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Mistakes Might Only be Made Once: Canada's Supply, Inspection, and Conservation of Munitions in the First World War

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Résumé de l'article

Le Canada a été un important producteur de munitions pour le front occidental pendant la Première Guerre mondiale. Il fournit environ un tiers des obus produits dans l'Empire britannique, passe des contrats avec des centaines d'entreprises et l'industrie a été le premier employeur du pays. Alors que la demande de munitions s'intensifiait, des experts en finance, en industrie, en science et en technologie ont cherché des solutions nationales pour répondre aux besoins croissants du pays en matière d'approvisionnement en munitions. Les investissements qui en résultent permettent de subventionner les commandes de guerre dans le domaine du forgeage et de l'usinage et de créer les composants nécessaires pour assurer un approvisionnement durable en armements sur le front. Ce faisant, ils ont également créé les premières industries chimiques du Canada.

Mistakes Might Only be Made Once: Canada's Supply, Inspection, and Conservation of Munitions in the First World War

Kyle Pritchard

Abstract: *Canada was a significant producer of munitions for the Western Front during the First World War. It supplied roughly a third of the shells produced in the British Empire, contracted hundreds of businesses, and the industry was the country's largest employer. As the demand for munitions intensified, experts in finance, industry, and science and technology searched for domestic solutions to the country's growing munitions supply needs. The resulting investment subsidized war orders in forging and machining and sparked the components necessary to sustain a lasting supply of armaments to the front. In doing so, they also created Canada's first chemical industries.*

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Keywords: First World War, Canada, Imperial Munitions Board, Munitions, Chemical Industry

On the evening of 14 October 1918, citizens in Trenton, Ontario were stunned by bright flashes in the sky. A powerful series of audible shockwaves damaged buildings, cracked chimneys, and littered the streets with broken glass. The blasts occurred at the British Chemical Company and could be heard as far away as Belleville, about five miles to the east (Fig. 1). Built three years before, the grounds were a model village, covering 255 acres with sparsely-packed chemical plants, office and electrical buildings, medical and leisure facilities, a post office, and a guardhouse (Fig. 2). The 3,000 employees who worked at the site included operators, inspectors, chemists, and government officials, and the boarding houses usually held 550 workers. Upon hearing of the fire and rushing to Trenton that night, Edward Fitzgerald, Auditor for the Imperial Munitions Board (IMB), remarked that he had been "advised by one of the train hands that our entire works in Trenton had been destroyed; large numbers had been killed and injured; the whole town was on fire; that even the Canadian Pacific Railway station more than a mile distant was destroyed."[1]

Rumours about the explosion were greatly exaggerated. While the plant's magazines could store up to 800,000 pounds of explosive powder, they only held about 200,000 pounds at the time of the blasts.[2] The facility, which usually operated twenty-four hours

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Figure 1. *Explosion and Fire at Trenton (with photos), 1918-1919, Vol. 42, File 4, MG30-A16, Library and Archives Canada (LAC).*

per day, was closed for the Thanksgiving holiday weekend. Only seven of the operators were working and the boarding houses were mostly empty. Over 400 patients diagnosed with influenza were resting in the main hospital, but like the boarding houses, these were located on the far side of the grounds and separated from the chemical plants. A report conducted by the IMB's Explosives Department on-scene foreman indicated that one of the TNT nitrators began acting unusual before bursting into flames. The nitrous fumes created volatile explosive salts on contact with the surrounding metal surfaces. Some of the workers attempted to extinguish the fire. The foreman activated the plant's siren before travelling first to the TNT office, where he could not get an outside connection, and then to the administration building to contact the Explosives Department and the local police service. On his way back, he met up with one of the site's chemists, the general manager, and the captain of the military guard. That is when the explosions started, the first of the bright flashes began, and fragments of steel and burning timber scattered into the sky.

A chain reaction had ignited several barrels of TNT inside the plant. Most of the workers had evacuated the area. The yardmaster Joe Berry coupled two boxcars of TNT and drove them to safety. The medical officer George Murray departed the site's hospital after he heard the siren, and with three other men, distributed some axes among them and severed the trestle line leading to the acid plant before the fire could spread. With the haunting memory of the Halifax Explosion only ten months earlier in December

Figure 2. *General view of Guncotton Lines, British Chemical Co. Ltd., Trenton, Ontario. Department of Militia and Defence supplementary photograph collections, Item 67, Page 21, Library and Archives Canada (LAC).*

1917, Trenton residents were ordered to evacuate their homes as explosions continued through the night. The IMB's Chairman Sir Joseph Flavelle described how the townspeople "took to the roads, some travelling as far as Brighton, some to Pembroke, some out in the country among the farms, some fell by the wayside exhausted and were later picked up by automobiles and carriages sent from the town. I believe the state of panic was almost indescribable." Eight members of staff received the Order of the British Empire for continuing at their post during the incident, including the first Canadian woman to receive the honour, Switchboard Operator Eva Curtis.[3]

During the First World War, Canada supplied between a quarter and a third of all British shells, about half of its chemical propellants, and about a fifth of its explosives. It produced 41.7 million pounds of TNT, 28.5 million pounds of cordite, and more than 41 million pounds of other chemical explosives as part of the wartime demand for munitions overseas.[4] But as in the case of the survivors of the 1918 Trenton Explosion, the handling of volatile chemical compounds sometimes came with serious consequences. The risk factors associated with the production of wartime chemicals represented a clear and present danger to Canadians that required a high degree of instruction and precision. The Ordnance Advisor of the IMB, David Carnegie, later described explosives production as having "hardly an operation which was not attended by distinct hazards; mistakes might only be made once in most of them."[5]

While the rapid expansion of munitions, arms, and chemical industries have been described in the literature as highly disruptive to the Canadian economy, it also demonstrates the highly adaptive response of the organizations connected to British munitions supply to urgently respond to the crisis caused by munitions and chemical supply shortages.[6] Yet when war began in 1914, neither the Central Powers nor the Entente had such a system in place. It had to be elaborated and developed over time. The Shell Crisis which emerged in the summer of 1915 sparked significant conflict within the political establishment of western governments. At the Battle of Neuve-Chapelle in March 1915, British forces had expended more shells than throughout the entirety of the Boer War, prompting a reorganization of the British war administration. Most public criticism targeted Secretary of War Lord Herbert Kitchener, who, while predicting a long-term engagement in Europe, had failed to recognize the significance of the effects of artillery bombardments on the battlefield. Over the summer of 1915, authority over munitions supply was removed from the War Office and Lord Kitchener and given to British politician and future prime minister, David Lloyd George of the newly established Ministry of Munitions.

Following the Shell Crisis in 1915, the IMB was instrumental in developing an approach that allowed for coordination and collaboration across industry. IMB also established dialogue that blurred the lines between military and academic science, especially as universities adjusted to aiding the war effort. The investment of British war orders subsidized and modernized Canada's first chemical industries, with each sector developing its own laboratory science to acclimate to international standards. The demand for experts with training in inspection, chemistry, and metallurgy, encouraged and provided opportunities for women in scientific fields to find employment in the munitions and chemical industries. Proceeding the demobilization of the military economy, chemical plants transitioned back to civilian production, and repurposed wartime chemicals for commercial use.

The first section examines the hurdles Canada's munitions boards faced to safely supply munitions and explosives to the Western front. The second section focuses on the creation of national plants in metals and chemical production necessary to meet the demands of munitions manufacturers. The third section assesses the munitions and chemical industries' fostering of scientific consultancy and inspection practices to improve the quality of shells, and the fourth section examines how the proper management and conservation of war materiel came to be an important component of managing munitions supply as the war progressed. This article argues that, despite a long period of disarmament following the war, the British munitions program in Canada, consisting first of the Shell Committee until late 1915, and after of the IMB until war's end, established the precedent of a centralized, managerial framework for military-industrial relations adopted on similar lines in subsequent conflicts throughout the century.

