From: B.J. Bowler, I.R. Morus, Making Modern Science (UCP: 2005).

CHAPTER 20

SCIENCE AND WAR

During the Scientific Revolution of the seventeenth century, Francis Bacon and others argued for the practical benefits that would result from the application of the new knowledge of nature. These appeals tended to focus on the benefits to industry and medicine, along with specialist applications such as navigational techniques. But from the start it was obvious that the same principle would apply to warfare and the arts of destruction—these, too, might be improved by the new sciences. Mathematics was already used for practical purposes in gunnery and the design of fortifications, and gunnery especially could benefit from a better theoretical understanding of projectile motion. By the nineteenth century, the involvement of science with industry was already beginning to include the design and manufacture of better explosives and guns, and there were suggestions of entirely new weapons such as poison gas. These trends were expanded by both sides in World War I, although to begin with, the successful interaction of science and the military was limited by lack of direct communications. These obstacles were largely overcome during World War II, when new inventions such as sonar (for detecting submarines) and radar played crucial roles. The application of a scientific way of thinking to complex practical problems led to operations research. But most obvious to succeeding generations, this war led to the creation of a new weapon with a destructive power so great that it potentially threatened the whole foundations of civilization: the atomic bomb. The Manhattan Project that generated the bomb started out from theoretical innovations in physics but led to the establishment of the first really large-scale integrated scientific-industrial-military research program. Continuing with the design of even bigger weapons based on nuclear fusion (the H-bomb) in the cold war, this area of interaction began to shape the environment within which a significant part of the scientific community would operate.

Some scientists feel very uncomfortable with the modern state of affairs. They know that the link between science and the military-industrial complex is seen by many as evidence that science itself is a harmful influence on our society. One avenue of escape is provided by the old argument that pure science generates impartial knowledge of nature—it is only applied science that can lead to harmful consequences, and then only when national emergencies focus efforts on military rather than peaceful applications. But modern historians of science are skeptical of such a separation between science and its applications. We know that, over the past several centuries, very few scientists have worked in total isolation from the world of applied science, especially as increasingly complex technical equipment became necessary to test hypotheses generated at a theoretical level. Many of the most innovative physicists of the nineteenth century, for example, were already concerned with practical questions generated by new industrial developments (see chap. 17, "Science and Technology"). Once that link was established, the involvement of scientists in the development of military technology became inevitable.

In some cases, the division between peaceful and warlike technologies is itself artificial. Better navigational techniques benefited all seafarers in the late eighteenth century, but it was Europe's navies that led the way—and the native peoples of many parts of the world would not have regarded the incursion of traders and colonists as a peaceful process. In the modern world, radar helps to make civil aviation safe but was applied first to detect military aircraft. New medicines such as penicillin and insecticides such as DDT were first developed under the pressure of war. Technologies developed to detect nuclear submarines provided information about the deep-sea bed that was crucial to the emergence of the modern theory of plate tectonics (see chap. 10, "Continental Drift"). There have been periods when scientists have openly rejected the call to do applied work for the military, but when their country or way of life seems threatened they do their patriotic duty like everyone else. Since the cold war ushered in an almost permanent state of anxiety about the safety of Western democracies, the possibility of stepping off the escalator of military development seems quite unrealistic—and Soviet scientists responded equally readily when their own country seemed under threat. Historians have to take it for granted that for most of the past century a significant amount of science has been done in collaboration with the military and must, therefore, explore the implications of this for the way science operates.

To simplify this question, in this chapter we will focus primarily on the direct application of science to military technologies. We begin with the first hesitant steps to use science to improve and eventually to design entirely new weapons, culminating with the somewhat fragmentary interactions with the military authorities in World War I. In the interwar years, there were efforts to intensify these connections even during the period when many hoped that war could be averted. Scientists then began to play a major role during World War II, providing the basis for new technologies such as sonar, radar, and the V-2 rockets that laid the foundation for later programs to design guided missiles. The project to build the atomic bomb will occupy a large proportion of the chapter, partly because it pioneered a new degree of intensity in the cooperation between the government, the military, industry, and the scientific community. But the bomb project also helps to focus our attention on the moral problems faced by scientists when they are asked to design weapons of mass destruction. The Allies raced for the bomb only to find out after the end of the war that their fears of a similar weapon being developed by Nazi Germany were unfounded. It has even been argued that German scientists actively avoided work that might have given Hitler the bomb. Then the American bombs were dropped on Hiroshima and Nagasaki, bringing home to everyone the horrors that would result from the widespread use of such weapons. Some scientists began to express doubts about participating in the arms race that accompanied the cold war with Soviet Russia—but others were anxious to help develop weapons that, they felt, were necessary to protect democracy. More disturbing still was the possibility that scientists were now actively suggesting new weapons so they could benefit from the resulting research funds. The moral and political dilemmas that face many scientists in the modern world became fully articulated.

The Chemists' War

It has been said that World War I was the chemists' war, while World War II was the physicists' war. This is an oversimplification, but it highlights the fact that much of the scientific effort that went into military applications between 1914 and 1918 was devoted to the production of better explosives and the first really new terror weapon—poison gas. In fact, neither side made effective use of its scientific expertise, and none of the weapons developed had a decisive effect on the outcome of the war. But at the very least, it had become apparent that the potential for the military application of science was considerable. The scientists themselves had been willing to offer their services when faced with a national emergency, and some quite senior figures had become directly involved with military research. The military establishment had been reluctant to take advice, however, and bridges between the two communities were only gradually and imperfectly built in the course of the war. In the end, perhaps the greatest legacy of this war was the creation of military research establishments that would go on to play a vital role in later conflicts (Hartcup 1988).

