At the end of November 1914 Lord Moulton (1844–1921) became the director of explosives production in the War Office. A 70-year-old jurist may seem an extraordinary choice, but he was an extraordinary man. He was Senior Wrangler at Cambridge, was elected to the Royal Society for research on electricity, and learned about chemistry as a barrister for dye and explosives manufacturers. He assembled an able team of administrators and chemists who designed and managed mammoth new national explosives factories. They could not make enough TNT and picric acid from obtainable precursors, so Moulton persuaded the reluctant armed services to adopt mixtures of TNT and ammonium nitrate, which enabled them to make even more than was needed. In mid-1915 they moved to the new Ministry of Munitions, where they also became responsible for fertilizers and poison gases. In 1917 they produced explosives at a higher rate than was attained in World War II.

Keywords: Lord Moulton; K. B. Quinan; David Lloyd George; World War I; Chaim Weizmann

On 18 May 1911 Kaiser Wilhelm II lunched in London at 28 Queen Anne’s Gate as the guest of the Secretary of State for War, Richard Burton Haldane FRS. After the meal the Kaiser drew his host aside, indicated a tall fellow guest and asked: ‘Who is this man? You say he is a judge, but he seems to know everything.’ Haldane confirmed that Moulton was truly an exceptional judge: ‘In apprehension he had perhaps the most rapid intelligence with which I ever came in contact.’ Field Marshal Kitchener was visiting England and was one of the party; neither he nor Moulton could have had an inkling of how fate would bring them together three years later.

Moulton was the third son of a prominent cleric. After attending the Kingswood School (a Methodist Public School), in the first Oxford–Cambridge local examination he came in first. After three years at University College London he entered St John’s College, Cambridge. To do so, he accepted the tenets of the Anglican Church, despite four generations of Moultons serving as a Methodist divines. He was awarded a three-year scholarship of £50 (£10000 today) per annum. He was president of the Union and an
Apostle. In 1868 he was Senior Wrangler in the Mathematical Tripos with the highest score on record and was elected to a fellowship at Christ’s College, Cambridge. Fellows were still prohibited from marrying; maybe that is why he read law in London. He was called to the bar in 1874 and married in the following year; as was the custom on such occasions, a slice of wedding cake was tucked into his letter resigning from Christ’s.

Long hours went to the law, but he also worked with William Spottiswoode (PRS 1878–83). They did hundreds of experiments on the conduction of electricity through tubes containing different gases in Spottiswoode’s private laboratory, unsuccessfully trying to determine whether there are two forms of electricity, positive and negative, or only one. They reported their work in 155 pages of Philosophical Transactions. Moulton was elected a Fellow in 1880. (Spottiswoode died three years later.) In 1883 Moulton served on the International Commission on Electrical Units that met in Paris, and was made a Member of the Legion of Honour.

He specialized in patent law, becoming Queen’s Counsel in 1885 when he was also elected as a Liberal to Parliament. He was in and out of the Commons until 1906 when appointed Lord Justice of Appeal, six years later he became Lord of Appeal in Ordinary. He was also the first chairman of the Medical Research Council, which administered £50000 per year.

THE OUTBREAK OF THE WAR

While R. B. Haldane ran the War Office from 1906 to 1912 he reorganized the Army. Infantry battalions were integrated into divisions—each with its own artillery, engineers, and the like—and the divisions into an expeditionary force. Its bullets and shells were propelled with cordite, its shrapnel bullet canisters were ruptured with gunpowder, and its high explosive was picric acid. The chemicals were supplied by national ordnance factories at Woolwich and Waltham Abbey; any additional needed was bought from chemical companies.

When Britain went to war in August 1914, Prime Minister Asquith was temporarily heading the War Office. He delegated Haldane, now Lord Chancellor, to oversee mobilization. Kitchener was persuaded to take over the War Office, foreign terrain to him. Haldane helped him find his way. At his first Cabinet meeting Kitchener bowled his colleagues over: predicting that they would need an army of millions to fight for years. An unstated outcome was that they would require vastly more explosives than they were making. Next, Haldane was appointed to chair a Committee on the Supply of Chemical Products. The loss of German imports was crippling because the British organic chemical industry was small and soon they would exhaust their stocks of German medicines and dyestuffs. At the committee’s first meeting they co-opted Lord Justice Moulton, who had appeared in numerous dye industry litigations. He was 70 years old (figure 1). He started to prepare contracts for such needed precursors as coal tar.

