FRONTLINE AND FACTORY

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Frontline and Factory: Comparative Perspectives on the Chemical Industry at War, 1914–1924

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‘Above all, we still owe a word to those who work in the powder and explosives factory, who in the war economy stand, so to speak, right at the frontline – and did so long before 1939.’

‘Ein Wort müssen wir nun vor allem noch den Menschen widmen, die hier in der Pulver- und Sprengstoff-Fabrik arbeiten und die im kriegswirtschaftlichen Sinne sozusagen direkt an der Front stehen – und zwar schon lange vor 1939.’

V. Muthesius (Berlin, 1941)

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PREFACE

It has been said that history is a debate between the present and the past about the future. Nowhere are these lines drawn more significantly than in the study of science and war. And nowhere is the discourse more relevant, than in the study of science and technology as foundations and multipliers of military power. This book is concerned with one particularly seminal aspect of this development — the history of chemical munitions during and immediately after the First World War. The Great War, as it came to be known, was not the first industrial war, but it was the first to involve all the major industrial nations of the world. Within four years, the world witnessed unprecedented feats of industrial development, many of which drew upon and extended pre-war reservoirs of scientific and technological knowledge. The experience comes down to us as a *conjuncture* of scientific, economic, political and, ultimately, military departures, which by their nature involved new ways of meeting crises, and eventually new forms of critical thinking. That these new forms emerged only gradually and unexpectedly is not to underestimate their capacity to endure, or to minimize their relevance. From the Great War came patterns, assumptions, and practices which were to make an indelible mark on science and technology for the rest of the twentieth century and beyond.

To understand how different nations, with different industrial and technical traditions, came to contrive very similar weapons, for very similar purposes — producing, in the process, very different outcomes — requires us to take a comparative view of developments from laboratory to field, and across the 'front', during the period 1914–1920. What for historians of science has often been glibly accepted (or dismissed) as a 'chemists' war', was in fact a complex history of industrial systems and economic networks, of scientific disciplines and government departments. Taken as a whole, their history formed part of the collective experience that produced the first modern 'academic-military-industrial complex'. They reflected, in particular, the changing role of munitions production in the structure of modern industry. Together, they informed a new discourse – of technological mobilisation, industrial efficiency, technology transfer, and 'dual use' – that began during the war, and gathered impetus in its wake.

To improve our grasp of these issues, we convened a workshop at the Institute of Advanced Studies of the University of Bologna in June 2002. To this we invited colleagues from Italy, France, Britain, Germany, The Netherlands, and the United States. We would like to express our warm thanks to the Director of the Institute, and especially to Professor Roberto Seazziere. Complementing facilities contributed by the Institute came generous assistance for American participants from the National

Science Foundation, and for French colleagues, from the CNRS. We wish to express our thanks to these and other organisations, including English Heritage, for their timely attempts to retrieve the architectural heritage of munitions manufacture.

We wish also to express our thanks to all who joined in our discussions, not least those who are not with us at the end of the day. At Villanova University, we are grateful for the assistance of the Research Office and the Department of History, and at the University of Sydney, we are grateful for the superb assistance of our interlibrary loan librarians, and for the help of Christopher Hewitt, Alanta Colley and Penelope Grist.

Roy MacLeod
Jeffrey Johnson

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JEFFREY ALLAN JOHNSON AND ROY MACLEOD

INTRODUCTION

The First World War was a significant turning point in modern history, in many ways marking, to use the well-worn phrase, the coming of 'nowadays'. With the end of three empires and the re-making of a fourth, and the rise of the United States to the status of a great power, came impressive transformations in military technique and technology that rendered many traditional ideas of warfare obsolete. The war embraced collective sacrifice on a vast scale. Ten million dead stood as a reproach to humanity. At the same time, the world brought a new set of relationships between knowledge and power.[1] Among those most affected were the institutions of science, and the industries concerned with the manufacture, supply and use of what later generations would call weapons of mass destruction. The consequences of this new relationship were profound. For some, it registered the idea that modern war was becoming simply too terrible to contemplate.[2] For others, it marked merely a fearful instalment in the history of the 'warfare state'.[3] It is within the context of this emerging dilemma and debate that this book has been written.

Historians have viewed the Great War in many ways. Yet, no one fresh to the subject now begins without reference to the fact that this was, in unprecedented ways, an industrial war, or as Hew Strachan puts it, a '*Materialschlacht*', a 'battle of materials'.[4] Armaments, produced in massive quantities, dominated Europe. Mobilisation led the conversion of peacetime producers into a war economy, which found both purpose and profit in working raw materials into weapons. For the first time, nation states were unable to look to the past for military solutions. As van Creveld has put it, warfare became completely permeated by technology, and governed by it. Thirty years of industrial progress preceding 1914 had put all nations on what van Creveld calls a technological 'treadmill', which required constant attention to remain in the same place.[5] The result came unevenly, but ineluctably. The machine gun, with its crew of two or three, produced a level of firepower equal to a Napoleonic battalion. Similar developments brought a vast increase in logistic requirements, with major implications for training, equipment, and lines of communication and supply. In its wake, came the development and repositioning of massive industrial infrastructures, throughout Europe, and across the Atlantic.

Unprecedented destruction was an inevitable result of this new 'war of *matériel*'. By the end of November 1914, the war had seen the end of pre-war strategic assumptions based on men and mobility. The Western Front had become a warren of trenches and obstacles, with armies reduced to deadlock and stalemate. Innovations in weapons were driven by tactical necessities. New weapons systems dominated the terrain. Above all, there was the artillery, as Strachan has put it, 'In the First World War, the artillery was the agent of industrial and social mobilization'.[6] While the tragedies of gas warfare remain indelibly printed on war art and literature, it was shrapnel and high explosive that were responsible for 80% of the casualties on the Western Front.[7] At the core of this contest was the ‘shell’, singing in its different calibres, a chorus of destruction.[8] The sounds of shell-fire – what Sassoon called the ‘din of war’ – brought to all sides a fear and loathing of modern technologies, and a contempt for those who produced them. At the same time, they were talismanic objects, the quintessence of modernism, yet the embodiment of tradition. Shells were the servants of the military, but the system that produced them was the work of science and commerce. Among its outcomes, were the ruins of Verdun and the carnage of the Somme. Their effects made a lasting impression on modern memory. By 1916, the stalemate seemed as if it would last forever. Then, the sciences came into their own.[9] The ‘protection’ ironically afforded by the trenches gave time needed to launch a second mobilisation. And among the industries most affected, those of chemistry led the way.

For most observers of the Great War, the chemical industry was the ‘ghost in the machine’. And although poison gas gave the war its chemical sobriquet, and its chemists everlasting notoriety, it was the explosives industry that claimed most attention, most resources, and most lives. In both cases, the chemical industry classically exemplified the nature of ‘dual-use’ technologies, well expressed by Brigadier (Sir) Harold Hartley, when overseeing the perfectly preserved Rhineland factories of defeated Germany in 1919: ‘In the future . . . every chemical factory must be regarded as a potential arsenal ...., ‘ he said.[10] Chemicals good for agriculture were equally useful in making explosives. After the war, no one could turn back the clock, although the victors at Versailles tried to do so. A new form of warfare had begun.