These hesitant steps built on a foundation that had been emerging over the previous century or more. Armies had included corps of engineers since the eighteenth century and were thus used to the applied sciences—what they were not prepared for was new initiatives coming from science and industry. The French revolutionary government had executed Lavoisier because he had collected taxes for the old regime, but France soon found that it did need chemists after all to suggest new means of producing saltpeter for gunpowder. In the course of the nineteenth century, new and more powerful explosives were developed, and some scientists even suggested the possibility of poison gas, although the military dismissed this as beneath its dignity. By the end of the century, however, the situation had begun to change. The inventor of dynamite, Alfred Nobel, was particularly effective in linking science with industry. He set up a research center in Berlin in 1897, with representatives of the armaments firm Krupps on the board of directors. In Britain, the Boer War in South Africa revealed alarming weaknesses in military equipment, and in 1900 the Ordnance Board set up an explosives committee headed by the eminent physicist Lord Rayleigh and containing among its members the chemist William Crookes. Crookes urged the use of TNT as a high explosive, although the British did not take this up until the start of World War I. Rayleigh also presided over an advisory committee on aeronautics to study the military use of the newly invented airplane.

Whatever limited preparations had been made, when war came in 1914 most European countries were slow to appreciate the potential for science to aid developments in military technology. Only in the following year did the British government, for instance, set up an advisory council of scientists, which soon became transformed into the Department of Scientific and Industrial Research under the direction of the physicist J. J. Thomson. Scientific teams were also set up in the Admiralty and the Ministry of Munitions. Even so, popular writers such as H. G. Wells continued to argue that the country's scientific expertise was being wasted. In 1916, a group of eminent scientists used the ineffectiveness of the military's handling of science to argue for a greater role for science education—as it was, most politicians and military officers were completely ignorant of science and hence could not appreciate its potential. The French government was somewhat more effective, setting up the Directory of Defense Inventions, which was linked to the universities. In Germany, the noted chemist Fritz Haber (who had invented a technique for "fixing" nitrogen to make fertilizers and explosives) placed his Institute for Physical and Electrochemistry at Dahlem in Berlin at the disposal of the military. It soon came completely under military control and in 1917 became the Kaiser Wilhelm Foundation for the Science of War Technology. In America, the founding of the National Research Council in 1916 was prompted by the increasing likelihood that the country would enter the war.

What did these various teams of scientists achieve? In some projects, quite a lot was done, although seldom without difficulties produced by the very different attitudes of scientists, industrialists, and the military. Chemists worked not only on new explosives but also on providing alternative means of manufacture when raw materials were in short supply. In Britain, J. J. Thomson and others worked on improvements in radio to aid military communications. A team from the Board of Invention and Research including Rayleigh, Ernest Rutherford, and W. H. Bragg helped to develop hydrophones for detecting submarines.

By far the most striking new initiative was the use of gas, and this was actively promoted by Fritz Haber as a weapon for the German army once it became clear that the conventional war had become bogged down in the trenches of the Western Front (Haber [1986]—a survey written by Haber's son). There was a Hague Convention forbidding the use of projectiles containing poisons, but Haber now suggested using chlorine from cylinders that would be released when the wind was in the right direction to carry it over the enemy trenches. With some reluctance, the army agreed to try out this idea. Haber's own institute provided the links with industry to set the program up, and a regiment was founded to deliver and operate the cylinders—it contained many young scientists who would go on to achieve eminence after the war. One hundred fifty tons of chlorine were released on 22 April 1915 on the Ypres salient, causing panic in the opposing French troops (although few fatal casualties). But the Germans gained little ground because the army was not ready to exploit the breakthrough. The British and the French responded much more rapidly than the Germans expected, and the rest of the war saw a succession of developments including the use of gas shells and the introduction of new chemicals such as mustard gas. Both sides also made advances in protecting against gas, various forms of masks being developed by teams of chemists and physiologists.

In the end, it was the Allies who made the most concerted use of their scientists—Haber always complained that despite his direct involvement with the army, the senior officers seldom took him seriously. The British set up a dedicated facility at Porton Down near Salisbury to work on chemical (and later biological) weapons. But it was the American Chemical Warfare Service that produced the most sustained scientific program in this area—by 1918 it included more university-trained scientists than all the other belligerents put together (Haber 1986, 107). Studies of poison gas continued, although neither side made use of it in the next war. The interwar years did, however, see the setting up of programs that developed weapons that were to have a far more substantial effect on the outcome of World War II.

World War II

Although most of the scientists recruited to help the military in the first war soon returned to civilian work, small numbers were retained on a permanent basis for defense research, especially by air forces and navies. There were now more applied scientists working in industry, including the armaments and aircraft industries. During the interwar years, many academic scientists looked down on their colleagues in industry and were reluctant to work on military research. A greater level of social awareness emerged in Britain during the 1930s when a prominent group of left-wing scientists began to criticize the extent to which applied science was being driven by military concerns. But the radicals were also aware of the growing menace of Nazi Germany, and when war came they, too, became willing to work on military research. The threat of bombing from the air became so apparent that the British government set up the Committee for the Scientific Survey of Air Defence in 1934 under Henry Tizard—this was to play a key role in the development of radar. But it was not all smooth sailing. The Marxist crystallographer J. D. Bernal led a movement to criticize the government's plans for civil defense, and it was only after the outbreak of war that he gained any influence on policy (Swann and Aprahamian 1999).

When the Nazis came to power in Germany they poured funding into a number of new weapons systems, including radar and long-range rockets. The Allies were warned of these new developments in the "Oslo report"—a paper smuggled to the British Embassy in Oslo in 1939 by H. F. Mayer, a German scientist whose sympathies were anti-Nazi. But in fact the more ambitious German programs had little effect—Hitler liked new military technology but had little sense of how to use it, and his regime consisted of a number of competing factions that often blocked each other's initiatives.