The same chemicals were indispensable for the War Office, which on 16 November appointed an Advisory Committee on Explosive Services with Moulton as chair. Members included Sir Sothern Holland (a 38-year-old South African who was now His Majesty’s trade representative to South Africa), and three expert explosives chemists: Dr C. Carpenter, Mr William Macnab and W. R. E. Hodgkinson, Professor of Chemistry at the Ordnance College. Moulton learned of his new assignment while assessing dye stockpiles in the west of England. He motored through the night to chair the first meeting.
Moulton had studied explosives for one of his most celebrated cases, as lead counsel for the Nobel Explosives Company Ltd in a suit charging the British government with patent infringement for manufacturing cordite, their propulsive explosive. Nitroglycerine was the first widely used high explosive. Each of its three carbon atoms has a nitrogen attached, and each nitrogen binds three oxygens. Oxygen–nitrogen bonds break easily when a carbon gets near; the molecule is then oxidized into hot gases. Nitroglycerine is far too easily detonated, a nudge can push oxygens on one molecule too close to carbons on another—there were many horrific accidents. The Swedish chemist Alfred Nobel immobilized the molecules by absorbing them onto diatomaceous earth, so even a sharp jolt does not bring carbons and oxygens too close. Dynamite is detonated by an intense pressure wave from a conventional explosive. Then Nobel made a colloidal suspension of nitroglycerine in guncotton (nitrated cotton), so both components are high explosives. In 1888 he made a colloidal suspension of nitroglycerine, guncotton and camphor. It contains more than enough oxygen to react with all of its carbon, so it explodes without smoke. It is so safe to handle that it can be heated and rolled into sheets or forced through sieves to form threads. Because it is a poor conductor of heat it burns from outside inwards, like gunpowder. Hence heftier particles burn more slowly, for as long as 40 ms, long enough to propel a shell out of a long gun barrel. Another advantage of slow burning is that less pressure is generated in the chamber at the moment of firing. Nobel put Ballistite on the market as a propulsive explosive.
To study his offer, the British appointed a committee that included James Dewar FRS and Frederick Abel FRS, Director of the Chemical Establishment of the War Department. In confidence, Nobel told the committee exactly how he made Ballistite. The committee varied his formula by mixing 58% nitroglycerine, 37% guncotton and 5% petroleum jelly in acetone. The mix was then pressed through orifices to form threads or cords. Named cordite, it was patented secretly. Nobel lost the infringement trial, and his appeal was denied in the Lords a year later. The deciding point was that Nobel’s patent specified guncotton of ‘the well known soluble kind’, whereas cordite was made by dissolving guncotton in acetone.

By this time Moulton had attained the eminence to be man of the day in *Vanity Fair* magazine: ‘He is an exceedingly able fellow whose word on a patent is practically law: consequently his word on a patent is in great request, and for it he receives big fees .... He is the rare example of the mathematical mind triumphant.’

**SETTING TARGETS AND DIRECTIONS**

After 10 days of committee meetings, Moulton submitted a report on 27 November. It succinctly responded to their charge. How much explosive should they make? As much as they could. For a long war the ‘only safe line of action therefore is to develop the production of these explosives to the utmost in every direction until the danger of shortage is removed.’ Demand would be enormous: reports from the front estimated that during 53 hours of intense fighting the Germans had fired 840 tons of high explosives. What high explosive should they make? They had used picric acid, but if contaminated with salts it was unstable and too often during the Boer war the fuse ignited the charge rather than detonating it—when this happened it was less powerful than gunpowder. Detonation had been solved at the laboratory at Woolwich by Oswald Silberrad, who was appointed as its first director in 1901 at the age of 25 years. A small packet was inserted into the shell adjacent to the fuse; the packet contained a series of booster explosives known as a gaine that set up a powerful pressure wave to reliably detonate the high explosive in the shell. Then Silberrad looked for a better high explosive. He backed the use of TNT (trinitrotoluene), which was stable enough to be accelerated out of a gun barrel safely and was reliably detonated by a gaine. It was also safer and cheaper. Silberrad was sacked in 1906 after a dispute over his compensation. His proposal inched through the bureaucratic maze for a decade; finally, in the summer of 1914, TNT was designated to replace picric acid.

Moulton recommended in a memorandum that they continue to make as much picric acid as possible. Production could not be expanded because it was received wisdom that picric acid must be made in specialized earthenware vessels, crafted only in Germany. (This problem was soon solved by Silberrad, by that time a successful industrial chemist, who made a sizable batch of picric acid at his home laboratory in a wrought iron container.) Picric acid was made from phenol; not enough was available to expand production markedly.