Between 1914–1919, the chemical industries fought as intensely as the military. But the history of their struggle is not well known and, beyond post-war apologetics, has never been thoroughly assessed. To do so requires fresh research, and at least three critical elements—new sources, a comparative perspective, and a set of fresh questions.

Within the last twenty years, and certainly since the end of the Cold War, it has become possible to consult records to which earlier generations of historians had no access. These give us a chance to re-examine the emerging relationship between science-based industry and modern industrial warfare, as it changed in ways which were all the more remarkable for being unplanned and unprecedented in speed, scale and impact. However, many of these sources remain geographically and commercially difficult to consult, and their successful use requires a degree of familiarity born of long association.

For this reason, the subject is best approached with a comparative perspective. Indeed, to neglect this dimension would risk missing points that, in their different ways, French, British, American and German historians consider essential. We agree with Niall Ferguson, writing in a different context, that ‘The literature on war … perfectly illustrates the dangers of writing national history without adequate comparative perspective’.[11] Accordingly, it is essential to cast our exercise in terms of the advancing front of scholarship on what French scholars call 'l'histoire totale de guerre'.[12] As the war became increasingly 'total' – which is to say, as opposing nations sought to mobilize resources of all kinds – solutions to unplanned problems provided at least part of the key to victory or defeat.[13] In this changing picture, the resources of science came to play an increasingly important role, as did the leadership of industrial science and engineering, which came to enjoy a high degree of integration with government and the military. Its history enables us to assess the extent to which the war accelerated the emergence of a 'triple helix' between science, industry and government, with its many consequences for an emerging 'academic-military-industrial' complex.[14]

To explore these relationships, with all the fresh materials and perspectives at our disposal, we have found it useful to cast our questions in a comprehensive context, and to look at the collective experience of the belligerent powers – and also the leading neutrals—in terms of what we can identify and describe as 'national systems' of applied science and production. In appropriating the idea of 'national systems', we have drawn on language made popular by Thomas Hughes, Richard Nelson, Nathan Rosenberg, and Giovanni Dosi, who have in different ways explored more recent 'national systems of innovation'.[15] The 'national systems' that dominated the 1914–18 War were products of a century of imperial and international development, which brought in train a world economy driven in large part by free trade.

At first, the coming of war disturbed few illusions – except perhaps the idea that any such war was absurd, and would be over quickly – but by early 1915, it was clear that many critical chemicals, from nitrates and sulphates to dyes and pharmaceuticals, were in short supply on all sides. All belligerents proceeded to make major adjustments, creating new organizations, rationalizing resources, replacing essential materials with import-substitutes, and expanding the production of war *materiel*. On both sides, new systems were grafted onto old, and new systems were created, shaped by and shaping developments in the war. Month by month, year by year, these competing systems were brought to the test. Efficient mobilization, followed by rapid deployment, could make long-term deficiencies irrelevant; equally, inefficient mobilization, or inefficient lines of production and supply, could nullify the advantages of the richest nation in the world.

A critical factor in mobilizing chemical munitions was the industry's relative level of what Hughes has called 'technological momentum'.[16] From late 1914, the chemical industry slowly adjusted itself— reluctantly, as we shall see, in Germany; and with difficulty in France and Britain – to wartime demands. The 'technological systems' of industrial warfare required not only plant and equipment, but also a supporting 'technological culture'. In each belligerent country, a national 'system' emerged, acquiring 'momentum' through expansion and innovation to overcome obstacles to growth ('reverse salients', in Hughes' terminology). In the broadest sense, the characteristics of a country's 'technological system' were reflected in rates of innovation and use of scientific expertise, resources and organization. They were also reflected in the changing relationship between military and civil production, and in the conflicting priorities of the public and the private sector. Looking at these factors across national frontiers can tell us much about relative 'success' and 'failure'—and the relative values accorded research, development, testing, safety and speed. These were the 'winning weapons' in the new business of 'machine warfare'. These were also to become vital to the success of the chemical industry for at least the next fifty years.

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In examining different national responses to the challenges of war, it would be ideal to take comparative cases that consider the same questions, similar institutions, and at similar moments in time. This ideal we have not achieved. Instead, as a first step, we have assembled a series of national studies that look – in some cases, for the first time – at emerging systems of innovation, and at their immediate consequences, during the war and the *après-guerre*. Using a European perspective, each author has looked through a slightly different national lens to explore comparative questions of mobilization and production. Together, they offer a range of insights into the many ways in which competing national systems deployed their differing traditions, where possible to advantage, in attempting to meet similar objectives.[17] That they did so at different rates, and with differing levels of success, forms an important part of our story. We have focused on the Western Front, although many of the features of industrial warfare were equally evident in other theatres, and outside Europe. Given the particular circumstances of static warfare in these areas, the industrial effort of the Allies and the Central Powers concentrated on an expanding variety and quantity of guns, shells and fuses.

The war was not, of course, an entirely 'chemical war', and no serious historian questions the relevance of other material resources – notably, steel and brass for shell manufacture, and the coal, iron and copper on which they were based – nor the wide range of other wartime technical innovations, including aircraft, tanks, and submarines, let alone the contributions made by agriculture, medicine, and the social sciences.[18] However, in ways that parallel the interests of artists, anthropologists, and cultural historians, it is important to make a start, and in this case, by examining how the great 'chemical munitions feat' was conceived, contrived, and remembered. In its overwhelming military success, it became a foretaste of the future use of science as a weapon against humanity, and in its widest expression, a tragic consequence of the Enlightenment.[19]

For convenience, the book is organized in three parts. In Part I, we examine the principal systems that went to war in 1914. Comparing the Central Powers, the German and the Austrian systems, Jeffrey Johnson follows two phases of the war – the first in response to the emergencies of 1914, the second, in response to the dramatic intensification of war in the West in 1916. A critical factor in saving Germany's war effort from collapse in 1915 was the capacity of its dye industry to adapt quickly, with relatively little change, to wartime needs. It was difficult to alter the 'technological momentum' of an industry dependent upon international markets, in which the Entente Powers were major customers. Yet, as Johnson shows, 'dual-use' technologies were the key factor in enabling peacetime industry to meet wartime needs. After the summer of 1916, both the German and Austrian systems were 'overtaxed' by the 'second mobilization' – the Hindenburg programme and its Austrian equivalent – with consequences that were to prove disastrous for both countries.

Comparable causes of relative success and 'failure' are recounted in the essays by Sophie Chauveau (who studies French mobilization in the pharmaceutical industry), by Wayne Cocroft (who surveys British chemical munitions, from the perspective of industrial archaeology), and by Sebastian Kinder, who has carefully revisited a Prussian powder factory near Berlin. The British followed the French in creating a virtually new industrial system, using a mixture of public and private strategies, and mobilizing technical expertise from the Empire, which was almost completely dissipated in the years following the war. In Germany, wartime mobilization was followed by successful re-conversion, a process which, as Kinder hints, is continuing to this day.