The year immediately preceding the outbreak of war in 1939 saw a rapid reinvigoration of scientific programs in Britain that effectively prepared the country for war. In America in 1940, Vannevar Bush of Massachusetts Institute of Technology persuaded President Roosevelt to set up a national defense research committee to coordinate scientific plans for war (Zachary 1999; more generally on science in World War II, see Hartcup [2000]; Johnson [1978]; Jones [1978]).

In the closing years of the first war, French scientists had proposed a technique for detecting submarines by reflecting sound waves off them underwater. The British continued this program, and although the system, known as asdic (later sonar) did not go into operation during this war, it was developed throughout the interwar years and was ready for use in the Battle of the Atlantic in World War II (Hackmann 1984). F. A. Lindemann was so confident in the effectiveness of asdic that he predicted the end of the submarine as a significant weapon (Hartcup 2000, 64–65). Events were to show just how wrong he was, since even with the new detection system British warships were unable to protect their convoys, and the country was nearly brought to its knees. A whole series of further developments in antisubmarine warfare were needed before the menace of the U-boats was defeated.

Perhaps the most important area of applied scientific research was the development of radar (Brown 1999; Buderi 1997; Price 1977). By the start of the war, both the British and the Germans had introduced radar systems for the detection of aircraft, although the British system was more efficiently applied. As noted above, the British had set up an aeronautical research committee in 1934, and one of its most important tasks was to work out a system for detecting incoming bombers. Scientists at the Radio Research Station showed that it was feasible to detect radio waves reflected from solid objects such as aircraft at considerable distances (curiously, the first calculations were done to disprove the idea of a "death ray" intended to destroy the aircraft). In the late 1930s, a large number of physicists from the Cavendish Laboratory at Cambridge were employed to develop the basis for what became known as the Chain Home radar stations. Working from large masts on the south coast of England, these played a vital role in the "battle of Britain" in 1940 when the German air force tried to gain control of British airspace as a prelude to invasion (fig. 20.1). The Oxford physicist F. A. Lindemann (later Lord Cherwell) encouraged work on other systems, including the detection of aircraft by infrared. Lindemann later became Winston Churchill's scientific adviser, and he and Tizard quarreled violently over the priority to be given to radar in the early years of the war.

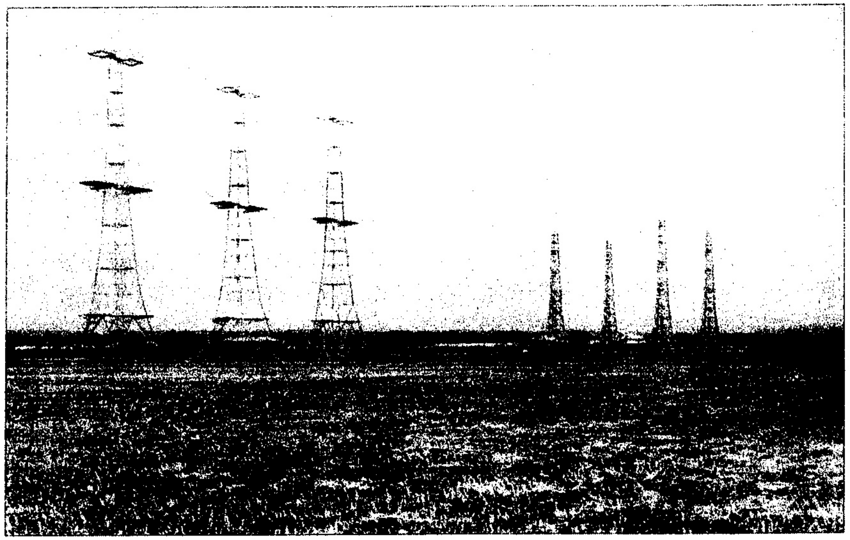

FIGURE 20.1 Chain Home radar station on the south coast of Britain, 1940. These enormous towers were able to detect German aircraft heading toward Britain from German-occupied France early enough to give the Royal Air Force fighters a chance to intercept them.

The navy and the air force also wanted a system of short-range, high-accuracy radar, and this required the use of short wavelength (microwave) radio. There was no system available for generating microwaves at a useful power level until British physicists developed the cavity magnetron in 1940. An early model of this was flown to America in August of that year by a team led by Tizard, and soon microwave radars were in production on both sides of the Atlantic. They were used by night fighters to close in on enemy bombers but, more important, also by naval patrol aircraft searching for submarines (which had to spend part of their time on the surface to run their diesel engines). Thus radar joined sonar as a key weapon in the battle of the Atlantic.

The Atlantic battle also provided a classic example of the benefits of a scientific approach to management, increasingly known as operations research. The physicist P. M. S. Blackett, who worked on a number of weapons including magnetic mines, formed the Operations Research Section of the Royal Air Force's Coastal Command and conducted a systematic survey of the factors that influenced the fate of a convoy. Against the advice of naval experts, Blackett introduced larger convoys and was able to demonstrate that the larger the convoy, the smaller the proportion of its losses, and the use of larger convoys played a major role in easing the problem of supply. Operations research was also applied successfully in the management of the air offensive against Germany. By the end of the war, scientists from a wide range of backgrounds were employed in operations research, advising on issues such as the effectiveness of bombing and the best way to use the available forces in the invasion of Europe. They were not all physicists, either—one of the most influential British advisers in the later stages of the war and thereafter was the biologist Solly Zuckerman (see Peyton 2001; Zuckerman 1978, 1988).

