Chapter 3
The Great War

3.1 Chemistry at War

In August 1914, the German plan of attack, the Schlieffen plan, was aimed at the rapid surrender of Paris and capitulation of France, while Russia was held at bay by a small force. It included riding roughshod over neutral Belgium. Anticipating a rapid German victory, several leading scientists and scholars volunteered for service at the front, some well over conscription age. They included Walther Nernst and the sociologist Alfred Weber. Scientific prowess played no part at this stage. Reality soon set in. The Schlieffen plan failed during the first two weeks of September 1914 at the banks of the River Marne. Many intellectuals returned to their institutions; some would not return. This foreshadowed the four years of extended trench warfare along a front that extended from Dunkirk to the border with Switzerland.

The Kaiser's army, and navy, had now to grapple with the ramifications. To maintain military strength, new strategies had to be called into play, particularly for the supply of the matériel of war, not least of which were aromatic nitro compounds for explosives, and also for the intermediates from which dyes were synthesized, now mainly field grey and navy blue. The availability of nitro compounds in turn relied on adequate supplies of nitric acid, and expansion of science-based chemical industry. Nitrogen products came to the fore. The Germans were fortunate, for a while, in that a substantial amount of Chile saltpetre, in excess of 20,000 tons, had been abandoned by the retreating Belgian army at Antwerp, while stocks were held by various companies in Germany. But these were hardly adequate for meeting the demands of prolonged warfare. Synthetic nitrogen products were required for machine gun and rifle bullets, mines, mortars, shells and torpedoes. Meantime, there were already threats to the sea lanes that stretched across the Atlantic. The military leaders needed to be made aware of the situation.

On 13 August 1914, Walther Rathenau, of AEG, was placed in charge of the War Raw Materials Office (Kriegsrohstoffabteilung, KRA) by the Prussian War Minister

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Erich von Falkenhayn, who one month later was appointed Chief of General Staff of the German Army, replacing Helmuth von Moltke. Rathenau was assisted by AEG engineer Wichard von Mollendörff (1881–1937), who had earlier drawn up the draft plan on which the KRA was based. In the first months of the war, and even until late in 1914, it was not just the German military that grossly underestimated the nitrogen requirements. The same was true of the chemical industry. Late in August, Bosch had advised Haber, who was working with Rathenau and the supplies section of the Prussian War Ministry, that he did not anticipate significant expansion of the Oppau plant, at least in the near future. This was apart from pre-war plans to increase Oppau's annual production to 130,000 tons of ammonium sulphate, for fertilizer, by the end of 1915.

The situation changed within weeks. On 30 September 1914, a Reich war chemicals corporation, the Kriegschemikalien AG (Kriegschemikalien AG zur Bewirtschaftung chemischer Rohstoffe), under the presidency of Gustav Aufschläger (1853–1934), for procurement of chemical raw materials and organization of their usage was created. It was one of several large government-supervised corporations established to ensure adequate supplies of war materials. Bosch, present at the inaugural meeting, was encouraged to increase the BASF output of ammonia. The challenge remained of conversion of ammonia to nitric acid suited to manufacture of explosives. Bosch, however, was not prepared at first to share details of progress at BASF into nitric acid work with other parties.

Organic chemist Emil Fischer (1852–1919) (Fig. 3.1) had just completed a review of the nitrogen situation for Rathenau's office. In his report of October 1, presented in Essen, Fischer recommended adoption on a large scale of the Haber-Bosch process, and conversion of the ammonia to nitric acid by a method that was far from technically perfect. Together with Haber he warned of the impending crisis in nitric acid supply [1, 2]. Rathenau, with the support of Haber, arranged for Carl Bosch to meet with representatives of the War Ministry in Berlin to discuss the nitrogen situation. Bosch was struck by the ignorance of basic scientific and technical knowledge among senior military personnel, and had to describe the various processes involved in production of conventional high explosives, the aromatic nitro compounds, in particular the need for nitric acid. That mainly relied upon the nitrates imported from distant Chile, the supply of which could not be guaranteed, and, in any case, took three months to arrive at Hamburg by sea. It was necessary to supplement this source of nitric acid with acid from the new nitrogen processes already worked in Germany and from the Norwegian electric arc factories.