They would be able to make more TNT; huge new factories would have to be built to manufacture it. It was synthesized from toluene with the use of expensive oleum (fuming sulphuric acid). Most toluene came from coal tar. The War Office should immediately requisition all toluene production not taken by existing contracts. But even all available precursors would not make sufficient picric acid and TNT, so they must find alternatives.
On the day of Moulton’s memorandum, Parliament passed the Defence of the Realm Consolidation Act, which empowered the government to seize any factory or its output. A clause inserted at the last moment commandeered the entire output of coal tar for explosives. Coal heated in the absence of oxygen produced coke, illuminating gas (a mixture of hydrogen and gaseous hydrocarbons) and coal tar, from which toluene was distilled. More miners could not be hired during an all-out war, so Moulton could calculate how much toluene would come from coal. In the short term they could also get toluene, which was a contaminant in substantial existing stockpiles of commercial benzene. It should be distilled off. Moulton’s concise memorandum covered much ground.

On the following day the War Office nationalized a distilling plant at Rainham to purify toluene for making TNT. Obviously Moulton thought that he could run the plant better—this was impressive self-assurance for an aged judge.

The committee submitted its report on 30 November, proposing that an executive should run explosives production. On the same day, Moulton, Holland and an accountant moved into the top floor of the Institution of Mechanical Engineers’ headquarters in Storey’s Gate. Soon they were joined by Holland’s close friend H. Ross Skinner, a 47-year-old former mining engineer in South Africa, where vast quantities of explosives were (and still are) used in mining.

The new legislation and the deep pockets of the Treasury gave them much authority, which they were ready to use. On 26 December, Kitchener established section A6 of the War Office for explosives supply, commanded by Brigadier-General W. C. Savile, with Moulton as director-general and Holland as his deputy. Eventually several dozen other talented administrators and lawyers were recruited. By the end of 1914, A6 was inspecting all explosive plants for quality and safety. Moulton and Kitchener worked well together. Both liked to make decisions face to face and had little time for verbal fencing or paper trails. Kitchener’s disdain for paper made life tricky for his War Office staff, who described his methods as chaotic; they were nevertheless assembling a large volunteer army.

There were few chemical engineers in Britain, so on 19 December a cable was sent to South Africa addressed to Kenneth B. Quinan. An American who had been taught on the job by his uncle, he was chief engineer at the de Beers mining company. They had come to South Africa in 1910 to erect the world’s largest explosives factory; the nephew took charge when uncle died. On the day he received the cable, Quinan left on the packet that sailed at 16:30. De Beers hired him out for £4000 a year. The 27-year-old chemist arrived in London in early 1915, his youth masked by a resplendent beard. Conan Doyle described one of his outstanding attributes: he had ‘the drive of a steam piston’. Soon four more chemists arrived from South Africa.

Ten new TNT contracts were signed in early 1915, so now there were 13 private producers. Chance & Hunt Ltd were contracted to erect and manage a huge TNT factory at Oldbury (west of Birmingham), paid for by the state. Quinan designed it meticulously. He started planning each workshop with a ledger of chemical inputs and outputs, displaying every step in his calculations. Next he determined the heat produced or absorbed and the needs for water, electrics, compressed air, and the like. Blueprints for buildings and diagrams of reaction vessels were annotated with elucidations. Ambitious Quinan aimed at making the Explosives Department a ‘great educational institution’. After the war William Macnab published some of Quinan’s notebooks as textbooks for training chemical engineers.
Construction at Oldbury began on 8 January 1915. Danger buildings were flimsy wooden sheds enclosed in earthen dykes. Storage buildings were brick with double iron doors—one million bricks were laid in 19 days. The plant went online in 100 days. Then it was nationalized and managed by Quinan, who was also designing the next plant. The British chemical industry had so little experience in making TNT that Moulton bet that well-managed national plants would be more productive and give taxpayers better value. They also disclosed the true costs of manufacturing, putting A6 in a strong position when negotiating contracts with private suppliers.