In Part II, four studies pose broadly similar questions in parallel, rather than in competing, contexts – Tsarist Russia, Italy and the United States; and The Netherlands which, as a neutral, remained precariously poised between the Allies and the Central Powers. Giuliano Pancaldi shows how the war brought a vital stimulus to Italian chemistry, which quickly disappeared when the conflict ended. Nathan M. Brooks traces the role of central government in managing munitions science in Tsarist Russia, while Kathryn Steen shows how American industry adapted private sector methods to meet Allied, then American military demands. Ernst Homburg shows how Dutch industry prospered during the war, delicately balancing profits and principle in its commitment to global trade.

Finally, the five studies in Part III explore contrasting national systems and their intersection with military and political objectives. Eric Langlinay shows how, with mixed success, one of France's largest chemical firms sought competitive advantage from wartime circumstances. John Kenly Smith, Jr., shows, through the history of DuPont – the largest American explosives manufacturer – how American industry decisively shifted the balance of power between the competing systems. In this light, the lesser-known history of Germany's scientific mobilization, as reconstructed by Manfred Rasch, comes in some ways as an unexpected story of institutional delay and poor communication between science and the military, with far-reaching consequences for Germany. Against this, Patrice Bret emphasizes the close relationship between science and the military in France, particularly in the context of the remarkable *Service des Poudres* – not alone, but in large part responsible for the 'miracle' that was the French response to the loss of its major industrial centres and natural resources to Germany at the start of the war. In the Epilogue, we have invited Seymour Mauskopf to reflect on wider European comparisons illuminated by the papers, not least in their relation to the *longue durée* and earlier visions of 'total war'. We are grateful to him for this exercise in stressing points that are particularly relevant to an understanding of the history of chemistry and chemical munitions.

In the concluding chapter, we return to some of these considerations in the light of the 'chemical occupation' of Germany in 1919 and afterwards. It is well known that, after Versailles, disarmament became a hopeless cause.[20] It is less well appreciated that it was doomed at birth. Chemical disarmament was, in turn, an illusion born of diplomacy and politics, rather than an idea nurtured by science or industry. In seeking a lasting peace, the victors sowed the seeds of a future war. That war, and its aftermath, would raise in a new form the same questions concerning the proliferation of 'dual use' technologies, and the consequences of an increasingly close relationship between science, government, and the military throughout the industrialised world.

NOTES

1 A fact fully recognised at the time. See A.N. Whitehead, *Science and the Modern World* (Cambridge: Cambridge University Press, 1926), 298 *et seq*.; see also Lewis Mumford, *Technics and Civilization* (New York: Harcourt Brace, 1934), 84–87, for its meaning in reverse: 'modern industrialism may equally well be termed a large scale military operation' (84).

2 For a powerful expression of the apocalyptic view, see Robert L. O'Connell, *Ride of the Second Horseman: The Birth and Death of War* (New York: Oxford University Press, 1995).

3 David Edgerton, *Warfare State: Britain, 1920–1970* (Cambridge: Cambridge University Press, 2006).

4 The literature is extensive. By way of introduction, see Roger Chickering and Stig Förster (eds.), *Great War, Total War: Combat and Mobilization on the Western Front, 1914–1918* (Cambridge: Cambridge University Press, 2000; Hew Strachan, *The First World War, Vol. I: To Arms* (Oxford: Oxford University Press, 2001); Trevor Wilson, *The Myriad Faces of War* (Cambridge: Polity Press, 1986); Robin Prior and Trevor Wilson, *The First World War* (London: Cassell, 2001); David Stevenson, *Armaments and the Coming of War: Europe*, *1904–1914* (Oxford: Clarendon Press, 1996).

5 Martin van Creveld, *Technology and War, from 2000 BC to the Present* (New York: Free Press, 1989), 224.

6 Hew Strachan, 'La Notion de Puissance de Feu: La Revolution de l'Artillerie', delivered to the Conference on 'La Mobilisation de la Nation', Centre des Hautes Études de l'Armement (CHEAr), Paris, 26–28 October 2004.

7 On the artillery war, see Tim Travers, *The Killing Ground: The British Army, the Western Front, and the Emergence of Modern Warfare, 1900–1918* (London: Unwin Hyman, 1987); David Zabecki, *Steel Wind: Colonel Georg Bruchmüller and the Birth of Modern Artillery* (Westport: Praeger, 1994); Erich Schoen, *Geschichte des Deutschen Feuerwerkswesen der Armee und Marine mit Einschluss des Zeugwesens* (Berlin: Paul, 1936); J. B.A. Bailey, *Field Artillery and Firepower* (Annapolis.: Naval Institute Press, 2nd ed., 2004); Frank E. Comparato, *Age of Great Guns: Cannon Kings and Cannoneers who Forged the Firepower of Artillery* (Harrisburg, PA: The Stackpole Co, 1965).

8 Nicholas Saunders, 'The Ironic 'Culture of Shells' in the Great War and Beyond', in John Schofield, William G. Johnson, and Colleen Beck (eds.), *Matériel Culture: The Archaeology of 20th Century Conflict* (London: Routledge, 2002), 22–40; and N.J. Saunders (ed.), *Materialities of Conflict: Anthropology and the Great War, 1914–2002*. London: Routledge, 2004).

9 Nowhere better encapsulated than in a work published for the US National Academy of Sciences, R[obert] M. Yerkes (ed.), *The New World of Science: Its Development during the War* (New York: The Century Co., 1920).

10 National Archives (Kew) MUN 4/6737, H. Hartley, 'Report of the British Mission Appointed to Visit Enemy Chemical Factories in the Occupied Zone Engaged in the Production of Munitions of War' (typescript, 26 February 1919), 13. A longer, printed version is in MUN 4/7056; the first part, containing this quotation, was published in 1921.

11 Niall Ferguson, *The Pity of War: Explaining World War I* (New York: Basic Books, 1999), 256–257.

[12] Jay Winter, Geoffrey Parker, and Mary R. Habeck, *The Great War in the Twentieth Century* (New Haven: Yale University Press, 2000), 9.

[13] Hew Strachan, 'On Total War and Modern War', *International History Review*, XX (2000), 341–370.

[14] For the re-invention of the 'Triple Helix' model in our time, see Loet Leydesdorff and Henry Etzkowitz, 'Triple Helix of Innovation: Introduction', *Science and Public Policy*, XXV (6), (1998), 358-364; Henry Etzkowitz and Loet Leydesdorff, 'The Endless Transition: A 'Triple Helix' of University-Industry-Government Relations', *Minerva*, XXVI (3), (1998), 203–218; Loet Leydesdorff and Henry Etzkowitz, 'The Triple Helix as a Model for Innovation Studies', *Science and Public Policy*, XXV (3), (1998),195–203; Loet Leydesdorff and Henry Etzkowitz (eds.), *A Triple Helix of University-Industry-Government Relations: The Future Location of Research?* (New York: Science Policy Institute, State University of New York, 1998); Henry Etzkowitzand Loet Leydesdorff (eds.), *Universities and the Global Knowledge Economy: A Triple Helix of University-Industry-Government Relations* (London: Cassell, 1997).