The Antwerp supply, and other stocks in hand of Chilean nitrate, which Haber during late 1914 believed to be around 14,000 tons, would not last long. In November alone, the requirement of sodium nitrate for use in manufacture of explosives was 20,000 tons [3]. The military needs of finished explosives, per month, were calculated to be 12,000 tons, or more, a 20-fold increase on peacetime production. This relied on the arrival of nitrate from Chile.

However, the availability of nitrate from Chile depended on the tide of war at sea, which was about to change. In September, the Germans won advantages

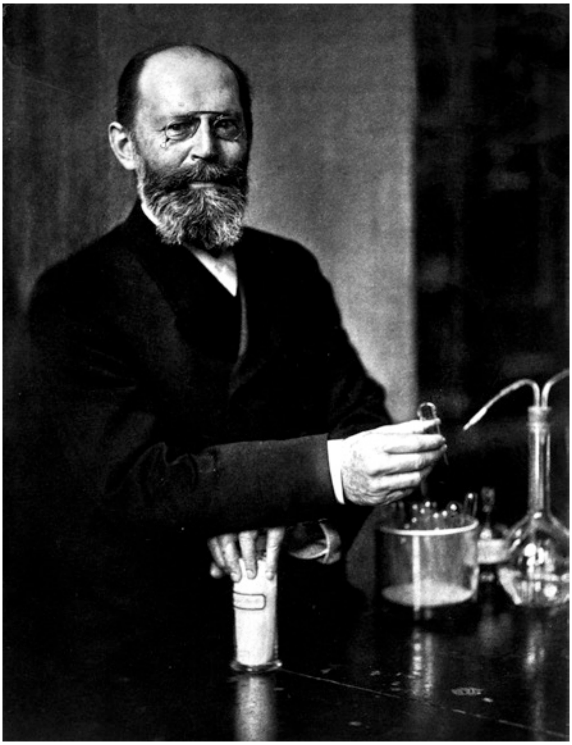

Fig. 3.1 Emil Fischer (Edelstein Center)

in commerce-raiding and submarine operations. On 1 November 1914, a British Royal Navy squadron in the South Pacific Ocean off the Chilean coastal city of Coronel suffered a major defeat in a duel with the German East Asia Squadron, commanded by Vice Admiral Maximilian Reichsgraf von Spee. Admiral Spee's squadron was now free to attack merchant ships loaded with consignments of nitrate destined for the Allies, and to help strategic supplies reach Germany. The situation was soon reversed, on December 8, at the Battle of the Falkland Islands, when Spee went down with his flagship, the *Scharnhorst*, and all but one of the German squadron (Fig. 3.2). From then until the end of the war Chilean nitrate was cut off from Germany by the British blockade. The export of nitrate, that had fallen considerably from August (Germany was a major customer), now recovered. Though the Allies continued to be hampered at sea, including by an intensive programme of submarine attacks between late February and mid-May 1915, and especially during 1916–1917, they were not denied access to nitrate.

For expansion of synthetic ammonia production, Haber, on behalf of the Reich, had already on October 24 drawn up a draft contract with BASF at Ludwigshafen. The final version was ready for signing in mid-November, but was then renegotiated to include further expansion, no doubt as a result of the loss of Chile saltpetre. The contract was made ready for signing in mid-January 1915. The total subsidy offered to BASF was raised from four to six million marks. For the