Canada's Munitions Industry: An Overview

The Canadian military and industrial establishments experienced a significant period of interdependence during the First World War. Arms, explosives, and equipment production served to benefit the expansion of capital-intensive Canadian industries to fulfill the procurement requirements of the British and Canadian military. Yet, at the outset of war, Canada had only the slightest experience with munitions manufacturing and primarily relied on experts, machinery, and resources from Britain, the United States, and elsewhere. Pivotal to the expansion of munitions production were the networks created by the government that brought together political organizers like Sir Sam Hughes and businessmen like Sir Joseph Flavelle, experts in munitions and chemistry like David Carnegie and Howard Murray, and academic scientists like James Watson Bain and John Bates of the University of Toronto, and Richard Durley of McGill University.[7] The creation of these networks were significant contributors to the effective scaling of munitions production, and their points of correspondence are elaborated upon later in this study. As the war's demand for munitions intensified, experts in finance, industry, and science and technology searched for domestic solutions to the country's munitions supply challenges under the impetus of controlling the government's escalating war debt. Escalating demand and the imperative for cost-cutting were key drivers of Canadian munitions and chemical research development, building bridges with academic science to establish plant laboratories and expand the capability of synthesizing chemicals for the war effort. This article suggests that the munitions' boards expansion of control over the munitions and chemical industries during the First World War led to advances in public and private investment in resources and technologies for essential wartime industries needed for large-scale arms production to provide higher quality munitions to the front. This effort of industrial expansion, in turn, laid the groundwork for health and safety routines in hazardous work environments in Canadian war industries in an effort reduce the probability of defective supplies to the front and accidental explosions at home.

Munitions officials kept meticulous records of resource consumption, scientific adaption, and armament exports both during and after the war. The Joseph Wesley Flavelle fonds and the records of the 1916 Royal Commission on the Shell Scandal at Library Archives Canada (LAC) represent the formal repository of munitions records and account for most of the archival material on Canada's First World War munitions industry.[8] The papers contain minutes and correspondence among munitions officials, politicians, scientists, and manufacturers. Correspondence with private and national contractors include war orders, production schedules, and inspection and welfare reports. They also contain financial information about industrial companies that detail expenditures on equipment and annual reports, import and exportation figures, and restrictions on essential munitions materials. The extensive range of information provided by these records allows for an intimate examination of the munition boards, science, and industry.

The abundance of government records captures a remarkable composition of Canadian industry's contribution to the war effort and the robustness of private scientific and manufacturing research prior to the organization of government research under the National Research Council (NRC).[9] Created in 1916, the reach of the NRC's programs developed slowly during the war years. The NRC offered $70,000 in research scholarships through an Assisted Research Scheme to military and industrial research projects, of which only $10,000 was actually released during the war, and an attempt to create a National Research Institute to connect scientific research departments did not pass in the Canadian Senate until 1930.[10] In contrast to the NRC, the investments of British organizations in Canadian munitions contributed to an enormous pool of scientific and industrial initiatives throughout the war. Correspondence between Flavelle, University of Toronto president Sir Robert Falconer, and James Watson Bain of University of Toronto's Chemical Engineering Department suggests that the NRC originated in part from the idea of replicating the munitions sector's successes within civilian industrial settings. On the surface, however, no official history of munitions production appears to have been published outside of what is documented in the *History of the Ministry of Munitions*, published by the Ministry of Munitions across twelve volumes in 1922.[11]

Yet, records maintained by the IMB and held at LAC reveal an official historian was commissioned. The IMB selected notable Canadian poet William Wilfred Campbell in 1917 to write the official history of the munitions production and its influence on Canadian manufacturing and the war. Campbell's research included documenting the actions of the Shell Committee and IMB, conducting interviews, and collecting wartime samples, blueprints, and photographs of industry. Campbell was inspired to offer insight into "knowledge of the conditions as they have existed since 1914 and [how] such knowledge applied to newer conditions at a time when future emergencies bring about the need."[12]

Unfortunately, Campbell died of pneumonia in January 1918, having completed his research but only writing three chapters of an unfinished manuscript. His findings were left unpublished. In an isolated project that also began in the final years of the war, the IMB's Director of Explosives, Howard Murray, investigated the scientific advances of the chemical industry under the Department of Explosives and their contributions to the war effort. "The Munitionment of the Canadian Forces for the Purposes of Defence" was produced in four volumes and completed in 1921, but only a handful of copies were ever distributed, with one specifically reserved for Sir Arthur Currie.[13]

No extensive text was widely available on Canada's industrial involvement in the war until 1925, when the IMB's Ordnance Advisor David Carnegie published his seminal book, *The History of Munition Supply in Canada*. Carnegie's authorial study has become somewhat of an 'unofficial' history of Canada's industrial mobilization during the First World War, covering an extensive array of topics, from manufacturing and finance to the political and industrial ramifications of war production. The topic of chemical production was revisited by C.J.S. Warrington and R.V.V. Nicholls in *A History of Chemistry in Canada* (1949), offering the most detailed account of the chemical industry up until that period, including the achievements of Canadian scientists and manufacturers in chemical synthesis, production and innovation.[14] Warrington and Nicholls also describe the emergence of specific chemical industries which came into being during the first half of the 20th century, and which later came to establish the backbone of industries which amalgamated in the interwar period.

As the century progressed, the study of Canada's war industries attracted writers from a range of fields. With the progression of Canadian social history in the 1970s, the study of munitions expanded to include perspectives from business, military, labour, and gender history.[15] This social lens also influenced the history of science to explore the social and intellectual history of scientists and technology.[16] Yet there is still a dearth of research on how chemical production impacted the war and how it was experienced by Canadians employed in the chemical industry and what impacts this had on traditional roles between different genders within industry. This is especially apparent regarding questions of the war's impact on industrial safety with the increased handling of explosive materials. The same cannot be said for the international literature, where the study of the military and scientific importance of chemical and munitions production around quality and safety has been highlighted and studied. However, even this is mostly a recent trend.[17]

Mechanical Difficulties: Early Developments in the Canadian Munitions Industry

Canada became a significant source of munitions for the Western Front. Between 1914 and 1918, Canada supplied roughly a third of all shells produced in the British Empire, and by war's end, over six hundred businesses were under war contracts and the industry became the country's largest employer. The First World War was Canada's first foray into industrialized warfare, yet its munitions orders were directed by branches of the British War Office and, after 1915, by the Ministry of Munitions. While there was plenty of popular support for industrial mobilization, at the war's onset, most of the investment in war materiel manufactured in Canada came from abroad, at first from Britain, and then later to some extent from the United States. As Canada lacked some of the essential scientific and manufacturing knowledge required to produce armaments on a large-scale, wartime weapons research and production was largely adaptive, focusing on learning, experimenting, and adjusting existing technologies. Yet in the first two years of the conflict, due to poor management decisions by munitions officials, as well as unexpectedly low war orders for arms and equipment from the British War Office, munitions and its subsidiary industries struggled to get off the ground.

Canada's civilian industries were woefully unprepared for war. Nations were still reeling from an international recession which occurred in the year prior, and while manufacturers maintained their industrial output, demand for products dropped by up to twenty per cent. The financial difficulties meant that manufacturers in metals, chemicals, and other sectors, which came to form the basis of war-related industries during the war, were stripped of the necessary funds to transition from civilian to war production without securing an influx of capital.[18]

The economic conditions leading into the war placed added strain on the relationship between munitions officials and manufacturers looking to secure war orders in Canada. Minister of Defence Sam Hughes was contacted in August 1914 to coordinate British munition contracts in Canada through the British War Office. Later that month, he formed the Shell Committee from seven metal manufacturers from across Central and Eastern Canada, and David Carnegie, an armaments expert trained at Woolwich Arsenal in Britain, was recruited as its Ordnance Advisor. Alexander Bertram of John Bertram & Sons Co. in Dundas, Ontario was made chair, and the first order was entirely divided between just four of the committee's members. Other Canadian businesses began receiving contracts following an order for 200,000 shell bodies in October, and throughout the following year, a much larger order for 5 million shells, along with minor components like shrapnel, sockets, plugs, steel discs and base plates, began the first large application cycle for Canadian war orders.[19]

However, domestic industries in the resource and machining sectors were not productive enough to meet all the necessary tool and materiel quotas required in the initial stages of the conflict to complete their contractual obligations by their order dates. In addition, competitive pricing from the United States meant that reliance on the importation of these essentials was imperative to transition civilian industries at the pace outlined in British war contracts. A reliance on trade with the United States began early with the need for machines and equipment. Over the course of four years, Canada imported $156 million, in metals from its southern neighbour to sustain its industries. In the forging sector alone, there was an increase from two to twenty-six plants during the war, requiring 162 forging presses to be imported from the United States.[20] The delays that accompanied the unexpected difficulty in acquiring important manufacturing products, and which included the need retrain workforces to use these products efficiently in the workplace, led to difficulties for contractors to meet obligations.

