

On Her Majesty's Service

WASC1130

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WASC 1130

Dear John,

As promised, a copy
of my lecture to the American
Chemical Society at Hawaii 1979.
Mac helped me with books +
references and Liddell provided
some useful information from Aodeer.

I avoided complicated scientific
terms and concentrated on history,
hope you won't be bored.

Yours sincerely

Jon

Good old Pantox - is he still alive?

The Role of Chemical Engineering in Providing Propellants and Explosives for the U.K. Armed Forces

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The decline in the importance of gunpowder and its replacement by nitrocellulose and nitroglycerine led the chemist and chemical engineer to play an increasingly dominant role in the production of materials upon which military capability was, and still is, critically dependent. The vital contributions of chemical engineering fall into five epochs from the early provision of plant and processes for cordite and picric acid before World War I to complex plant design for the development of TNT, RDX, plastic propellant, and nitroguanidine. A major role in the founding of the Institution of Chemical Engineers was played by those engaged in explosives manufacture. The importance of adopting modern trends in plant design for explosives is emphasized and the manner in which this is achieved in the United Kingdom is examined.

For 500 years gunpowder served the Armed Forces as a propellant for guns and as an explosive. The art of manufacture was highly developed especially at the Royal Gunpowder Factory, Waltham Abbey in England but its preparation was largely a grinding and mixing operation attended by great hazard (1).

Associated with the start of the Industrial Revolution early in the 19th Century was an intense interest in chemical matters and by 1847 both nitrocellulose (NC) and nitroglycerine (NG) had been prepared. The industrial scene was fertile ground for the exploitation of these materials on a manufacturing scale but the conversion to large-scale production led to tragedies. In England a disastrous NC plant explosion at Faversham in 1847 killed 21 people and similar events occurred at Le Bouchet and Vincennes in France (2). Nobel set out to develop Sobrero's invention of NG but his work was set back temporarily by the violent explosion at the Heleneborg works in Sweden in which his brother was killed.

These events delayed but did not prevent the adoption of NC and NG. Their great potential was realized and more science and ingenuity was brought to bear on their manufacture. Nobel expanded his activities to other European locations including Ardeer in Scotland. The British and French government supported work on the new propellants and explosives. In 1884 Vieille, a French engineer, invented Poudre B, a NC propellant which was adopted for the Lebel rifle and about this time work commenced on NG and NC manufacture in the Royal Gunpowder Factory, Waltham Abbey. During this period the vital importance of processing, especially stabilization, and its influence on the quality of NC became known. Meanwhile, pursuing applications of NG in 1887 Nobel invented and produced ballistite, a mixture of 12.6% N NC with 50–60% NG. The British government set up a committee which included such eminent scientists as Dewar, and, under Sir Frederick Abel's leadership, in 1889, the committee formulated the idea of cordite. This also combined NC with NG but used a more highly nitrated cellulose than Nobel's ballistite, with 13.1% N (guncotton) to give a more powerful propellant which was extruded in the form of cords. The name cordite, derived from the extrusion process, distinguished it from the ballistite made by Nobel at Ardeer.

Ample supplies of acids and other chemicals became necessary and, in company with the expansion of work on NC and NG, chemical manufacture became a rapid-growth industry; as the size of the acid plants increased it became important to design equipment of all kinds far more carefully than in earlier times. It was evident that a new era of large-scale fine chemical manufacture had begun. Even in 1895 the Royal Gunpowder Factory at Waltham Abbey was producing 500 tons/year of cordite and at a private cordite plant run by Kynoch Ltd at Arklow in Ireland 300 people were employed making a similar quantity. The new materials for the armed forces depended on the availability of chemicals and on the design by competent chemical engineers of safe and efficient plants.

This presentation examines how the chemical engineer translated proposals into manufacturing plants and so enabled the armed forces to obtain their essential supplies of explosives and propellants on a massive industrial scale. It is convenient to divide the history of the industry into five epochs broadly defined as: the period leading up to World War I and including the years of the Boer War; the 1914–1918 War; the post-war years up to 1935 when rearmament began; from 1936 to the end of World War II and the post World War II period up to the present day. The five epochs and the products prepared during them are outlined in Figure 1.

The first period was largely a NC era and towards the end saw the introduction of trinitrotoluene (TNT). The second period saw the intense activity produced by war conditions and shows how vitally impor-

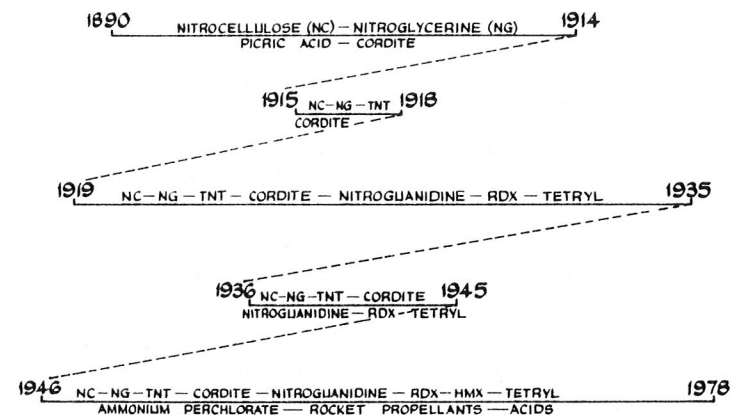


Figure 1. The five epochs in explosives and propellants manufacture

tant the provision of high explosives and propellants (especially TNT and cordite) was. After the war the tempo relaxed and until 1935 there was only a small effort devoted to the manufacturing side. But the change occurred in 1935 when the possibility of war again loomed over Europe. For the ten years from 1936 there was again an acceleration of effort, and plant design for the production of new materials as well as the established explosives became important. Cyclotrimethylene-trinitramine (RDX) and nitroguanidine became vital needs of the services. After the 1945 armistice until the present day the technology of defense has undergone extensive change. The requirements have become more exacting and more chemical engineering expertise has been needed; nevertheless, for various reasons there has been an acute shortage of chemical engineering expertise within government establishments so that insufficient advantage has been taken of the considerable advances in the application of science to process design. The few chemical engineers available have worked only in restricted fields and have relied on the importation of expertise from private industry to compensate for the small numbers.

1890–1914: *The Nitrocellulose and Nitroglycerine Era*

In 1890 Sir Frederick Abel's committee recommended using cordite for the British Services in place of gunpowder as a propellant and in 1891 its production began at the Royal Gunpowder Factory at Waltham Abbey—this was a somewhat more rapid development than could be hoped for today.