[15] Thomas Parke Hughes, *Networks of Power: Electrification in Western Society, 1880–1930* (Baltimore: Johns Hopkins University Press, 1983); and 'Technological Momentum in History: Hydrogenation in Germany, 1898–1933', *Past & Present*, No. 44 (August 1969), 106–132; Richard R. Nelson, *National Innovation Systems: A Comparative Analysis* (New York: Oxford University Press, 1993); Giovanni Dosi, *Technical Change and Industrial Transformation* (New York: St. Martin's Press, 1984); Giovanni Dosi, Keith Pavitt, and Luc Soete (eds.), *The Economics of Technical Change and International Trade* (New York: New York University Press, 1990); Giovanni Dosi, Renato Giannetti, and Pierangelo Maria Toninelli (eds.), *Technology and Enterprise in a Historical Perspective* (Oxford: Oxford University Press, 1992); Giovanni Dosi, *Innovation, Organization and Economic Dynamics: Selected Essays* (Cheltenham: Edward Elgar, 2000).

[16] Hughes, 'Technological Momentum', *op. cit.* note 15.

[17] For a comparison of wartime 'mentalities', see Jeffrey A. Johnson and Roy MacLeod, 'War Work and Scientific Self-Image: Pursuing Comparative Perspectives on German and Allied Scientists in the Great War', in Rüdiger vom Bruch and Brigitte Kaderas (eds.), *Wissenschaftssystem und Wissenschaftspolitik: Bestandsaufnahmen zu Formationen, Brüchen und Kontinuitäten im Deutschland des 20. Jahrhunderts* (Stuttgart : F. Steiner, 2002),169–179.

[18] See also J.P. Harris, *Men, Ideas and Tanks: British Military Thought and Armoured Forces, 1903–1939* (Manchester: Manchester University Press, 1995).

[19] For instructive cultural comparisons, see Douglas Mackaman and Michael Mays (eds.), *World War I and the Cultures* of Modernity (Jackson, Miss: University Press of Mississippi, 2000).

[20] For a recent treatment of these issues, see Richard Shuster, *German Disarmament after World War I: The Diplomacy of International Arms Inspection, 1920–1931* (London: Routledge, 2006).

JEFFREY ALLAN JOHNSON

TECHNOLOGICAL MOBILIZATION AND MUNITIONS PRODUCTION: COMPARATIVE PERSPECTIVES ON GERMANY AND AUSTRIA

INTRODUCTION

The First World War is rightly considered a milestone in twentieth-century history, marking a fundamental change in the system of production of modern industrial nations. This paper examines the relative successes and failures of the German and Austro-Hungarian systems in mobilizing their chemical industries for the development and production of explosives and propellants for munitions. The key to 'chemical mobilization' lay in part in the speed and efficiency with which industrial systems could grasp the inherent possibilities of their peacetime capacities. Once cut off from international trade, and involved in an extended war of attrition, these systems faced serious disadvantages in resources, both human and material. But superiority in technological mobilization was critical to victory. This required new measures to increase the productive capacity of existing private and government-owned plants, while finding the resources to supply them, and while converting peacetime chemical industries to wartime use.

The most important example of this conversion took place in the dyestuffs industry, one of Germany's most profitable and strongest near-monopolies. Following Thomas Parke Hughes, the successful conversion of an industry depended in part upon its 'technological momentum', a measure of the pace and direction of its development.[1] In the case of the German dye industry, despite the high prewar profitability of dyes, and the extensive factories and staff devoted to their production, the industry had only a relatively low technological momentum, as most of its facilities were inherently flexible. Hence its initial conversion to wartime production presented only minor problems, and the industry adapted itself smoothly to the unfamiliar needs of a war economy.

This paper will focus upon Germany's – and to a lesser extent, Austria's – wartime experience.[2] The story is a familiar one of military unreadiness and belated administrative leadership, coupled with a less familiar history of industrial flexibility in plant design and apparatus, a capacity to survive losses of raw materials and intermediates, and an ability to improvise and innovate in a domain of chemicals needed for explosives production. The war was also to expose stark contrasts between Germany's privately-owned research-intensive dyestuffs industry, and the less sophisticated Austrian chemical industry, in which state-owned or controlled factories played a dominant but less efficient role.

R. MacLeod and J.A. Johnson (eds.), Frontline and Factory, 1–20.

Wartime chemical mobilization in Germany and Austria took place in two stages, reflecting the intensification of the war. The first began as early as August 1914, in response to the unexpectedly high demands for munitions resulting from the ill-fated Schlieffen Plan. This ‘makeshift mobilization,’ which gathered speed by the spring of 1915, involved the impromptu completed expansion of temporary facilities. Anticipating an early return to peace, Germany’s major dyestuffs firms refused for several months to manufacture explosives, until excess capacity led them reluctantly to respond to an explicitly temporary objective. Then, for nearly fifteen months, the Central Powers developed their munitions industries incrementally. However, in the autumn of 1916, following the losses at Verdun and on the Somme, came a second major ‘mobilization, driven by the grandiose demands of the Hindenburg Programme, which called for dramatic increases in munitions production. As Hew Strachan has pointed out, this effort arose from the concept of *Materialschlacht*, the ‘battle of materials’.[3] By the end of the war, Germany was beginning to build permanent, efficient ‘readiness plants’, which were to be converted to peacetime use after the war, but which were to be kept ready for quick re-conversion. In this way, Germany committed itself to something close to ‘total’ economic planning, and pressured the Austrians to follow suit.

In retrospect, these efforts came too late, and went too far, overtaxing the infrastructures and resources of their weakened systems and ultimately contributing to the collapse and defeat that so many pre-war observers had feared. Nonetheless, in some respects the Hindenburg Program substantially aided the German chemical industry’s recovery in the postwar era, in particular by expanding its capacity to produce nitrates that could also be used for fertilizer. At the same time, however, the development of such dual-use technologies also helped to direct the postwar technological momentum of the chemical industry in ways that would keep it at the centre of German military planning for a future war.

GERMANY AND AUSTRIA ON THE EVE OF WAR

Germany entered the war with a mixed system of explosives supply. Each of the major German states (Prussia, Bavaria, and Saxony) had state munitions complexes, including factories for explosives production. Prussia had a munitions complex in Berlin-Spandau, and supplementary facilities elsewhere, including a powder plant in Hanau. Bavaria had a powder plant in Ingolstadt, as did Saxony in Gnaschwitz. Most of these produced only propellant, as the principal shell in use by the army was shrapnel, rather than explosive.