The Germans used their applied scientists to develop a number of new weapons, but the confused state of the chain of command under Hitler (along with Hitler's own unstable temperament) often interfered with their introduction. The Germans had a good radar network but did not have a coordinated system for passing information on to their pilots. They also developed the jet engine, paralleling similar research led by Frank Whittle in Britain. In the later stages of the war, much attention was focused on the V weapons ("revenge weapons") designed to strike at long range. The V-1 was a pilotless aircraft driven by a pulse jet. Far more imaginative in terms of its future potential was the V-2, the world's first long-range rocket, developed by a team under the physicist Werner von Braun (Neufeld 1995). When used against Britain in the last year of the war, it was unstoppable, but by then it was too late for its impact to turn the tide against Germany. Von Braun and his team had solved a host of technical problems and were anxious to continue their work—like most rocket scientists of the time, they had they eyes on the exploration of outer space. At the end of the war, von Braun surrendered to the Americans and was soon leading the development of their program to develop rockets both for military ends and for space exploration. The Russians also scooped up a number of German experts and began employing them for the same purposes.

The Atomic Bomb

One question haunted the Allies throughout the war: Had the Germans begun to develop a bomb based on the energy released by radioactive elements (the atomic bomb)? The revolution in early twentieth-century physics had revealed the enormous power that was locked up in the atom (see chap. 11, "Twentieth-Century Physics"). Although most scientists were skeptical, there were occasional predictions that this power could be unleashed to give a bomb that might destroy a whole city. The first calculation that such a bomb might be feasible was made in 1940 by Jewish physicists who had fled the Nazi regime in Germany. But there were still eminent physicists left in Germany, most notably Werner Heisenberg, whose national loyalty might lead him to develop a bomb in wartime even if he disapproved of Hitler and his policies. It was the fear that Hitler might acquire such a superweapon that led the Allies to pour resources into what became the Manhattan Project to develop the bomb; unlike the V-2, the atomic bomb could have turned the tide in Germany's favor even at the last minute. In fact, German physicists had come nowhere near to developing a bomb, and their only nuclear reactor was virtually useless. When Heisenberg and his colleagues were interrogated after their capture by the Allies, it became clear that they had vastly overestimated the critical mass needed to start a chain reaction in uranium and had told the German military that the bomb could not be made. Controversy has continued ever since over the question of whether this overestimate was simple carelessness or a deliberate attempt to ensure that the Nazis did not get the bomb (Powers 1993; Rose 1998). A successful Broadway play, *Copenhagen*, was based on a notorious confrontation between Heisenberg and his mentor, the Danish atomic physicist Niels Bohr, in 1941, during which Heisenberg seems to have raised the issue of the bomb (Frayn 1998).

Unaware of the Germans' lack of interest in creating an atomic bomb and suffering from daily raids by conventional bombers, it was the British who made the first moves to explore the possibility of building a nuclear bomb (Gowing 1965). By 1939 it had become clear to Bohr and others that the only way to derive significant amounts of energy from the fission (breakup) of radioactive atoms was by starting a "chain reaction." Normally, the nuclei of such atoms fission spontaneously at a very slow rate, each liberating a small but significant amount of radiation. But some radioactive elements, most notably uranium 235 and the artificial element plutonium, also liberate neutrons, and these particles are capable of initiating fission if they collide with another nucleus. In small quantities of the radioactive element, the neutrons mostly escape before they can hit another nucleus, but if the quantity exceeds a "critical mass" the neutrons will begin to fission enough extra atoms to produce a cascade of further collisions—the chain reaction. In a nuclear reactor or "pile," the chain reaction is sustained at a level that will produce a constant amount of energy. But in an uncontrolled chain reaction, the whole mass of atoms will disintegrate in a fraction of a second, liberating a vast amount of energy in the form of an explosion. The simplest form of atomic bomb thus consists of a device to bring together two subcritical masses to create a critical mass, which will immediately explode. By 1940, a number of physicists had begun to think about this situation, and the central problem was: What is the critical mass? Heisenberg casually assumed it would be many tons, making a bomb impractical—but what if it were much less, say only a few kilograms?

The calculation was actually done in March 1940 by two German scientists, Otto Frisch and Rudolf Peierls, who had fled to escape the Nazis and were now working in England at the University of Liverpool. The answer was about five kilograms, certainly small enough to form a usable bomb—although there was as yet no way of extracting anything like that amount of fissionable material from natural sources. Most natural uranium consists of U-238, which cannot form a chain reaction; only 0.7% is the vital U-235, and to make a bomb some means of extracting the U-235 in quantity would have to be devised. But Frisch and Peierls' memorandum was sent to Henry Tizard, and a committee was soon set up to investigate the possibility of separating the isotopes and making a bomb. It was called the MAUD committee—Bohr had written of "Maud" in a telegram from Denmark, and it was thought to be a code word, although actually it was the name of a woman he knew in Britain. Its members included leading physicists: G. P. Thomson, James Chadwick, Mark Oliphant, and P. M. S. Blackett. Work began at Oxford on devising a process of isotope separation by gaseous diffusion, eventually under the cover name of Tube Alloys.

Blackett and other members of the committee felt that, with the imminent threat of invasion, the actual production would be best done in the United States. Oliphant visited America in August 1941 to discuss radar research, but he was also instructed to convey to the Americans the importance now being attached to the bomb project by the British. So far, the Americans had been inactive, although in 1939 Albert Einstein, prompted by the Hungarian physicist Leo Szilard, had written to President Roosevelt warning of the dangers. Now Oliphant gained the attention of Ernest Lawrence, who convinced the administration's key scientific advisers Vannevar Bush and J. B. Conant that the project was likely to be successful. On 6 December 1941 (the day before the Japanese attack on Pearl Harbor), Roosevelt approved funds for research, and by the summer of the following year, pilot plants for production were being planned. Work also began on the design of the bomb itself (Hoddeson et al. 1993).