Cordite was 58% NG, 5% mineral jelly, and the remainder was 13.1% N NC; it was fabricated by mixing in acetone as solvent. The two

nitro compounds used the natural raw materials, glycerine and cotton, and required extensive quantities of concentrated nitric and sulfuric acids, which in turn needed the recovery or disposal of the spent acids after nitration. The acetone was obtained by the destructive distillation of wood via the thermal decomposition of calcium acetate. The production of cordite required the support of a considerable chemical factory. Even in 1872 Waltham Abbey was producing 250 tons/year of guncotton (3) which would have required the handling of several tons per week of acids. By the time the expansion of the new works there, at the Quinton Hill site, had been completed for cordite manufacture in 1905 the capacity had been increased fivefold.

For one of the last of his 15 worldwide sites to manufacture NG Alfred Nobel had chosen a suitably remote location in Scotland at Ardeer where production started in 1873. P. A. Liedbeck became Nobel's chief chemist and he both designed and operated the plants, the products of which were principally dynamite and blasting gelatin for mining purposes. There is an apocryphal story that the miners at nearby Kilwinning highly prized Nobel's NG because when burned in their lamps it gave a far better light! Nobel's exploitation of NG was towards the safer use of the material and it was perhaps a natural extension of blasting gelatin to make a product that did not explode but gave controlled burning. Nobel mixed larger quantities of 12.6% N NC with NG and invented ballistite (4). Lundholm and Sayers working in the Ardeer chemical research department devised a safe procedure for mixing large amounts of the soluble 12.6% N NC with 50% dry weight of NG by using an aqueous slurry process. The slurry was dewatered to form a paste which then was treated in heated rolls to consolidate it into a sheet. The sheet was chopped into small squares to form the propellant ballistite which is suitable for small arms. This processing has been retained up to the present day in a modified form as a basis for mixing many propellants. It is worth pondering on the effect of the prompt patenting action taken by Nobel to forestall any imitators. His patent may have led Abel to avoid using the safer wet-mixing process and use the highly dangerous dry guncotton (13.1% N) to avoid contravening the patent in government factories. Abel found that the guncotton mixed with NG formed a stiff, horny material. The dry guncotton was placed in lead trays and NG was poured onto the fibrous powder. To convert the mixture to a workable dough suitable for extrusion acetone and mineral jelly were added in a Werner Pfliederer and Perkins mixer. The dough was extruded into cord from a hydraulic press to form Mark I cordite. The mineral jelly was added originally with the intention of lubricating the gun barrel but in fact it acted as a diluent and stabilizer. Aromatic components absorbed nitrous gases thus contributing to the safe storage of British ammunition.

Abel's method of nitrating cotton was not elegant. The plant was a series of water-cooled cast-iron pots containing mixed acid into which cotton hanks were dipped. J. M. Thomson from Ardeer and his brother came to work at Waltham Abbey and in 1905 devised the displacement process. William MacNab describes the operation:

"In this beautiful process the acid is contained in a series of shallow circular earthenware pans provided with perforated false bottoms. The charge of cotton is forced under the acid and sectional perforated earthenware plates laid on top to keep the cotton down and a thin layer of water is run on top of the acid to prevent the escape of fumes. When nitration is finished the spent acid is allowed to run off slowly from the bottom while water is distributed at the same rate over the surface and displaces almost completely the acid from the nitrocotton" (5).

MacNab points out the need for extensive chemical engineering knowledge to enable this process to be effected since there is much associated equipment in the way of pipes, pumps, and valves to control correctly the corrosive liquids. At this time Sir Frederic L. Nathan had been Superintendent at the Royal Gunpowder Factory, Waltham Abbey for five years. He was the first of the scientific superintendents and was destined later to participate in the formation of the British Institution of Chemical Engineers.

Four years earlier in 1901 Dr. Robertson (later Sir Robert) and Rintoul devised scrubbing towers for acetone recovery and the payoff for this work was to be seen early in World War I when acetone was in short supply. Acetone was prepared by the destructive distillation of wood via calcium acetate and in 1915 the United Kingdom was burning 1400 tons of wood each week for the manufacture of this essential commodity. Rintoul's work therefore had an important effect many years after his foresight had provided the process. Rintoul, as chemist-in-charge of the NG plant at Waltham Abbey was not satisfied with the hazard presented by the stoneware cocks used on the Nobel-designed nitration plant and so he had, with Nathan, devised the displacement nitrator for NG which eliminated the moving part which had contributed so much danger to manufacture in the earlier years. His design of a cockless batch nitrator enabled 1633-kg batches of NG to be made, in much greater safety than with the old design using stoneware cocks.

It is not altogether surprising to learn that in 1909 both Nathan and Rintoul, the leading explosives technologists of their time, left government service to become General Manager and Chief Chemist, respectively, of the Nobel's Explosives Company at Ardeer, Scotland. At Ardeer the manufacture of NC and NG were well established and there is every indication that the newcomers were most welcome and set a new course

of collaboration between government and industry. This enabled the Ardeer factory to turn rapidly to the manufacture of cordite in 1914 and for other areas of cooperation to be established which persist to the present day.

When considering the developments over this period the words of F. D. Miles in his history of the Nobel Division of Imperial Chemical Industries Ltd are worth quoting.

"Nearly always the fundamental development was the work of one enterprising man. It has been the fashion to ascribe the industrial development of the last 150 years to the 'advance of science,' meaning by this, the growth of pure science in the hands of scientists not interested first of all in the applications of their discoveries. To do this is to ignore the fact that industrial developments as often as not owed comparatively little to pure scientific knowledge or academic work. The industrial revolution was the combined work of ingenuity and business ability!" (6).

To include men like Nathan and Rintoul, the acknowledgment should include the qualities of drive and duty that undoubtedly have motivated many excellent men in government service.

Several other factories were set up for making propellants and Kynoch Ltd of Birmingham operated the largest. Their plant at Arklow in Ireland was designed by an engineer, John Morrison. At this time Kynoch's was a competitor of Nobel's for government contracts to supply cordite and their production helped to supply the British army in 1914. Kynoch's, who eventually was to be absorbed into the ICI Ltd complex, used well designed plants for many operations including solvent manufacture.

Up to the start of World War I in 1914 picric acid, trinitrophenol, had been used as a high-explosive shell filling. It largely had replaced black powder and was termed melinite by the French and lyddite by the British. Trinitrophenol was a relatively easy batch-reaction nitration which had been carried out as a nonexplosive operation in the dyestuff manufacturing industry until a disastrous explosion took place in Manchester when a chemical factory caught fire.