Indeed, in the decades preceding the war, there was limited state interest in producing explosives. In 1904, Spandau had begun the production of high explosive, but in 1914 private companies still supplied half or more of Germany’s military and naval munitions.[4] Most private firms belonged to a profit-sharing alliance of the British-German Nobel-Dynamite Trust [which was dissolved in 1915] and the German powder group. The principal German member of the Nobel trust was the Deutsche Sprengstoff AG, directed by Alfred Nobel’s former associate, Gustav Aufschläger; the three main firms in the powder group were the

Vereinigte Köln-Rottweiler Pulverfabriken; the Rheinisch-Westfälische Sprengstoff AG in Troisdorf; and the Westfälisch-Anhaltinische Sprengstoff AG (WASAG) in Reinsdorf.[5] As the Kaiserreich had never established an Imperial Ministry of War or of Munitions, it was the Prussian War Minister who drew up the military budget and presented it to the Reichstag, and the Prussian War Ministry's *Feldzeugmeisterei* (Ordnance Department) was supposed to coordinate overall production and supply in time of war. Together with Prussia, the principal smaller German states, such as Bavaria and Saxony, also had their own War Ministries, which relied upon liaison officers to maintain communications.

Austria, by contrast, had a state monopoly over military propellants and explosives, which was administered from 1908 by the Powder Department (7P) of the Austro-Hungarian Imperial War Ministry. This was the one area of artillery munitions not placed under the competence of the War Ministry's Inspector of Technical Artillery (ITA) in 1912, in the wake of the first Balkan war, which led to legislation enabling the War Ministry to assume control over the economy during a war emergency. While the ITA attempted to modernize the artillery and set up a network of civilian contractors to supplement the state arsenals, the production of military propellants remained concentrated in a few locations – principally the Blumau state powder factory near Wiener Neustadt, which was not known for its efficiency. But until the outbreak of war in 1914, the Powder Department apparently saw no need to utilize civilian firms such as the Dynamit-Nobel AG in Poszony (today Bratislava).[6]

The private and state-owned manufacturers of explosives and propellants in both countries obtained critical raw materials and intermediates from commercial sources, which in turn were partially dependent upon foreign imports, and thus remained vulnerable to a naval blockade. Glycerine, required for nitroglycerine (NG) propellant, came mainly from soap manufacturers, which had to import some of their fats; cellulose, required for nitrocellulose (NC) propellant, came mainly from imported cotton. The two standard high explosives were trinitrotoluene (TNT), and picric acid (or trinitrophenol). Although toluene and phenol (once imported from Britain) came from German sources (coal tar distillation or as by-products of coking and urban gas plants), the lack of a process to synthesize toluene set limits on the production of TNT. The critical component common to all military explosives and propellants was, of course, nitric acid – in 1914, made primarily from imported Chilean nitrates. Concentrated sulphuric acid and oleum (concentrated sulphuric acid with anhydrous SO_3), needed for the production of nitric acid, was made largely from Spanish pyrites. Given a British blockade, the main hope for overcoming wartime shortages lay with the chemical industry – once it had converted from peacetime to wartime production.

THE PRE-WAR GERMAN DYE INDUSTRY AND EXPLOSIVES PRODUCTION

In July 1914, the Germany dye industry seemed little interested in military production, indeed, recognising that a major war could destroy its 85% dominance of the global market. Yet, there were already signs of changes in the industry's technological momentum. Germany's most profitable pre-war producer of dyes and pharmaceuticals was the Rhineland company Bayer (more properly, the Farbenfabriken vorm. Friedr. Bayer & Co.), which in 1904 formed a profit-sharing alliance– the so-called 'little IG' – with Agfa (Aktiengesellschaft für Anilinfabrikation) in Berlin and BASF (Badische Anilin & Sodafabrik) in Ludwigshafen on the upper Rhine. Neither they nor their principal competitors – the Frankfurt/Main regional alliance (also formed in 1904) of Höchst (the Farbwerke vorm. Meister, Lucius & Brüning in Höchst) and the firms of Cassella, and Kalle – produced explosives. Yet, they were not unfamiliar with key explosives technologies, as in producing dyes and intermediates they commonly nitrated various aromatic compounds, including phenol and toluene – albeit normally only to the non-explosive mono- and di- (or bi-) nitro stages (though they produced picric acid in rather limited quantities as a dyestuff or intermediate).[7] Hence they could (and did) supply intermediates to the explosives industry, as well as to the state arsenals.

The third and largest company, BASF, had a longstanding interest in producing nitrates, which culminated shortly before the war in the achievement of the Haber-Bosch process for synthetic ammonia. However, BASF's relatively small output of 30,000 metric tons of Haber-Bosch ammonia in 1914 was used chiefly to make ammonium sulphate for agricultural fertilizer; there was no plant for oxidizing synthetic ammonia to nitric acid, an essential step before it could be used to produce explosives. Although the chemist Emil Fischer brought the process to the Kaiser's attention in January 1911, shortly before Fritz Haber's appointment as director of the Kaiser Wilhelm Institute for Physical Chemistry, the Prussian War Ministry rebuffed Haber's subsequent efforts to establish a connection between his Institute and the Prussian military. Hence, there is little evidence to support the postwar Allied myth that Haber-Bosch ammonia played a crucial role in pre-war German military planning.[8]

Military attitudes were slow to change. But commerce marched to a different rhythm. Whatever their views of military contracts, Germany's dye firms entered 1914 uncertain of their future and interested in prospects for diversification. BASF's move into nitrates arose in part from a perception, widespread from the turn of the century, that there would be few new developments in the field of synthetic dyestuffs to compare with the huge success of synthetic indigo. Despite the substantial sums spent in research and development, the most promising new dye group after indigo – the vat dyes – presented many technical problems to producers and dyers alike. Dyestuffs also seemed in many ways technologically unattractive. With the exception of alizarin and indigo, they generally entailed relatively small-scale, batch production, and were traditionally tied to the changing tastes of the textile industry, so required constant innovation to remain profitable. Dyes were also labour-intensive – on the factory floor, in sales, and in the laboratory. Of course, the production of synthetic indigo, together with its raw materials and intermediates, had demonstrated the profitable possibilities of large-scale, continuous processes. This, BASF successfully followed up with the Haber-Bosch process.[9] Turning plant to military use would require not new plant, but new policy.

MOBILIZATION PLANS

Historians agree that German (and Austrian) pre-war military planning showed little regard for industrial mobilization, or the need to stockpile strategic materials. The Schlieffen Plan of 1905 was designed to effect a quick victory, which as a matter of principle made pointless any long-term considerations. Schlieffen intended to overwhelm Germany's opponents in the West with a quick strike with overwhelming force, while holding the line in the East against the slower-moving Russians. Artillery, especially heavy artillery for breaking down enemy fortifications, would play a crucial role. To this end, by 1914 Germany amassed more than seven thousand artillery pieces (including two thousand field howitzers and heavier pieces) with a reserve of some twenty million shells. This was more than the French and Russians had together, and was thought sufficient to last until the state-owned and private factories could begin meeting quotas set by mobilization plans. These plans anticipated that monthly production would not need to exceed 200,000 shells (requiring about 150–200 metric tons of propellants and perhaps 250 tons of high explosive) until the third month of the conflict.[10] Had the war lasted only six months, this would not have severely strained the German economy.