As yet no chain reaction had actually been observed, and the theory was not confirmed until December 1942, when Enrico Fermi built a reactor in the basement of a football field at the University of Chicago and initiated a controlled chain reaction. One function of the reactor was that it would convert uranium-238 into plutonium, another potential source of fissionable material for a bomb. In fact, the construction of reactors to make plutonium offered a better way to make fissionable material because it could easily be extracted by chemical means, while the separation of U-235 and U-238 involved very delicate physical processes using gaseous diffusion or electromagnetic techniques. Plans went ahead on both fronts, with the aim of making bombs with both U-235 and plutonium. Brigadier General Leslie Groves was put in charge of what became known as the Manhattan Project. Groves was highly experienced in managing large projects, and his organization skills were vital—yet he was not a scientist and was disliked by many of the scientists recruited for the project, who found his military approach uncongenial. He was also anti-British and for a while British scientists were excluded from the project, although this situation later changed, and even Bohr joined the project after he escaped from occupied Denmark.

The scale of the project became truly enormous—the plants built at Oak Ridge, Tennessee, to extract U-235 and at Hanford, Washington, to make plutonium both used more hydroelectric power than a large city (fig. 20.2; Hughes 2002). The technical skills of the scientists and engineers who designed the equipment were taxed to the limits. Meanwhile, design of the bomb itself began at Los Alamos, New Mexico, under J. Robert Oppenheimer. Oppenheimer was a leading figure in the American physics community, which had now developed to the stage where it was on equal terms with the long-established European traditions (Goodchild 1980; Kevles 1995). He then faced a new challenge, in which his abilities as an inspired leader would be put to more practical ends. Significantly, although the Manhattan Project as a whole was organized by Groves and the military, the scientific teams working on technical problems were all civilians and were led by scientists. This meant that they were not simply taking orders from the military and were free to think about the consequences of what they were doing. Eventually this freedom would allow major debates to emerge over the morality of working on the bomb, but in the short term, the perceived threat from Nazi Germany encouraged most scientists to throw themselves into the work.

Although a brilliant physicist, Oppenheimer knew that in this new environment where practical results were all that mattered, the scientists' traditional individualism would not work. He found it necessary to adopt a quasi-military style of management that required the whole team to focus on the immediate goal but still left room for individual creativity in the solution of the problems. Oppenheimer also became skilful at working with government and military committees, emerging as a new kind of scientific leader, as much at home in the corridors of power as in the laboratory. In a

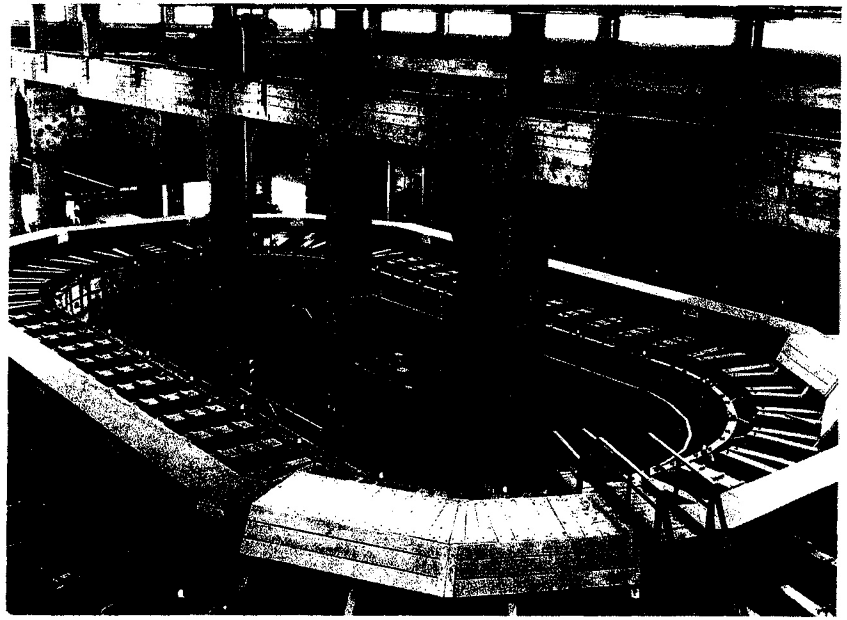

FIGURE 20.2 The Alpha-1 racetrack, Y-12 Plant in 1944. (U.S. Corps of Engineers, Manhattan Engineering District, Oak Ridge, Tennessee. Photograph by James E. Westcott). The Alpha-1 racetrack was used in the separation of uranium isotopes. This device gives some impression of the scale at which big science began to operate when the resources of the military-industrial complex were thrown behind it. The wiring used 6,000 tons of silver obtained from the U.S. treasury.

sense, the Manhattan Project was changing the way science was done, requiring leading scientists to engage in much closer cooperation with military and industrial interests. Oppenheimer realized that scientists would have to learn to work in these new ways if they were to have any influence over what was being done with their work.