Although picric acid was in use during the years up to 1914, the first stirrings of a revolutionary change were taking place. Sanford (7) noted in 1896 that trinitrotoluol may be prepared by nitrating toluol from coal tar sources and refers to its properties as a high explosive, what seems to be undiscovered at that time was the greater complexity of the nitration and the consequences in terms of plant and process. The need for chemicals involving much more complicated processes greatly changed the scene and underlined the contribution of plant and process design tailored to fit the chemical reactions.

From 1900 onwards some work commenced on TNT in private industry and a batch process was available producing up to 10 tons/week but it was not adopted officially as a high explosive by the U.K. government until 1914.

Picric acid and TNT both require using "boosters" for conveying detonation to the main charge from the detonator and tetryl (2, 4, 6-trinitrophenylmethyl nitramine) came into use for this purpose mainly because of the availability of diphenylamine in the dyestuffs industry. The Woolwich Arsenal Research Department had developed a batch process for its preparation by 1910 and it continued to be made by a similar method until World War II.

We see the end of this era as one where both complexity and scale were increasing in the explosives and propellants industry, calling for more sophisticated designs with even greater attention to the economics and safety of the operations.

1914–1918: World War I Era

In 1914 Britain was in an unprepared state for war. H. Levinstein (8) in his Presidential Address to the Institution of Chemical Engineers said that a nation makes war with the whole of its resources including industry. Because industry was not expecting war in 1914 it took an immense effort to mobilize the chemical and engineering capacity of the country to supply the needs of the greatest force the Army and Navy had ever fielded. Shells, guns, and cartridges were needed urgently. Private industry was the only producer of TNT at the rate of only 20 tons/week. Private cordite manufacture amounted to about 200 tons/week and the Royal Gunpowder Factory at Waltham Abbey was making 57 tons/week.

The position was critical but eventually a tremendous expansion of production took place and in a short time many new explosives and propellants plants were designed and built. Waltham Abbey raised its cordite output first to 140 tons and then to 200 tons/week while private industry expanded production to about 1300 tons and the great new government factory at Gretna was making a further 1000 tons/week by 1917. TNT manufacture had to be increased to match the total of 42,000,000 shells produced during the four war years and 230,000 tons of TNT in all were produced by the national explosives factories.

How was the expansion achieved so rapidly? Undoubtedly by the most intensive plant design effort, completely new designs were produced for TNT, and some new designs were produced for propellants. In the case of TNT the problems of scaling up were serious obstacles and chemical engineering contributed largely to the achieved success. Levinstein was at the heart of the action as General Manager of the Dyestuffs

Company in Blackley where the expertise on nitration of aromatics resided. His Presidential Address in 1937 includes a valuable summary of events and he records the assistance rendered by Du Pont in the United States who supplied 31,000 tons of TNT in 1915 to bridge the gap in supplies. Somewhat tardily the government recognized the principal task after 3½ months of war and in November of 1914 set up a powerful committee under Lord Moulton. It included William MacNab who later helped to found the Institution of Chemical Engineers. The government realized that factories had to be built and men of suitable training to design and run them had to be found. Unfortunately, unlike Germany, who had 5000 trained chemists, mostly in industry, Britain had only 500 chemists, mainly teachers. Teaching was reckoned in some circles to be a more honorable occupation than industrial activity for intellectuals. Lord Moulton brought out the importance of the national interest and, to the chagrin of the dyestuff industry, pushed the chemical industry in the direction of TNT. The paramount importance of supplies was recognized eventually by the setting up of the Department of Explosives Supply under Lloyd George who was made Minister of Munitions in June, 1915.

Events in 1914 had included the despatch of Colonel Sir Frederic Nathan to London to assist in the setting up of a large scale TNT plant at Pembrey in Wales. Reader's (9) history of the Imperial Chemical Industries Ltd describes how the expansion of TNT production was assisted by every means. Nobel's provided expertise, Messrs Chance and Hunt, acid manufacturers, built a factory at Oldbury and new sites were sought wherever nitric acid was available. An important feature was the mononitration of a mixture of 55% toluene and 45% petrol—Borneol petroleum. After the mononitration the MNT was separated from the petrol by distillation and used for the DNT and TNT stages. The Oldbury plant is believed to have been the first effective continuous process and it operated on a countercurrent principle. MNT was fed in at one end of a chain of nitrators each of which was fitted with a separator. After passing through 14 such vessels at temperatures ranging from 40° to 100°C, TNT was run off at the far end. This application of a new chemical engineering technique marked a major change in the industry to a higher level of complexity and hazard requiring new scientific ideas. By 1916, 16 private firms and 12 government factories were producing 1000 tons/week. One notable achievement of chemical engineers and others which enabled this expansion to take place was the design and erection of oleum plants which were essential for the nitration. German supplies had been relied upon before 1914 and sulfur burning units had to be put up in record time.

It was the same story of rapid expansion in the field of propellants. In the case of cordite no new processes were devised but better handling of

the subsidiary processes became necessary. Acetone was a bottleneck and it was Rintoul's recovery process which helped to extend the utilization of available supplies. The situation became so acute by 1917 that a new form of cordite called RDB was adopted which, with lower nitrogen NC, could be gelatinized or colloided with ether and alcohol. Another method of overcoming the shortage was devised by Weizmann at the government factory at Holton Heath using a fermentation method to produce acetone from starch. Earlier in 1915 fermentation methods of making glycerine had been started with the accompanying need for designing countercurrent extraction plants using isopropyl alcohol as solvent.

The rate of growth of complexity was increasing rapidly and a good example was the need to expand the guncotton drying capacity without increasing the hazard. A chemical engineer, K. B. Quinan, at Waltham Abbey in 1916 designed drying stoves that are still in existence and use today. The principle of preparing warm, dry, filtered air and forcing it through fluidized beds of guncotton restrained from escaping by covers of special fine cloth was a brilliant solution well ahead of its time. It probably increased the output of the cordite factory by 50% by reducing the throughput time.

Ammonium nitrate production became a major factor towards the end of World War I once the merits of amatol, an 80:20 mixture of ammonium nitrate and TNT, had been accepted by the Services as the most expedient method of extending the limited TNT supplies. Nitrogen fixation for fertilizers was the objective of the Haber process for ammonia and the successful chemical engineering of this process had made Germany independent of the Chile nitrate supplies by 1918. The plant at Oppau made 25 tons/day of ammonia. The British requirement for ammonium nitrate was 4000 tons/week by the end of the war, which was met largely with gas works ammonia, Chile nitrate, and some manufacture via a Birkland-Eyre oxidation furnace and calcium nitrate.

