of ammonia alongside the reliance of the USA on importation of nitrates exposed its economy to risk [8].

The scientific leadership of the USA, like contemporary societies, was led by a nongovernmental organization, the NAS. The position of the NAS as a national academy was unique. Both the Royal Society and Leopoldina would directly advise their respective governments and public to

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further the development of science. The NAS was, however, reluctant to directly influence the US executive branch of the US [10]. Its political neutrality protected the NAS from criticism but also prevented the government from being a direct benefactor to the sciences through patronage. The NAS soon underwent a rapid structural change as it was reorganized from a body of loosely connected individuals towards today's National Academy [11].



Fig. 1. Excerpt from the New York Globe, 1st September 1914 highlighting the risk the associated instability in the chemical imports due to the ongoing European war [9].

The transformation of the NAS was achieved by George Ellery Hale. Hale matriculated into the Academy in 1903 and would later become the Academy's Foreign Secretary in 1910 [12]. He was instrumental in increasing both the size of the NAS to 300 members and introducing an engineering section to the Academy [13]. Though World War I began in 1914, the Academy did not directly interact with the President of the United States. Hale would propose the direct collaboration between the executive branch and the NAS [11]. This resolution passed unanimously in 1916 and Hale became the chairman of this new National Research Council (NRC) which composed of a crossbody committee of academic, civilian, and military personnel [14]. Its main aim was towards offloading research projects and funding which directly contributed to solving any challenges that threatened the US due to WWI. Although many academics were dismissive of this council, due to its removed nature from the dayto-day challenges of research, it did provide a direct root to government that directly influenced research direction within academia. The Naval Consulting Board, led by Thomas Edison, provided a method to coordinate the industrial response to the war effort. America would declare war on the German Empire in 1917, one year after creating the NRC which aligned the American war effort and academic researchers [15].

Through the actions of the NRC, a collection of committees was founded to direct research of key strategic importance. The most pertinent for ammonia synthesis was the N₂ fixation committee. The inspired name would later change to the Subcommittee on Nitrates and Ammonia (Oct 1917) and finally the Nitrates Investigation Committee (Jul 1918) before being disbanded [16]. Ammonium nitrate was both the foundation of the intensive farming America required to feed the nation whilst also being the basis of the munitions required to supply allies and participate in the Western Front [17]. Nitrogen was described as "the all-important element" with a stark warning: "Without ample supplies, not only would our crops fail but our army and navy would be helpless and our lands would become the spoils of the first well-equipped enemy" [18]. The dominance of Chilean nitrate imports for both the production of fertilizer and munitions were of military importance. Identified as a risk to the security of the USA, the Department of War was also involved in the fixation of nitrogen [19]. The two avenues for research, through the civilian effort lead by the NRC or through the military, were often independent of each other with much of the overall decisions led by the Department of War.

The Department of War was empowered by the National Defense Act of 1916 (Section 124) [20] which provided the department with USD \$20 million for nitrogen fixation, equivalent to USD \$0.5 billion in 2024. Initial reporting to the Department of War's Nitrates Committee outlined the known domestic sources of fixated nitrogen to remove America's dependence on Chilean imports [21]. The Birkeland-Eyde Arc process through the DuPont company, the Frank-Caro Cyanamid process through the American Cyanamid Company [22], the Bucher Process through the Nitrogen Products Company and a Haber-Bosch synthetic ammonia process through the General Chemical Company (GCC) [23]. In addition, ammonia was produced as a coke by-product. Combined, the demand for fixed nitrogen was lacking by 200,000 tons per annum, a daunting process to correct when considering this was equal to the combined output of the established German Haber-Bosch plants at Oppau and Marsberg [24]. Only the American Cyanamid Company plant at Niagara Falls was a major operational plant during the prelude before WWI [25].



Fig. 2. Consumption and supply of inorganic nitrogen to America between 1900 and 1920[26]. Details are provided in Appendix A.