Other complications that caused delays occurred closer to home. The Shell Committee quickly developed a reputation of unreliability among manufacturers, who petitioned the committee to diversify their distribution of contracts across a wider array of industries to sustain their industrial output. Characterized by laissez-faire, private initiatives, contracts were vaguely written, lacked legal professionalism and oversight, and consistently needed clarification months after being drawn up. As manufacturers crept beyond the contractual obligations outlined in their orders, it became increasingly clear that the Shell Committee had no measures to penalize manufacturers if they failed to meet their contractual obligations. The situation created significant delays throughout the latter half of 1915, especially in the fuse industry, whose manufacture was complicated and required expert knowledge, precision machinery, substantial capital, and a large workforce to sustainably turn a profit. By the Battle of Loos in September 1915, there were still around 25 million empty shell bodies lying useless on Canadian factory floors.[21]

Circumstances became so dire that the Ministry of Munitions dispatched two representatives, politician David Thomas and businessman Lionel Hitchens, to Canada in November 1915, while also suspending further munitions orders until a solution could be found. After their report, presented to Prime Minister Robert Borden in November 1915, the members of the Shell Committee were asked to resign. Stressing the importance of business expertise and managerial oversight, Hitchens approached the industrialist Joseph Flavelle to chair the newly formed Imperial Munitions Board. Alexander Bertram and David Carnegie were retained for their wide experience, and Hughes continued as an honourary president, though he ultimately held no genuine influence over the munition board's decisions.[22]

By the time Canada's munitions program was transferred to the IMB the following month, 138 companies had been contracted with war orders. Yet only 4.1 million shells had been produced out of the 22 million orders placed with the Shell Committee through the War Office, meaning less than a fifth of shell orders had been fulfilled.

Collectively, the Shell Committee's order fulfillments accounted for only six percent of the shells and explosives Canada's total volume through the war period.

To rectify the issues Canadian manufacturers encountered while acquiring raw materials and equipment, the IMB created subsidiary departments for labour, production, purchasing, transportation, insurance, and construction "the establishment of great national plants." Seven plants were established in total, each as its own privately-owned limited liability company, to resolve issues of scarcity in Canada's supply chains so that war industries were less reliant on importation, and especially from the United States.[23] Two of these were related to metal manufacture, three were related to explosives, one produced acetone, and a final company acquired later in the war attempted to develop aeroplanes. The first under construction was the British Munitions Company, completed in Verdun, Quebec in July 1916. Hiring over three thousand women as operators, the plant was built to fulfill the urgent need to complete empty shells.

Meanwhile, Hughes found himself embroiled in a series of scandals, first as minister of defence in the War Purchasing Scandal in 1915, and then his part as a member of the Shell Committee in the Shell Scandal in 1916. The War Purchasing Commission, formed in May 1915, was responsible to the Privy Council and granted the power to oversee all Canadian war purchases, expedite contracts and impose price controls, which only further restricted his involvement in industrial policy.[24]

A Chemical Romance: The Supply of Propellants and High Explosives

The Imperial Munitions Board's overhaul of munitions policy in 1916 prioritized a more rigorous, managerial approach to industrial oversight, with an emphasis on simplifying and expanding production, standardizing the testing of chemicals used as shell propellants and explosives, and increasing the inspection procedures shells and explosives were put through to reduce defect rate. The board contracted industries in every province except Prince Edward Island, expanded its inspection department to more than four thousand examiners, and through the Munitions Resource Commission, established in November 1915, took responsibility for the supply and distribution of scarce raw material.[25] The supply issues outlined by the Ministry of Munitions prompted the IMB to establish three national plants in chemical production. Along with the contracts issued to small-scale private manufacturers, the British Chemical Co. in Trenton, the British Cordite Co. in Nobel, and the British Explosives Ltd in Renfrew, all located in Ontario, were built to mirror similar national project in Britain, such as Woolwich Arsenal and H.M. Factory, Gretna.

Early orders for Canadian-produced chemicals for war purposes were infrequent and relied on a handful of small-scale, private manufacturers. As Director Howard Murray of the Explosives Department describes the situation in chemical production at the beginning of the war: "Canada had no means of obtaining nitric acid except by the importation of Chilian nitrate. All pyrites being mined was already utilized. Sulphur must be imported from Louisiana; cotton from the Southern states; alcohol from the corn belt; oleum from New Jersey; toluol from various steel plants; while all machinery devoted solely to the processes involved must likewise be imported."[26] At that time, Germany was a major international supplier of important explosive chemicals, and the country's withdrawal from trade with enemy combatants was a critical threat to the materials needed for Entente war production.

In contrast to the national plants, production from Canadian Explosives Ltd had been grandfathered in from the time of the Shell Committee. Formed through the merging of seven chemical companies in 1910, most with experience producing black powder, the new company was jointly owned by DuPont in the United States and Nobel's Explosives in Scotland. The merger consolidated their holdings by purchasing over 5000 acres of land near Ambo, Ontario, renaming the village Nobel in 1912 in tribute to the inventor of dynamite, Alfred Nobel.[27]

Canadian Explosives Ltd was the only producer of explosives in Canada when the war broke out, which had been supplying the Dominion Arsenal with reserves of rifle cordite from their plant in Beloeil, Quebec. Before the IMB's formation in July 1915, Canadian Explosives Ltd opened their plant in Nobel, located near the British Cordite Co., to coordinate the large-scale production of cordite. Following the IMB's takeover of the munitions program, there was a concerted effort to cut back on the scale of private chemical companies by terminating relations after their orders had been fulfilled, or by allowing them to continue as suppliers of base reactants like toluol or oleum. By September 1917, all contracts for nitrocellulose and cordite with private chemical manufacturers had been terminated in place of the Crown-leased national plants, with a few private companies supplying some of the raw materials needed to synthesize explosive chemicals, and except for Canadian Explosives Ltd in Nobel, the same was true for TNT.

The IMB's expansion into domestic industries to support the supply of munitions came at significant cost to the Canadian government. Throughout the conflict, Canada's ability to support its financial commitments hung by a thread. Starting in June 1916, the federal government agreed to cover the cost of British war orders placed with Canadian manufacturers through the IMB. Over the course of the year, costs doubled from $25 million to $50 million per month. Minister of Finance Sir Thomas White instituted the Business Profits Tax, and war profits above twenty-five per cent were subject to seventy-five per cent duty. However, munitions were purchased in bulk, meaning the tax was too low to apply to anything but the largest of orders. Income tax was then introduced the following year to help compensate for the government's deficit.[28] The upfront costs of war orders were first funded through a series of credits and loans with major Canadian banks, government advances, and at times were only afforded by emergency payments from the Canadian Patriotic Fund, the Canadian Pacific Railroad, and the Treasury. By war's end, the total cost of munitions orders placed in Canada was more than $1.3 billion.[29]

The IMB's investment in its national plants was costly, totalling $17 million, and yet the facilities managed to come close to recovering their initial construction costs by the end of the war. The plants sought to fill the gaps in necessary materials that had failed to be developed in great enough sums by private industries. This was especially so as access to traditional markets for bespoke metallurgical and chemical substances from belligerent nations was no longer available. By doing so, Canada's war industries became less reliant on the importation of expensive resources from overseas and were more readily able to meet the demand for completed shells on the frontlines.