The closure of the major plants at the beginning of 1919 gave time to think about the requirements of the chemical industry and chemical engineering became a major topic of discussion including a lecture at the Faraday Society (10) and of course it was given close attention in the explosives industry itself.

1919-1935: The Inter-War Years

Not unnaturally the scene in explosives after the war was one of contraction of manufacturing capacity. The Waltham Abbey plant practically closed down and, of other government plants, only the huge Gretna plant was operational. Attention turned to experimental and investigational work in the government area and to civilian uses of explosives in mining and associated activities for the private industry plants.

Government sought to avoid the lack of preparedness demonstrated in 1914 by concentrating teams of scientists onto the problems of the day. Three important fields were recognized. TNT plants needed improvement to avoid the explosion hazard, guns needed flashless propellants with reduced barrel erosion, and if possible a new high explosive was required. The Research Department at Woolwich Arsenal looked at the last two problems and made excellent progress; in fact their flashless solution is still so important today that actions arising will be described in some detail in both this and subsequent sections. TNT manufacturing methods were reviewed and new plants were devised. A new high explosive was selected for development but in the manufacture of the propellant ingredients, NG and NC, little progress was made—effort being concentrated on interesting chemical investigations.

The development of a flashless, low-erosion propellant neatly demonstrates the substantial contribution made by a small team of dedicated men in Britain to the support of the Armed Forces in World War II and to events even up to the present day. When Marshall's *Explosives (II)* was published in 1917 the reasons for gun erosion and for gun flash were known—it records that erosion was related to combustion temperature. Sir Hiram Maxim in 1901 advocated the addition of carbon black as a flash suppressant and to reduce erosion. Sir George Beilby knew in 1904 that nitroguanidine was an effective flash suppressant. Vieille found in 1912 that nitroguanidine incorporated into cordite would reduce gun erosion by a factor of two and by a factor of three in ballistite; but he also found that it made the propellant brittle and ruined the ballistics. In 1914 William MacNab suggested using nitroguanidine combined with a tetranitro compound bound with rubber to yield a flashless propellant but the idea was not pursued even though it anticipated by some 30 years the composite propellants used today in rocket motors. It is interesting to note that MacNab became President of the Institution of Chemical Engineers in 1934 and he is commemorated by the MacNab Medal awarded annually for the best Home Paper.

In 1921 Sir Robert Robertson, when he was chemist-in-charge of the Woolwich Arsenal Laboratory, decided to investigate nitroguanidine thoroughly and appointed J. N. Pring to carry out the task. He thus set in motion a tremendous train of events which was to extend over 60 years up to the present day. Nitroguanidine when suggested by Beilby was rejected on cost grounds but in 1921 it was acceptable because advances in chemical manufacture had lowered the price of calcium cyanamide and therefore nitroguanidine. Pring rapidly demonstrated the effectiveness of nitroguanidine as a flash suppressor for small-caliber guns and showed that particle subdivision was the clue to its utilization in cordite. The preparation on a manufacturing scale of the fine material was a difficult chemical engineering task which took some years to achieve.

By 1925 trials had been carried out in 6-in. breech-loading guns with compositions containing 10–70% of the nitroguanidine prepared in a coarse form in an edge-runner grinding mill. The trials were successful so more attention was focused on the method of manufacture. In 1925 the factory at Waltham Abbey began to produce nitroguanidine from calcium cyanamide. The aqueous suspension of calcium cyanamide was treated with carbon dioxide to give cyanamide which was then reacted in an autoclave to yield guanidine nitrate. The latter was converted to nitroguanidine by treatment with sulfuric acid and the crude product, after filtration, was recrystallized from hot water and dried. The product after milling in an edge-runner mill was termed petrolite.

At this stage Pring encountered difficulties with ballistic regularity and identified the problem still as one of particle size; therefore efforts were directed towards alternative methods of obtaining finer material. Holden at Woolwich designed a somewhat cumbersome but effective shock-cooling technique using a rotating gunmetal cylinder cooled on the outside with brine acting internally as a crystallizer. Improvements in both the process and the crystallizer were effected by the chemical engineers at the Royal Gunpowder Factory in Waltham Abbey who polymerized the unstable cyanamide to dicyandiamide thus increasing the yield. They also introduced a new vortex crystallizer—more suitable for production—which gave the fine crystals required; the product was renamed picrite. By 1931 several tons per week were being produced and further plants were designed for the Admiralty factory at Holton Heath and Nobel's at Ardeer. Nobel's, by this time had passed through a transition of being first part of Explosives Trades Ltd and then being absorbed with Brunner Mond and British Dyestuffs into the giant Imperial Chemical Industries complex.

With the manufacture of picrite well established in the early 1930's, Pring continued to promote the case for its use; the events leading up to World War II and the eventual adoption of this important ingredient of service propellant by 1938 will be described below.

The work of the Research Department at Woolwich on high explosives established that cyclotrimethylenetrinitramine, also known as hexogen or cyclonite and termed RDX, was likely to be the most powerful explosive available and only a marginally superior substitute could be foreseen. This significant prediction has stood the test of time but, more importantly, being made at an early stage it allowed attention to be given to the critical problem of the large-scale production of RDX. Work started in 1922 and three names—Simmons, Forster, and Bowden (two of them chemical engineers)—were associated with the development (12). The process involves the manufacture of hexamine, its nitration with 98% nitric acid, and an ingenious continuous decomposition of the by-products after diluting with water. The adoption of the novel principle of con-

tinuous operation was crucial to the success of the enterprise. Decomposition of the by-products produced large quantities of nitrogen peroxide that needed collection, conversion to nitric acid, and recycling. By 1933 a small unit producing 75 lb/hr had been designed and was operating at Woolwich. The further development of this vital material belongs to the subsequent era of 1936 to 1945.

Some effort was directed towards the further development of the TNT process. According to Knapman (3) the factory at Waltham Abbey was allowed to become almost derelict but it was decided to locate some work there on the improvement of the Oldbury continuous TNT plant in the development of which William MacNab (13) had played an important part in 1916. The Chemical Engineering group of the Ordnance Factories examined the whole problem of ensuring adequate supplies of explosives and propellants in the event of war and it was clear that although the Oldbury plant was an outstanding development, considerable modification would be required to produce high-set-point TNT. A new pilot plant was constructed at Waltham Abbey which introduced screw lifts for the nitrobody between nitrators, a reduction in the size of the acid-nitrobody separators, and an increase in the number of nitrators. The plant was the work of Bowden and Smith (14). Their patent is remarkable in that it retains the secret that it is actually applicable to TNT. The pilot plant produced Grade 1 TNT continuously at the rate of 2 tons/week and was probably a world leader in this respect.