The USA's dependence on imported Chilean nitrates is highlighted in Fig. 2 which starkly indicates that a country of ~80,000,000 people is reliant on a foreign nation to provide the raw materials for agriculture, military explosives, and chemical industry [27]. Other combatants within World War I though were in a similar predicament. Countries with established N₂ fixation capabilities, such as Sweden, Italy, Switzerland and Norway, were able to profit and expand their industries [27,28]. Germany had invested in its N₂ fixation capability and between this internal resource and the stockpiling of nitrates prior to the outbreak of war was able to meet the initial demand for nitrates. Germany, however, was not fully prepared for a war of attrition initially aiming towards a brief and decisive victory in Europe. During the war, Germany was able to threaten Chile and its exports to the wider world for a short time until the Battle of the Falklands (1914) which reduced the threat of the Imperial German Navy's surface fleet significantly [29]. The UK entered the war without any nitrogen fixation capability being reliant on Chilean nitrates making securing capital and safe transit of these critical supplies' paramount. Britain's main focus concerning N₂ was not chemical synthesis but directly combating the raids on merchant vessels. To this end, the UK further developed convoy strategies rather than create a new N2 fixation infrastructure [30].

By request of the Secretary of War, the NAS and its Nitrate Committee were asked to report on the best way to secure nitrates for the USA. Consisting of academics, military and industrial experts including American Chemistry Society (ACS) president, Charles H. Herty, the committee submitted a preliminary report in early June, 1916 [31]. By this point, the demand on Chilean exports had doubled the price of fixated nitrogen. The report provided three conclusions for which the government should Cummings et al. (2025)

act. Firstly, it was necessary to purchase a two-year stockpile of nitrates from Chile as this would provide sufficient time to build a nitrates plant. Secondly, the production of ammonia as a by-product of coke ovens was of a large enough quantity to support immediate domestic needs and, thirdly, provided an overview of the synthetic nitrate processes, emphasizing the need for these processes to be investigated thoroughly [29]. This report echoed the conclusions of the internal military report from the Naval Consulting Board authored by Willis R. Whitney in March of the same year [30].

With the threat of German Unterseeboot (U-boat) demonstrated by the sinking of the RMS Lusitania and the attack on the SS Sussex (3 American deaths), the import of nitrates to America was considered at risk [27]. Furthermore, U-151 would cut telegraph cables to New York and would later sink 6 US ships near New Jersey highlighting this new form of warfare and the difficulties the USA faced without internal supply of fixed nitrogen [31]. an Mobilization of both the military and civilian components of society towards protecting America's interests were paramount. Through the actions of the ACS, a voluntary census of trained chemists was performed of which many were stationed in research laboratories for development of war technologies [32]. With the efforts of Hale, the larger American science community was beginning prepare for accelerating technological to development. Additional government legislation freed foreign patent restrictions via the Alien Property Custodian and managed by the Chemical Foundation allowing for material gains from previously restricted intellectual property [33].

At the start of WWI, four plants were available for nitrogen fixation. One Cyanamid plant at Niagara Falls, Ontario, a Bucher plant at Saltville, Virginia, a modified arc process at Nitrolee, South Carolina, and a small Haber-Bosch based plant at Laurel Hill, New York. Furthermore, ammonia harnessed from coke was used but ultimately 75% of nitrates were imported from Chile [34]. The only major industrial plant for nitrogen fixations was situated in Canada, a British Dominion.





Fig. 3. Locations of the American nitrogen fixation facilities: ▲ Nitrate Pant #1, Sheffield Alabama, ■ Niagara Falls, Ontario, ● Saltville, Virginia, ● Arlington Farms, ● Nitrolee, South Carolina Virginia, ◆ Laurel Hills, New York.

The National Defense Act provisioned funds for the fixation of N₂ but was deemed underfunded by the ACS secretary, Charles Lathrop Parsons [35]. The provisions allowed planning for four industrial plants and three experimental stations: Sheffield, Alabama, Laurel Hill, New York, and Arlington Farms, Virginia. These experimental stations were aimed at solving the errors and problems at Nitrate Plant #1, an industrial sized pilot plant at Sheffield, Alabama, and #2, a Cyanamid plant at Muscle Shoals. Plants #3 and #4 were only mildly influential overall. The aim of the Defense Act was to provide solutions to emerging and current practices though this was met with skepticism from industry who were concerned modifications to the practices would nullify their patents [36].

In January 1917, Parsons prepared a report with Eysten Berg having toured France, Italy, England, Norway, and Sweden in late 1916 under the direction of the Secretary of War [37]. This report reinforced the conclusions of the previous report in June. It recommended to provision of new, cheap, electrical supplies in the form of hydroelectric power so that interested private businesses could compete to supply fixated nitrogen to the government. Members of the War Department were dissatisfied with the lack of urgency communicated. The report provided a long-term plan over five years which did not consider the ongoing war in Europe or how the US may become involved. President Woodrow Wilson would declare war three months later [38].