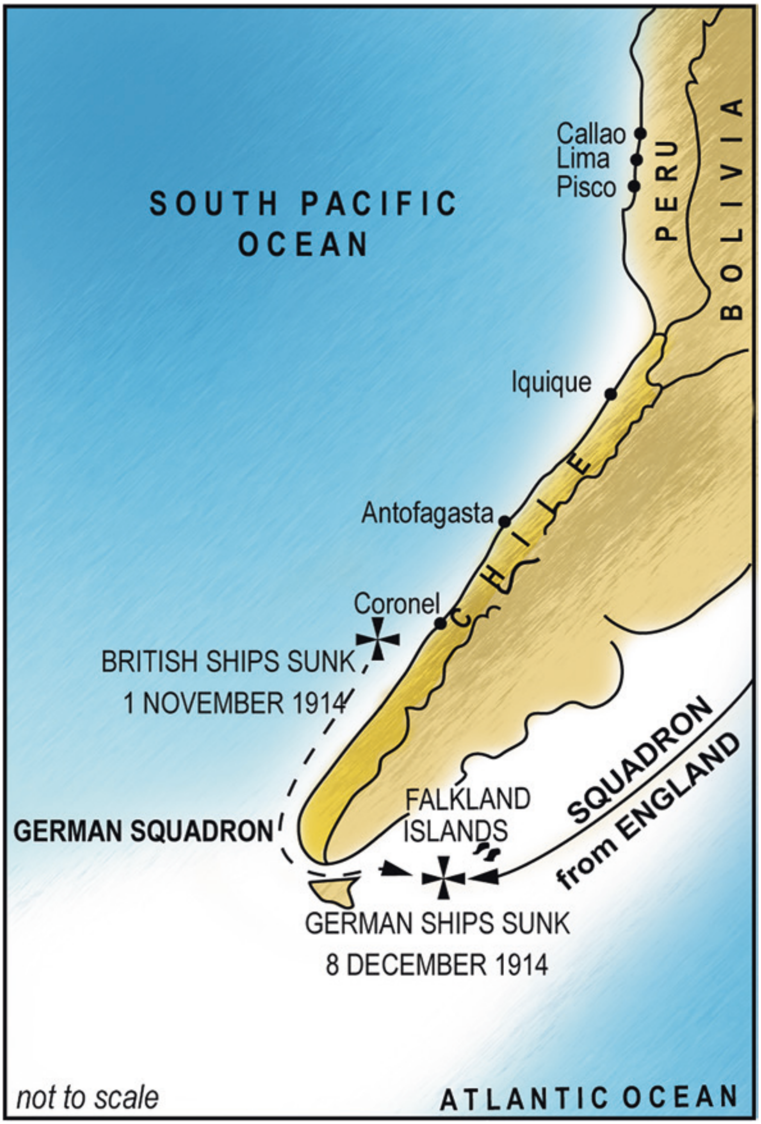

Fig. 3.2 The battles of Coronel and the Falkland Islands, 1914

concentrated nitric acid required by manufacturers of explosives, ammonia was at this time oxidized to dilute nitric acid, that was converted into sodium nitrate, from which concentrated acid was obtained [4].

Bosch was pushed by Fischer to start adding capacity to the Oppau facility even before contracts with the War Ministry had been finalized [5]. There was widespread and behind the scenes rivalry, as well as over-optimistic, if not downright exaggerated, claims by manufacturers anxious to participate in the expanding nitrogen business, not only during the war, but also in anticipation of peacetime conditions.[1] A great deal was at risk, and not just the German war effort. Great profits as well as royalties on inventions were to be had from wartime manufactures based on the latest chemical inventions. Then as now, shareholder value and dividends had to be maintained, which would certainly be enhanced if the government placed orders, made guarantees, and subsidized the building of factories for war production. This also held out possibilities of formerly unthinkable expansions, and profits that would continue to be generated long after cessation of hostilities.

Wilhelm Ostwald and Eberhard Brauer, as well as the coal industry for which they acted as consultants, favoured the nitric acid process adopted at Gerthe. The owners of Gerthe promised Fischer that they were in a position to build twenty plants with an output of 6,000 tons of sodium nitrate from coal gas ammonia every month. Fischer also considered the electric arc method of the Pauling brothers, which though simple suffered from short electrode life (however, the Paulings claimed that they could produce concentrated acid), and the Birkeland-Eyde and Schönherr furnaces. BASF had already, in 1911, dropped its interest in the Schönherr furnace, convinced that the process based on Haber's work was superior to the electrothermal processes. Thereafter the Schönherr furnace was relegated to a topic of mainly academic interest [6, 7].