An Absolute Science: Inspection, Consultancy, and Conservation

The expansion of Canada's war industries through the establishment of the Imperial Munitions Board's national plants assisted in resolving shortage issues that private manufacturers were experiencing in producing shell components and importing the base chemicals needed to produce propellants and explosives. However, the strain that these initiatives placed on Canada's national debt and natural resource industries led to further reorganization of how war materiel was tested and conserved, demonstrating the industry demands to consolidate resources, cut costs, reduce defect rates, and conserve war materiel as the conflict escalated. In so doing, the IMB centralized its inspection initiatives, created stronger ties between war industries and academic consultants, and recycled the scrap material produced by munitions and explosives plants into the forging and chemical industries.

Canadian shells were far from flawless, especially in their formative years of production, but even as manufacturers began to improve, defect rates continued to hamper the capacity to meet order requirement. For one private fuse manufacturer, roughly a third of shell fuses in their first two orders were defective, with the War Office reporting that the company's fuses were being thrown out "by the bucket full."[30] In the first half of the war, the Shell Committee relied exclusively on a private firm in Montreal called Canadian Inspection and Testing Laboratories for the testing quality of metals like steel, zinc, lead, and copper. The small quantities of chemicals being produced by private industries, like nitrocellulose and toluol, were being tested at Dominion Arsenal in Quebec City. The Shell Committee further contributed to inspection procedures by erecting a large munitions proofing butts costing $87 million in Little River, Quebec in 1914. Rather than having inspectors on site, manufacturers were expected to submit samples for ballistic and chemical testing. The station was expanded throughout the later years of the war to include an inspection room, a detachment office, and a storage facility capable of holding some 25,000 pounds of explosive material.[31] The single most frequent request from manufacturers in correspondence with the Shell Committee was the need for precise gauges for measuring shell components to meet the exacting standards required. In many cases, the shells' casings had been improperly sealed due to small, yet imprecise, fluctuations in the machining of the shell's various components.[32]

Following the creation of the IMB's Department of Inspection, Gordon Ogilvie of the Department of Defence was brought on as chief inspector and Richard Durley, a former professor of mechanical engineering from McGill University, became inspector of gauges. The department soon acquired gauges manufactured in the United States, and by October 1916, the Ministry of Munitions sent the Assistant Deputy Director General of Inspection William Edwards to Canada to become director of the Inspection Department, where he was tasked with establishing an examiners' training school in Ottawa which helped send officials to Britain for instruction. The following year, twenty businesses were manufacturing gauges for inspection in Canada.[33]

In the decade prior to the war, some private manufacturers had steadily begun to approach university laboratories for industrial research and scientific testing, but an increasing number of men and women entered academic and industrial chemistry to support the war effort.[34] The demand for inspection and consultancy of domestic war material came to rely heavily on academic scientists at Canadian universities. One of Canada's foremost academic chemists, professor James Watson Bain, amended his title from applied chemistry to chemical engineering at the University of Toronto, and developed a post-graduate course which "combines with a knowledge of chemistry the constructive skill of the engineer," emulating similar departmental changes taken at the Michigan Institute of Technology.[35] To encourage graduates' career trajectories in chemical engineering, the fourth year of U of T's bachelors program was cut for any graduate who decided to join the IMB as a chemical consultant, along with graduates who had chosen to enlist. Writing in *Canadian Chemical Journal* later in the war, Bain criticized how "the chemist in the past has been too content to shut himself up in his laboratory, instead of organizing the industries which his own talent can create."[36] As the war progressed, Bain continued to encourage academic scientists to enter industry, articulating the particularly important role of industrial chemists in the war effort.

The drive to increase Canada's capacity to produce chemicals coincided with some significant shifts in the demographic make-up of academic institutions which were refocusing their scientific departments to support the country's industrial capacity. With so many men enlisted overseas, the need for industrial testing in metallurgy, machining, and chemicals furthered opportunities for early-career women scientists to work in positions previously available to men. Bessie Cook and Marion Grimshaw, two graduates of McMaster University, began their careers as chemists at Canadian Explosives Ltd in Nobel in 1915, before being hired at British Chemical Co. in Trenton, and continued at the American Cyanide Co. in Niagara Falls after the war (Fig. 3). U of T's 1917 Senate report surveyed the occupational ambitions of graduates, showing for men unable to enlist, munitions work represented their preferred method of completing national service. Around 600 women, almost half of the graduating class in the Faculty of Arts, selected munitions as their first career choice. Graduates from these programs were hired as consulting chemists working in on-site laboratories installed at the national chemical plants at Nobel, Renfrew, and Trenton to perform in-house testing of explosives. In that same year, two-thirds of the chemists employed at the Algoma Steel Co. laboratory were women who had graduated from chemical programs.[37] As labour shortages created by wartime enlistment deepened, the employment of increasing numbers of women in chemical industries influenced the expansion and diversification of academic departments, as institutions recognized the untapped potential within their student body. The wartime emphasis on applied science and industrial collaboration laid the groundwork for enduring connections between academia and industry, ensuring that the chemical field continued to benefit from a diverse and skilled talent pool.

A retrospective January 1918 editorial published in *Canadian Chemical Journal* on Queen's University's chemical laboratories, which had recently been expanded with a grant from the Ontario government to include facilities and equipment for industrial chemical testing, highlighted that in the early years of the war, munitions and chemical industries had not taken full advantage of the potential to collaborate with academic institutions that had metallurgical and chemical departments capable of testing and inspecting the quality of war materiel. As the editorial described:

> The exigencies of the Great War have awakened us rudely to the fact that Canada is very backward in this respect. But manufacturers, now that they see the point, are acting with

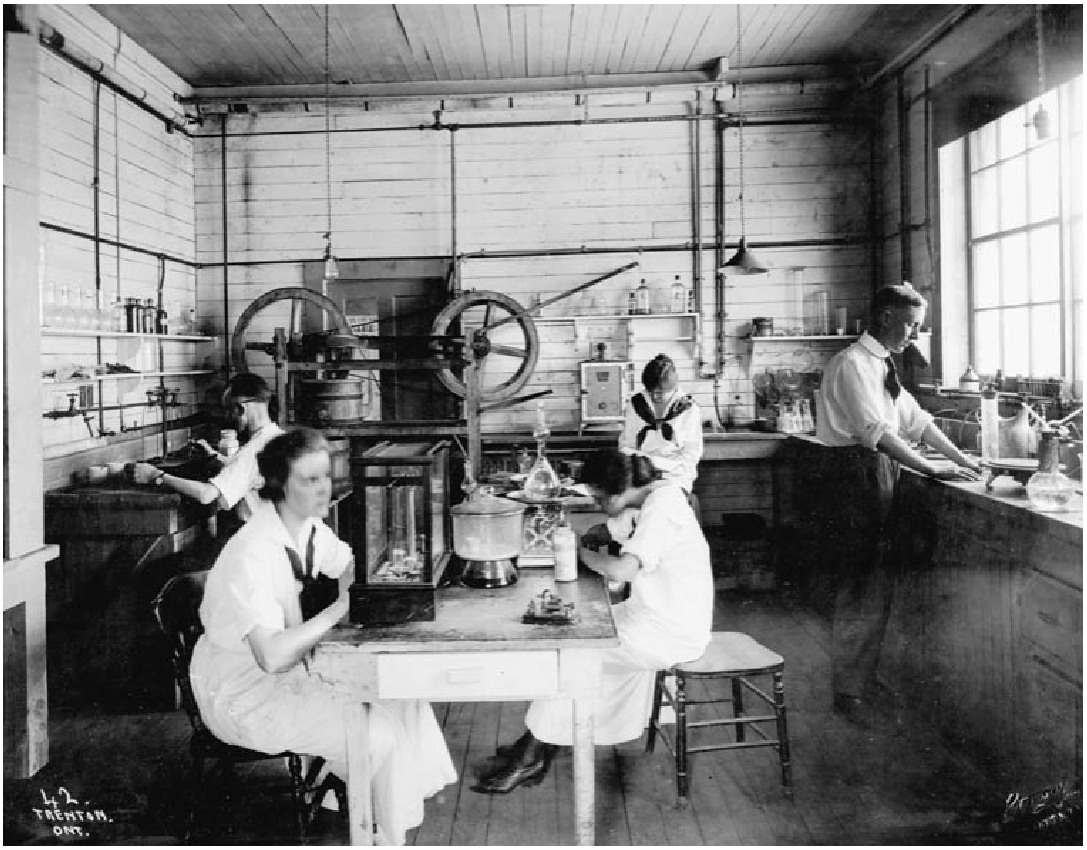

Figure 3. *General Service Unit - Research Room in Main Laboratory, British Chemical Co. Ltd., Trenton, Ontario, Department of Militia and Defence supplementary photograph collections, Vol. 67, Page 61, Library and Archives Canada (LAC).*

> characteristic energy. There is such a demand for young chemists, for any chemists at all, that it is impossible to meet it. Students who have not yet finished their course can easily secure good positions. 'Women chemists not objected to' is a significant quotation from a letter recently received from a large Canadian manufacturing company.