Inquiries from industry and private individuals flooded the War Department with competing bids for the extraction of N2 from the air. Frank Washburn, from the American Cyanamid Company, directly vied for governmental supporting in building a new Cyanamid plant at Muscle Shoals requiring government aid in both building a new hydroelectric dam and securing the building materials and equipment for this new plant [39]. Washburn had been petitioning the US government for assistance in building a new hydroelectric dam prior to the War and the National Defense Act provided the funds to support his desire to build a new dam near Muscle Shoals, Alabama. In private letters to General William M. Crozier, Army Chief of Ordinance, Washburn was dismissive of the Haber Bosch process [40] but his passion for securing power generation on the Tennessee river for a Cyanamid plant would also provide a suitable energy supply for a Haber-Bosch plant.





Fig. 4. Photo, taken in 1923, of the construction of the Wilson Dam which was built to power Nitrate plants #1 and #2. Photo is taken facing towards the North shore of the Tennessee River [41].

Construction of the Wilson Dam was necessary for the production of nitrates, aiming to supply cheap energy to the surrounding area. It was a colossal undertaking being the largest hydroelectric project up until this time. Both the physical infrastructure to support this work and the accommodation for the workforce and their family was needed to build the dam. An entire town was built near Sheffield, Alabama, for the workforce including 112 homes and 2 schools. At its peak, the dam had 19,000 men helping in its construction. The dam was finished in 1924 well after the war. Power for both nitrate plants were secured from the building of a new power plant from the Alabama Power Company and purchasing electricity for local suppliers.

With the Armistice, it was questioned whether there was sufficient demand for these nitrate plants. Funding from the National Defense Act funded 4 plants. Plants #1 and #2 were built near Sheffield and Muscle Shores, Alabama, respectively whilst plants #3 and #4 had sites chosen in Toledo and Cincinnati, Ohio, respectively [42]. Of the four plants, #1, #2, and #4 where used. Plant #3 was

never used with its foundations built by the end of WWI but never completed. The site was eventually turned over to the salvage board [43]. Due to an appeal from the French High Commission, Plant #4 had a little use for N_2 being used to make sodium cyanide *via* the Bucher process. The plant produced around 7,600 pounds of total sodium cyanide.

The Bucher process produces sodium cyanide from sodium carbonate, coke and nitrogen forming carbon monoxide as a by-product in an exothermic reaction [7]. Initially it was claimed to have a number of advantages such as low energy demands and abundant materials. However, the side reaction of CO with the iron within the reactor walls and kinetics made the process economically unviable. Plant #4 was salvaged under the joint responsibility of the Nitrate Division and Chemical Warfare Service [44].

A trial operation of Plant #2 was considered successful and placed on standby ready for government use. The dual purpose of Plant #2 being to provide the raw materials for explosives





Fig. 5. Image of part of Nitrate Plant #2 in 1919 showing the catalyzer buildings [45].

manufacture and fertilizers in both war and peacetime [47]. Ultimately, Plant #2 was not influential in the outcome of WWI, however, it successfully fixed nitrogen. After WWI and the completion of the Wilson Dam, Plant #2 would produce cyanamide under a joint venture between a subsidiary of American Cyanamid Company and a local power company with external financial support [46]. This cyanamide would later be used in both World War II and the Cold War. However, the decision to use the Wilson Dam to power Plant #2 after WWI was initially met with opposition. The power used for Plants #1 and #2 also provided an opportunity to cheaply power other economic ventures. Henry Ford had shown some interest for using the dam to power a car manufacturing plant but the dam was eventually used for both Plant #2 and the surrounding counties [47]. American Cyanamid existed until 1994 where it was eventually subsumed into what is now part of Pfizer.

The operation of Plant #2 was able to convert limestone, air, and coal into calcium cyanamide, with its peak production record being 110,000 tons annually [48]. Initially, air was compressed and

cooled using a Claude apparatus to produce N_2 with water being removed over heated copper. Limestone, sourced from a local quarry and later from a government owned quarry, was crushed and heated to form calcium oxide. The introduction of coke to the calcium oxide formed calcium carbide. This process is endothermic requiring continuous heating within an electric furnace to form the molten calcium carbide [49].