The NG manufacturing process also was being made continuous but the work was taking place outside the United Kingdom. The Schmid continuous process appeared in 1927 (15) and eventually was first installed in a British government factory at Holton Heath in 1937.

NC manufacturing in the United Kingdom was considered adequate and little attention was given to it. The mechanical nitration processes developed by Du Pont in 1926 were not favored. Developments did occur in the manufacture of solventless cordite and a feature of this at the RNCF Holton Heath was the overdue adoption of the principle of wet mixing of NC and NG as originally employed by Nobel. The drying of guncotton with its attendant risks therefore was eventually abandoned by the government factories at the end of World War II.

1936-1945: The Hitler War Period

With the gathering of the war clouds in the mid-1930's, plans were put in hand for a comprehensive scheme of rearmament by sea, land, and air. Ordnance Factories were planned for erection in various parts of the country, the necessary labor recruited and a comprehensive production plan formulated. By 1939 23 Royal Ordnance Factories (ROFs) had been planned and officially approved. By the time war came, seven

of these were in actual operation, four were engineering factories, two, Holton Heath and Irvine in Ayrshire, were explosives factories, and the only filling factory ready for action at the outbreak of war was Hereford. The factories at Waltham Abbey, Enfield and Woolwich Arsenal had been maintained at readiness during the inter-war period.

Thus ten ROFs out of the eventual 44, together with a limited number of specialist firms, were ready to equip the Navy, Army, and Air Force when war broke out in September, 1939. The location of these factories within the limited confines of the British Isles in the midst of the competing claims of other vital manufactures was a classic chemical engineering exercise in itself, and was carried out by the newly appointed directors of the various manufacturing groups—explosives, engineering, and filling. Propellant and high-explosives manufacturing were allocated to separate factories; likewise were the operations of filling and engineering. The new ROFs started with a considerable inheritance of expertise in production but with so many new establishments to be staffed and managed, experienced staff from the parent factories augmented by specialist staff from private firms with explosives-manufacturing experience could only be spread around very thinly. It says much about the ability and dedication of these men that they were able to pass on their technical and managerial skills so rapidly and effectively to the new recruits coming from the universities, colleges, and other industries in the critical stages of the build-up to full output. In the case of picrite the development assumed a new level of intensity. The need for fine crystals had been established but the method of producing them in quantity had not. The installation of improved pilot plants at Holton Heath and Ardeer had shown that picrite propellants were a viable and essential contribution to the Armed Forces. By 1938 the British Army and Navy were convinced of the advantages of a flashless propellant with lowered erosivity which could be produced in quantity. The production of fine crystals remained the limiting factor until after war had commenced. The original crystallizer produced only 15 lb/hr from three sprays. The Holton Heath design with six sprays had twice the output giving approximately 8 to 15 tons/week.

In 1940 the British Purchasing Commission of the Ministry of Supply arranged with American Cyanamid for the erection of a 1625-ton/month plant at Welland, Canada. The application of American chemical engineering design teams made this a successful enterprise which was in full production by 1941 and its output by 1943 had been raised to 2300 tons/month. The production of cordite N using this picrite was investigated in the United States and Canada and led to the adoption of picrite propellants by the United States in 1944.

Although the crystallization process was studied extensively and at Welland trials were carried out to spray hot solutions upwards into a

hot-air stream, the successful process was evolved at Ardeer. Jackson and Miles demonstrated that picrite could be sprayed from superheated water solutions into a brine-cooled crystallizer to give the correct product. Shortly afterwards in the United Kingdom the development of this idea, combined with vacuum cooling, led to the modern technique still used today. This chemical engineering design is the key to modern gun propellants and the difficulty of the task can be judged from the long period taken to solve the problem. A shorter time than 1925 to 1942 might have been needed if, during those years, more chemical engineers had been employed in government service.

The story of picrite does not end here. As will be seen later, prompted by the realization of its importance, further work was undertaken in the United Kingdom to ensure the economics and adequate supply of this vital chemical in 1950.

RDX was expanded in production from 75 lb/hr to 225 lb/hr in 1939 by the installation of a double-size Woolwich unit at Waltham Abbey. The scale-up was by the unadventurous method of putting in two lines instead of one. The considerable problem of acid recovery and recycling had not been worked out so that there were tremendous pressures on the government factories when the need for production arose. A chemical engineering approach in the pre-war years would have reduced this difficulty. There was a collaborative effort between the Research Department and the government factories to design a 90 ton/week plant (1200 lb/hr) for installation at Bridgwater in Somerset and Simmons, Forster, and Bowden (12) described the details.

Scaling-up of the nitrator resulted in a fairly inefficient multiple-stage cascade reactor with severe cooling requirements. The solid separation used a Dorr-Oliver raking classifier in a novel way. Considering the extremely restricted time and effort available and the unfamiliarity of those engaged with either chemical engineering, or the hazards of explosives in the case of plant contractors, an excellent result was achieved in the time scale required, but with hindsight effort should have been expended years earlier. This was less true of the acid, hexamine, and fume recovery plant associated with RDX manufacture. These were obtained from specialist plant manufacturers. Bamag Ltd dealt with ammonia oxidation for nitric acid manufacture and nitrous fume recovery while ICI Ltd (Fertilizer and Synthetic Products Division) provided plants on the hexamine side.

During the years 1941-1945 improvements were effected in the nitration plant by careful analysis of the operation by chemical engineering analysis. Denbigh, Bransom, and others (16, 17) worked out the behavior of the nitrator and optimized the continuous-process operating conditions. The control of the hexamine-nitric acid ratio is fundamental to the economics of the process. An output of 90 tons/week of RDX requires 405 tons of sulfuric acid to be concentrated daily in 20 Bamag pot stills since

this is required to prepare the pure nitric acid. The alternative Bachman process developed in the United States reduces this problem but has its own difficulties associated with the acetic anhydride cycle.

The situation on TNT production was more satisfactory than in World War I. The 25 ton/week unit using the Bowden-Smith process incorporating screw lifts for the nitrobody and special separators for easy cleaning was erected in 1936 at Irvine. After some delays caused by a serious fire it was used in 1939 both as the production unit and as a prototype for 24 units set up in four factories at Drigg, Irvine, Pembrey, and Sellafield. These produced 324,000 tons of TNT during the war and were augmented by batch production of 93,700 tons at the agency factories—Allen, Ardeer, Girvan, and Powfoot. No major improvements were possible during the war years.

