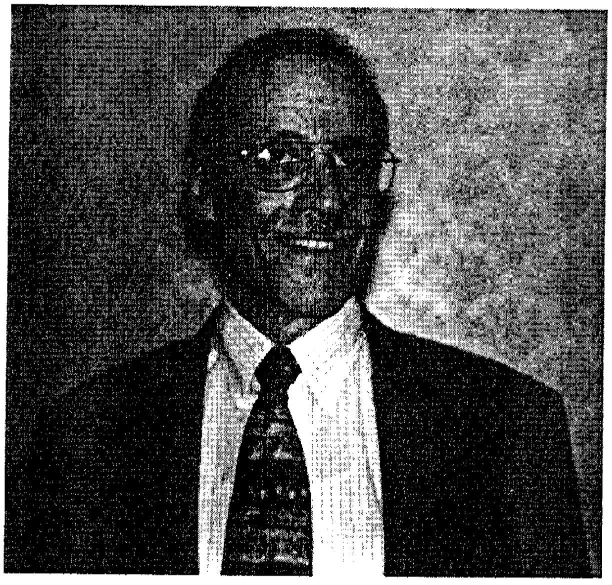
THE 1998 DEXTER AWARD ADDRESS

"FROM AN INSTRUMENT OF WAR TO AN INSTRUMENT OF THE LABORATORY: THE AFFINITIES CERTAINLY DO NOT CHANGE" CHEMISTS AND THE DEVELOPMENT OF MUNITIONS, 1785-1885

Seymour H. Mauskopf, Duke University

I am deeply pleased and honored to be this year's recipient of the Dexter Award. I might add that I was also somewhat taken aback when I was informed that I had been nominated, for I recognize that I have been something of a "prodigal son" regarding the history of chemistry. I left the field for about fifteen years to co-author a book with my life-long friend (and chair of this session) on a subject very different from the history of chemistry (1). Moreover, my research in the field has been somewhat unorthodox; I have sought out topics that have seemed interesting to me but had not attracted much scholarly attention, at least at the time I began my study. And the focus of these topics has been less on chemistry *per se* than on the interaction between chemistry and other domains of the physical sciences. It was therefore all the more heartening to have my research honored in this most signal way.

The quotation in the title of my talk, which I have also used as the epigraph of one of my publications, is taken from the "Cinquième mémoire sur la poudre à canon (2)"of Joseph-Louis Proust. It is important that I honor Proust by the use of one of his quotations because he has played an important role in the trajectory of my own research in the history of chemistry. Originally, I was interested in the aspect of his work for which he is best know—analytical chemistry and the Law of Definite Proportions—but with the unusual context of the relationship of Proust's Law to the concept of fixed mineral species in contemporary French crystallography and mineralogy. My orientation was traditional and "internalist" (to use the terminology of the time). Although I was led to give some attention to social and institutional contexts of Proust's career when I wrote my biographical essay on him for the *Dictionary of Scientific Biography*, I was still quite firmly focused on the Law of Definite Proportions there. For example, I remember quite well looking over



Seymour H. Mauskopf

quickly—and passing by—nine late and lengthy publications by Proust on "poudre à canon." However, while researching the DSB essay, I had secured a copy of two sets of lectures Proust had delivered during the years he spent in Spain (1785-1806), and datable internally to the first years of the nineteenth century. These lectures were the basis of my return to the history of chemistry in the 1980s. My orientation was now much more attuned to the context—one might say the problematic—of Proust as a practicing chemist in Spain, a backwater for chemistry throughout the eighteenth century. This led me to turn to Proust's applied chemistry, particularly his military chemistry, for he had been invited to Spain in 1785 to teach chemistry to the cadets of the Royal Artillery School in Segovia. After re-examining Proust's lectures, I noted that three or four of fifty lectures per set had been devoted to the chemistry of gunpowder. This caused me to return, with renewed interest, to his nine articles on "poudre à canon." The result was my article, "Chemistry and Cannon," published in *Technology and Culture* (3). The new focus on the chemistry of gunpowder led me back to Lavoisier and eighteenth-century chemical and physical analysis of gunpowder and its explosive reaction and, more recently, forward through the nineteenth century. A stay at the Beckman Center for the History of Chemistry helped me to initiate these studies, and grants from the Hagley Museum and the National Science Foundation have enabled me to pursue them in the interstices of a busy teaching and administrative schedule.

When I began my studies in the 1980s, I found the recent scholarly literature on the development of munitions and, particularly, on the role of scientists in this development, to be sparse, to say the least. There was, of course, Partington's classic *A History of Greek Fire and Gunpowder* (4). But, as the title implies, this book concentrates on the medieval and early modern period; it has very little to say about post-1700 developments. Another important study for the early modern period, if more distantly related to my focus, was Hall's *Ballistics in the Seventeenth Century* (5). But for the more recent period, there was a virtual absence of scholarship, the honorable exceptions proving the rule by their small number. These include Multhauf's study of Lavoisier's attempt to deal with the late eighteenth-century French problem of saltpeter supply (6) and Gillispie's discussion of Lavoisier's role in the *Régie des Poudres*, the French gunpowder administration, in his magisterial treatise (7).

In the past decade or so, the scholarly situation has improved noticeably. Steele has made an important contribution to the study of ballistics in the eighteenth century, centering around the mathematician and ballistics expert, Benjamin Robins (8). Bret has been producing comprehensive studies of the organizational changes in the French gunpowder administration and technical improvements in gunpowder making during the late eighteenth and early nineteenth century, giving particular attention to the role of chemists and scientific training (9). The inception of something like a coherent research group on the history of gunpowder is symptomized by the recent sessions devoted to it at the biannual meetings of ICOHTEC (10) and organized by Dr. Brenda Buchanan. One result was the publication of the first modern set of studies on gunpowder (11).

If a start has been made in the study of eighteenth- and early nineteenth-century munitions centering on gunpowder, the same can hardly yet be said about the development of organic high explosives in the later nineteenth and twentieth centuries. There have been two dissertations on the early development of smokeless powder but neither has been published (12). Studies by two of today's participants, Richard Rice, on Mendeleev and Russian munitions, and Jeffrey Johnson (and Roy MacLeod) on armaments on the eve of World War I, should initiate a sophisticated historical literature on this period.

The general historical problematic behind my studies of munitions is the question of how science and craft interacted—and came together—between the last quarter of the eighteenth and the last quarter of the nineteenth centuries. The subject of munitions is, of course, part of a much more general problematic concerning the science and technology of materials in this critical era.. My historical studies of munitions have focused on their use as military propellants, as opposed to other military uses (as fuses, rockets, explosive shells, etc.) or civilian uses. The traditional military propellant was gunpowder—"black powder"—the ancient mixture of saltpeter, sulfur, and charcoal. Although other, more explosive materials (like potassium chlorate) were considered as military propellants from time to time, the first really serious rival to gunpowder was "guncotton," a highly nitrated form of cellulose, made by treating cotton with concentrated nitric and sulfuric acid, discovered by Christian Friedrich Schönbein in 1846 (13). Nitrocellulose was to have a great and varied industrial future in the nineteenth and twentieth centuries (14), but what most notably attracted Schönbein's and his contemporaries' attention was the explosive property of guncotton. It was, weight for weight, more powerful than gunpowder and burned completely without producing smoke and, apparently, without fouling guns. Yet it took forty years to develop an effective nitrocellulose-based smokeless powder as a military propellant. What I want to focus on is a part of that story: the work of the English munitions chemist, Frederick Abel, who tried to "tame" guncotton for use as a military propellant in the 1860s. Abel achieved part of this objective by 1865 and appeared to be very optimistic about developing a smokeless military propellant from guncotton that would replace gunpowder; he abruptly abandoned this research in the late 1860s and instead embarked on a massive study of the function of gunpowder in guns of all calibers.

What follows is a "systemic" approach that I have found to be of heuristic value in conceptualizing the relationship of science to the development of military propellants (15). Of the three such systems (two "physical" and one "social") I shall focus on gunpowder to illustrate the physical systems.