Calcium carbide can react with water to form acetylene gas, a potential explosive, so it required further handling under N_2 [53]. Prior to the formation of calcium cyanamide, CaC_2 is ground to a fine powder and combined with a catalyst. Initially, $CaCl_2$ was selected as it lowered the activation barrier for $CaCN_2$ formation, but its hydroscopic nature made the use of CaF_2 more advantageous due to both its natural abundance as fluorspar and its similar catalytic nature [51]. Heating of the $CaC_2/catalyst$ mixture under N_2 produces $CaCN_2$ exothermically. The product produced at Plant #2 contained 61 % $CaCN_2$ with the





Fig. 6. Process diagram of the cyanimide process to create NH₄NO₃ used at Plant #2 [49].

main impurity being CaO. The resulting material required treating with water and mineral oil to make it safer to handle due to the dust being toxic.

After the War, the US government, *via* the Fixed Nitrogen Research Laboratory (FRNL) [52], highlighted a number of research problems concerning cyanamide. Firstly, could cyanamide be used as a fertilizer and if not, how cyanamide can be used to produce ammonium nitrates or phosphates. Secondly, the manufacturing process to improve both the chemical reaction and the physical properties of the product. And finally, cyanamides potential in further research for amino acids.

Development of a fertilizer directly from cyanamide came to an end with Urephos. Initial testing of direct use of CaCN₂ was difficult due to its alkaline nature and side reaction with acid phosphates to make it unavailable for crops. Urephos was created by reacting CaCN₂ with sulphuric acid and neutralizing the resulting solution with phosphates. However, the cost of Urephos was not competitive compared to other products available [53].

Research into the handling of cyanamide continued. The product was produced as a fine toxic powder with unreacted CaC_2 and so lowering the toxicity to those handling it was paramount. The optimum conditions to remove CaC_2 from the $CaCN_2$ was studied with focusing on selectively hydrolyzing the CaC_2 . Handling conditions were also improved by extruding the resulting water mixture to form granules. Unfortunately, it was found that storing dry $CaCN_2$ is difficult due to it swelling from water absorption and a side reaction to form the dicyanodiamide- $Ca(C_2N_3)_2$ [54].

Out of the N₂ fixation plants built from the National Defense Act, Plant #2 was the most productive with its operation continued after WWI. Plant #1, however, provided a foundational understanding and testbed for NH₃ production in the USA. Plant #1 was built at Sheffield, Alabama, close to the planned Wilson Dam being constructed for both Plants #1 and #2. The overall design being modelled on the Haber process utilized at the BASF plant in Oppau, Germany. Plant #1 was a new technology for the US government with GCC being the key industrial expertise in America.

In the lead up to WWI, government information for industrial nitrogen fixation practices were sourced from the American Cyanamid Company. GCC, however, had purchased the patent rights for North America and had built a small experimental plant at Laurel Hill, New York. The US government funded both the construction of a new industrial plant and a series of experimental laboratories to develop the GCC process further and enable the production of nitric acid and ammonium nitrate.

Construction of Plant #1 began in 1917 with both the plant and permanent infrastructure to support future employees and their families. The plant took 10 months to build and would produce ammonia in September 1918, producing ammonium nitrate the



Fig. 7. Process diagram for the process used at Nitrates Plant #1 [55].

day after the signing of the Armistice on the 11th of November 2018.

monia

Though production of NH₃ and NH₄NO₃ was achieved, it was realized early that the process developed by GCC was not as efficient as first portrayed. Therefore, alongside constructing Plant #1, the Department of War's Nitrate Division instructed the experimental laboratories to focus on alleviating the concerns raised. Staff for these laboratories were sourced from the Department of War and the ACS's chemist census. Working alongside employees of GCC, the laboratories set out to solve the issues arising from Plant #1's development. Though GCC had based their process on the process used at Oppau, the differences caused a number of problems that needed to be addressed.

In both Germany and America, it was quickly realized electrolysis of water would be insufficient to supply the H₂ needed for production of the desired scale and so both used water gas by reacting steam with coal to form H₂ and CO. The CO was then further oxidized using the steam in the water-gas shift reaction to recover additional H₂ and CO₂. Subsequentially the CO₂ would be removed by stripping it with water and subsequently allowed to escape into the environment.