Tetryl production was essential to the war effort and a continuous plant was set up in 1941 at ROF Pembrey which satisfied the needs for all of the stores. Improvements were effected in the control of particle size by "flash" graining which in turn enabled a more reproducible "exploder" pellet to be produced.

In the propellant field new chemical engineering designs were being evolved to improve economics and safety; safety was particularly important in the case of NG which has had the dubious record of at least one major explosion per year since manufacture started (2). The Schmid continuous process (15), the first successful continuous process which appeared in 1927, was installed at Holton Heath and was adopted also for the Ranskill plant.

The Schmid process embodied some radical improvements on the former plants in that it used mechanical stirring in a calandria-cooled nitrator, an inclined baffled separator of novel design, and a cocurrent washing system composed of glass-sectioned columns through which the NG was passed by jet pumps or eductors. Air was introduced simultaneously to aid dispersion and improve contacting (18). Although the holdup of detonable NG was relatively much less than in batch units of similar throughput, it was still considerable and in a 900 kg/hr Schmid nitration plant it normally would amount to some 800 kg.

In 1935 Dr. Mario Biazzi introduced a further method of continuous manufacture based on the use of stirred vessels for the washing stages and characteristic onion-shaped separators with tangential entries to impart a gentle rotary movement to encourage coalescence and separation (19, 20). Most important perhaps was that this particular arrangement was amenable to remote control from a protected position. It was with the introduction of the Biazzi plants that lead was replaced by stainless steel for reactors and subsequent stages.

Little alteration took place in guncotton NC manufacture although the process patented by J. R. Du Pont in 1922 was exploited elsewhere.

The United Kingdom adhered to the displacement method until well after the end of the Second World War. However, the Royal Naval Cordite Factory in association with the Research Department at Woolwich developed a method of making 12.2% N "soluble" NC from wood pulp paper in the same displacement equipment as that used for the nitration of cotton linters to guncotton (13.1%N). The Abel boiling and pulping procedure after nitration was retained with effort directed towards improving the efficiency of the stabilizing operation rather than varying the basic process.

A system of continuous boiling of NC during passage through a long serpentine pipe was developed by Milliken (21) in 1930 and this has been re-examined in recent years; however it was not adopted in the U.K. factories because of doubts about the reliability of continuous systems with such unstable materials as NC. The 12.2% N NC was used for solventless cordite manufacture because of its ease of working when mixed with NG. It was during this work that a major change took place in the mixing operation; it was derived from Nobel's original method but mechanized to suit the needs of bulk production. NC was handled exclusively as an aqueous slurry adjusted to a known concentration and NG was added through a spray rose in an open-spiral-tracked trough. The NC-NG mix was dewatered on a paper-makers' sheeting table. It was not until 1943 that this method was adopted for the solvent cordite process in the government factories, probably following the explosions which occurred while handling dry guncotton at Bishopton in 1941 and 1943.

The mixing and finishing processes for cordite remained virtually the same with the same type of machines as those used in 1900.

It is appropriate here to give some attention to the supply of nitric and sulfuric acids. Most of the problems of acid supply involved chemical engineering and their solution lay in improved plant and process design. The First World War gave a considerable impetus to the development of all types of plant for the production and concentration but by the early 1920's the momentum in Britain seemed simply to die away while in the United States and on the continent endeavors continued without interruption (22). The concentration of dilute nitric acid by dehydrating agents was pursued vigorously in the United States and on the continent while the use of nitrogen tetroxide and oxygen was researched mainly in France and Germany (23).

The greatest item in the cost of concentrating nitric acid using sulfuric acid as the dehydrating agent is the cost of reconcentrating the sulfuric acid. The alternative nitrogen tetroxide process therefore was of great interest and led to the choice of the "Hoko" process for ROF Irvine in which dilute nitric acid, nitrogen tetroxide, and oxygen were auto-claved together at a pressure of 50 atm.

Oleum was produced in nearly all of the factories in standard commercial sulfur-burning units while concentration of sulfuric acid was carried out in a variety of plants including pot stills, drum concentrators, or Gaillard towers. The vast experience accumulated over the years of the Second World War has been collected together in a summary volume under the auspices of the Acid Plant Design Committee (24).

The manufacture of picrite posed an extremely difficult problem in sulfuric-acid recovery for the substantial amount of spent acid produced contained only about 18% sulfuric acid. Submerged combustion was applied to this duty at ROF Bishopton and while this procedure functioned well as far as actual concentration was concerned, corrosion of the equipment by the nitrate ion present was so severe that the process could only be run intermittently and eventually had to be abandoned leaving the acid to be dealt with by neutralization with limestone followed by prolonged drainage in settling lagoons.

It now is considered that three- or four-stage vacuum concentration in a glass-lined tantalum plant is probably the best long-term solution but even here there are problems in the disposal of the ammonium sulfate which is unavoidably produced in the course of concentration.

Pot stills are inefficient owing to the high working temperature and the poor heat transfer through the pots which demand a correspondingly higher furnace temperature (900°-1000°C) with a high loss of heat by radiation and in the furnace gases.

Drum concentrators utilize direct heat from the furnace gases which pass through the acid and are consequently more efficient but suffer from the disadvantage that owing to the high acid temperature in the concentrated acid stage much acid spray is evolved which requires mist precipitators to remove and which moreover are costly to maintain.

As a postscript to this important period it is worth noting some remarks made during his address in 1965 by the eminent chemical engineer, the late Dr. A. J. V. Underwood (25). He refers to the policy pursued in 1943 by Lord McGowan, then Chairman of ICI Ltd. This policy boiled down to proposing that large organizations ideally should employ only chemist and engineer teams and, accordingly, before 1958 the ICI Billingham Division employed just ten chemical engineers. Underwood goes on to say that it is only fair to add that some years ago ICI Ltd ceased to hold this view and by 1964 the Division, after splitting into two, employed 100. To some degree this attitude and the subsequent change has been reflected in other areas including government and as will be seen later, the post-1945 years started off with a considerable thrust towards injecting more chemical engineering expertise into the government explosives industry. Although only partially achieved, it has had a small measure of success.

1946–1978: Technological Change

The final epoch, following the end of World War II, has seen rapid changes in the methods adopted in chemical industry for processing, major changes in the requirements of the Services, and above all the alteration of the Defense picture by the advent of atomic weapons.

Continuous operation with more sophisticated control has been a feature of all manufacturing processes and one can no longer deal with the complex problems in the ad hoc manner of the past. Rockets and their attendant demand for special propellants have become a significant factor in the Armed Forces while social changes have modified considerably attitudes to safety and have altered the economics of production.