But what if it lasted longer? Considering this possibility, Schlieffen's successor, the younger Moltke, modified the Schlieffen Plan in 1911 to avoid marching through The Netherlands. The idea was to leave open a supply line through which to obtain critical imports in case the plan failed.[11] Ironically, this modification might have been sufficient in itself to cause the plan to fail, by narrowing the front through which the German army could march. Moreover, the likely imposition of a British blockade and British influence would reduce Germany's chances of obtaining material through neutral Holland.[12] As late as August 1914, the German military had failed to assemble a strategic reserve of critical nitrates and toluene. It is all the more remarkable that the government had begun discussing civilian mobilization with businessmen in 1912 – although the principal concern was food, not raw materials.[13]

THE MUNITIONS CRISIS AND 'MAKESHIFT MOBILIZATION', 1914–1915

In the initial campaigns, the demand for munitions proved far greater than Germany had anticipated. As early as 13 August, when the modified Schlieffen Plan seemed likely to succeed in the West (while in the East, the Germans still awaited the advancing Russians), the War Ministry's Allgemeines Kriegs-Departement (General War Department) sent an anxious memorandum to the Ordnance Department: 'The consumption of munitions in the initial battles has been so great that we must employ all means possible to draw upon and make use of every potential source for munitions production'. The Ordnance Department was to provide a list of 'private companies, machines, raw materials, etc.' for this purpose.[14] One may ask why contingency plans had not been developed before the war; to be sure, in early July, the War Minister had ordered one – due on 1 January 1915![15]

The problem certainly worried thoughtful civilians. Walther Rathenau of the AEG (German General Electric Corporation) and a subordinate, Wichard von Moellendorf, were quick to recognize the failure of military planners to establish a system of rationing, or even a means of coordinating the confiscation and distribution of captured supplies. Rathenau seized the initiative, and communicated with the War Minister who, on 13 August – the same day as the memorandum to the Ordnance Department – authorised the creation of the *Kriegsrohstoffabteilung* (KRA, or War Raw Materials Department), under Rathenau's direction. The KRA coordinated the industrial mobilization through a series of 'war corporations', established as consortia for the production of various types of war materials, with the Imperial government as co-investor. The second of these (established on 30 September following a corporation for non-ferrous metals set up on 2 September), was the Kriegschemikalien AG (KCA, War Chemicals Corporation). This included twenty-six producers of explosives and intermediates, under the presidency of Gustav Aufschläger, of Deutsche Sprengstoff AG. Through confiscation, rationing, and controlled distribution, the KCA was to ensure reliable supplies of war chemicals.[16]

The KCA appeared after the death of the Schlieffen Plan on the Marne put an end to dreams of quick victory in the West, even as outnumbered Germans in East Prussia used superior artillery and mobility to drive back the Russians. The defensive now predominated over the offensive. Having used large-calibre guns to reduce the great fortresses of Liège in the first days of August, the German army (like their Austrian allies) expected to rely on shrapnel – or the newly developed *Einheitsgeschoß* (combined shell), joining shrapnel with high explosive – in the field.[17] In the East, where lines remained more fluid, this approach was effective, especially in the first year of the war. However, with the advent of trench warfare in the West, attention returned to intensive bombardments, using heavy artillery and high explosive. This required vast quantities of nitrates. Despite the military's failure to amass reserves, the KRA and KCA located supplies in domestic industry, in agriculture, and in importers' warehouses, as well as in captured Belgian ports, and purchased more in adjacent neutral countries. Without these stocks, equivalent to about 35,000 of the 55,000 tons of pure nitrogen equivalent used for explosives in 1914–1915, Germany could not have carried on the war. As it was, the Germans had time to find alternative sources.[18]

DUAL-USE TECHNOLOGIES AND MOBILIZATION

The advantages of having 'dual-use' capacities soon became apparent, as Troisdorf and other firms that produced NC propellant as well as commercial products increased their military production by shutting down their celluloid factories immediately after the outbreak of war.[19] By contrast, the dye industry rejected the government's urgent appeal to begin production of TNT or picric acid or both.[20] Carl Duisberg of Bayer believed that the Prussian Ordnance Department was exaggerating the shortage, and he dreaded the idea of producing high explosives on a large scale. By the standards of the *Berufsgenossenschaft*, the chemical industry's insurance company, Bayer's employees were neither properly trained nor were its buildings properly equipped with safety features to handle explosives production (with protective earthen walls in areas where TNT was made).[21] The directors of Höchst put it more simply: 'we are not an explosives factory and, moreover, cannot create facilities to produce TNT and picric acid'.[22] In any case, why risk converting existing plant when the world dye market might reopen in a few weeks? In the meantime, they reasoned, the dye firms could simply increase their production of intermediates (e.g. dinitrotoluene) for the explosives firms.

Similarly, BASF's management rebuffed Haber's inquiries on behalf of the War Ministry, requesting the use of its synthetic ammonia to produce nitrates for explosives. The company had a process, but not yet a pilot plant for the oxidation of ammonia to nitric acid; the directors saw no way to achieve full-scale production in time to influence what they expected to be a short war. In the first few weeks of August, it had lost half its workers to the army, and been forced to shut down production lines, even its synthetic ammonia plant.

However, the existence of that plant was to initiate a decisive shift in the weeks following the Marne. Along with Haber, Emil Fischer now emerged as a mediator between the KRA and the branches of industry that could produce nitrogen products.[23] Although Haber could boast ties to BASF, and especially to Carl Bosch, the director of its nitrogen division, Fischer enjoyed much wider respect in the dye industry generally (reflected in his becoming the sole academic on the supervisory board of the KCA). His pre-war efforts to establish a *Kaiser Wilhelm Institut für Kohlenforschung* (Institute for Coal Research) had also brought him close to the Ruhr coal producers. To this group, assembled in Essen on 22 September, Fischer outlined the looming crisis, with an urgent plea to increase their production of by-product ammonia and coal-tar products, including toluene. He then asked his friend Duisberg to urge Bayer's partner firm, BASF, to develop its ammonia oxidation process, and to share this and related technologies with other firms. This BASF agreed to do, albeit reluctantly.[24]