Quinan managed as well as he designed. With easy affability and willingness to listen he did not ruffle feathers. Everyone addressed him as KBQ. The doors of his plants were open to contractors interested in his inventive methods. At his monthly meeting with plant managers his criticisms were ‘enlivened by unique powers of linguistic extravagance’. 22

They needed more toluene. Petroleum from Borneo contains 10% toluene; some was extracted in Rotterdam by the Asiatic Petroleum Company. Moulton purchased their plant in January 1915 and moved it to Oldbury, where it produced 8000 tons yearly, equal to the total British prewar toluene production. When gas companies distilled coal, some toluene had been allowed to go over with the gas because it enhanced the light emitted by burning; by law the gas had had to yield a minimum candle power. This proviso was outdated by wartime because radiation was augmented by gas mantles. The law was modified and the gas companies installed scrubbers to retrieve toluene.

A pilot plant at Woolwich started producing TNT on 17 January 1915 by a new process developed by R. C. Farmer that did not require oleum. MNT (mononitrotoluene) was nitrated to TNT in 96% sulphuric acid by carefully controlling the temperature with steam and cold water coils around the reaction vessel. This reaction ran four times faster than the oleum method. The nitric acid remaining in the waste was used to make more MNT. 23

AMATOL

Moulton’s second memorandum (his last major memorandum during the war) was issued on 28 February 1915, based on more realistic estimates of military needs. 24 They wanted 5730 tons of high explosive per week. A6 could make 750 tons of picric acid per week and 1650 tons of TNT per week. Three hundred and fifty tons of the TNT had to be purified by crystallization for the Navy and for Army operations in warm climates where raw TNT was unstable. Crystallization was done by experienced workers at Woolwich—trying and dangerous work. This left only 1300 tons for other users—well short of need. More could be bought abroad, but it was expensive. Moulton decided that the shortfall must be filled with ammonium nitrate. This was too hygroscopic to be used by itself. However, tests at Woolwich proved that TNT–ammonium nitrate combinations were not hygroscopic, exploded more violently than TNT, and could be made with unpurified TNT. Combinations were already used by the Austrians, Germans and Russians. Kitchener backed him strongly, authorizing Moulton ‘to produce every form and kind of explosive that could be made in England.’ 25

Moulton’s scheme was stoutly contested by both Services, who were unwilling to endanger their men with inadequately tested novelties. Moulton did persuade the Trench Warfare Department to accept ammonal (65% ammonium nitrate, 15% TNT, 17% powdered aluminium, 3% charcoal) for grenades and mortar bombs. Moulton kept
pressing his case, strengthened by additional test results from the respected Woolwich laboratory. At last, in April 1915, the Ordnance Board authorized the use of 45% unrefined TNT and 55% ammonium nitrate. However, when produced on an industrial scale the ‘porridge’ was too stiff to pour into shells. They shifted to 40% ammonium nitrate and 60% TNT—known as amatol. If Moulton had not prevailed, the British would never have made sufficient high explosives. In November 1915 they began to fill smaller shells, such as the 18-pounder for the field guns, with amatol mixed in a bread-making plant. The intense shock wave from the gaine was enhanced by pressing the amatol into solid blocks or by compressing it into the shells during filling. By this time they were producing more amatol than there were shells to fill; the excess was stored coated with paraffin wax.

**PROPULSIVE EXPLOSIVES**

Preparing cordite gives an idea of what munition workers do. They start with two treacherous ingredients. Twenty-five pounds of dried, cooled guncotton is weighed into an India rubber bag. The required volume of nitroglycerine is added gingerly, usually with a metered hand pump. The concoction is poured onto a table and warily kneaded by hand until well mixed; the mixture is less tetchy. It is pushed through a sieve, acetone is added and it is mixed mechanically for seven hours at 40 °C; halfway through mineral jelly is added. Finally the brownish-yellow mixture is pressed through a die with a diameter suitable for its intended use and reeled onto drums, which are dried at 40 °C for days or months, depending on cord diameter. The dried cords have the consistency of horn and the colour of black liquorice sticks. Before the war, cordite was manufactured at the Royal Gunpowder Factory and by six contracted firms. Their output was shared between the Army and Navy. Far more was needed. Acetone was so expensive that the Woolwich laboratory was developing a variant, RDB cordite, in which the solvent was 45% diethyl ether in alcohol.