I. The Systems

The first system is that of the propellants themselves. It includes the physical and chemical properties relevant to their functions as military propellants. In the case of gunpowder, it was through the pneumatic chemical discoveries and the general reconceptualization of chemical substances and reactions during the Chemical Revolution that the first approximation to the modern understanding of the chemistry of gunpowder came about. There was initial optimism that chemical understanding itself would lead fairly directly to improved gunpowder. But by the first part of the nineteenth century, it became apparent that physical characteristics of gunpowder— the size, shape and density of powder grains, the manner in which wood was converted into charcoal, the way in which the three components were "incorporated" together"—were at least as important as purely chemical considerations in determining the way gunpowder functioned. "Function" here is relational. So my second system is the relation between the propellant and the instrumental complex in which it operates, in this case, of course, the guns and their projectiles (bullets, cannon balls and shells). Here a number of different issues arose. One was whether military propellants functioned the same way in field guns as they did in laboratory test tubes. The issue is brought out well in Proust's epigraph: "From and instrument of war to an instrument of the laboratory, the affinities certainly do not change." Proust, more than any other chemist, attempted to develop gunpowder chemistry into a useful military application; the context of the quotation was his assertion that the saturation proportion between charcoal and saltpeter, determined in the laboratory, was precisely the same as that in a gun (16).

Another issue concerned the relationship of changes in the propellant to guns and projectiles (and vice versa). It was the introduction of an English-derived powerful gunpowder into France in the early 1820s, which was soon blasting test cannon out of commission, that led French investigators to concentrate on studying the physical parameters of gunpowder in order to control its ballistic force. By the late 1850s, attention was turned to major changes in all aspects of guns: the materials out of which they were made, the mechanism of loading and, above all, their power. It now became more important than ever to determine and control the rate at which the ballistic force of the propellant was released and built up in gun bores. Although French investigators had been moving towards this recognition earlier in the century, it was an American, T. J. Rodman, who seems to have been the first to determine the relationship between powder grain (or cartridge) size, burn rate, and gun bore pressure. What enabled Rodman to come to his insight was his invention of an ingenious device, the Rodman gauge, to measure pressure as the projectile moved down the gun bore under the impulse of gunpowder explosion. Rodman also made important improvements in cannon casting and was particularly concerned with controlling pressure in his large, smoothbore "columbiad" cannon. The Rodman gauge and Rodman's general principle, that the size and shape of powder grains had to be adapted to the caliber of the gun in which they were used, were rapidly accepted throughout Europe (17).

In 1857, at almost exactly the same time that Rodman was developing practical means of measuring and controlling gun bore pressure, a more theoretical and laboratory-based advance in determining explosion pressure and other physical parameters was being made in Germany. Its authors were the chemist Robert Bunsen and the Russian artillerist and munitions chemist, Leon Schischkoff. The basis of their determination was an unprecedentedly detailed analysis of the products of gunpowder explosion and a calorimetric measurement of the heat produced from it. From this data, they applied thermochemical considerations, only then recently come into use, to determine the temperature of the explosion and, from that, the pressure and the theoretical work (18). Neither Bunsen nor Schischkoff developed this research further, but it was hailed as "the model for all subsequent research on this subject (19)," and taken by all munitions investigators as the watershed in the scientific understanding of explosion and detonation.

The two systems outlined so far have dealt with the physical materials of military propellants and their relationship to guns and projectiles. However, there is one other system to which I would like to give some attention: that dealing with the social contexts of the scientific investigators themselves and the nature and "style" of their investigations. It would involve such parameters as national scientific tradition, scientific and technological formation, motivation for investigation, patronage/employment, and relationship to the military propellant manufacture. My renewed and reoriented interest in Proust was focused on these parameters, and I have since extended my purview to the French, English, and American investigative traditions in the eighteenth and nineteenth centuries. This third system is illustrated with a brief overview of the development of munitions research in France and England in these centuries.

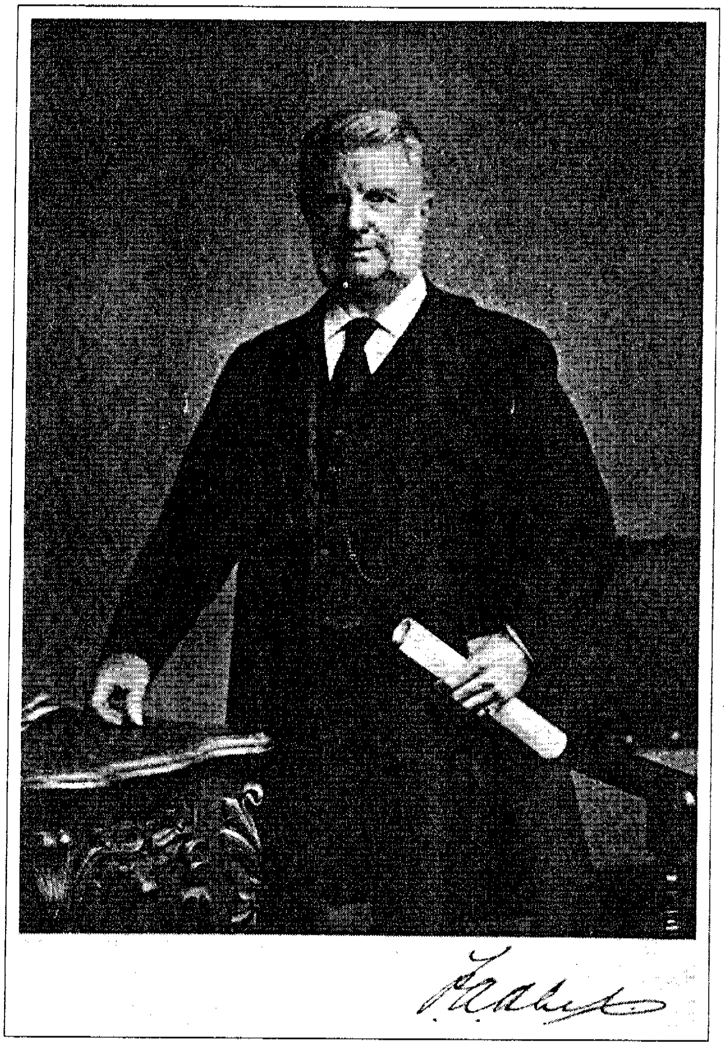
With the appointment of Lavoisier in 1775 as one of the four *régisseurs des poudres* and *de facto* chief of the *Régie des poudres*, the reformed French gunpowder administration, scientists were introduced into the industry as they had already been in other industries such as dyeing and metallurgy (20). Until then, gunpowder making was a craft in France and elsewhere; the detailed rules for gunpowder production and testing that had been laid down in France in 1686 were, to the best of my knowledge, generated without scientific input. Although Lavoisier's best known activity as a *régisseur* was his attempt to develop saltpeter production, he also instituted tests concerning many aspects of gunpowder production: which wood source produced the best charcoal for gunpowder; which process of trituration and incorporation (stamping mills or edge runner wheels) was best, etc. (21). He also instituted what Gillispie has termed "scientific administration (22)." This included the scientific training of all future *commissaires des poudres*, the directors of French powder mills. One recipient of this training was E. I. Dupont.

The institutionalization of science in the French gunpowder administration survived the vicissitudes of French politics throughout the nineteenth century. However, there ensued something of a disciplinary dialectic in the investigative tradition concerning munitions in the course of this century. During the French Revolution, chemists were in its forefront; but the Napoleonic regime ordained that all gunpowder administrators be graduates of the *École polytechnique.* From that time through the Franco-Prussian War the primary disciplinary orientation was physical rather than chemical, even though such distinguished chemists as Gay-Lussac and Pélouze served on the *Comité consultatif* of the powder administration, established soon after the *Restauration* (23). I would suggest that this change in research orientation represented the intersection of two systems in my mode of analysis: the physical system of propellant and gun (the crisis engendered by the introduction of a new type of more powerful powder ca. 1820, mentioned earlier) and, in the social system of the scientific investigator, the requirement of an *École polytechnique* background in military engineering. It should also be mentioned that contemporary American munitions investigators, such as Rodman, received analogous training at West Point and carried out research in a style similar to that of the *polytechniciens.*

The period after the Franco-Prussian War was marked by the collaborative activities of the chemist, Marcellin Berthelot, with the *polytechniciens*, Émile Sarrau and Paul Vieille. This great trio of French investigators brought the chemical and the physical traditions into synthesis through the union of thermodynamics and thermochemistry, in part because of the pioneering paper of Bunsen and Schischkoff. It should be noted that munitions production and research were solely a state activity and, for much of the century, under the administrative control of the Ministry of War (24).