Though reliable quantitative figures for German nitrogen manufacturing capacities, according to products and processes, vary, they can be used to draw up a rough guide of overall production, and of the relative contributions, not long before the outbreak of war. Comparisons with the following years will demonstrate how the technology of nitrogen production changed rapidly. Until August 1914, Chile saltpetre and gas works ammonia were major sources of nitrogen by far. According to an account appearing in the *Frankfurter Zeitung* on 23 November 1919, nitrogen consumption by Germany in 1913 was made up as follows: Chile saltpetre, 750,000 tons (of which the nitrogen content was 116,000 tons); ammonium sulphate, from gas works, 460,000 tons (nitrogen, 92,000 tons); Norwegian nitrate, from the electric arc processes, 35,000 tons (nitrogen 4,500 tons); calcium cyanamide, 30,000 tons (nitrogen 6,000 tons); and Haber-Bosch derived ammonium sulphate, 20,000 tons (September to December; nitrogen 4,000 tons). The total, calculated as nitrogen, was 222,500 tons [8]. Fritz Haber, when addressing the Society of Chemical Industry in Liverpool during November 1913, indicated that 36,000 tons of cyanamide were manufactured annually (in Germany alone), for use directly as a fertilizer, or by conversion, with steam, to ammonia [9]. Haber was then of the opinion that the recently introduced Haber-Bosch process of BASF would have little impact on other producers of nitrogen products, since demand for nitrogen was so great.

The German press report certainly drew attention to the overriding importance of Chilean nitrate. Germany had since the turn of the century been the main

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[1] Historian Margit Szöllösi-Janze has undertaken an in-depth study of the politics and various personalities involved, including their affiliations [1]. See esp. pp. 100–103, and 106–118.

importer, mainly for the agricultural sector. The supply of nitrogen was under the remit of the Ministry of Agriculture, and mainly the concern of soil chemists. This was very much the situation in September 1914, by which time the Haber-Bosch process had been in operation for just one year. In 1913, the monthly output of the Haber-Bosch process at Oppau, according to BASF, and in contrast to the 1919 press report, was 600 tons of ammonia, converted into 3,000 tons of ammonium sulphate, a rate that was increased by the autumn of 1914.

3.2 Badische versus Bayrische

While soldiers of Germany and Austria-Hungary, the Central Powers (joined by the Ottoman Empire in October 1914), and the Allies, Britain, France and Russia, fought on battlefields with nitrogen products, men of science and industry fought in German boardrooms and government offices over contracts and subsidies for nitrogen products. Sometimes this fighting included vendettas going back over previous years, and efforts to exclude rivals through outrageous claims. At other times it involved struggles over available competing technologies. Adversaries included personalities as well as companies.

Shortly after the outbreak of war, Nikodem Caro negotiated with Emil Fischer for additional electrical power for the Bayrische Trostberg cyanamide works in order to meet the needs of the agricultural sector. Caro wanted sufficient power to increase production of cyanamide at Trostberg at least fourfold. Eberhard Ramm, of the Prussian Ministry of Agriculture, became engaged in discussions with Caro concerning expansion of the cyanamide process, towards which some preference was shown. The cyanamide factories were well established and the manufacturing process perfected. Moreover, not only had conversion of cyanamide to ammonia been achieved, but oxidation of the ammonia had been integrated into the Trostberg facility. In addition, the cyanamide process required much simpler equipment than the Haber-Bosch process, though the energy requirements were considerably greater.