BASF formed pure nitrogen in a separate reactor by purifying air over hot coke in a separate reaction chamber. However, at Sheffield, the initial plan was to inject air directly into the CO gas converter using catalyst to form CO₂. Injection of the air and subsequent reaction provided the necessary heat but also converted some of the H₂ present to H₂O. At this stage, the desired 3:1 H₂/N₂ ratio had been achieved though with a significant amount of CO₂ (29 %/vol) [56]. This had the unfortunate effect of also oxidizing the H₂ present with the reactor. CO₂ would be removed by a single water scrubbing step. Removal of the residual CO (3 %/vol) was achieved by its absorption in a cuprous ammonium carbonate solution. The final purification at Sheffield was achieved by a combination of refrigeration and desiccation using NaOH and CaO (soda lime).

The decision to design Plant #1 in a way to avoid the BASF patents had a series of impacts on its operation. The CO converter at BASF was two reactor columns with catalyst packed into shallow grids to minimize packing effects and damage to the catalyst itself. The plant at Sheffield, instead, used a singular pack bed column which reduced the materials effectiveness and was prone to breakages [57]. Though never built, advice from the experimental laboratory at Laurel Hill recommended a second column to both improve the purity of the gas and introduce redundancy in the system [58]. Further research at Laurel Hill focused on the regeneration of the CO absorber.

At Sheffield, the reactant gas was heated using a superheating steam method prior to entering the ammonia converter which was deemed inefficient and expensive [59]. The GCC catalyst used was also highly sensitive to impurities using elemental sodium with the iron catalyst and the reactant gas



was never attained with the desired purity to prevent damage to the catalyst. Though small production runs of ammonia were achieved, the plant was never under continuous operation [55]. Removal of ammonia from Plant #1 was achieved by compression and refrigeration with the remaining reactant gases recirculated.

Prior to the opening of the war, research into a method to convert the ammonia to nitrates was performed at the experimental station in Arlington Farms, Virginia. Originating from the Department of Agriculture, this lab was transferred to the Nitrates division in mid-1918 to further the efforts of Plant #1 [59]. This laboratory was then used to study improvements on the GCC catalyst.

The original GCC catalyst centered around creating a porous iron structure impregnated with sodium supported on kaolin. Each step in creating this catalyst was lengthy and difficult to reproduce [60]. Undesirable side reactions between sodium and the silicate-based kaolin were highlighted in correspondence with Prof Victor Grignard as damaging for the catalyst making the long-term operation of Plant #1 questionable. Plant #1 was closed in 1919 and not reopened with the site being sold to Reynolds Aluminum.

Due to the National Defense Act, a cyanamide plant had been built for both peace and wartime. Furthermore, the development of a series of nationally run laboratories for N_2 fixation had a long-lasting impact on American science. With the introduction and mobilization of scientists, the NAS's secondment to the Executive Branch and the split from European scientific leadership, America had built the foundations to both for further research alongside sustaining the country's agriculture.

In trying to find an alternative to the catalyst used in Plant #1 a series of other materials were studied. One of the more peculiar choices made at the Laurel Hill site was to study elemental uranium. First discovered in 1789 in Berlin as an oxide and later isolate in Paris, 1841 [61], uranium had been studied by both Haber and the US for its capability to synthesis NH₃ under high pressures and temperatures [62]. Reports from Haber highlighted uranium as a suitable catalyst for NH₃ production but chose to use osmium during the early prototypes of his process. Mittasch would later develop an ironbased catalyst which provided both the activity required and low cost compared to rarer osmium and uranium catalysts. Disagreeing with Haber, research performed at Laurel Hill, independent of the German effort, showed that elemental uranium was not an effective catalyst [63]. Little is discussed of the

physical or chemical nature of this catalyst, preferentially desiring the catalytic activity over understanding the underlying processes to evaluate why uranium was a suitable candidate for Haber but ineffective for the Department of War. Uranium, found from natural oxide deposits, would contain different trace quantities of impurities. Access to these deposits would be restricted by geographic considerations and the nature of these impurities vary. This may account for varying results between Germany and America.

Interest in uranium for N₂ fixations did not end in the 1920s. Later research showed that elemental uranium nitrides could synthesis NH₃ at operational pressures [64]. The nitridation of uranium towards U_2N_3 can be achieved at 850 °C under a N₂ stream. A U_2N_3 -UN₂ was studied more in-depth by Segal and Sebba who studied the catalytic performance of nitride under different partial pressures of N₂ [65]. They inferred that the catalyst was able to absorb N₂ into the structure of the catalyst alongside surface species to provide a mechanism step to synthesis NH₃. This work also highlighted the poisoning of the nitride catalyst *via* its oxidation which were inactive for NH₃ synthesis [65].