In England there appears to have been no comparably coherent tradition of institutionalized scientific involvement in munitions prior to the appearance on the scene of Frederick Abel (1827-1902). A charter student (and one of the most esteemed) of W. A. Hofmann at the Royal College of Chemistry, Abel left the college in 1851 to take a post as Demonstrator of Chemistry at St. Bartholomew's Hospital, London. Two years later he secured the position of Lecturer in Chemistry at the Royal Military Academy, Woolwich, upon the retirement of Faraday. Founded in 1741 to train cadets in artillery and engineering, the Royal Military Academy had instituted a scientific and technical curriculum in the 1770s and had some distinguished faculty, such as the mathematician and ballistics expert, Charles Hutton; but, to the best of my knowledge, Faraday was the first Professor of Chemistry. Faraday had delivered an annual course of lectures on chemistry and related subjects to the cadets from 1830 to 1851 (25). Abel moved to the Woolwich Arsenal and soon began to carve out a new professional niche in munitions as Scientific Advisor to the War Office (1854), a position soon elevated to "Chemist of the War Department (26)."

When Abel moved to Woolwich, "there was some uncertainty as to his duties (27)." There did exist a Royal Laboratory at Woolwich dating back to the seventeenth century (28), in which, after 1783, the manufacture of military powder at the government powder mills was supervised (29). In the late eighteenth and early nineteenth centuries, experiments very similar to the contemporary ones of Lavoisier and Proust were carried out at the Royal Laboratory under the direction of William Congreve (1743-1814) to ameliorate the quality of gunpowder, which had sunk to a deplorable level (30). In the words of Congreve's student (31):



F. W. Abell

> Through his systematic practical research into the manufacture of gunpowder and his ability to enact change Congreve had transformed British powder from one of notorious quality to a world standard.

The French certainly shared this positive view of British powder in the post-Napoleonic period. However, it does not appear that the investigative activities at the Royal Laboratory were pursued after Waterloo. I certainly know of nothing in England before the late 1850s comparable to the investigative tradition of the French *polytechniciens* of the period.

The early 1850s were certainly propitious for a scientist to develop a career in munitions. Abel had scarcely settled into his position when the post-Napoleonic détente gave way to the Crimean War. In this first multinational war in forty years, the changes in artillery were very apparent, as the opening lines of the official report of an American military observer testified (32):

> The introduction of the long gun to fire shells horizontally,both for land and sea service, with a tendency to increase the calibers; and of the rifle, with various modificationsfor all small arms, may now be considered as the settled policy and practice of all the military powers of Europe. (Moreover), an attempt is being made by several of the European powers to adopt the rifle principle to the heaviest artillery.

These changes "spurred England into action...to revolutionize the whole field of artillery (33)" during the rest of Abel's career.

Institutional changes in the British military establishment also began in the mid-1850s with the establishment of a consolidated War Department. By the late 1850s, the continued tumultuous international scene, combined with concern over the rapid changes in artillery, led to the enlargement of the facilities of the governmental powder mills at Waltham Abbey (34) and to the establishment of ongoing committees to investigate both the new guns and their ammunition requirements: in 1858, the Ordnance Select Committee, subcommittees of which studied gunpowder and guncotton; and, in 1869, a Committee on Gunpowder and Explosive Substances (35). Abel either served directly on the committee, as he did on the Committee on Gunpowder and Explosives throughout its existence, or he served in an advisory capacity as Chemist of the War Department.

II. Abel and Guncotton

Abel described his entry into the field of guncotton (36):

> Early in 1863, by desire of the Secretary of State for War, I entered upon a detailed investigation of the manufacture of guncotton, the composition of the material when produced upon an extensive scale, its behavior under circumstances favourable to its change, and other subjects relating to the chemical history of this remarkable body.

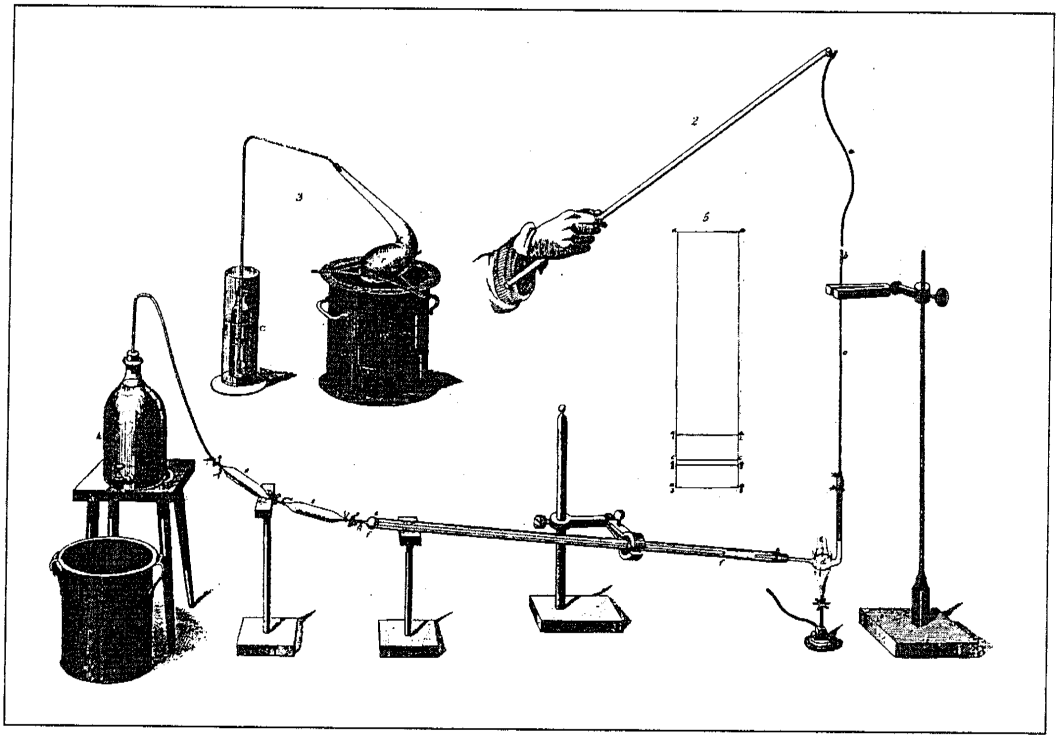
When Abel took up the investigation of guncotton as a military propellant, it had already sustained almost two decades of a very checkered history since its discovery in 1846. News of favorable behavior in the field was mixed with reports of disastrous explosions at production sites, leading to prohibition of manufacturing and testing. The question of the stability of guncotton was thus of the utmost practical importance. A few years after Schönbein's discovery, and after most governments had abandoned the investigation of guncotton for military use and had even banned its production, a method of producing what promised to be a pure and stable guncotton was developed by an Austrian artillery officer, Wilhelm Von Lenk. Von Lenk refined each step in the procedure for making guncotton: he used rovings of cotton (long skeins of yarn for textile manufacture) as the basic material, which he steeped in a mixture of the strongest commercial nitric and sulfuric acid for forty eight hours. After a preliminary cleansing, the modified yarn was subjected to a running water bath (in a stream) for at least three weeks, dried, and finally immersed in a weak solution of potash and water-glass (37). The resultant product appeared to be remarkably uniform and stable (38). In 1853, Von Lenk obtained leave from the Austrian government to establish a factory for the production of guncotton. Although opposed by some artillerists, Von Lenk succeeded, by the early 1860s, in securing the right to manufacture guncotton in Austria and for the adoption of guncotton into the Austrian artillery service. It was at this moment, when "..it was considered as definitively settled that Gun-cotton would before long be introduced into the service in place of gunpowder, for artillery purposes (39)," that the Austrian government permitted Von Lenk to communicate his method to the British (40). Although the British had their own earlier experience with a major explosion at a guncotton factory, they were impressed with Von Lenk's improved guncotton and the promise it afforded to replace gunpowder (41). Von Lenk himself came to England in 1863 to report on his procedure to a blue-ribbon committee of the British Association for the Advancement of Science (BAAS). Production was begun by Messrs. Thomas Prentice and Co. of Stowmarket.