The editorial also emphasized the importance of facilities like those developed at Queen's University had in preparing chemists for testing and inspection positions in essential war industries, writing that "as most, if not all, manufacturers require[ed] the services of chemists to make products for war purposes or essential in some way in the prosecution of the war, it is quite obvious that the chemistry departments of the university should be considered as Military Training Depots, quite as necessary as those in which men are prepared for military service at the front."[38]

With its establishment in late 1915, the IMB significantly overhauled Canadian munitions and chemical industries. One way this overhaul occurred was through the collaboration with scientific experts in post-secondary institutions. This collaborative network between munitions officials and academic scientists sought to further the advancement of early-career researchers into munitions and chemical industries and provide the services of university laboratories. Additionally, the submission of scientific research through the establishment of the IMB's inventions department contributed to the board's body of experimental designs while reassuring the wartime anxieties of a concerned Canadian public. The academic push into industrial research positions led to improvements in the inspection standards of shells, propellants, and explosives to the front. As these scientific experts began to enter industries, they identified significant shortfalls in the munitions and chemical sector. In collaboration with the IMB, these experts further explored the impacts of chemical synthesis on more easily produce substances to produce complex explosives like TNT and nitroglycerine. This novel experimentation in chemical compounds worked in tandem with the reuse and conservation of war materiel to ease supply issues and reduce the financial cost of the war.

We Now Know Our Troubles are Over: Industrial Synthesis, Conservation and Recovery Schemes

As supply from the national plants and effective inspection procedures became more routine, munitions output scaled-up to meet the requirements of Canadian and British forces on the front. This increased output drove a movement to conserve war materiel, which was motivated by the fear that raw materials might become scarce, or that the cost of war might become unsustainable. The movement was in part influenced by Germany's success in industrializing the process of nitrogen fixation. Nitric acid was an essential chemical in the production of wartime propellants, such as cordite. Scientists had developed an awareness of nitrogen in the atmosphere and several attempts had been made at fixating nitrogen from the air into nitrogen-based chemical. The German chemist and father of chemical warfare, Fritz Haber, was the first to develop a chemical process which resulted in successfully fixating nitrogen from the atmosphere into a nitrogen-based chemical on an economic scale. Haber synthesized ammonia in his laboratory in 1909, which was an essential precursor for the manufacture of nitric acid. The Haber process was then replicated in a factory setting by the chemist Carl Bosch at the Baden Aniline and Soda Factory in 1913. The saltpetre industry had been monopolized by British companies in the previous century, taking ownership of the reserves in Chile and India as well as the sizable reserves found in Scandinavia. Once the war began, Germany's limited set of alliances created significant importation restrictions for nitrogen-based chemicals. By enabling the production of synthetic ammonia, which could then be used to manufacture nitric acid on an industrial scale, Haber's process resolved the primary issue of war supply as it began to surface in the German explosives industry as the war progressed.[39]

In the years prior to the war, Britain, Canada, and the United States had relied on importations of Chilean saltpetre, or sodium nitrate, to produce nitric acid. While Germany's creeping nitrogen crisis was eventually overcome in 1916, it created an additional impetus for developing domestic solutions to resource security. For Entente nations, the impact of submarine warfare on Atlantic shipping lanes resulted in substantial delays in the transportation of raw materials needed for chemical and munitions manufacture. The Shell Crisis which emerged in 1915 due to a failure to procure essential war materiel like explosives, propellants, and fuses led the newly formed Ministry of Munitions in Britain and the Imperial Munitions Board in Canada to go to great lengths to secure stable supply chains for these resources. In addition, fears of resource scarcity in the west spurred on initiatives for the conservation and recovery of war materiel. In the metals industry, this came in the form of salvaging defective shell casings and scrap metal turnings by melting them down into ingots and blanks to be forged again at a future date. In the explosives industry, the substitution of important chemicals like acetone, glycerine, and their alternatives used in the production of TNT and cordite, enabled chemists within Canadian industries to preserve the supply of crucial war materiel needed in the manufacture of explosives. In both the metal and chemical industries, these conservation and recovery schemes acted to relieve some of the country's reliance on international trade.[40]

The demand for acetone was in many ways the British and Canadian equivalent of Germany's nitrogen problem. As Germany was the main supplier of acetone before the war, the Entente faced significant shortages when the conflict began. Acetone was typically made through the distillation of hardwoods, which proved ineffective at an industrial scale needed for the war effort. Initially, Canadian manufacturers had relied on imported acetone ordered by the Shell Committee from the Standard Chemical Co. in the United States, with the IMB continuing this legacy by placing an order for 700,000 pounds in June 1916. An alternative solution was discovered by Canadian chemist John Bates. A recent doctorate graduate from Colombia University, Bates found employment at the Canadian government's Forest Products Laboratories, a branch of the Department of the Interior, established in Montreal in 1913. With the assistance of some pre-war German chemistry textbooks, Bates and a few of his fellow graduates synthesized acetone from fermented calcium carbide. While the largest repositories of natural calcium carbide in the world were in Germany, the Shawinigan Water and Power Co. in Quebec had been producing calcium carbide since Canadian inventor Thomas Leopold Wilson developed an industrial process to manufacture carbide in 1901. Under the umbrella of the Canadian Electro Products Company, the group collaborated with Shawinigan Water and Power Co. to begin the production of acetone domestically beginning in the latter half of 1916.[41]

A breakthrough in the expansion of the British and Canadian supply of war materiel came with the discovery of the Weizmann process to produce acetone. Chaim Weizmann, a former chemist and bacteriologist with the Synthetic Products Co. in Britain, had been working on a process of bacterial fermentation for producing acetone from starch, patenting his success in March 1915 after several years of experimental fermentation. As supplies of acetone used in propellant production began to deplete, the Ministry of Munitions established an acetone plant at the Royal Naval Cordite Factory at Holton Heath in Dorset in early 1916. The process made acetone significantly more cost-effective to produce on an industrial scale.[42]

The chemist Horace Speakman of the Ministry of Munitions was hired under the IMB as the head of bacteriological department at British Acetones Ltd in Toronto just as the Weizmann process was gaining traction as a solution to chemical shortages. In May 1916, Speakman transported bacterial cultures used in the Weizmann process from Britain to the plant. Previously operating as the Gooderham and Worts distillery, which had been producing whisky since 1832, the newly formed British Acetone was offered to the IMB by Colonel Albert Gooderham for the British and Canadian war efforts. The work was performed in collaboration with faculty at the University of Toronto, where a "finely equipped laboratory for the purpose of conducting investigations in the process

Figure 4. *Distillation Routine Laboratory, British Acetones Toronto Limited, Department of Militia and Defence supplementary photograph collections, Vol. 68, No. 150, Library and Archives Canada (LAC).*

of fermentation" had been installed (Fig. 4). As Speakman later describes, "It was only by going back to the earlier, more successful work in the laboratory, carried out under properly controlled conditions, that sound principles were formulated to guide the work in Toronto." The IMB invested a further $1 million into refitting the plant with equipment capable of using the Weizmann process to convert grain into acetone.[43] By the following year, British Acetone had produced almost the entire quantity of acetone across the Entente nations. The dramatic uptake in this synthetic solvent resolved further issues with the British and Canadian supply for explosives manufacture, which had been affected by the disruption of the Entente's trade networks.