As before, in 1919, the run down of production from wartime levels had to take place in 1946. There were differences however. Research departments recognized the need to emphasize manufacture and there was an appreciation of the role of chemical engineers throughout industry. At Waltham Abbey the production factory was closed but a chemical engineer, Dr. F. J. Wilkins, was made Chief Superintendent of the Chemical Research and Development Department and he made a break with the old industrial chemist–engineer system adopted by McGowan by putting together a Chemical Engineering and Engineering Service Group under a chemical engineer and by recruiting suitably qualified staff, both new graduates in chemical engineering and experienced plant chemists. There was a very real attempt to avoid the mistakes of the past and this was to bear fruit in promoting the immediate further development of the picrite work. Unfortunately the excellent start was short lived and after a few years following the appointment of more academically oriented staff some of the benefits began to fade as less attention was given to the needs of production. There were, however, areas where the new approach was sustained. A Scientific Advisory Council Committee was set up on which some of the country's leading chemical engineers were invited to serve. Professor F. H. Garner and Dr. A. J. V. Underwood were among the well-known names on the Committee. Eventually, however, after much valuable work, the Committee was disbanded because of lack of support for the chemical engineering projects with which it was concerned.

For picrite development the new approach sustained an activity which was to continue for nearly ten years. It was conceded that it was required in large quantities and several chemical routes were explored in the laboratory followed by pilot-plant design and trials. Nitrolim or crude cyanamide was retained as the starting material but new conditions were worked out to provide for higher yields based on fixed nitrogen than had been obtained previously. The pilot planting of this process to provide a 100 lb/hr continuous unit, operating virtually automatically, marked a substantial advance in plant and process design. The process

was called the British Aqueous Fusion (BAF) process and the Waltham Abbey design was scaled up and copied in several locations. A team of a few chemical engineers enabled this to be done and although other processes have been tested on pilot scale the BAF process remains a firm leader.

The crude calcium cyanamide is reacted directly at just above 120°C with concentrated ammonium nitrate to yield guanidine nitrate contaminated with soluble and insoluble impurities. The beauty of the process is the manner in which guanidine nitrate is recovered from this mixture without loss of fixed nitrogen. The product then is treated with either sulfuric acid or oleum in a special plant to form nitroguanidine. The importance of nitroguanidine has fluctuated considerably but it is certain that it now holds an important position in the propellant field as long as the potential threat of conflict remains and conventional weapons are retained to guard the peace. Nitroguanidine has taken its place alongside NG and NC to be joined but not displaced by new materials.

New technology has had its impact since 1946 on both NC and NG production and both are made now in continuous plant with a very high content of chemical engineering design although here the expertise has been derived from private industry with notable contributions from ICI Ltd and other specialist companies.

The problem with all continuously operating explosives plants, particularly those concerned with NG is that of securing and maintaining an effective detonation break between the various processing stages. Schmid solved the problem by using eductors to send the NG through connecting pipelines in the form of a water dispersion. Experience has since shown that the effectiveness of this method is dependent on the material of construction of the pipelines and on their diameter in relation to the strength of the emulsion or dispersion with adequate turbulence over sufficiently long lengths to ensure interruption of detonation, should an explosion take place in some stage of the process. Before these requirements were appreciated fully some multiple incidents occurred which otherwise might have been confined to a single plant or building.

Pursuing means of reducing the holdup of NG at the nitration stage still further, Nilssen and Brunnberg of the Nitroglycerin Aktiebolaget, Gyttopp (26) in 1952 developed a NG process in which conventional processing vessels were dispensed with altogether, a jet pump or eductor serving as the nitrator, the mixed acid being refrigerated before passing to the eductor jet (27). This process also took the bold step of applying DeLaval centrifugal separators, suitably modified, to the separation of NG from the spent acid. The holdup of such separators is of the order of 4.5 kg compared with 50 kg or so for one of the most efficient static separators of equivalent throughput.

Line-washing processes have been developed both at the government factory at Bishopton and at the Nobel's Explosive Company de-

signed to reduce the hazards attendant on the washing processes when these take place in bulk in a single building.

NC manufacture by mechanical nitration gradually became accepted, eventually overcoming the innate conservatism of the system controlling the acceptance of new ideas for manufacture, so that by 1956 a unit was installed, and in due course it was shown that the whole of the nitration of NC could be effected in continuous nitrators of the Du Pont type.

In the 1950 period there was a new area of activity which the explosives industry was called upon to take up. Rocket propulsion had come to stay and the competing merits of liquid and solid systems were to become the center of controversy. While at the time the liquid fuels like hydrazine seemed to have some advantage, the smaller nonspace rocket motor seems now to be settled in the solids field and an extensive development of solid propellants has taken place. The British (28) invented plastic propellant, a composite of ammonium perchlorate and a polyisobutene binder, while the cast propellant system was developed in the United States together with the curable rubber system.

In the United Kingdom the plastic propellant required the manufacture and recrystallization of ammonium perchlorate and while the scale was small compared with the U.S. effort in this field a substantial expertise was accumulated at Waltham Abbey. Crystallizing and milling equipment was devised to give particle-size ranges of 2 to 400 μ since this new brand of propellants showed remarkable sensitivity to particle-size variation. The United Kingdom also imported the expertise from Hercules Corporation in the United States for making the double-base charges cast in situ in a rocket motor case. This process was tried out first at Waltham Abbey under government control and when the technique had been worked out for U.K. conditions staff were sent from Imperial Metal Industries Ltd (at the time a division of ICI Ltd) to be trained in the casting process. Production was transferred then to the Summerfield Research Station and operated by IMI as an agency factory. Although there was little chemical engineering in the casting operation, the manufacture of the special casting powders utilized all of the know-how and equipment used for cordite and had to be made either at ICI Ltd Nobel Division or, if for research, at Waltham Abbey. At the latter establishment studies are still in progress to improve upon the older mixing techniques and to introduce new methods of controlling the quality of the ballistic modifiers used in these propellants. The exceptional advantages of this cast double-base propellant lie in its smokelessness and increased safety because of the unique ballistic properties. The U.K. plastic propellant does not show these benefits but it has the advantage of cheapness and ease of manufacture.

Both cast and plastic propellants find extensive application for the Services. In both cases the production of the propellants has called for a

completely new range of chemical manufacture and in most of these the unit processes of comminution and crystallization rank high in the control of the product.