Meanwhile, technical problems were emerging that required even closer cooperation between the theoretical physicists and the engineers. These problems demanded new theoretical concepts for their solution, and the theories could not be tested without building the hardware for the bomb. Far from seeing applied science as a chore to be done reluctantly under pressure of war, the physicists often found themselves fascinated by the theoretical innovations they were forced to make to solve problems generated by practical applications. The original design for a bomb was based on a

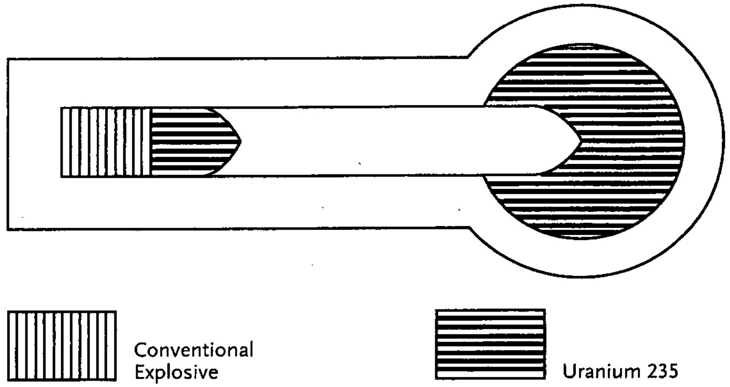

FIGURE 20.3 Diagram to show the "gun" method of exploding a uranium-235 bomb. A charge of conventional explosive fires the small slug of uranium down the barrel of the gun into the larger body on the right, raising it above the critical mass and allowing the chain reaction to begin.

"gun" that fired a slug of U-235 down a barrel to smash into a target of the same material (fig. 20.3). The combined mass was above the critical point and would instantly undergo an uncontrolled chain reaction. But in the spring of 1944, tests with plutonium showed that the gun method would not work with this element because it had such a high spontaneous fission rate that each subcritical mass would begin to fragment even before the two pieces had come together. This would disrupt the fissionable material before it could be combined in a small enough region for an effective chain reaction to take place. A whole new type of bomb had to be designed using an "implosion" method in which a slightly subcritical mass is compressed by a carefully shaped sphere of conventional explosive to achieve a critical state. British physicists (including the German refugee Peierls), now back on the project, did much of the work on this new design. But the proposal was so radical that science advisers such as J. B. Conant doubted that it would work. This was why the plutonium bomb was tested in the desert at Alamogardo, New Mexico, on 16 July 1945. It yielded an explosion equivalent to 20,000 tons of TNT, even more than the scientists had predicted (figs. 20.4 and 20.5). On witnessing the explosion, Oppenheimer famously quoted a line from the Hindu epic the *Bhagavad-Gita:* "I am become death, the destroyer of worlds." Another physicist, Kenneth Bainbridge, made a more down-to-earth comment: "Well, now we're all sons of bitches" (quoted in Schweber 2000, 3).

The actual use of the bombs followed quickly to end the war with Japan

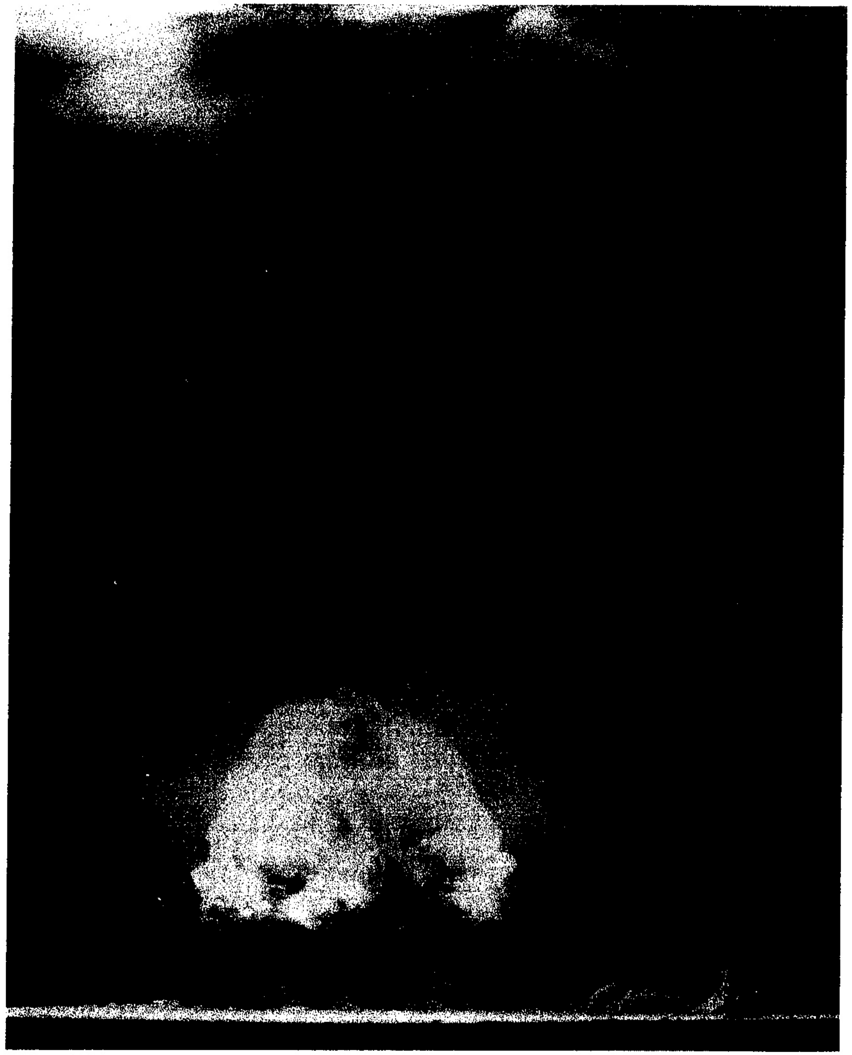

FIGURE 20.4 Explosion of the first atomic bomb.