Despite favorable reports like the one from the BAAS committee, studies in France and elsewhere challenged the claims about safety and stability of Von Lenk's guncotton. In fact, there was an explosion at the Stowmarket factory soon after production of guncotton commenced (42). As a result of these positive and negative developments, Abel took up the study of guncotton and, in the mid 1860s, performed the most comprehensive and detailed experiments up to that time. Initially, he shared the optimism of the BAAS committee about the feasibility of substituting guncotton for gunpowder.

In terms of my mode of analysis, there were challenges facing the adoption of guncotton as a military propellant that pertained both to its material nature and to its function in the system of propellant and gun. Abel's research was primarily focused on the first of these challenges. It involved considerations of the chemical nature of the material and of the means to promote and insure purity and stability. Although it was recognized early on that nitrocellulose was formed by a process of nitration with the release of water, and that higher degrees of nitration produced more explosive materials, there was great uncertainty and considerable controversy as to how many chemical varieties of nitrocellulose existed and how stable they were. This last issue was obviously of special importance for guncotton. In England it had become accepted that there were three forms of nitrocellulose, corresponding to the introduction of one, two, or three units of nitration in the cellulose. Guncotton, the most highly nitrated form, was in fact trinitrocellulose. The three forms were distinguishable by their differential solubilities in ether-alcohol mixtures. However, this analysis was challenged on the continent, and Paul Vieille could write as late as the early 1880s, shortly before he developed Poudre B (43):

> Very different formulae have been suggested to represent the composition of the nitro-products derived from celluloses, and particularly the composition of products of maximum and minimum nitration. These products were, moreover, obtained by processes differing at the same time both as to temperature of reaction, concentration of acids, and the nature of the sulpho-nitric mixture employed. Therefore the results were not susceptible of any general interpretation.

Abel subscribed to the English chemical view of nitrocellulose and satisfied himself that Von Lenk's procedure produced a distinct and stable chemical substance, trinitrocellulose. But this view (and the stability of Von Lenk's product) had been challenged by a number of continental researchers, the most formidable of whom was the French chemist, Jules Pélouze, whose analysis of guncotton signaled a lower level of nitration than that indicated by Abel's formula for trinitrocellulose (44). Abel argued that the results obtained by Pélouze were the outcome of incomplete nitration of the cotton, either because of an insufficient period of acid digestion, the use of too weak an acid or an insufficient amount of acid, or choice of a low quality cotton. As an *experimentum crucis*, Abel showed that subjecting the less highly nitrated cellulose to a second acid digestion raised its weight to the level Abel had obtained for guncotton. At that level, the product was far more stable than the French and others had claimed. Nevertheless, Abel admitted that even he had not achieved complete nitration; there was always a small residue of lower-level nitrocellulose products. It was to these that the French attributed guncotton's dangerous instability, especially upon exposure to light and heat. Abel, in fact, found the very opposite; indeed, the addition of dilute collodion (a less highly nitrated cellulose than guncotton) actually seemed to promote stability "probably because the fibres are partially sealed, or in some other way mechanically protected (45)." Of more concern, Abel discovered, was the presence of partially oxidized organic impurities present in the cotton. It was the decomposition of these to which Abel assigned the cause of the instability even in Von Lenk's product. To remove these impurities, Abel recommended a final washing of guncotton with an alkaline carbonate.

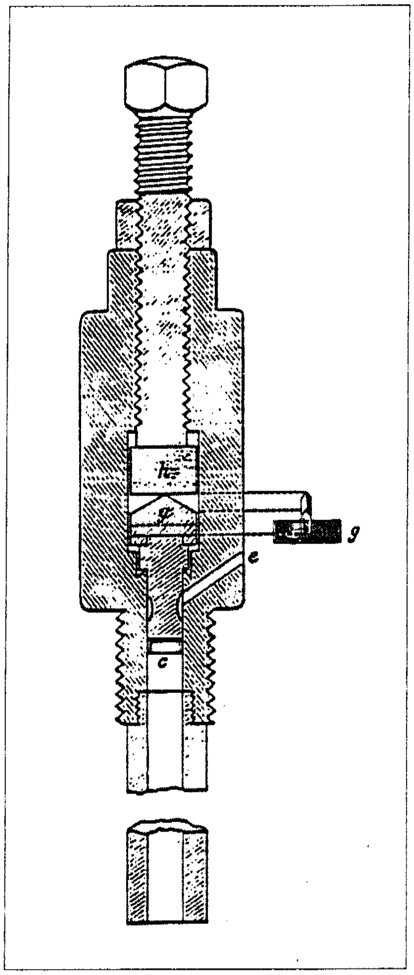


The apparatus of Bunsen and Schischkoff from "On the Chemical Theory of Gunpowder"

Even more important than the chemistry was a physical procedure instituted by Abel: pulping the cotton before nitration "according to the method commonly employed for converting rags into paper (46)." Because of the tubular structure of cotton fiber, impurities survived even the most rigorous washings; by destroying this capillary structure and agitating the pulp in a large volume of slightly alkaline solution, an exceptionally pure and stable guncotton was obtained. Abel's pulping procedure became standard for the rest of the century. Moreover, if immersed in water or impregnated with moisture, guncotton seemed all but indestructible and certainly safer to handle and transport than gunpowder.

The question of guncotton's stability was very important but only a part of the larger issue of whether guncotton could be substituted for gunpowder as a military propellant (47). In the mid 1860s, that certainly remained the *desideratum* of military study of the material. But, regarding the functioning of guncotton in the field, the main problem was the rapidity and force of guncotton detonation. Von Lenk had attempted to control its rate of burn by twisting skeins of guncotton around hollow wooden cylinders. Although at first very promising (48), this soon proved to be ineffective in guns (49). However, the development of the pulping process and of procedures to dilute guncotton with more inert substances (e.g. less highly nitrated forms of nitrocellulose or even cotton) (50) seemed to offer new possibilities for controlling the force of guncotton by converting the pulp by pressure into solid masses of any suitable form or density, as was done with gunpowder (51):

> Some results, which are admitted by the most sceptical as encouraging, have already been arrived at, in the systematic course of experiments which are in progress, with the object of applying the methods of regulation...to the reduction of guncotton to a safe form for artillery purposes. Its arrangement in a form suitable for small arms is a much less difficult problem, which may be considered as approaching a perfect solution.



Rodman gauge

This optimistic scenario for guncotton as a military propellant was taken from the second talk Abel presented to the members of the Royal Institution in 1866. There is a third in this series entitled "On the More Important Substitutes for Gunpowder," given in May, 1872. The disheartening mood of this one regarding guncotton is sounded in the opening line (52):

> No progress has been made since 1868 in the application of explosive agents, other than gunpowder, to artillery purposes.

Abel noted that even the very promising cartridges for small arms sporting guns were "wanting much in uniformity" although they were free from smoke and gun fouling (53). He did suggest an improvement: compressing guncotton pulp under pressure and impregnating the compressed mass with an inert material such as paraffin, stearine, or india rubber to control the speed and violence of detonation. This had been successfully tested in small arms and rifles but "the experiments upon this system of preparing cartridges have not been pursued for the last four years (54)." Abel also mentioned a guncotton diluted with sugar and saltpeter which had shown "considerable success" in "repeated trials," and "Shultze powder," devised by a Prussian artillery officer in the mid 1860s by nitrating wood shavings or sawdust and mixing the result with saltpeter. However, Abel characterized this latter as an "imperfect kind of gun-cotton," that was "scarcely bidding fair to compete in uniformity of action with the excellent gunpowder now manufactured for breech-loading rifles (55)."