The manufacturing methods for gun propellants have continued to be largely modifications of existing methods devised in the early cordite days with the attendant disadvantages of high cost and poor reproducibility. Much effort has been devoted to rocket propellant development, no doubt with the expectation of rockets displacing guns in the future although present trends seem to disprove this. One recent development in gun ammunition, probably the most interesting in the 30 years since the war, has been the combustible cartridge case, developed at Waltham Abbey and now in quantity production. The original proposals were made by G. I. Nadel (29) but R. A. Wallace, a chemical engineer at Waltham Abbey, led the way to a production process. The operation consists of felting a suitable case from a slurry of NC, kraft fiber, and synthetic rubber latex. Their manufacture has been taken up by a number of countries.

In the high-explosives field there have been some significant developments. Tetryl is produced by a continuous process. RDX manufacture has been improved marginally while a number of other nitro-bodies have been made on a pilot-plant scale.

The major changes in the United Kingdom have been in connection with the manufacture of TNT although naturally the requirement for this material in peacetime is negligibly small.

Despite the simplifications and improvements that had taken place, the Bowden and Smith plant was still fairly complicated and maintenance was heavy. The dwell time required was relatively high so that the output was lower in relation to the plant size. The main advantage was that the process did not require the use of oleum and therefore could operate on a closed cycle. The advent of the sulfuric acid cracking process in Germany during World War II however opened up the possibility of using oleum with its economic advantages while still allowing the acid cycle to be closed. With the end of the war, work on this aspect of the process was discontinued until the early 1950's when the Chemical Engineering Committee of the Scientific Advisory Council reopened the subject and Waltham Abbey demonstrated the feasibility of a three-stage countercurrent process using either 20% oleum or the concentrated oil of vitriol (COV) and offering three times the output for the same volumetric capacity.

About the same time a novel liquid-liquid or solid-liquid countercurrent contacting system was being developed by W. H. Morris (30, 31) at ROF Pembrey who proposed its use for the manufacture of TNT as one of a number of applications (including the manufacture of antibodies and other solvent-extraction applications and ion exchange).cThe equipment

consists essentially of a rectangular tank divided along its length by cross partitions to form mixer sections agitated by gate paddle stirrers alternating with an agitated transfer section and with a phase-separating section at either end.

The dispersion in the mixer sections is swept under the dividing partitions into the adjacent transfer sections. If the dispersed phase is the less dense of the two its droplets rise up through the transfer sections against the down-coming flow of continuous phase after which they pass to the next mixer section where the process is repeated. Unlike a mixer-settler the ROF contactor does not depend for its operation on the coalescence of the dispersed phase in separating compartments and in its application to the nitration stage of the TNT process nitrobody separates out only at the product end where a smaller unstirred compartment operates as a true separator.

In the remainder of the nitration vessel the nitrobody exists as a dispersion in the spent acid. This may not carry the advantage it was once thought to have, however, and recent American investigations indicate that even a 15% solution of TNT in nitrating acid can be brought to detonation. Be that as it may the ROF contactor is quite clearly a significant advance on the previous plants not only for its simplicity but for its safety, cleanliness, and ease of operation.

It is one of the particular attractions of the Morris contacting system that it is able to function with solid-liquid systems as well as with liquid-liquid systems. Advantage of this is taken in applying it also to the purification stage of the TNT process which no longer handles the TNT in the molten state as in the Holley-Mott system but granulates it and subjects the granules to countercurrent treatment with sodium sulfite solution in the cold with a useful reduction in sulfiting loss.

Acid manufacture continues to be an important activity in making propellants and explosives. Perhaps the most outstanding development in acid manufacture coming from the ROFs was a process for the continuous production of concentrated nitric acid by the action of liquid nitrogen peroxide and air on weak nitric acid under moderately elevated pressures. The process of W. H. Morris was built and run successfully on the pilot-plant scale at Pembrey and has been developed by Humphreys and Glasgow Ltd into a full-scale commercial process known as the "peroxide process" which is both simpler and less costly than the "Hoko" process and operates on a continuous basis under a pressure of only 8 atm compared with the 50 atm required by the latter. It is to be noted that the peroxide process does not impose any penalties with regard to materials of construction beyond those normally met in conventional concentrated nitric acid processes.

The process already has met its commercial test and at least one full-scale unit has been operating since 1967.

Epilogue

The story since 1890 demonstrates a steady progression towards the use of a wider variety of explosives and propellants by the Armed Forces. At the same time the chemical plant to produce them has become more complex and with the introduction of more continuous processes has called for an increasing chemical engineering content in its design. More pilot-plant work has become essential and scale-up factors have assumed greater importance especially where the size increase from pilot to full scale has been of the order of ten or even 100. More recent activities in the field of high explosives have shown the need to explore thoroughly all aspects of the plant prior to adoption for large-scale production. Tetra-nitrocyclotetramethylene tetramine (HMX) was one material examined in this way in recent years and a similar procedure has been adopted for new rocket propellant systems and their ingredients.

Not unexpectedly the industry is hard pressed in times of war to provide adequate supplies for the Services, while in peacetime it is difficult to maintain sufficient effort to keep abreast of world developments and to justify the installation of expensive manufacturing facilities. The lowest cost activity is laboratory research and any movement towards chemical engineering development entails a sharp escalation of cost and an extension of the time scale to several years. There is clearly a need to compromise between the higher cost of taking a process to pilot- or full-scale development and the unpreparedness which results from excessive economy.

The early chemical engineers—Davis, Mond, Nathan, Quinan, Cul-len, and others—enabled laboratory processes to be translated onto an industrial scale. They were selecting and designing processes, designing plants, choosing suitable materials of construction to resist highly corrosive chemicals, and overcoming the hazards and difficulties of the industrial environment. These were the functions defined by the British Institution of Chemical Engineers in 1924 as appropriate to the profession. In the early days recruits to the technology were trained chemists who developed new techniques as they established manufacturing processes. In the course of time the gap between laboratory chemistry and plant design was widened tremendously with the extensive study of unit operations and the scientific treatment of heat and mass transfer. Consequently the concepts of the 1930's when Lord McGowan of ICI Ltd encouraged the use of chemist-mechanical engineer teams now has been abandoned almost completely by industry and the need for chemical engineering specialism has been established.

In government service there is an encouraging understanding in the ROFs of the role of chemical engineering in production. As far as the research departments are concerned, at one, Waltham Abbey, the prob-

lem is to attract the number of high-grade chemical engineers required for research and development in the face of the keen competition encountered from the heavy demands of industry. Experience in guiding decisions in the explosives and propellants field can be obtained only by actually working with the materials and their hazards. It really is no solution to award contracts for design work to specialist private firms except for those parts of the plant that are of more universal use, e.g. acid concentration plants. For explosives and propellant manufacture, development, and research in plant design, chemical engineers always have been required "in house" and the need for them is even greater today than it has been ever in the past.

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