(Germany had already surrendered). On 6 August, the B-29 bomber *Enola Gay* obliterated the city of Hiroshima with a "Little Boy" uranium bomb. Three days later a "Fat Man" plutonium bomb was dropped on Nagasaki. Controversy has raged over the actual motivations for using the bombs. The official position was that they forced a rapid Japanese surrender, thereby saving hundreds of thousands of American soldiers who might have died in an invasion. But this was certainly an overestimate, and suspicion has

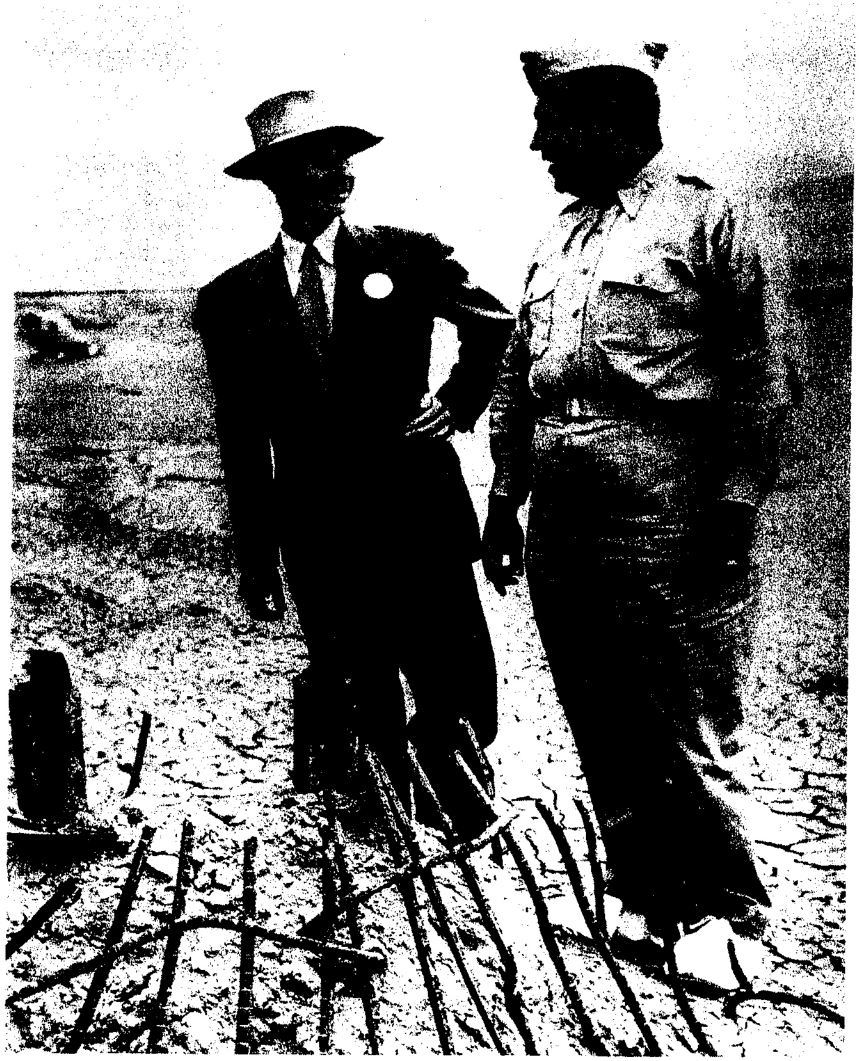

FIGURE 20.5 J. Robert Oppenheimer and General Groves at the Trinity site after the explosion of the first atomic bomb (Popperfoto/Retrofile.com). Oppenheimer was a brilliant physicist, but in the new world of big science he had to learn to cooperate with figures in authority within the military and big business.

lingered that the new American president, Harry Truman, used the bombs to gain extra leverage over the Russians in postwar negotiations (Alperowitz 1996; Giovannitti and Freud 1965; Walker 1996).

More relevant to our own theme is the question of how the scientists themselves felt about their involvement in the creation of so devastating a weapon. There can be little doubt that the initiative to create the bomb came from those scientists who realized that it might be possible to exploit nuclear fission in this way. Had the scientists not promoted the idea, the project would not have begun—this was what actually happened in Germany. But with the fear that the Nazis might explore the same possibility, there seems to have been little reluctance among British and, later, American scientists to push ahead. It was a brutal war anyway, and cities were already being obliterated by conventional bombing. The crunch came when Germany collapsed, leaving Japan (which had only a small nuclear program) as the only target. At this point, some scientists did begin to argue that the bomb should not be used or, at least, should be dropped in a remote location in Japan first, as a warning. Leo Szilard, who had originally encouraged Einstein to write to Roosevelt about the possibility of a nuclear weapon, then emerged as a leading critic of the military's policy to use the bombs. He pressured the Committee of Social and Political Implications under the physicist James Franck to issue a report arguing for a demonstration first (reprinted in Giovannitti and Freud, 111–15). But many scientists refused to endorse Szilard's proposals, some because they accepted the argument for saving American lives, others because they were still so deeply involved in the last-minute technical problems that they had no time to step back and rethink their position. Oppenheimer himself accepted the view that it would save American lives and seems to have done little to encourage debate at Los Alamos—although after the war he became a leading critic of the decision to build the even more powerful hydrogen bomb.