In early 1915 Winston Churchill, in his capacity as First Lord of the Admiralty, erected a new naval cordite factory. To supply the needed guncotton, Moulton offered to build them a factory on a derelict industrial site he had leased at Queen’s Ferry, near Chester. They shook hands on it, but when Moulton next met with the Admiralty in May, Churchill had been driven off in disgrace. Sir Fredric Nathan, a former artillery officer who had designed and managed one of Nobel’s plants, was now the Admiralty’s advisor on cordite supplies. Moulton began to report on the construction. Nathan cut him off: the plant was unnecessary; private companies would supply all needed guncotton. Work on Moulton’s new plant was well under way and he was sceptical about relying on private companies: contractors were better at promising than delivering. It is likely that the discussion was getting heated when by chance Kitchener walked into the conference room. He heard the issue and straight away accepted the new plant for the Army. Any excess would be welcomed by their allies. Moulton did not want to relive such an imbroglio; a few weeks later A6 was put in charge of cordite for both Services.

A6’s next major project was a huge national RDB cordite works. On a weekend scout, Moulton found near Gretna an isolated seven-mile stretch of wasteland extending from Scotland into England, far enough west to be beyond the range of aerial bombardment. Quinan did the planning. Cooling would take six million gallons of water per day. It was pumped from the river Esk into a 33-inch pipe 5.5 miles long. On the site they also
built plants for making sulphuric and nitric acids and distilling glycerol for nitroglycerine. Eventually more than 20,000 workers were trained by mentors from the Nobel Company. Unforeseen snags delayed production, so A6 filled the gap by propelling non-incendiary bullets and heavy howitzer shells with nitrocellulose powder from the USA. This was a bonanza for the Americans: between 1914 and 1915 the net earnings of the Du Pont Company increased tenfold.

LLOYD GEORGE AND THE MINISTRY OF MUNITIONS

On 15 June 1915, A6 was transferred to the new Ministry of Munitions led by David Lloyd George, where it became the Explosives Supply Department (ESD) with Moulton as director-general, Holland as his deputy and General Savile as military adviser. Moulton negotiated the merger judiciously: ESD retained their own financial and contracting offices and controlled their railway transport. With an office staff of roughly 400 they directed the prewar national plants and laboratories at Woolwich and Waltham Abbey, the new national factories, and contracts with private manufacturers. Moulton was the only Ministry of Munitions director not handpicked by Lloyd George. They did not always see eye to eye. In his memoirs Lloyd George wrote of Moulton: ‘As usually happens his subtlety caused distrust and misunderstanding amongst blunter minds.’ As will become evident, Lloyd George’s was one of the blunter; perhaps this is why in the autumn of 1915 he had Nathan transferred from the Admiralty to ESD to take charge of propellant supplies, replacing Moulton’s man. Despite their earlier run-in, Moulton and Nathan worked together smoothly. By the end of the war ESD ran 32 factories.

Lloyd George also established what he called national factories, but they were not owned or managed by government. The metalworking industry had a firm base, so ongoing firms were contracted to build and manage new plants. Construction and start-up costs were from the public purse while output was purchased at a guaranteed price. By the beginning of 1916 there were 73 of these factories, by war’s end there were 218.

CHEMISTS

The British government had not planned to mobilize scientists for the war, so many sat impatiently on the sidelines for many months. Moulton involved them from the start, and eventually ESD had about 250. Some of them came from the Empire. At each plant, chemists ensured the quality of precursors and products. Before they were all in place, some routine tests were done in university laboratories organized by the Royal Society and in the laboratory at Woolwich. A. C. G. Egerton (FRS 1926), who had been the chemistry instructor at Woolwich, joined Moulton’s staff. Chemists in the new plants also did some research. Moulton also recruited for special projects; for instance, he asked the chair of Colour Chemistry and Dyeing at the University of Leeds, Arthur George Green FRS, to find a pathway for making phenol from benzene. Explosives paid for a laboratory assistant and supplies. Green started his synthesis with chlorodinitrobenzene, which brought the price down from £500 to £67 per ton, saving £3 million a year and expanding picric acid production.

Enough nitrate was available from Chile and Norway, but the pathways for making the ammonium salt needed to be upgraded. The major producer was Brunner Mond & Co.
Their chief chemist, Francis Arthur Freeth (FRS 1925), aged 30 years, had been mobilized with the Territorial Army. In March 1915 Major Freeth was ordered home from France. He refused to leave until threatened with arrest, and always preferred the title ‘Major’ to ‘Doctor’ or ‘Professor’. The synthesis could be done in three ways. Freeth used his knowledge of chemical equilibria to determine the conditions in which each worked most efficiently. At an uncertain juncture while his methods were still in the works, Moulton, with his footman and chauffeur, arrived after an all-night drive in his elderly chain-driven Daimler. He took Freeth ‘by the arm and said, “My dear Freeth do you realize the safety of England depends on this?” to which the laughing reply was, “In that case, Sir, I’ll tell you the truth, I’m certain that these processes will all work”—and they did.’ (At least it is a great story.) A tricky feature of ammonium nitrate is that it exists in five polymorphic forms, one of which is best for filling into shells. Thomas Martin Lowry FRS, then Professor of Chemistry at Guy’s Hospital Medical School, determined the transition temperatures between the states and the velocities of the transitions, so they could make it in the most favourable state.