Like acetone, glycerine was an important base chemical in the manufacture of explosives. Used in an early chemical process in the production of cordite, Canadian dependence on glycerine imports from the United States and the limited capacity it faced in its own industries led Noble Pirrie of the IMB's Explosives Department to seek out alternative sources. In July 1917, Pirrie, who also acted as a consulting chemist for the Ministry of Munitions, left for the Commercial Research Co. in New York to report on experiments performed with propylene glycol as an alternative to glycerine in propellent production. He returned with American manufacturers to the British Chemical Co. in Trenton, and the following month an agreement was made along with the Hercules

Powder Co. of Delaware to open a US branch plant in Canada. The chemical was cheaper to produce, available domestically, and although the process proved to have its own share of problems and was more chemically unstable, it provided an alternative to the industry's steadily depleting reserves of glycerine.[44]

The War Trade Board of the United States also played a role in compelling Canadian manufactures to conserve war materiel more efficiently by refusing to renew export licenses to Canadian manufacturers without recovery facilities. As part of the effort to increase the supply of domestic alcohol to produce acetone, vegetable oil to produce glycerine, and other household chemical substitutes needed to manufacture explosives, Canada became almost wholly reliant on animal fats, corn, and other grains from the United States.[45] By the latter half of the war, acid recovery systems were installed at all chemical plants across Canada as part of a larger industrial effort to conserve and recycle resources.

The introduction of resource conservation and recovery schemes brought about a significant turning point in munitions and chemical production. Following a 40 per cent cut in Canadian munitions orders by the Ministry of Munitions to $30 million per month in July 1917, these schemes produced a substantial excess of chemicals which could instead be used for export. Within a year of the Shell Scandal, these schemes had cut the cost of TNT in half, making it cheaper to produce wartime chemicals in Britain than Canada. As demand lessened in Britain for supplies of chemicals from Canada, the country continued to fulfil the shortfall in the manufacturing of British propellant, covering half of its total output in the summer of 1916.[46] As a result, the IMB's Explosives Department had produced 3.7 million pounds of excess cordite at the national plants in Trenton, Nobel, and Renfrew which were projected to stay in storage had the British Chemical Co. not negotiated contracts with the Italian Government later that December to redirect explosives originally meant for Britain.[47] The plants had thus not only corrected many of the shortfalls in production, but in fact could now export these compounds to supply British allies.

The IMB's rectification of early war policies regarding munitions orders in the areas of supply, inspection, and conservation had a significant impact on the capability to scale production and the overall output of war material. In the chemical industry, this resulted in large surpluses during the latter half of the conflict. By early 1918, storage facilities in Trenton, Nobel, and Renfrew were reaching capacity. Specifically at Nobel, the British Cordite Co. held around 3 million pounds of cordite, had filled its warehouses, and was now beginning to store materiel outside. In May, the IMB commissioned another munitions warehouse in Longue Point, Quebec, adding to the already established storage facilities in Dorval, L'Assomption, Flavelle siding and Upton's Pit on the coast of the St. Lawrence River. The sites were ideal for allowing vessels to dock opposite the warehouses so war materiel could be loaded directly onto the ship. Once the sites were erected, 3,365 train cars of explosives passed through Montreal within a seven-month period, allowing the facilities to relieve capacity issues at plants which were now outproducing their storage requirements.[48]

Some advancements in chemical conservation occurred too late in the conflict to have a significant impact on the war effort. By 1918, the IMB's three national chemical plants in Renfrew, Trenton, and Nobel were relying on 2.5 million pounds of alcohol per month to meet their scheduled output of propellants and explosives. That February, Borden wrote to the IMB advocating for maximizing alcohol production in Canada for the purpose of manufacturing explosives. This action exerted lobbying pressure on the decision to implement prohibition in the subsequent months.[49] In response, the British Acetones Ltd spent $600,000 on the testing of methyl ethyl ketone experiments to produce butanone, an alternative solvent to acetone with more concentrated properties. The new process, first developed in Britain, produced alcohol as a byproduct, which could be reutilized in other parts of the chemical industry. Yet the shift in production only began months before the war ended. As such, these byproducts had little benefit to manufacturers in the post-war environment of civilian production.

The global backlash against war profiteering and push for demilitarization caused extensive changes to Canada's defence industrial base. In the interwar period, munitions manufacturing virtually disappeared. Canada's subsidization of contracts for munitions production accounted for over half of all war debt. The munitions sector was by and large responsible for limitations on the government's ability to respond to periods of post-war financial downturn. The decline of the wartime boom in explosives caused most munitions manufacturers to vacate the industry and return to pre-war operations. Canada's chemical producers converted manufacture to civilian purposes, repurposing leftover wartime materiel for lacquers, paints, varnishes, agricultural fertilizers, and pyroxylin plastics.[50] Other industries entered the lumbering and construction markets, selling explosives for hollowing out rock and clearing forests. The Explosives Act, passed in 1914 but not promulgated into Canadian law until 1920, established government licensing and restrictions on explosive manufacture, formally placing the industry under government supervision.[51]

Conclusion

The Canadian munitions industry of the First World War was aggressively expanded in 1916 and quickly dismantled in the years following the Armistice. Despite the industry's shortcomings, wartime advances in production methods, expertise, and technologies in associated industries carried forward important ramifications for Canadian politics and the national economy. The transformation of Canada's munitions program from a small committee relaying military contracts to a centralized, managerial body operating large-scale limited liability companies was critical to the country's industrial mobilization efforts. This article has examined how in the process of accelerating manufacturing output, the mandate of the munitions program in Canada expanded to involve adapting civilian industries to military production, assisting with scientific consultation, and managing the supply and conservation of war materiel. Further, as high levels of enlistment removed men from the workforce, women in chemistry labs and on factory floors were better positioned to advance into careers in the munitions and chemical industries. The supply issues in the munitions sector also highlighted the importance of safety reform in high-risk industries which had grown by orders of magnitude during the war years.

Established first through the Shell Committee in August 1914, before being replaced by the IMB in December 1915, Canada's munitions organizations corresponded with significant political, industrial, and scientific figures, describing in rich details the needs of munitions supply on a national scale. The collaboration between various sectors served an important role in facilitating the supply, inspection, and conservation of war materiel. Focusing on the domestic munitions and chemical industries in particular, advances in public and private investment in wartime technologies laid the groundwork for the essential industries needed for large-scale arms production to provide higher quality munitions to the front. While outside the scope of this article, munitions as an area of study could benefit from inquiry into the political, industrial, and scientific connections formed in the First World War. Some significant directions for further query include exploring the pivotal position that the supply of materiel played in coordinating wartime industrial decision-making, the implications of munitions investments on scientific research initiatives, the demand for women in science fields to work in industrial settings, and the importance occupational safety had on the conditions of workplaces in the years following the war.

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Endnotes

1 Howard Murray, Director, Explosives Dept., Imperial Munitions Board, 1917-1921, Vol. 17, File 175, and Explosion and Fire at Trenton (with photos), 1918-1919; Vol. 42, File 4, MG30-A16, Library and Archives Canada (LAC); and Leroy Westman, ed. *Canadian Chemical Journal* 3, no. 6 (Toronto: Canadian Institute of Chemistry, June 1919): 187

2 Construction of warehouse below Montréal for temporary storage of explosives. Cost of handling tonnage at storage warehouses in Montréal District, 1917-1918. Vol. 12, File 118, MG30-A16, LAC.

3 Explosion and Fire at Trenton (with photos), 1918-1919. Vol. 17, File 175, MG30-A16, LAC; and United States, *Industrial Process Profiles for Environmental Use: The Explosives Industry* (Cincinnati: Environmental Protection Agency, 1977).