BASF had already antagonized cyanamide manufacturers with public statements to the effect that the grey-black cake of calcium cyanamide was little more than intractable dark muck. The Ludwigshafen firm also claimed that the quality of its ammonia was superior to that obtained from calcium cyanamide. Probably that did not go down well with Karl Helfferich—a member of the board of Deutsche Bank which had invested heavily in cyanamide—who was appointed secretary of the Imperial Treasury Office in December 1914. Walther Rathenau, who had expended much effort into advancing nitrogen fixation as one of the most important strategic projects, favoured cyanamide and recommended construction of new facilities, particularly for supplying the agricultural sector. However, cyanamide was not then sufficiently widely used as fertilizer, and many farmers were not happy with the novel product, particularly when confronted with problems of application during the spring dressing. A competition was announced for the design of a suitable spreading device, which became available by the end of 1915 [10].

Norsk Hydro, incidentally, held contracts with both German and Allied firms, and was anxious to continue supplying all parties with nitric acid and ammonium nitrate. Though Eyde was perceived by French investors in Norsk Hydro to be pro-German, the French armed forces received over half the output, mainly as the nitrate, and the Germans just 13 %, and perhaps less after the German contracts were completed in 1915 [11]. In 1916, Rjukan produced 80,000 tons of ammonium nitrate for supply to the Allies.

Haber, as an important government officer engaged in procuring essential chemicals, and though obliged to deal with all the nitrogen firms, certainly favoured BASF, whose chemists and engineers were working on a commercially feasible means for oxidizing synthetic ammonia to nitric acid. No less important was their emphasis on concentrating the acid, for use in manufacture of explosives, without conversion first to sodium nitrate.

Rivalry for lucrative, long-term nitrogen contracts became increasingly aggressive, with Bosch and BASF pitched against Caro and the Bayrsiche Stickstoffwerke. A nitrogen commission, whose purpose was to draw up contracts with manufacturers, was established on 28 November 1914 (Commission for the Preparation of Contracts for the Purpose of Increasing Nitrogen Production; Kommission zu Vorbereitung der Verträge zwecks Steigerung der Stickstoffproduktion). The Ministry of Agriculture was closely involved in the work of the commission, whose policy was invariably formulated, understandably, by those with the greatest experience, and also the greatest vested interests.

Though Rathenau, as head of the KRA of the German War Ministry, oversaw the work of Haber as head of the Chemical Section, he had little time for academics, whether scientists or economists. As a result he had a falling out with Haber and Fischer, who favoured BASF ammonia (as well as with Richard Willstätter (1872–1942)) at the beginning of October 1914, from which time he took over total control of planning for war raw materials, in particular nitrogen products.[2]

Following Rathenau's considerable emphasis on cyanamide-derived ammonia, the Reich Treasury in early 1915 agreed to provide funds and guarantees that enabled an unprecedented programme of expansion and construction of new facilities. Trostberg underwent expansion from 1915, following agreements with Caro, and sales guarantees from the Reich. However, there was a limit to the facility's capacity, and new works elsewhere were essential. On 5 March 1915,

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[2] Robert Le Rossignol, while at Karlsruhe, married a local girl and in 1909 they moved to Berlin, where, on Haber's recommendation, in July he joined the laboratories of the Auer-Gesellschaft, manufacturer of the Osram lamp. For a time he continued with work on the ammonia process, but without making any further useful contributions. As an enemy alien living in Germany, Le Rossignol was interned at the outbreak of war. Haber intervened and arranged Le Rossignol's release in 1915. He then returned to the laboratories of the Auer-Gesellschaft. Le Rossignol left Germany for England on 6 December 1918. In 1919, he joined the Hammersmith (London) laboratories of the British Osram Company Ltd., a firm sequestered as enemy property, and which from 1916 was wholly owned by the General Electric Company. From 1923, General Electric research was carried out at purpose built laboratories in North Wembley (Fig. 2.20, p. 55). There, Le Rossignol developed large high-powered transmitting valves for radio communication.