By 1868, then, Abel seems effectively to have ceased experimentation on guncotton as a substitute propellant for gunpowder. Research did continue for developing other military uses, for example, in bursting shells, torpedoes, and blasting agents. What had caused him to abandon so precipitously a research topic that had looked so promising? Such accounts as there are of Abel's research claim that he abandoned research on guncotton because he was unable to get it under complete control, especially concerning its rate and temperature of burning (56). Although this is true enough, I doubt that this alone explains Abel's abrupt cessation of research. However, Abel himself gave an explanation in a comprehensive account on munitions and explosives research delivered to the British Association for the Advancement of Science in 1871 (57):

> A very decided advance had been made towards the successful employment of guncotton in field guns before the Government Committee on Guncotton ceased to exist in 1868; and if the experiments on this subject, which were then suspended, as well as those relating to the employment of guncotton in military small arms, have not been resumed, it is only because the Committee on Explosives, to whom the further investigation of these matters has been entrusted, has hitherto been fully occupied with the more immediate important investigations relating to gunpowder.

Under the auspices of this committee, Abel himself had returned to focus his research on gunpowder. Over a decade, starting in 1868, in tandem with Andrew Noble, a polymath in gunnery and munitions, Abel pursued research on the function of gunpowder in guns of all calibers that was the most comprehensive ever carried out (58).

The context for Abel's return to gunpowder research lay in the developments of the decade before, associated with T.J. Rodman and with Bunsen and Schischkoff. These offered researchers unprecedented opportunities to understand and control both interior and exterior ballistics through the determination, measurement, and control of the ballistic force of gunpowder explosion. Guided by the scientific paradigm of Bunsen and Schischkoff and employing Rodman's gun bore pressure data and an improved version of his pressure gauge (the crusher gauge), Noble and Abel carried out systematic and comprehensive chemical and physical tests. As Abel himself stated (59):

> Well, at about the time that Rodman was working at this subject in America, and Bunsen in Germany, we English. once more bestirred ourselves in this matter, and set to work in earnest to improve gunpowder, and to advance the knowledge regarding its action and the conditions to be fulfilled for bringing its force under better control.

In order to overcome the challenge of approximating field conditions of a large gun bore in the laboratory, the investigators made use of an "explosion apparatus" designed by Noble. They also did comparative tests in guns of all calibers to tabulate the total work realized per lb. of powder for every gun, charge, and description of powder in the English service. From this tabulation, it was possible to deduce the velocity of any standard projectile in any standard large gun (60). As for the practical impact of their work (61):

> The results of their [Noble and Abel] labours, as time went on, was to produce much slower-burning forms of gunpowder than those which had found favour in 1870 and earlier. The production of these new types of powder characterized by gradual combustion exercized a far-reaching influence over what came to be regarded as the correct form of built-up gun construction.

In the evaluation of technological change, there is, I think, a natural tendency to read backwards from some *ex post facto* state of affairs. In this case, it would be the supplanting of gunpowder by a guncotton-based military smokeless powder. In fact, this began in the mid-1880s after the first one, "*poudre B*," was developed by Paul Vieille. By the end of the decade, variants (sometimes with nitroglycerine as well as guncotton) had been devised in all European countries and in the United States. Abel himself came out of retirement to devise one of the best, "cordite," in collaboration with James Dewar. The age of gunpowder gave way to that of high-explosive, smokeless powder. But in the late 1860s, gunpowder itself was very much a technology undergoing transformation and improvement. Abel's disparagement of Schultze's powder in comparison with "the excellent gunpowder now manufactured for breech-loading rifles" certainly indicates that Abel saw gunpowder in this light. Therefore, to interpret Abel's abandonment of guncotton research as simply a case of failure to control it as a military propellant is to miss the real advances that had been and were being made in its principal competitor, gunpowder, in its systemic relationship to changes in gunnery. Although gunpowder did lack the attractive feature of smokelessness, these advances had made it superior to guncotton in most other ways. Corroboration for this view is found in a popular lecture by Abel on "gun cotton" in 1873 (62):

> Gun cotton can be made more controllable for small arm purposes, but we have not yet been able to tame it sufficiently to allow of its being used with any degree of confidence in great guns. The attempts made up to the present time to moderate its action have only been partially successful in the smallest cannon, and there appears no prospect whatever of our taming it sufficiently for use in larger guns.
>
> I have here a diagram representing different kinds of gunpowder now in use, and here are also specimens of the different descriptions used for heavy artillery. Twenty years ago these small grains of powder represented the cannon powder in universal use. Then we began to build larger guns, and after some time this larger-grained powder was introduced as a safer powder to use in such guns. Powder burns rapidly in proportion to the size and density of its grains or masses, and the fine powder was found to act injuriously upon the big guns, although we had then only got up to the 100-pounder Armstrong gun. We considered we had taken a great stride when we passed from that small grain to this larger grain; but rapid progress was made in developing the size of our artillery, and it was found necessary to pass from grains of powder to pellets or pebbles and prisms of powder — that is to say, we converted powder into masses which burned, comparatively speaking, very slowly when ignited in the air, but which, when ignited in charges of 80 to 120 lbs., still burned very rapidly in the gun, and produced occasionally an unduly violent action, which it was desirable to moderate. We are talking of building very much bigger guns than

> the 35-ton gun, which requires a charge of powder weighing 120 lbs., and we shall therefore want a much tamer powder for those guns. I am consequently pretty certain that, as far as big guns are concerned, gun cotton has no future.

To carry out a complete comparison, one would have to factor in analyses of the other systems outlined above: the function of these incipient smokeless powders in military rifles and guns, the challenges of manufacturing guncotton (the safety problems were not completely solved in the 1870s), and above all, perhaps, the social and professional context of Abel's employment as War Office chemist. Abel was certainly not a completely free agent in his choice of research subjects (63).

III. Towards Smokeless Powder

In conclusion, I suggest that a set of analyses similar to the ones that have been put forth in the preceding parts of this paper could be extended to the revolutionary advent of smokeless powder in the 1880s and 1890s. The scheme can be followed with specific examples below.

The propellant system: guncotton to smokeless powders. Abel had succeeded in purifying and stabilizing guncotton by his method of pulping the material but had apparently ceased his research before he had achieved reliable control of its ballistic force in the military gun. This was accomplished by Paul Vieille by colloiding a mixture of guncotton and a less highly nitrated form of nitrocellulose in a suitable solvent under high pressure (64). This resulted in "plasticizing" the nitrocellulose and thus destroying completely its fibrous nature. Although Vieille was the first to succeed in producing a military smokeless powder, his success was not without precedent or context. The influence of two earlier developments on Vieille remains veiled: (1) various near colloidal powders produced as "sporting powders" in the early 1880s, about which a contemporary observer wrote, "The French military authorities took early note of their results (65)." (2) The invention of celluloid by the American, John Wesley Hyatt, in 1870, in his quest for a material from which to fashion the perfect billiard ball. Celluloid was a colloid of pyroxyline (collodion) achieved by subjecting a mixture of pyroxyline and camphor to heat and intense pressure (66). The American munitions chemist, Charles Munroe, implied a connection between the procedure for making celluloid and Vieille's for producing smokeless powder, which has recently been reiterated by Norman (67). (3) Finally, there was Alfred Nobel's invention of gelatinized nitroglycerine blasting explosive in 1875; this soon led Nobel to explore "double" smokeless powders (nitroglycerine/nitrocellulose base), resulting in the invention of "ballistite" shortly after Vieille's breakthrough.

The propellant-gun-projectile system: shotguns to military weapons. As already implied, in the 1870s and 1880s, there existed a market for guncotton where its characteristic of smokelessness was most attractive: as a propellant for sportsmen. In addition to Schultze's powder, about thirty other compositions of pulped guncotton with oxidizing agents such as potassium or barium nitrate, or combustible diluents and binding agents sugar, cellulose, charcoal or sulfur, and gums, resins or paraffin, appeared on the commercial market. None was reliable enough for military use but served the sportsmen well enough to be commercially successful (68). A good technological analogy to the role of smokeless sporting powders of the 1870s and early 1880s is that of the transistor between its invention and the development of the microchip. In this interim, the transistor found a multitude of commercial uses in radio, hearing aids, etc.