4 Canada, *House of Common Debates*, April 25, 1919; United Kingdom, Ministry of Munitions, *History of the Ministry of Munitions Vol. II, Part IV* (London: King's Printers, 1922): 79; and David Carnegie, *The History of Munitions Supply in Canada, 1914-1918*. (Toronto: Longmans, Green and Company, 1925), 74.

5 Report on National Plants by W.L. Millar, Welfare Officer, 1918. Vol. 15, File 162, and Explosion and Fire at Trenton (with photos), 1918-1919. Vol. 17, File 175, MG30-A16, LAC; David Carnegie, *The History of Munitions Supply in Canada, 1914-1918* (Toronto: Longmans, Green and Company, 1925), 157; Michael Warner, "The Kaiser Sows Destruction: Protecting the Homeland the First Time Around" *Studies in Intelligence* 46, no. 1 (2002); and Graham Hill and Howard Bloch, *The Silvertown Explosion: London 1917* (Stroud: Tempus Publishing, 2003).

6 Douglas McCalla, "The Economic Impact of the Great War," in *Canada and the First World War: Essays in Honour of Robert Craig Brown,* edited by David Mackenzie, 138-153 (Toronto: University of Toronto Press, 2005).

7 Shell Committee Contract, Statement by Major-General Sir Sam Hughes, 1916, Vol. 1, File 1, R1141-0-X-E (RG33-61), History of the Imperial Munitions Board, 1919, Vol. 55, File 3, MG30-A16, LAC; *The University Monthly*, Alumni Federation of the University of Toronto, Vol. 17, 1916-1917: 274; and Carnegie, *The History of Munitions Supply in Canada,* 237.

8 56 Volumes, MG30-A16, Sir Joseph Flavelle Papers, and 2 Volumes, RG33-61, Canada Royal Commissions Collection, LAC.

9 Established as the Honorary Advisory Council for Scientific and Industrial Research of Canada. See Wilfrid Eggleston, *National Research in Canada: The NRC, 1916-1966* (Toronto: Clarke, Irwin, 1978); and Rod Milliard, "The Crusade for Science: Science and Technology on the Homefront, 1914-1918," in *Canada and the First World War,* edited by Mackenzie, 300-322.

10 Eggleston, *National Research in Canada*, 22-25.

11 Office of the President Correspondence: Flavelle, Joseph Wesley (Imperial Munitions Board, Ottawa; Member of Board of Governors), Vol. 38a, File 85, and Office of the President Correspondence: Bain, J. Watson, Vol. 41, File 13, UTA 0116, University of Toronto Archives; and Michael Bliss, *A Canadian Millionaire: The Life and Business Times to Sir Joseph Flavelle, Bart. 1858-1939* (Toronto: MacMillan, 1978); United Kingdom, Ministry of Munitions, *History of the Ministry of Munitions Vol. I-XII* (London: King's Printers, 1922).

12 History of the Imperial Munitions Board, 1919, Vol. 55, File 3, MG30-A16, LAC.

13 Murray, Howard, Director, Explosives Dept., Imperial Munitions Board, 1917-1921, Vol. 42, File 4, MG30-A16, LAC.

14 Carnegie, *The History of Munitions Supply in Canada, 1914-1918*; C.J.S. Warrington and R.V.V. Nicholls, *A History of Chemistry in Canada: Complied for the Chemical Institute in Canada* (Toronto: Sir Isaac Pitman and Sons, 1949).

15 Peter Edward Rider, *The Imperial Munitions Board and Its Relationship to Government, Business, and Labour, 1914-1920* (PhD diss., University of Toronto, 1974); Michael Bliss, *A Canadian Millionaire*; Tom Traves, *The State and Enterprise: Canadian Manufacturers and the Federal Government, 1917-1931* (Toronto: University of Toronto Press, 1979); Ronald Haycock, *Sam Hughes: The Public Career of a Controversial Canadian, 1885-1916*. (Waterloo: Wilfrid Laurier University Press, 1986); Desmond Morton and Jack Granatstein, *Marching to Armageddon: Canadians and the Great War.* (Toronto: Lester & Orpen Dennys, 1989); Linda Kealey, *Enlisting Women for the Cause: Women, Labour, and the Left in Canada, 1890-1920*. (Toronto: University of Toronto Press, 1998).

16 Rod Millard, *The Master Spirit of the Age: Canadian Engineers and the Politics of Professionalism, 1887-1922* (Toronto: University of Toronto Press, 1988); Guy Hartcup, *The War of Invention: Scientific Developments, 1914-18* (Lincoln: Potomac Books, 1988); Suzanne Zeller, *Inventing Canada: Early Victorian Science and the Idea of a Transcontinental Nation* (Montréal: McGill-Queens Press, 2009); and Edward Jones-Imhotep and Tina Adcock, eds. *Made Modern: Science and Technology in Canadian History* (Vancouver: UBC Press, 2018).

17 Roy MacLeod, and Jeffrey Johnson, eds. *Frontline and Factory: Comparative Perspectives on the Chemical Industry at War, 1914-1924* (New York: Springer, 2007); Michael Freemantle, *The Chemists' War: 1914-1918* (Cambridge: Royal Society of Chemists, 2014); and Kathryn Streen, *The American Synthetic Organic Chemicals Industry: War and Politics, 1910-1930* (Chapel Hill: The University of North Carolina, 2014).

18 Malcolm C. Urquhart, "New Estimates of Gross National Product, Canada, 1870-1926: Some Implications for Canadian Development," in *Long-Term Factors in American Economic Growth*, edited by Stanley L. Engerman and Robert E. Gallman (Chicago: University of Chicago Press, 1986): 31; and Victor Zarnowitz, *Business Cycles: Theory, History, Indicators, and Forecasting* (Chicago: University of Chicago Press, 1996).

19 Contracts placed by the Shell Committee with Firms who were Represented on the Board as Members, 1916. Vol. 6, File 56, and History of the Imperial Munitions Board, 1919. Vol. 55, File 2, MG30-A16, LAC.

20 John C. Hopkins, *The Canadian Annual Review War Series, 1917* (Toronto: Canadian Annual Review Ltd., 1918), 386.

21 Privy Council Office (Canada) - Canadian General Electric Company - Proposal for munition manufacture, 1915, Vol. 254, File P-2-56, R219-109-2-E (RG25-B-1-b), LAC; Leslie Barnes, *Canada's Guns: An Illustrated History of Artillery*, 72-5; John Connor, "The War Munitions Supply Company of Western Australia," 797-800; and Carnegie, *The History of Munitions Supply in Canada*, 307.

22 Shell Committee Contract, Statement by Major-General Sir Sam Hughes, 1916. Vol. 1, File 1, R1141-0-X-E (RG33-61), LAC.

23 History of the Imperial Munitions Board, 1919; Canada, *House of Common Debates*, April 25, 1919, Vol. 55, File 2, MG30-A16, LAC; and Carnegie, *The History of Munitions Supply in Canada*, 107.

24 Canada, Economics, Resources and International Affairs Division, *The Evolution of Defence Procurement in Canada*, edited by Martin Auger (Ottawa: Parliamentary Information and Research Service, 2016).

25 G.C. Mackenzie, R.G. McConnell and the Canadian Munitions Resources Commission, 1915-20. Vol. 1, File 15.1, GR-0265, Royal British Columbia Museum; and Thomas Cantley, and George Mackenzie, *Munitions Resources Commission: First Report of the Work of the Commission* (Ottawa: The Mortimer Co., 1918).

26 Murray, Howard, Director, Explosives Dept., Imperial Munitions Board, 1917-1921. Vol. 42, File 4, MG30-A16, LAC.

27 History of the Imperial Munitions Board, 1919, Vol. 55, File 2, MG30-A16, LAC.

28 Graham Taylor and Peter Baskerville, *A Concise History of Business in Canada*. (Oxford: Oxford University Press, 1994), 390. and Michael Bliss, *Northern Enterprise: Five Centuries of Canadian Business*. (Toronto: McClelland and Stewart, 1987), 250.