By the end of September 1914, as BASF and other dye firms (again reluctantly) joined the explosives firms as co-founders of the KCA, BASF agreed to produce 5,000 tons of sodium nitrate from ammonia per month within six months – i.e., by April 1915.[25] This so-called 'saltpeter promise' represented a decisive shift toward war production, BASF's directors insisted that their first plant was an expedient, necessarily using imperfect technology that would have no commercial value in peacetime. Strongly supported by both Fischer and Haber, they requested subsidies for its construction. The Prussian War Ministry agreed to pay six million marks, and the *Landwirtschaftsministerium* [Ministry of Agriculture] added more for fertilizer production. Fischer also applied pressure on the Höchst Farbwerke, which had a process for producing nitrates from dilute by-product ammonia. In October 1914, while Bosch's team was feverishly transferring BASF's ammonia oxidation process from plan to full-scale production (bypassing a pilot plant), Höchst and Bayer (using an older BASF process) began building nitrate plants of a obsolescent type, which they expected to dismantle after the war. Similar plants were rushed to completion elsewhere in Germany and at the Blumau and Magyarovar state powder factories in Austria-Hungary.[26]

In the long run,, BASF and its Haber-Bosch ammonia would play a critical role in explosives production, if ammonia could be efficiently oxidized to nitric acid on a sufficiently large scale. As yet, only one small company, Zeche Lothringen, had a working plant for ammonia oxidation, but its scale (and that of similar processes) was limited by the need for an expensive platinum catalyst. BASF had, however, already identified a cheaper catalyst for its own plants, and the company was able to fulfil its promise. By mid-October, BASF's stockholders already perceived the long-term dual value of 'our ammonia manufacture', as likely to be of 'great significance. . .not only in peace but also in war', as well as a major source of future profits in either case.[27] Bosch's team rushed several new plants to completion, all without adequate testing, solving problems that arose as new plants were built. Hence, it was possible for BASF's partner, Agfa, to benefit from the improved technology in mid-to late 1915, when it finally agreed to produce nitrates.[28]

In November 1914, private companies were ordered to use chlorate-based explosives as 'substitutes' in non-military applications such as mining, in order to save nitrates for military use. By January 1915, the companies had complied.[29] However, nitrate mining explosives proved unsatisfactory for artillery shells, in part because they could not be poured but only packed in.[30] There were also frequent barrel detonations, especially when the Germans used unstable mixtures of ammonium nitrate and impure TNT with NG in cheap, easily-produced cast-iron shell-casings which the military arsenals tried to substitute for steel casings. By the time enough steel was available (summer 1915), Germany had millions of filled iron shells, whose explosives the chemical industry had then to recover. By this time, however, the Prussian *Militärversuchsamt* (Military Testing Office) at Spandau had also devised a '60/40' filling, a mix of TNT with ammonium nitrate in this ratio, which conserved toluene and could be poured, resulting in greater stability and reliability.[31]

THE AUSTRIAN CASE: COMPARATIVE ASPECTS

According to a postwar account prepared by a former official of the Austro-Hungarian War Ministry, the Austrian army entered the conflict far from prepared. The modernization of its artillery, begun in 1912, was incomplete; pending the adoption of new types and calibers, the army had minimal reserves for the older models. In mid-July 1914, the General Staff called for doubling the reserve of infantry propellants, and the Powder Department contracted with civilian firms (Poszony and Troisdorf), but the much smaller artillery reserve was thought to be adequate. Once the fighting began, Austria faced 'serious munitions crises' as neither Blumau nor civilian firms could cover even minimum demands for shells. Faced with its own crisis, Germany in August-September sent only thirty-two tons of TNT against the Austrian request for 1,000. By mid-October, with extensive losses of supplies as a result of early reverses on the Russian front, Austria was forced not only to halve its production of infantry ammunition, but also to strip supplies from the Italian border, leaving fortifications vulnerable when their erstwhile ally attacked in May 1915.[32]

Austria hoped to obtain resources from Germany, but the export of machine tools was banned, forcing the Austrians to seek these in neutral Switzerland. Like the Germans, they subsidised new and expanded plants in both state and civilian firms, including TNT works in Blumau and Poszony. Unlike the Germans, the Austrian War Ministry began by putting civilian plants under direct military supervision. Still, they could not catch up; as the generals' demands grew, so did the deficit. By the spring of 1915, their domestic explosives plants, including private companies, could still produce only 3.5 tons of TNT per day. By summer 1915, when they had reached a planned daily capacity of 16 tons (the amount needed in September 1914), the daily demand for high explosives had already reached 20 tons and rose to 30–35 by the end of the year. Only part of the deficit could be made up by using mixtures such as ammonal (ammonium nitrate, aluminium, and approximately 30% TNT), or by producing picric acid, for which a process was licensed from Bayer in October 1915.[33]

Much the same was true with propellant. In Germany, the private NC producers, with their 'dual-use' technologies, accrued advantages in increased output and overall efficiency. Having to produce for a commercial market evidently helped them fare better than the state factories, especially those in Austria. By subsidizing Nobel's expansion in Poszony and building new plants in Blumau and Magyarovar, the Austrian Powder Department had nearly doubled its output of NC by June 1915.[34] Even so, it was insufficient. In both Austria and Germany, the lack of propellants remained the chief limiting factor in artillery shell production during the first three years of the war.

In Austria, as in Germany, few senior officers or bureaucrats clearly understood the production capabilities of their chemical empires. But lacking a Rathenau, Austria created no KRA, and was slow to follow the German model of war corporations. In September 1914, Germany persuaded Austria to adopt this model of mobilization, leading in November to the first Austrian *Zentrale* (Centrals) to coordinate the production and use of strategic materials such as metals. Only the chemical industry remained 'decentralized'. The Austrian Powder Department followed the precedent of the German KCA, however, beginning confiscations of by-product ammonia, carbide products, and nitrate fertilizers in March 1915. These stocks proved insufficient, so by the end of the year, the Austrians contracted to receive regular shipments of nitrates as well as explosives from BASF, Bayer, and other sources.[35] Ultimately, both Central Powers endorsed a 'mixed' approach of state factories and private companies, with the Austrians putting more emphasis upon the former, despite their relative inefficiency. But for both, it was going to be a long, expensive war.

EXPANDING EXPLOSIVES PRODUCTION, 1914–15: PLANTS AND MATERIALS

If the events of August and September 1914 had not demonstrated clearly enough the need to multiply Germany's capacity for propellants and explosives, by late October there was unmistakeable evidence of shortages. The Prussian General Staff estimated that the artillery would need 1.25 million shells in November, but would fall short by 150,000 shells, even after reducing supplies for the navy and substituting NG for NC. This forced the arsenals to shift propellant from infantry bullets to artillery shells, until additional propellant plant could come on-line in February 1915.[36]

With time the critical factor, the Reich began pouring funds into construction subsidies. Of more than 113 million marks that went to state-owned factories during the first year of the war, more than half (60,840,350 marks) went to powder factories (mainly for propellants). An additional 78 million marks in outright subsidies went to privately-owned factories, of which powder factories such as Köln-Rottwell received more than a third (27 million marks), with most of the rest going to nitrate or nitric acid plants.[37] Of course, it was not possible simply to expand every factory; the Prussian state factories, in particular, were either too close to the Western Front (like Hanau, near Frankfurt on the Main) or, like Spandau, too close to the expanding city of Berlin. In November 1914, the War Ministry decided to build a huge new powder plant, to be located in a sparsely inhabited, agricultural district on the Plauener See in the Province of Brandenburg. Despite the necessary haste of construction, the plant buildings were clearly built to last; the Prussian War Ministry seized the opportunity offered by the war for a large, permanent increase in its productive capacities. Within six months, the factory began large-scale production of NC propellant, later adding NG as well.[38]