the treasury, with Rathenau's backing, commissioned Bayrische Stickstoffwerke to erect and manage state-owned cyanamide production facilities at Piesteritz (Reichsstickstoffwerke Piesteritz; the Imperial Nitrate Works), on the River Elbe, near Wittenberg, and at Chorzów (German: Königshütte), near Katowice (German: Kattowitz), northwest of Cracow, with a plentiful supply of local coal, in Prussian Upper Silesia. Both were producing cyanamide by the end of 1915. Piesteritz began large-scale production in early 1916. Also commissioned was a large brown coal-fired electrical generation facility, from Braunkohlen Golpa-Jessnitz AG (BG-JAG), to serve the Piesteritz works. Brown coal was also the source of electrical power for the Chorzów facility. Even allowing for vested interests by those responsible for commissioning these works, their orders were hardly based on bad decisions. Haber-Bosch synthetic ammonia had yet to come to the fore.

After arranging the increases in cyanamide production with Bayrische, in March 1915, Rathenau resigned. He returned to the management of AEG.

Fischer and Haber enabled additional and very favourable financial arrangements to be made with BASF, particularly after the departure of Rathenau. Fischer believed early on that the Haber-Bosch process was superior to the other nitrogen fixation processes. The product was cleaner, certainly more so than the coal distillation processes, and the labour requirements were less. Once large-scale production by the various nitrogen-capture and nitric acid processes was successfully underway he began to favour the Haber-Bosch process, at least for military explosives. As a result, by January 1916, the output of Oppau had been increased fourfold to 80 tons of ammonia every day.

Electric arc methods also received some support. Fischer had considered the Pauling process in September 1914, when he was advised that it was capable of producing a concentrated nitric acid. The Pauling brothers' firm subsequently erected a new factory near Bitterfeld at Muldenstein, drawing power from a coal-fired generating station that served Germany's first long-distance electrified railway (from Bitterfeld to Dessau, opened in 1911; it reverted back to steam traction in August 1914, as a result of the war). The Pauling nitric acid plant ceased production early in 1917, mainly as the result of shortages of brown coal. In any case, its output was not great. Problems of electricity supply also reduced capacity at the cyanamide works.

Max Sering (1857–1939), of the University of Berlin, who headed the War Ministry's Scientific Commission (Wissenschaftliche Kommission), founded in 1915, wrote in that year, perhaps somewhat optimistically: "The complete cutting off of the supply of Chili saltpetre during the war has been made good by our now taking nitrogen directly out of the air in large factories built during and before the war. With extraordinary rapidity the question has been solved of how the enormous quantities of the needed ammunition were to be produced, a question which in England still meets with difficulties, in spite of the help from America" [12].

Much of this expansion in nitrogen was in fact then still at the planning stages, or at best about to be implemented. Certainly German synthetic ammonia, available from both the cyanamide and Haber-Bosch processes, was converted into nitric acid, required in the production of explosives, far more than into fertilizer. Overall control and production had become a state monopoly, directed by Julius Bueb (1865–1944), Reich Commissioner for the Nitrogen Economy (Reichcommissar für die Stickstoffwirtschaft).

3.3 The Explosives: Nitro Compounds

Throughout World War I, military shells containing high explosives were filled with aromatic nitro-compounds, of which 2,4,6-trinitrotoluene, TNT, or trotyl, was used more largely than any other. TNT was manufactured from toluene, an aromatic coal tar hydrocarbon closely related to benzene; both were obtained from the distillation of coal tar [13]. The wartime demand for toluene often exceeded the supply. As a result, in Germany ammonium nitrate was mixed with trotyl—as was the case in Britain—in order to conserve and extend the use of toluene. The German mixture known as Gestrecktes Füllpulver contained 40 % ammonium nitrate and 60 % trotyl [14]. In Britain, the similar product was called amatol, for which the Allies produced over a million tons of ammonium nitrate: from calcium nitrate (the Norsk Hydro product); by ammoniating Chilean nitrate; and by reacting the Chilean nitrate with ammonium sulphate and fractionally crystallizing the product from solution.