29 Shell Committee Contracts, Exhibits 1-165, 1916, Vol. 1, File 2, R1141-0-X-E (RG33-61); and History of the Imperial Munitions Board, 1919, Vol. 55, File 1, MG30-A16, LAC. The IMB's national plants came to produce $16-million-worth of war materiel in total, leaving a discrepancy of $1 million in expenditure by the time the war concluded. The remaining sum of war orders was distributed among private industries. Although these figures provide some context to the financial output of the IMB's investments in the national plants while under its authority, they do not highlight the impact this funding will have had to these industries in the post-war period. For statistics on the post-war explosives industry, see Canada, Mining, Metallurgical and Chemical Division, S.J. Cook, *The Explosives, Ammunition, Fireworks and Matches Industry in Canada* (Ottawa: Department of Trade and Commerce, 1925).

30 Peter Edward Rider, *The Imperial Munitions Board and Its Relationship to Government, Business, and Labour, 1914-1920*. (PhD diss., University of Toronto, 1974), 104.

31 Building for Shell Inspection at Proof Butts, Little River and Liquidation, 1919. Vol. 5, File 54, MG30-A16, LAC. and Leroy Egerton Westman, ed. *Canadian Chemical Journal* III, no. 6 (June 1919): 187.

32 History of the Imperial Munitions Board, 1919. Vol. 55, File 3, MG30-A16, LAC.

33 History of the Imperial Munitions Board, 1919. Vol. 55, File 3, MG30-A16, LAC. and David Carnegie, *The History of Munitions Supply in Canada, 1914-1918*. (Toronto: Longmans, Green and Company, 1925): 237.

34 Canada, Mining, Metallurgical and Chemical Division, S.J. Cook, *The Explosives Industry in Canada in 1918* (Ottawa: Dominion Bureau of Statistics, 1921): 1-2. Cook reported that the explosives industry employed an average of 4,700 workers during the war, peaking to 5,710 in 1917. This included 141 women workers actively employed in the chemical sector in 1918.

35 *The University Monthly*, Alumni Federation of the University of Toronto, Vol. 17, 1916-1917: 274.

36 Leroy Egerton Westman, ed. *Canadian Chemical Journal* 2, no. 6, (Toronto: Canadian Institute of Chemistry, June 1918): 156.

37 *The University Monthly*, Alumni Federation of the University of Toronto, Vol. 17, 1916-1917: 274-80; and Vol. 19, 1918-1919: 174.

38 Leroy Egerton Westman, ed. "Laboratories of Queen's University" *Canadian Chemical Journal* II, no. 1 (January 1918): 17-18.

39 United Kingdom, Ministry of Munitions, *History of the Ministry of Munitions. Vol. II* (London: King's Printers, 1922): 47; Guy Hartcup, *The War of Invention: Scientific Developments, 1914-18*. (Lincoln: Potomac Books, 1988); Roy MacLeod, "The Chemists go to War: The Mobilization of Civilian Chemists and the British War Effort," *Annals of Science* 50, no. 5, (1993): 464; and Anthony S. Travis, *The Synthetic Nitrogen Industry in World War I: Its Emergence and Expansion* (New York: Springer, 2015): 93.

40 Fixation of Nitrogen, 1917-1918, Vol. 7, File 81, MG30-A16, LAC; "The Nitrogen Problem and the Work of the Nitrogen Products Committee," *Chemical News*, 117 (18 November 1917): 240-2; Grinnell Jones, "Nitrogen: Its Fixation, Its Uses in Peace and War," *The Quarterly Journal of Economics* 34, no. 3 (May 1920): 427; and Guy Hartcup, *The War of Invention: Scientific Developments, 1914-18* (Lincoln: Potomac Books, 1988). Toluol, benzol, and xylol were also listed as important chemicals whose extraction or synthesis was being investigated for the war effort. See *The Globe* (Toronto), 16 July 1918: 4.

41 Acetone - Canadian Electro Products Co. (Shawinigan), 1917, Vol. 7, File 83; Acetic Acid - Admission of Machinery for Plant at Shawinigan Free of Duty, 1918, Vol. 12, File 119, MG30-A16, LAC; A.F.G. Cadenhead, "What Canadian Chemists at Shawinigan Falls Have Done to Win the War," *The Canadian Chemical Journal* 3, no. 8 (August 1919): 267–9; United Kingdom, Ministry of Munitions, *History of the Ministry of Munitions. Vol. II* (London: King's Printers, 1922): 48; Martha W. Langford, *Shawinigan Chemicals Limited: History of a Canadian Scientific Innovator* (PhD diss., Université de Montréal, 1987); and James P. Hull, "The second Industrial Revolution and the Staples Frontier in Canada: Rethinking Knowledge and History," *Scientia Canadensis* 18, no. 1 (1994): 32.

42 It is an important note to make that Chaim Weizmann, while considered the father of industrial fermentation, later became the first president of Israel in 1949, a year after the nation gained independence. See Jehuda Reinharz, "Science in the Service of Politics: The Case of Chaim Weizmann during the First World War" *English Historical Review* 100, no. 396 (1985): 572; and MacLeod, "The Chemists go to War," 463.

43 *The University Monthly*, Alumni Federation of the University of Toronto, Vol. 19, 1918-1919: 313; A.T. Wilgress, *Report of the Board of Governors of the University of Toronto* (Toronto: The Ryerson Press, 1919): 13; and A.E. Gooderham, *Report of the British Acetones Toronto, Limited, Toronto, Canada, May 1916-November 1918* (Toronto: University of Toronto Press, 1919). Speakman continued a career at the University of Toronto after the war in the Department of Zymology. In 1928, he was appointed Director of Research at the Ontario Research Foundation. In his 1949 memoir *Faith of a Scientist*, he recalls being approached by Banting to assist in a secret war project on bacterial warfare. See Marian A. Packham, *100 Years of Biochemistry as U of T: 1908-2008: An Illustrated History* (Toronto: University of Toronto Press, 2008): 10-11; and Horace B. Speakman, *Faith of a Scientist: Science, Humanism and Christian Education* (Toronto: Clarke, Irwin & Company, 1949).

44 Propylene Glycol, 1917. Vol. 8, File 87, MG30-A16, LAC.

45 Export of caustic soda from U.S.A, 1918. Vol. 14, File 131; Import of corn from U.S. for manufacture of alcohol and acetone, 1918, File 129; and copies of records relating to explosives, 1915-1918, Vol. 56, File 3, MG30-A16, LAC; United Kingdom, Ministry of Munitions, *History of the Ministry of Munitions. Vol. II* (London: King's Printers, 1922): 48; and MacLeod, "The Chemists go to War," 463.

46 William Van der Kloot, "Lord Justice of Appeal John Fletcher Moulton and Explosives Production in World War I" *Notes and Records of the Royal Society of London* 68, no. 2, (2014): 171-186.

47 T.N.T, 1916-1918, Vol. 15, File 163; Murray, Howard, Director, Explosives Dept., Imperial Munitions Board, 1917-1921, Vol. 42, File 4; and History of the Imperial Munitions Board, 1919, Vol. 55, File 1, MG30-A16, LAC.

48 Construction of warehouse below Montréal for temporary storage of explosives. Cost of handling tonnage at storage warehouses in Montréal District, 1917-1918, Vol. 12, File 118, MG30-A16, LAC.

49 Import of corn from U.S. for manufacture of alcohol and acetone, 1918, Vol. 13, File 129, MG30-A16, LAC.

50 John C. Hopkins, *The Canadian Annual Review War Series, 1917* (Toronto: Canadian Annual Review Ltd., 1918): 386; and McCalla, "The Economic Impact of the Great War," 143.

51 *Canadian Forestry Journal* 16, no. 8, May 1920: 244; Canada, *House of Common Debates*, June 18, 1920; and Canada, Mining, Metallurgical and Chemical Division, Cook, *The Explosives Industry in Canada in 1918*.