Moulton’s dinner parties were hosted by his daughter-in-law; he had been widowed twice. One evening he entertained Silberrad and several young artillery officers home on leave who vividly described how firing emitted a giant sheet of flame; the flash made them easy to spot. Silberrad undertook to make flashless, smokeless cordite. The formula he came up with was not adopted, on the grounds that it did not work in two high-velocity guns, though it did well with all other British pieces. At the end of the war the Germans were using propellant that had been made flashless by lowering the temperature of the explosion by the addition of nitroguanidine, the same molecule that Silberrad had used.

Chaim Weizmann was the British chemist made most famous by the war; he was widely credited with saving Britain by producing acetone for making cordite. In his memoirs Lloyd George extolled him as the great scientist of the war, whose justified reward was the Balfour Declaration. In July 1915 Weizmann and his friend, mentor and informal scientific and political agent C. P. Scott, the editor of the Manchester Guardian, lunched with Lloyd George, who previously had met Weizmann as an advocate of Zionism. Now he learned that Weizmann, a lecturer in chemistry at Manchester, had discovered a bacterium that fermented maize into acetone and butyl alcohol. He was trying to scale up production, with support provided by Nathan in the Admiralty. Lloyd George was exhilarated by his new protégé and dreamt of oceans of acetone, which was on the world market but expensive. Moulton was ordered to provide additional money for development. Weizmann wanted to go to France and Switzerland to recruit scientists. ESD thought they already had adequate brainpower and suspected that Weizmann’s real business abroad was personal; his passport remained locked in Moulton’s safe. Scott protested bitterly to Lloyd George, who discussed Moulton’s ‘incompetence, vanity, and obstructiveness’. Lloyd George forced the issue. He boasted to Weizmann and Scott that he had ticked off Moulton, Nathan and Quinan for high-handed disobedience and told them that he would gladly accept their resignations—a dubious yarn. Weizmann did not recruit any scientists on his trip.

Weizmann’s fermentation produced cheaper acetone, largely in the New World because maize took up far more cargo space than acetone. Phasing in RDB cordite reduced the need for acetone. By 1917 Weizmann was working within the Foreign Office to obtain Palestine for the British by modifying the secret Sykes–Picot treaty signed the year previously. The Balfour Declaration guaranteed access to Jews and the British obtained...
Palestine. Scott negotiated with the Chancellor of the Exchequer for royalties for acetone that made Weizmann rich.

EXPLOSIVES WORKERS

Chemists were, of course, a tiny fraction of Moulton’s workforce. Workers were hired while a new plant was being constructed. Limitations on working hours were suspended for the duration: for instance, women were now permitted to work more than 60 hours per week and on Sundays. They earned high wages: an experienced hand could make £3 per week by working an eight-hour shift every day; this was close to the pay of a lieutenant of infantry. There were no holidays; free time meant forgoing wages. High wages brought needed hands but outraged some well-off onlookers, who feared that the characters of young workers, especially females, would be blighted for life by easy money, while others were upset because men served in the ranks at the front for far less. Most of the new workers had to move closer to the remote plants, so living quarters, dining halls, churches, recreational facilities and the like were built nearby.

Each plant required a medical officer to screen job applicants and then monitor their health. Some of the chemicals were toxic. For instance, incautious exposure during TNT manufacture caused jaundice—the sufferers were dubbed ‘canaries’. In 1916 there were 181 cases and 52 deaths. On the recommendation of the Royal Society, Dr F. Shufflebotham, a specialist in industrial diseases from the Potteries (Stoke-on-Trent), was made responsible for medical care at all ESD factories in February 1917.

Instructors for the new hands were borrowed from existing national factories or temporarily hired from companies such as Nobel. Some experienced men were brought in from the Empire. The instructors instilled the care, caution and cleanliness needed for handling explosives safely. No bit of metal, match or cigarette was allowed to pass through the plant guards. Women were prohibited from wearing a corset under their working gear for fear that a dislodged button might trigger a devastating explosion. At the end of each shift everything was meticulously cleaned. There was a consistent rise in the number of women working in munitions: in summer 1916 there were 400000, by the end of the war there were more than 1000000.