By the 1880s, a demand for a smokeless powder was developing in the military with the appearance of powerful breech-loading, rapid-firing rifles, and machine guns. Also, the caliber of military small arms was growing smaller as the projectiles became lighter and more elongated for more precise trajectories, necessitating a more powerful propellant than gunpowder. Thus, the advantages of a powerful, nonfouling, smokeless powder became insistent (69). Already in France, smokeless powders based on picric acid had been developed, one of which (Brugère's powder) gave good results in the Chassepôt rifle and continued to be tested until it was superseded by Vieille's Poudre B (70).

The system of the scientific investigators: research style of Paul Vieille. As mentioned earlier, Paul Vieille (1854-1834) was a graduate of the *École polytechnique*. He then joined the corps of engineers of the gunpowder service, where he worked closely at the *Depôt [later Laboratoire] central des Poudres et Salpêtres* with Émile Sarrau, another *polytechnicien*, and with the chemist, Marcellin Berthelot, who had assumed a leading role in munitions research and organization after the Franco-Prussian War (71). Rice has characterized Vieille as an "engineer and explosives expert" in contrast to academic chemists like Mendeleev. He sees this contrast expressed in the type of smokeless powder each developed: Vieille was willing to use chemically inhomogenous explosive mixtures, whereas Mendeleev searched for chemical homogeneity (72). I shall conclude by expanding a bit on Rice's perceptive observation. I would argue that Vieille's research, often carried out in tandem with Sarrau, represented the coming together of virtually all of the research traditions of military munitions described above. It was the culmination of the French physicalist tradition of the *polytechnicien* military engineers. But it also built on the research of Rodman and of Noble and Abel, as well as the thermochemical tradition of Bunsen and Schischkoff, and of Berthelot.

This synthesis of research methodology was exemplified by Vieille's invention of the "bomb calorimeter" (*bombe calorimétrique*) in 1878. Essentially a refinement of Noble's "explosive apparatus (73)," it was employed by Vieille in the early 1880s to study systematically the explosions not only of black powder but also of guncotton. Critical to these studies was another refinement made by Vieille: to the crusher gauge, which he used to measure explosion pressure, he attached a recording device that could indicate pressure change throughout the course of the explosion (74). At this very time, Vieille was carrying out comprehensive studies of the chemistry of nitrocellulose and what proved to be the classic study of the manner in which explosives of all types actually burned (75).

Although the exact route Vieille took to the development of smokeless powder remains shrouded in mystery, it is likely that all of these investigations played their part in leading him to *Poudre B.* To illustrate this, I shall end by quoting from the most recent of the very few studies devoted to the background of this critical invention (76):

> These experiments [with the bomb calorimeter] displayed correlation between the development of pressure of a given explosion and two characteristics of that substance: its compactness and its geometrical shape. Vieille thus saw why guncotton and other nitrocelluloses which normally have a fibrous structure exploded in a closed vessel with such an extreme rapidity as to render impossible use in a military gun. He conceived that guncotton would be susceptible to burn at a moderate speed after having been put into a sufficiently compact form. This is what he did in "gelatinizing" it by means of a volatile dissolvant, which could afterwards be eliminated. The material, in the form of thin plates, had a speed of combustion that could be regulated by modifying their [the plates'] thickness.

REFERENCES AND NOTES

1. S. H. Mauskopf and M. R. McVaugh, *The Elusive Science: Origins of Experimental Psychical Research, 1915-1940*, Johns Hopkins University Press, Baltimore, MD, 1980.
2. J-L. Proust, "Cinquième mémoire sur la poudre à canon," *J. phys. chim. et d'histoire naturelle*, **1811**, *73*, 390.
3. S. H. Mauskopf, "Chemistry and Cannon: J.-L. Proust and Gunpowder Analysis," *Technology and Culture*, **1990**, *31*, 398-426.
4. J. R. Partington, *A History of Greek Fire and Gundpowder*, W. Heffer, Cambridge, 1960. Recently, Hall has published a magisterial work on firearms and gunpowder in the early modern period: B. S. Hall, *Weapons and Warfare in Renaissance Europe*, Johns Hopkins University Press, Baltimore, 1997.
5. A. R. Hall, *Ballistics in the Seventeenth Century: A Study in the Relations of Science and War with Reference Principally to England*, Cambridge University Press, Cambridge, 1952.
6. R. P. Multhauf, "The French Crash Program for Saltpeter Production, 1776-1794," *Technology and Culture*, **1971**, *12*, 163-181.
7. C. C. Gillispie, *Science and Polity in France at the End of the Old Regime*, Princeton University Press, Princeton, NJ, 1980, Ch. 1.6, 50-73. I would hazard a suggestion for a reason for this inhibition of scholarship on modern munitions. It has to do with the paradigm that has dominated discussion of early modern military history: that of the "military revolution." Although military historians have disagreed intensely about what this "revolution" was (or, indeed, whether it was a single revolution), there has been agreement over the general point that, although the introduction of firearms was central to the early modern military transformation, their development had largely run its course by the end of the seventeenth century and was not to undergo major change until the second half of the nineteenth century. Hence, munitions must also have been a static (and historically uninteresting) technology in this period. This overlooks, among other things, the development of the role of science and science-related technology in the production and improvement of munitions.
8. B. D. Steele, "Muskets and Pendulums: Benjamin Robins, Leonhard Euler, and the Ballistics Revolution," *Technology and Culture*, **1994**, *35*, 348-382.
9. The most recent is P. Bret, *Lavoisier et L'Éncyclopédie méthodique: Le manuscrit des régisseurs des Poudres et salpêtres pour le Dictionnaire de l'Artillerie (1787)*, Leo S. Olschki, Firenze, 1997.
10. "Gunpowder Section," International Committee for the History of Technology. Twenty one papers were presented at this section at the 1996 ICOHTEC meeting in Budapest.
11. B. J. Buchanan, Ed., *Gunpowder: The History of an International Technology*, Bath University Press, Bath,

1996. Mention should also be made of the pioneering book on English powder-making: J. West. *Gunpowder, government, and war in the mid-eighteenth century* [Royal Historical Society, London], Boydell Press, Woodbridge, Suffolk and Rochester, NY, 1991.