Further to the use of uranium as a heterogenous catalyst, bimetallic small molecular catalysts have been synthesized as potential avenue for ammonia synthesis. Work on these species have focused on either isolating and characterizing $U \equiv N$ and $U-N_2$ species. For instance, King et al isolated the $U \equiv N$ through the use of large sterically hindering ligand groups [66]. On hydrolysis, ammonia is released from this complex, yet it would not be suitable for direct activation. This complex, N_2 $[UN(Tren^{TIPS})][Na(12-crown-4)_2 \text{ where } Tren^{TIPS} =$ $[N(CH_2CH_2NSiP_{r_3}^i)_3]_3$ and $Pr^i = CH(CH_3)_2$, uses NaN₃ as the N source rather than direct activation of N₂. Direct activation of N₂ has been achieved by the diuranium species $[K_3{[U(OR)_3]_2(\mu-N)}]$, where $(R=Si(OtBu)_3)$, which is able to directly bridge N₂ and subsequently have NH₃ liberated from the complex [67,68]. Only a few examples of direct NH₃ synthesis have been achieved using small molecular catalysts but this remains an open avenue of research for synthetic chemists [69].

Cobalt molybdenum nitrides, and other binary nitrides, have had a significant amount of interest for the synthesis of ammonia [70]. Co_3Mo_3N was first reported as an ammonia catalyst in 2000, alongside other binary nitrides [71]. The specific focus on Co_3Mo_3N was due to its activity at 100 bar which was further enhanced by addition of Cs [72]. Mixed metal systems, however, were of key interest for both Mittasch and the Americans at Sheffield



Experimental Plant [73]. Declassified documents from the American Department of War show that a range of bimetallic mixtures were studied for ammonia synthesis. Fe/Mo and Co/Mo were both independently studied by the US's Nitrates Division and the BASF Nitrates Division Haber and shown to have high activities in comparison to other catalysts studied at the time. Though it is unlikely the CoMo mixture utilized by the Nitrates Division was Co₃Mo₃N due to the conditions studied, its reported activity from 1918 [74]. Synthesis of Co₃Mo₃N is typically achieved via the nitridation of the mixed metal oxide from the calcined mixed nitrates. Speculating on this knowledge with the benefit of the knowledge we know now belittles the achievements of those who independently discovered these breakthroughs. However, it is intriguing to know which pieces of information may have inspired current and future research.

At the end of the WWI, much of the information was classified but the knowledge was passed on. During WWI, American chemists had developed two leading catalysts and studied a myriad of others. The research framework that led to this success would be carried further by the FRNL which beyond the study of NH₃ synthesis catalysts would become a training facility, developing project-orientated team research environments still utilized today. The ACS had mobilized chemists to engage with the war effort whilst the NAS had reorganized from a group of loosely connect eminent scientists to a national body directly engaging with the President of the United States. The development of the ammonia industry in America catalyzed the building of America's scientific foundation into the 20th century and beyond.

Notes

Dependent on years chosen, the rollcall for each respective National academy varies. During the years leading up to World War I, the Royal Society averaged 451 members, Leopoldina numbered around 700 whilst the NAS had approximately 150 members prior to the changes to implemented by Hale. Both Haber and Bosch would join Leopoldina in 1926 (matriculation numbers 3749 and 3704 respectively). Mittasch would join later in 1937 (matriculation number 4414).

The US Department of War was the predecessor for the Department of Defense. It was split into the Department of the Air Force and Department of the Army in 1947 and eventually became the current Department of Defense in 1949.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results

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Appendix A Table 1: Table of production, imports and exports for the United States of America from 1911-1920

	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920
	Tonnes of Nitrogen									
By-Product Production	24805	29367	39330	38470	49273	59383	66382	77936	84852	140545
Fixed Nitrogen Production	0	0	0	0	0	0	300	300	300	300
Exports	0	37	0	1667	4241	9441	12216	8516	5768	24720
Chilean Imports	95201	84975	109351	94658	134918	212867	269630	322371	71200	230966
Other Imports	20816	14475	18884	21565	13584	8838	11206	9805	13067	14835
Total Consumption	140822	128760	167565	153016	190498	271647	335802	401896	163651	325926
% provided by domestic production	17.6	22.9	23.4	25.1	24.2	21.9	20	19.4	52	32.2