Drunken and hung-over explosive workers were dangerous and unproductive. ESD nationalized the pubs around Gretna. Landlords became civil servants charged with preventing overconsumption. Customers were not allowed to drink both beer and spirits during a visit or to buy drinks for their friends. (These restrictions remained in force until the 1970s.) However, many of the workers who mixed RDB cordite left their shifts reeling from ether and alcohol fumes.

Moulton also worked all-out. On weekdays he was at work at 09:00, trotting up the stairs to his top floor office after glaring at anyone standing in the lobby waiting for the lift. When petrol rationing began, he came to work by underground to save his coupons for weekends, when he was off by motor car to scout for sites for new facilities, to inspect their plants, and to talk face to face with managers and workers, using the thoughtful, interested demeanour that worked so well with witnesses in the courtroom. There was a plethora of problems; he delighted in telling about one solved by the workers. The men wanted to avoid white feathers thrust at them on the streets by wearing badges showing that they were doing essential war work. The War Office repeatedly refused. Finally at one plant Moulton was offered an
unanswerable case: the male workers would put down their tools to march to the recruitment office to enlist as a body. The War Office issued badges.

PRODUCTION

ESD’s success is illustrated by the tonnage of explosive produced per month during 1916 (figure 2a). TNT and ammonium nitrate output increased manyfold, and picric acid output more than doubled (figure 2b). By year’s end, storehouses were overflowing because they had made more explosive than there were shells or mines to be filled. General Savile was responsible for storing the excess. RDB used 1.4 times more glycerol than ordinary cordite, so Moulton took over all of the British soap boilers. Fats are esters in which three long-chain fatty acids are attached to the short glycerol framework; the glycerol is liberated by boiling with alkali. ESD also produced 9000 tons of glycerol per year from whale oil. To obtain needed solvents, the Ministry of Munitions took over all of the distilleries, producing more industrial alcohol and less spirits.

In early 1917 ESD became responsible for producing fertilizer, which also required acids and nitrates.

Light sleepers in London were awakened by an earth tremor early on 7 June 1917. Its source was the largest man-made explosion to date: 447 tons of ammonal simultaneously detonated in 22 mines under the German field fortifications on the Messines Ridge. Allied infantry rounded up or drove off the dazed survivors. By that time ammonal production was being phased out because aluminium was needed for aircraft. Nonetheless, 401 tons had been made in December 1916, so the colossal explosion consumed little more than a month’s output of a single high explosive.

In the last two years of the war, ESD waged ‘a continuous struggle against the stringency of economic conditions’ and the squeeze on transatlantic cargo space. British gold was swapped for sulphur pyrites from Spain, nitrates from Chile, and explosives from the USA and Canada. ESD imported less high explosive but continued to import propellant, which required far less shipping tonnage than precursors. To save money they made less
picric acid. In 1917 they produced TNT at 47% of the cost of the year before, and at 40% of the cost of imported TNT. Used sulphuric acid was regenerated by removing the water added during the synthetic reactions. The solvents released from drying cordite were collected assiduously: acetone lost while producing 100 tons of cordite was reduced from 33 to 23 tons. The entry of the USA into the war saved Britain from bankruptcy.

THE FINAL YEAR

The major problems in explosive production had been surmounted: at the end of 1917 the British were producing explosives at a faster rate than they ever did in World War II (figure 3). So much explosive was stockpiled waiting for shells that production was cut back and some workers were made redundant. Holland became the Controller of Cultivation in the Food Production Department, where now his administrative talents were needed more. Less explosive was made in 1918 than in 1917. High explosives for which precursors were on hand were made in Britain (figure 3a), but much propellant was imported to save precious cargo space, as explained above (figure 3b).

In April 1918 ESD was made responsible for supplying poisonous gases. Their irrational but predictable reaction was disgust: somehow explosives were clean, but gases were dirty. They were ordered to raise weekly production from 350 to 795 tons, producing the extra in parts of explosive plants no longer in use. Winston Churchill was now Minister of Munitions; for 1919 he demanded at least 200 tons of mustard gas, which the Germans had introduced in July 1917. British chemists had deciphered its structure within days, but synthesis was challenging. An experimental production plant at Avonmouth went into operation on 15 June 1918, using a synthetic pathway devised by William Jackson Pope FRS, Professor of Chemistry at Cambridge. Yield was poor and the product was contaminated. They turned to a pathway developed by A. G. Green for the private Levinson works. It worked, and from 12 September until the Armistice they turned out more than 500 tons.
ESD wanted to slash their outlay for nitrates, which was soaring as a result of strikes in Chile, by fixing atmospheric nitrogen, as Germany had done since 1914. Following Fritz Haber they produced ammonia in the laboratory at high temperatures and pressures and with a metal catalyst. Doing so on an industrial scale was quite a different matter. Quinan struggled and failed.\textsuperscript{60} Carl Bosch received a Nobel prize in 1931 for designing the German plants.