German nitro compounds employed in aerial bombs and torpedoes often contained such mixtures as trotyl and hexanitrodiphenylamine, on account of their great shattering power. There was also picryl sulphide, again a nitro compound, used for similar purposes by the Germans.

The French relied extensively on picric acid, made from phenol, another coal tar product, obtained by distillation of the “carbolic acid” fraction. The fraction was treated with sodium hydroxide, dissolved in soda solution, separated from oil, and the crude phenol was liberated with sulphuric acid or carbon dioxide. It was then fractionally distilled. Nitration of phenol commenced with sulphonation, in sulphuric acid, followed by addition, with stirring, to concentrated nitric acid, giving, in two steps, the picric acid, 2,4,6-trinitrophenol, which was melted and poured into shells. The nitro compound mixed with guncotton (nitrocellulose) was called melinite in France, and lyddite in Britain. At times the supply of phenol was scarce, and demand was such that picric acid was manufactured during the war from benzene, in five steps: conversion to nitrobenzene, then to chlorobenzene, dinitrochlorobenzene, dinitrophenol and finally the trinitrophenol, picric acid. The process was developed at the United Alkali Company in Britain [15]. An alternative process involved sulphonating benzene, followed by neutralization, as its sodium salt, and fusion with sodium hydroxide. The latter, the sulphonate melt, was dissolved in water, the phenol was liberated, and purified, as in the usual process.

Britain before the war and during the early stages had relied mainly on lyddite. The British subsequently developed the manufacture of TNT to a high standard, and replaced lyddite by TNT, and amatol. Much of this effort was due to American-born chemical engineer Kenneth Bingham Quinan (1878–1948), who was brought to England late in 1914 by the Committee on Supply of High Explosives from the Nobel explosives factory near Cape Town. He immediately implemented a programme of construction of new munitions factories. Among the innovations was a continuous process that employed toluene produced from petroleum, rather than coal tar [16].

Two important high explosives did not require the valuable toluene. Both were made from benzene. Tetryl, nitramine (tetranitromethylaniline, trinitrophenylmethylnitramine), a violent explosive, was used to transmit the explosion of the

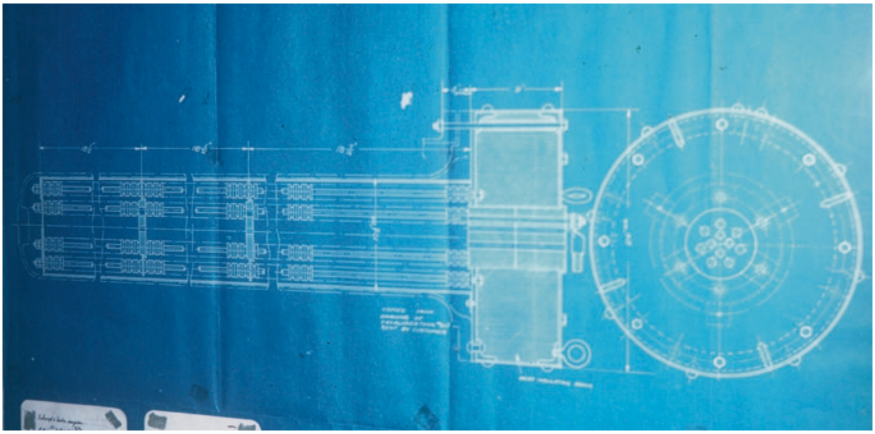

Fig. 3.3 Blueprint of vessel for Chaim Weizmann's fermentation process used in the production of acetone during World War I. (Photo by author, Weizmann Institute of Science, 1985)

detonator in a shell to the less sensitive TNT or picric acid. The high explosive TNA (tetranitroaniline) was made in Germany, and also in the United States by the Calco Chemical Company of New Jersey [17].

The concentration of nitric acid required to produce explosives varied. Nitration takes place in mixed acid, made up of nitric acid and sulphuric acid. As nitro groups are successively introduced into aromatic compounds, such as toluene, it becomes increasingly necessary to exclude water, and as a consequence to employ more concentrated acids.