The vulnerability of its plant to air attack led Köln-Rottweil to look eastwards. The plant begun in July 1915 in Premnitz, Brandenburg, ultimately added 50% to their NC capacity, making them Germany's leading manufacturer of propellants. The chemical stabilizer they had developed, Centralit II, made it possible to dispense with imported camphor. But their most significant contribution came from the Düneberg plant (near Hamburg), which produced NG propellant for heavy artillery. Just before the war, Köln-Rottweil had developed a new solventless NG technology that shortened the drying process from months to days, thus greatly accelerating production and saving acetone.[39]

Germany's expanded capacities were still in the future on 18 December 1914, when the Prussian Ordnance Department assumed responsibility for coordinating the distribution of all German military and naval explosives (having taken responsibility for regulating their production on 30 August). Stocks of 'high quality explosives' (mainly TNT) were rationed. Substitutes were sought in chlorate-based mining explosives, but these proved unsuitable.[40]

However. there was another way – through the production of toxic gases. This was an area in which the dye companies could easily apply their technical expertise, and both Bayer and Höchst tested chemical shells in the autumn and winter of

1914–1915.[41] Bayer and Höchst's early work on chemical shells, together with their production of nitrates, thus became an industrial bridge to the military. Invited to join a commission appointed by the High Command in October 1914, Duisberg developed ties to the munitions industry and with Major (later Colonel) Max Bauer, one of the few technically-savvy members of the Prussian General Staff. In November 1914, ten days after the first large-scale (and ineffective) test of Bayer's chemical shells on the Western Front, Duisberg agreed that Bayer would produce TNT, albeit 'solely from patriotic interest'.[42] In December, Höchst, which was developing a competing irritant shell, and which had begun producing ammonium nitrate, agreed to do the same.[43]

This change of heart can be partly explained by the fact that, by the close of 1914, it was clear that the war would not end quickly. It followed that international dye markets would not recover in the near future, and that firms would have excess capacities on their hands, which they might as well turn to both military and financial advantage. Thus Höchst, whose dye production in 1915 was less than a quarter of its output in 1913, began producing explosives and irritants in converted dye works.[44] In any case, by the autumn of 1915, if the dye companies were to produce anything in quantity, it had to be war *materiel*, as the KRA had confiscated, or the KCA was rationing, critical raw materials, leaving little or nothing for the commercial economy.[45]

The process of transition entailed plant conversions and expansions, and the establishment of on-site shell-filling stations. The Government subsidized some, but not enough to satisfy the firms – which complained that the Ordnance Department set prices that were too low. Procurement contracts were irregular, and it was difficult to avoid bottlenecks and maintain production.[46]

The experience of Bayer and Höchst are worth looking at more closely. During 1915, Bayer converted many of its facilities to explosives production; built a few new but explicitly temporary plants for nitric acid and picric acid production; and added shell-filling stations in Flittard, some distance to the south of its main Leverkusen plant. During the next two years, Bayer's production of TNT (using an improved process for the use of sulphuric and nitric acid) increased from 100 tons to 1,300 tons per month.[47] Bayer thereby became Germany's largest single producer of TNT – or at least until, as Duisberg had feared, an explosion destroyed the Flittard facility in January 1917.[48] By then, however, Bayer was already building a permanent plant in a safer location.

In December 1914, Höchst's initial goal for TNT production was 200 tons per month. The Farbwerke based its process on the dinitrotoluene process of its smaller competitor, Griesheim-Elektron, which in August was the only dye company to agree to produce explosives. As the process had peacetime commercial value, Griesheim disclosed it reluctantly, and probably only after the intervention of Haber or Fischer. The first nitration plant went on-line in February, and a second building was added when the War Ministry raised its quota to 400 tons per month. This was achieved in stages by July 1915. By mid-1916, Höchst introduced a new process, which conserved resources by producing TNT directly from the 'mononitro' product, by-passing the ‘dinitro’ stage that had caused the original controversy. This was a major step towards a dedicated explosives technology. Producing 26,300 tons of TNT and 17,900 tons of other high explosives, the Höchst Farbwerke stood second only to Bayer by the end of the war.[49]

COMPLETING THE FIRST MOBILIZATION, 1916

By August 1916, the three dye companies (Bayer, Griesheim, and Höchst) had already developed more than twice the capacity to produce high explosives as the entire pre-war German explosives industry. They achieved this by converting idle plant and apparatus, with little new construction (except for government-subsidized nitrate plants). Their scientific and technical capabilities allowed them to make crystallized TNT that was purer (and thus safer) than the explosives industry’s product. They also produced the bulk of Germany’s picric acid, as well as virtually all of its ‘substitute explosives’ (mainly trinitroanisol and dinitrobenzene). These compounds were familiar from dye manufacture, so they could be dealt with more effectively, thus minimizing the disastrous explosions and poisonings that plagued explosives firms.[50]

While BASF at first avoided explosives production, they did make large quantities of synthetic ammonia and nitrates, along with other raw materials and intermediates, most of which went to military uses (including chlorine for chemical warfare). By 1916, they had perfected their ammonia oxidation process and were licensing it to other firms in Germany and Austria.[51] The expansion of their Oppau ammonia plant complex took place roughly in accord with pre-war plans, which the war simply accelerated. The same was not true of BASF’s decision to build a completely new ammonia plant at Leuna in central Germany, far from Oppau, whose production was suffering repeated disruptions by air raids.[52]

By March 1916, Germany had gained the capacity to produce 60,000 tons of nitrates and nitric acid per month from plants built mostly at BASF, Bayer, Griesheim-Elektron, Agfa, and Zeche Lothringen. Nevertheless, shortages of ammonia left almost half that capacity unused.[53] After months of negotiations, BASF contracted in April 1916 to build a new synthetic ammonia plant with a capacity of 36,000 tons, approximately doubling its total output. This seemed so risky that the company obtained an outright subsidy of 12 million marks from the Reich, plus a long-term loan of 64 million marks, in return for a commitment to share excess profits with the Reich and to share the market with other nitrogen producers.[54] When it began production in April 1917, the Leuna plant would lay the basis for further expansions in explosives production.

As a result of munitions production, the leading dye companies’ sales and profits, which dropped in 1914–15, now far exceeded pre-war levels. Even so, the firms would no doubt have gladly reconverted to peacetime production, had the war ended in 1916. Yet as with the Leuna project, military contracts led the dye industry to institutionalize their dual-use technologies and to accept the likelihood of mobilizing