12. S. L. George, The Origins and Discovery of the First Nitrated Organic Explosives, Ph.D. Thesis, University of Wisconsin, Madison, 1977; S. L. Norman, Guncotton to Smokeless Powder: The Development of Nitrocellulose as a Military Explosive, 1845-1929, Ph.D. Thesis, Brown University, 1988.
13. The highly explosive guncotton, unlike collodion and other less highly nitrated forms, is insoluble in alcohol and ether.
14. See E. C. Worden, *Nitrocellulose Industry*, 2 vol., D. Van Nostrand, New York 1911; R. Friedel, *Pioneer Plastic: The Making and Selling of Celluloid*, University of Wisconsin Press, Madison, WI, 1983.
15. For background in the historiography of technology, see W. E. Bijker, T. P. Hughes, and T. J. Pinch, Ed., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, MIT Press, Cambridge, MA, 1987.
16. Ref. 15, Footnote 1.
17. See S. H. Mauskopf, "From Rumford to Rodman: The Scientific Study of the Physical Characteristics of Gunpowder in the First Part of the Nineteenth Century," in B. J. Buchanan, Ed., *Gunpowder: The History of an International Technology*, Bath University Press, Bath, 1996, 285-289.
18. R. Bunsen and L. Schischkoff, "On the Chemical Theory of Gunpowder," trans. E. Atkinson, *London, Edinburgh and Dublin Philosophical Magazine and Journal of Science*, **1858,** 4th series, *15*, 489-516; first published in 1857. The paper of Bunsen and Schischkoff is detailed in S. H. Mauskopf, "Bridging Chemistry and Physics in the Experimental Study of Gunpowder," presented at the Workshop on "The History of Chemistry," April 11-13, 1996, Dibner Institute for the History of Science and Technology (in press).
19. J. Uppmann and E. von Meyer, *Traité sur la poudre, les corps explosifs et la pyrotechnie,* trans. E. Désortiaux, Dunod, Pari, 1878, 462. In his authoritative work, Oscar Guttmann, *The Manufacture of Explosives*, 2 vol., Whittaker and Co., London, 1895, Vol. 1, 337, termed these experiments "epoch-marking.
20. Ref. 7.
21. Ref. 9, pp 54-57.
22. Ref. 7, pp 65-66.
23. For Gay-Lussac's activities, see M. Crosland, *Gay-Lussac: Scientist and bourgeois*, Cambridge University Press, Cambridge, 1978, 181-187. He was involved in research concerning a number of different aspects of powder: refinement of saltpeter, analysis of powder composition, study of fulminates (with Liebig). He was also instrumental in getting the ballistic pendulum into use in France, as well as in the chemistry of the cannon.
24. The most cogent accounts are: É. Sarrau, "Notice sur le service des Poudres et Salpêtres," *Mémorial des Poudres et Salpêtres*, **1894**, *7,* 7-31 and E. Désortiaux, "Aperçu historique sur le Service des Poudres et Salpêtres," *Mémorial des Poudres et Salpêtres*, **1894**, *7*, 32-75.
25. See F. A. J. L. James, "The Military Context of Chemistry: The Case of Michael Faraday," *Bull. Hist. Chem.*, **1991**, *11*, 36-40. Faraday was paid very handsomely. For details concerning Faraday's appointment, see F. A. L. James, Ed., *The Correspondence of Michael Faraday*, Vol. I (1811-1831), Institute of Electrical Engineers, London, 1991.
26. Details from obituary by J. Spiller, *J. Chem. Soc. Trans.*, **1905,** *87*, 565-570; see also Sir Sidney Lee, Ed., *Dictionary of National Biography*, Smith, Elder & Co., London, 1912, Vol. 1, 5-6. 1901-1911, Vol. 23, 5-6.
27. O. F. G. Hogg, *The Royal Arsenal: Its Background, Origin, and Subsequent History*, Oxford University Press, London, 1963, Vol. 2, 749. There apparently had been a position of "ordnance chemist and assayist of metals," which, however had been abolished in 1825; the last incumbent (of some twenty years), a Dr. McCulloch, was pensioned off. (Hogg, *ibid.*, Vol. 1, 661.
28. For a brief account, see Col. Sir H. W. W. Barlow, "The Royal Laboratory, Woolwich," in *The Rise and Progress of the British Explosives Industry* (VIIth International Congress of Applied Chemistry), Whittaker & Co, London, 1909, 307-315.
29. West, Ref. 11; W. D. Cocroft, "William Congreve (1743-1814), Experimenter and Manufacturer," ICOHTEC Conference, Budapest, 1996 (unpublished 'speaker's text'), p 2. Faversham Mills (Kent) were acquired in 1759; Waltham Abbey Mills (Essex) in 1787.
30. One result was the adoption of a new means of preparing charcoal in sealed retorts, apparently suggested by the chemist/cleric Richard Watson.
31. Cocroft, Ref. 29, p 6.
32. Col. R. Delafield, *Report on the Art of War in Europe in 1854, 1855, and 1856,* George W. Bowman, Printer, Washington, DC, 1861, 5, 9. Delafield was a member of an official military commission sent by the Secretary of War.
33. O. F. G. Hogg, *Artillery: Its Heyday and Decline*, Archon, Hamden, CT, 1970, 82.
34. P. Everson and W. Cocroft, "The Royal Gunpowder Factory at Waltham Abbey: The Field Archaeology of Gunpowder Manufacture," in Buchanan, Ref. 11, pp 387-393.
35. The minutes of the Ordnance Select Committee (1860-1869), the reports of this committee (1863-1869) and the reports of the Committee on Gunpowder and Explosive Substances are to be found at the Royal Artillery Library, Old Royal Military Academy, Woolwich Arsenal. The Committee on Explosive Substances issued its final report in 1880. There was also another committee on guncotton in the early 1870s.

36. F. A. Abel, "Researches on Gun-cotton: On the Manufacture and Composition of Gun-cotton," *Phil. Trans. Roy. Soc. London*, 1866, *156*, 273.
37. F. A. Abel, "System of Manufacture of Gun-Cotton as carried out in the Imperial Austrian Establishment;" "On the Composition, and some Properties, of Specimens of Gun-cotton prepared at the Austrian Government Works," Appendices I and II to J. H. Gladstone *et al.*, "Report on the Application of Gun-Cotton to Warlike Purposes," Report of the Thirty-Third Meeting of the British Association for the Advancement of Science, **1863**, 8-13.
38. F. A. Abel, "Memorandum with reference to Experiments in progress bearing upon the Manufacture of Gun-cotton," Appendix III to Ref. 37, pp 14-25.
39. F. A. Abel, "On the Chemical History and Application of Gun-cotton," *Proc. Roy. Inst. Gr. Brit., 1862-1866*, **1864,** *4*, 247.
40. In fact, after an explosion destroyed the magazine at Simmering, the opponents of guncotton won the day and the Austrians reverted to gunpowder. Norman, Ref. 12, pp 56-57. They continued to use it in shells.
41. Ref. 37, pp 6-7.
42. F. A. Abel, "Researches on Gun-cotton — Second Memoir. On the Stability of Gun-cotton," *Phil. Trans. Roy. Soc. London*, **1867**, *157*, 181-184.
43. P. Vieille, "Recherches sur la Nitrification du Coton" (1883), trans. J. B. Bernadou, *Smokeless Powder, Nitrocellulose, and the Theory of the Cellulose Molecule*, John Wiley & Sons, New York, 1901, 81. Writing in the 1890s, Oscar Guttmann noted that both the earlier trinitro-compound theory and that of Vieille had been supplanted by a theory of Eder postulating six nitro compounds; Guttman, Ref. 19, Vol. 2, pp 61-63.
44. Theoretically, 100 parts by weight of pure cellulose ought to increase 83.3 % in conversion to trinitrocellulose ($C_6H_7N_3O_{11}$). In studying Von Lenk's process, Pélouze and Maury had found a maximum increase in weight of only 77.8 % and had assigned a formula indicating a lower level of nitration ($C_{24}H_{36}O_{18}$, $5N_2O_5$). Abel had found an increase of weight ranging between 81.8 and 82.6 %. Abel, Ref. 36, pp 306-308.
45. Ref. 42, p 208.
46. Ref. 42, p 219. Patent on this dates from 1865. Rice has noted that Abel was anticipated by three years by someone named John Tonkin: "Smokeless Powder: Physical Mixtures and Chemically Pure Substances," presented at History of Science Society Annual Meeting, "Science and the Development of Munitions," 1994. Tonkin was the manager of the Cornish Blasting Powder Co.; see Brown, Ref. 39, p 130.
47. Abel mentioned that the pulping procedure had been developed in connection with experiments on substituting guncotton for gunpowder as a military propellant; Ref. 42, p 219.
48. Abel, Ref. 39, p 253.
49. F. A. Abel, "On Recent Progress in the History of Proposed Substitutes for Gunpowder, " *Proc. Roy. Inst. Gr. Brit. 1862-1866*, **1866**, *4*, 625. Gas pressure in the gun bore neutralized guncotton cartridges' resistance to very rapid detonation.
50. This had been developed by the powder makers at Stowmarket [Messrs. Prentice] for cartridges for sporting guns. Abel did not yet have in mind Alfred Nobel's development of dynamite; Ref. 49, pp 625-626.
51. Ref. 49, p 626.
52. F.A. Abel, "On the more important Substitutes for Gunpowder," *Proc. Roy. Inst. Gr. Brit.* **1870-1872**, *6*, 517.
53. Ref. 52, p 18. A contemporary artillery officer summarized the problems as follows: "A course of experiments carried on in 1865, at Woolwich, soon sufficed to show that gun-cotton, as then manufactured, was not suitable for artillery purposes. The great local violence of its action, and rapidity of its ignition when confined, as in the chamber of a gun, rendered it extremely destructive to the piece. Experiments were made with a view to diminish the destructive energy of the gases generated on the combustion of the cotton, but so far as they were carried out, it appeared that in reducing its explosive force, and diminishing these destructive effects, its power as a propelling agent was similarly reduced, and it was for the time decided to give up the idea of employing it for artillery. It has, however, still many supporters as an explosive for sporting purposes, though I am not aware that when made of such strength as to cease to be injurious to the gun, any great superiority over gunpowder, as regards hard hitting, is proved for it, though undoubted benefits arise from its freedom from smoke and fouling." Col. A. à'Court Fisher, "Gun-Cotton Applied to Demolitions," [Lecture: June 10, 1870], *J. Roy. United Service Inst.*, **1871**, *14*, 419-447 (421).
54. Ref. 52, pp 518-519. The rifles were Enfield and Snider. At just this time, tests were underway to convert muzzle-loaders to breech-loaders: see. P. Labbett, *British Small Arms Ammunition, 1864-1938*, P. Labbett, London, 1993, Ch. 1-2.
55. Ref. 52, pp 518-519.
56. George, Ref. 12, p 163; Norman, Ref. 12, p 79.
57. F. A. Abel, *On Recent Investigations & Applications of Explosive Agents* (BAAS Lecture, August, 1871), Edmonston and Douglas, Edinburgh, 1871, 20. Schupphaus, in his excellent article on the evolution of smokeless powder, wrote that Abel "experimented at Woolwich [1867-68] with cartridges built up from compressed gun-cotton fired from bronze field-guns, but found little encouragement, though the results were ahead of those obtained with Von Lenk's cartridges," "The Evolution of Smokeless Powder," *J. Mil. Serv. Inst. US*, **1896**, *18*, 173.
58. A. Noble and F.A. Abel, "Researches on Explosives — Part I (1876) and Part II (1880) [published in the *Phil. Trans. Roy. Soc. London*], in Sir A. Noble, Ed., *Artillery*