In addition to high explosives, there were also the propellants, based on nitroglycerine and nitrocellulose, the main constituents of the smokeless powders, such as cordite. The nitration was also achieved with mixed acid. For nitroglycerine, nitric acid of 98–99 % concentration was required. In Germany during the war, wood cellulose was often used instead of cotton. Manufacture of tetryl and cordite required plentiful supplies of acetone, a solvent that was in short supply in Britain, until the novel fermentation process of chemist Chaim Weizmann (1874–1852) was introduced on a large scale from 1915 (Fig. 3.3). Maize, rice, various cereals, and, less successfully, horse chestnuts, were the starting materials [18, 19].

References

1. Szöllösi-Janze M (2000) Losing the war, but gaining ground: The German chemical industry during World War I. In: Lesch JE (ed) The German chemical industry in the twentieth century. Kluwer, Dordrecht, pp 91–121, on 97–98
2. Stoltzenberg D (2004) Fritz Haber: chemist, Nobel laureate, German, Jew. Chemical Heritage Foundation, Philadelphia, pp 128–131
3. Stoltzenberg D (1994) Fritz Haber: Chemiker, Nobelpreisträger, Deutscher, Jude. VCH, Weinheim, pp 234–236

4. Meinzer L, Gerling B, Janz LW (chronology) (1990) 125 years BASF. Milestones in its history 1865–1990. In: Kokott D (ed), project director, Chemistry looks to the future. BASF, Ludwigshafen, column headed “1914”
5. Moy T (1989) Emil Fischer as ‘chemical mediator’: science, industry and government in World War One. Ambix 36:109–120, on 110–113
6. Lunge G (1916) Handbuch der Schwefelsäurefabrikation und ihrer Nebenzweige, 2 vols. Friedr. Vieweg & Sohn, Braunschweig, vol. 1, pp 265–269
7. Mantell CL (1940) Industrial electrochemistry, 2nd edn. McGraw-Hill, New York, pp 575–576
8. Lefebure V (1923) The riddle of the Rhine: chemical strategy in peace and war. Chemical Foundation, E.P. Dutton & Co., New York, p 38
9. Haber F (1914) Liverpool section. The Hurter memorial lecture. Modern chemical industry. J Soc Chem Ind 33(2):49–54, on 53
10. Haber LF (1971) The chemical industry 1900–1930: international growth and technological change. Clarendon Press, Oxford, pp 200–201
11. http://www.yara.com/about/history/1906-1919/index.aspx. Accessed 12 Aug 2014
12. Lefebure V (1923) The riddle of the Rhine: chemical strategy in peace and war. Chemical Foundation, E.P. Dutton & Co., New York, p 211
13. Martin G, Barbour W (1915) Industrial nitrogen compounds and explosives. Crosby Lockwood & Son, London
14. Marshall A (1923) Modern explosives. In: Sadtler SS, Lathrop EC, Ainsworth Mitchell C (eds) Allen’s commercial organic analysis. P. Blakiston’s Son & Co., Philadelphia, pp 595–713
15. Reed P (1915) Making war work for industry: the United Alkali Company’s central laboratory during World War One. Ambix 62(1):72–93, on 83
16. McLeod RM (1998) Chemistry for king and kaiser: revisiting chemical enterprise and the European war. In: Travis AS, Homburg E, Schröter HG, Morris, PJT (eds) Determinants in the evolution of the European chemical industry, 1900–1939: new technologies, political frameworks, markets and companies. Kluwer, Dordrecht, pp 25–49, on 33
17. Travis AS (2004) Dyes made in America. The Calco Chemical Company, American Cyanamid and the Raritan River. Edelstein Center, Jerusalem, pp 47–50
18. Freemantle M (2014) The chemists’ war: 1914-1918. Royal Society of Chemistry, London, pp 95–119
19. Travis AS (1992) Chaim Weizmann: colour chemist, biochemist and father of biotechnology. The Biochemist (August–September), pp 15–19