Holland was created Baronet in 1918.\textsuperscript{61} Quinan was awarded a CH (Companion of Honour); the order had been created in 1917. With his reputation he must have turned down many offers in Britain. He returned to South Africa to start a fertilizer company, which failed in the 1920s. He became a successful fruit grower, specializing in grapes.\textsuperscript{62} His approach to engineering was instilled by Macnab at University College London and by Egerton, who when he became chair of Chemical Technology at Imperial College established an undergraduate degree programme in Chemical Engineering.

At war’s end Moulton had no swords to convert, but could make leftover cordite into fertilizer.\textsuperscript{63} He had been made a KCB (Knight Commander of the Bath) in 1915 and GBE (Knight Grand Cross of the Most Excellent Order of the British Empire) in 1917. The government feared that all too soon the Germans would again dominate the dye industry, so Moulton was asked to consolidate the British organic chemical plants into a cartel on the German model and to build new facilities to meet the needs of the Empire. He also feared resurgent Germans, but would only serve for one year because he loved the law and after serving two more years on the bench he would qualify for a pension of £3200 a year.\textsuperscript{64} In 1920 he delivered the Rede Lecture at Cambridge on ‘Science and the War’.\textsuperscript{65} He described how the scientific advances of earlier decades fashioned the novel horrors of the war and how research during the war had met unforeseen problems. He died in 1921. He was not a man for boasting but did like to recall that ‘they never kept a shell waiting.’

R. B. Haldane provided a perfect summation:

I choose my words carefully when I say that I greatly doubt whether it would have been possible for the war to have been brought to a successful conclusion when it was, but for the part Lord Moulton took in it. I hope the country will not soon forget the extraordinary work of this most remarkable man .\ldots\textsuperscript{66}

\textbf{Acknowledgement}

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\textbf{Notes}

Only a crude estimate can be given for how the value of a currency changes over the years. A 200-fold decrease between 1914 and today gives a rough idea. W. Van der Kloot, World War I fact book (Amberley, Stroud, 2010).


J. Junior, ‘Man of the day. Mr John Fletcher Moulton’, Vanity Fair (4 October), 237 (1900).


Parliamentary Papers LG/D/10/1/14.
Lord Moulton produces explosives

29 Routledge, op. cit. (note 17).
30 Public Record Office, op. cit. (note 32).
33 Parliamentary Papers LG/D/10/1/12.
34 Lloyd George, op. cit. (note 32), p. 343.
35 MacLeod, op. cit. (note 20).
36 MacLeod, op. cit. (note 18).
42 Wilson, op. cit. (note 41).
45 C. Richardson, Connie’s war: a young girl’s life in the munitions factory at Gretna in the Great War of 1914–18 as told in letters to her family with additions by her daughter Ann Kerry (David R. Neal, Gwynedd, 2005).
46 D. Lloyd George, op. cit. (note 32), p. 353.
47 MacLeod, op. cit. (note 20).
50 S. I. Levy, Modern explosives (Sir Isaac Pitman & Sons, London, 1920). The Germans needed all of their fats for eating, so they made little soap and were desperate for glycerol. They were saved by Karl Neuberger’s discovery that glycerol is produced when yeast ferments sugar in the presence of sodium sulphite. The Germans set up 53 factories that produced 1000 tons per month. R. Furness, The fermentation industries (Ernest Benn, London, 1924).
51 Public Record Office MUN 5/192/1502/1.
52 Ministry of Munitions, op. cit. (note 14), p. 77.
54 Ministry of Munitions, op. cit. (note 14).
57 Total British production of high explosives in 1914–18 had only 24.4 times the power of the atomic bomb dropped on Hiroshima.
61 ‘Sir Sothern Holland’, *The Times* (15 September), 6 (1948).
63 Parliamentary Papers LG/F/2/6/10. A letter from A. H. Stanley at the Board of Trade to the Prime Minister.
66 From Moulton, *op. cit.* (note 2).