and Explosives, John Murray, London, 1906. See Mauskopf, Ref. 18.

59. F. A. Abel, "The Modern History of Gunpowder," [A Lecture Delivered in the Free Trade Hall, Manchester, January 29, 1879], *Science Lectures for the People: Science Lectures Delivered in Manchester, 1877-78-79. Ninth and Tenth Series*, John Heywood, Manchester N.D., Tenth Series, p 118 (entire essay, pp 107-129).

    The heavier ordnance used in the Crimean War was cited as the context for the origin of this investigative program. Regarding the introduction of large grained gunpowder for heavy ordance, Abel wrote: "This was the first very large powder which was introduced in England for heavy guns, but a very large grained powder had just previously been introduced in America, under the name of mammoth powder, and a much larger powder, of prismatic shape, also of American origin, was adopted about the same time in Russia and Prussia." (p 123). At the end of the talk, Abel discussed other measures taken to design the powder cartridge to avoid "wave-pressure" and to fit "gas checks" on the base of the projectile to control the otherwise destructive force of the charges in very large guns. (pp 124-127).

    In an 1871 address by Noble, he credited Rodman as being "the first person who experimented on the effect of size of grain, and proposed prismatic powder" and wrote that Bunsen and Schischkoff's experiments "may justly rank among the most important which have been made on our subject." Noble, Ref. 58, pp 58, 63, respectively.

60. Noble and Abel, Ref. 58, Part I, pp 204-205.

61. Major-General Sir C. Callwell and Major-General Sir J. Headlam, *The History of the Royal Artillery*, Royal Artillery Institution, Woolwich, 1931-1940, Vol. 1, 172-173. They went on say that, "The discoveries made in respect to the propellant, coupled with additional experience gained in relation to ballistics in general, may in fact be said to have brought about a revolution in the accepted principles of gun construction, as they were understood in this country."

62. F.A. Abel, "Gun Cotton." [A Lecture Delivered in the Hulme Town Hall, Manchester, on Wednesday, November 19th, 1873], *Science Lectures for the People: Fifth Series of Science Lectures delivered in Manchester, 1873*, John Heywood, Manchester, 1874, 69.

63. Abel had not abandoned hope for developing a guncotton propellant for use in military rifles and, as late as the mid-1870s, was still pleading for further research: *Progress Report of the Committee on Explosives Substances, with Appendices. 1st April 1876*, Her Majesty's Stationery Office, London, 1877, 74-75.

64. Insoluble nitrocellulose: 68.2 %; soluble nitrocellulose, 29.8%; paraffin: 2.0%, gelatinized in acetic ether. A. Marshall, *Explosives*, J. & A. Churchill, London, 1917, 1932, 2d ed., Vol. 1, 294. This was the result of an external analysis since the process and recipe were a military secret, perhaps the first such in the history of modern munitions.

65. Schupphaus, Ref. 57, p 174. See Guttmann, Ref. 19, Vol. 2, pp 236-237 for a description of two of these: E.C. powder and J.B. powder.

66. Friedel, Ref. 14.

67. C. E. Munroe, "On the Development of Smokeless Powder," *J. Am. Chem. Soc.*, **1896**, *18*, 829-830; Norman, Ref. 12, p. 78-81.

68. Munroe, Ref. 67, pp 828-829; see also Worden, Ref. 14, Vol. 2, Ch. 18.

69. Munroe, Ref. 67, pp 823-824; see also Schupphaus, Ref. 57, p 174. The ascendancy of new types of gunnery like the machine gun directly impelled the British military authorities to renew the search for a smokeless powder in 1886 and to involve Abel in this search. See the dossier at the Public Record Office: SUPP 5 568, "Experimental Powder from April 1885- 17-7-91." In one letter, Abel berated the Superintendent of the Royal Gunpowder Factory, Waltham Abbey, for not allowing him to use the testing facilities there: "I regret that you do not see your way to continue to afford facilities for the working out of the experiments made with a view to ascertain whether a smokeless powder for machine guns is attainable, a subject which was referred to us jointly to investigate." Abel to Superintendent, Royal Gunpowder Factory [W. H. Noble], August 17, 1887.

70. Schupphaus, Ref. 57, pp 173-174; according to Guttmann, Ref. 19, Vol. 2, p 237, Vieille's original smokeless powder was made of both picric acid and guncotton.

71. L. Médard, "L'oeuvre scientifique de Paul Vieille, 1854-1934," *Rev. Hist. Sci.*, **1994**, *47*, 381-404.

72. Rice, Ref. 46, pp 9-11. He linked Abel to Vieille in this regard.

73. I have not yet found evidence of a direct affiliation between the two.

74. The relationship between Noble's crusher gauge and the instruments used by the French was spelled out by Paul F. Chalon: "Le crusher, ou écraseur, de la commission anglaise des matières explosives a été perfectionné par M. Berthelot, et il est actuellement employé par la commission des matières explosives et dans les expériences exécutées par l'artillerie de marine, en France." *Traité théorique et pratique des explosives modernes et dictionnaire des poudres & explosives*, E. Bernard et C^{ie}, Paris, 1889, 2d ed., 191-192.

75. P. Vieille, "Étude sur le mode de combustion des matières explosives," *Mémorial des poudres et explosives*, **1893**, *6*, 256-391.

76. Ref. 70, p 402; see also L. Médard, "Paul Vieille et son oeuvre," *Mémorial de l'artillerie française*, **1986**, *60*, n^{o} 2, 11-23.

ABOUT THE AUTHOR

Professor Seymour H. Mauskopf has been a member of the faculty of the History Department at Duke University, Durham, NC 27708, since 1964, becoming full professor in 1980. His research interests have spanned widely, from chemistry and medicine to psychology, all with a common theme of his fascination with continuities in scientific thought and the interaction of scientific traditions. Since being named the first Edelstein International Fellow in the History of Chemical Sciences and Technology of the Chemical Heritage Foundation in 1988-1989, Professor Mauskopf has served as an advisor to CHF and a coordinator of many of their special programs.