Science and the Cold War

In the postwar era, international tensions continued with the Soviets replacing the Nazis as the perceived threat to Western democracies. Once the muted hostilities of the cold war fell into place, it was easy for scientists on both sides to revive the old argument that involvement in military research was justified. Only a few influential figures stood out against the trend, and they faced the risk of being ostracized for disloyalty. But there were other reasons to keep up the involvement with what was now becoming known as the military-industrial complex. It was only under the threat from external powers that governments were likely to invest the huge sums of money that were needed for research in areas of "big science," where even the testing of theories required the building of vastly expensive equipment. The temptation for scientists to involve themselves with, perhaps even to encourage, projects with military applications was thus immense—it often seemed the only way of getting the funding to do research at this level. The atomic bomb project had also required an interpenetration between pure and applied science that made it difficult to distinguish between theoretical innovation and practical application. Many areas of science thus remained wedded to the military-industrial complex, and scientists would sometimes initiate projects with military implications so they could obtain funding for research they wanted to do anyway (Mendelsohn, Smith, and Weingart 1988).

The Soviets were quick to respond to the threat of the American atomic bomb (Holloway 1975). Before the war, their physicists had done good research in this area, despite government indifference. The environmental scientist V. I. Vernadskii had encouraged the search for uranium as a raw material in the hope that it could be used for peaceful purposes. During the war, Soviet officials got some information about British and American nuclear projects from spies, but when it became clear that the Germans were not involved, Stalin lost interest. His henchman Beria even suspected that stories about the Manhattan Project had been planted to encourage the Soviets to waste money in this area. Once it became clear that the Americans had the bomb, however, Stalin soon decided that it was a major threat to Soviet influence in the world, if not an actual threat that might be used in war, and a crash program was begun to build a bomb. Soviet scientists cooperated because they shared Stalin's feeling that the Americans should not be allowed to wield this power on their own. Partly as a result of information transmitted by spies, their progress was rapid, and to the consternation of the Americans they exploded their first bomb in October 1949. In the course of the 1950s, the world moved into a state of nuclear stalemate, as both sides acquired enough weapons to eliminate the other completely.

The British, too, felt left out of the nuclear club. They had initiated this area of research and had played an important role in the Manhattan Project. In the postwar era they had lost much of their international influence and saw the development of an independent nuclear deterrent as a way to preserve at least a semblance of their old position in the world. They went on to build bombs of their own, and the aircraft to deliver them, but as the superpowers moved into the age of intercontinental missiles and nuclear submarines, their status as a second-rank power became more apparent. Even so, the cold war led to Britain's scientists benefiting more than those of any other European country from the funding made available for military research (Bud and Gummett 1999). That scientists actively promoted new military projects was confirmed later by the government's scientific adviser, Solly Zuckerman: "Our 'experts' would then inform and persuade their civil service and military colleagues—not a difficult task—and the idea would then find its way upwards until as often as not it reached Ministers" (Zuckerman 1988, 390). All too often, the resources needed to put the project into operation were beyond those available to a second-rank power —although the research had been done before operational constraints became apparent.

In America, the explosion of the first Soviet atomic bomb threw another debate into sharp relief. It was apparent to physicists that there was another, yet more powerful, bomb that could be made by fusing the atoms of hydrogen together, in effect duplicating the power source of the sun itself. This would only be possible using the immense temperatures and pressures reached in the explosion of an atomic bomb, so the hydrogen bomb would require an atomic bomb as a detonator. The architect of the program to build this "superbomb" was the physicist Edward Teller (York 1976). As a Hungarian Jew by origin, Teller had relatives in Europe living under Soviet occupation. He was acutely conscious of the threat posed by the Soviets' determination to impose their system on the world and saw the retention of American superiority in the arms race as essential. He had begun working on the physics of the fusion bomb at Los Alamos and lobbied relentlessly for support within the military and the government. News of the first Soviet atomic bomb added a new urgency to his campaign. In October 1949 the General Advisory Committee of the Atomic Energy Commission, chaired by Oppenheimer, recommended the development of improved atomic bombs but rejected Teller's arguments for the superbomb. Teller saw this as tantamount to surrender and began to use all his contacts with government to undermine Oppenheimer's position. Oppenheimer was vulnerable because he had had contacts with left-wing organizations as a young man, and this was the era of the anti-Communist witch hunts led by Senator Joseph McCarthy. After a lengthy investigation, Oppenheimer's security clearance was revoked in 1954, and he was evicted from the whole atomic energy program. J. B. Conant, who shared Oppenheimer's reservations about the H-bomb project, was also marginalized.

In 1949 the Atomic Energy Commission had supported Teller and his fellow "hawks" and rejected the advice of Oppenheimer's committee. In the following year President Truman, under the advice of the National Security

Council, authorized the development of the hydrogen bomb. The key technical problem was overcome with the invention of the Teller-Ulam device at Los Alamos. The first bomb was exploded at Eniwetok Atoll in the Pacific late in 1952, yielding the equivalent of 10 million tons of TNT—one thousand times the power of the bomb that had destroyed Hiroshima. The American lead was short-lived, however: the Soviets solved the technical problems in a different way and exploded their own first hydrogen bomb late in 1955. The possibility that nuclear weapons might destroy civilization, if not all life on earth, was now all too real and had a powerful effect on the public (Boyer 1994). Many scientists felt uncomfortable with Teller's hawkish strategy, which had given America only a temporary superiority and had ratcheted up the arms race to a new level of danger. Oppenheimer had become a somewhat isolated figure, even within the scientific community, although many were stirred by his assertion that the freedom necessary for scientific enquiry required an equivalent degree of freedom in society as a whole. Resistance to the unrestrained use of science to develop new weapons came more effectively from the German émigré Hans Bethe at Cornell University, who would eventually receive the Nobel Prize for having worked out the theory of nuclear fusion within stars (Schweber 2000). Although he had worked on the nuclear weapons project, Bethe became increasingly concerned about the implications of a nuclear war and played an important role as an adviser to the American team that negotiated the test-ban treaty of 1963.

The development of more powerful nuclear weapons was not, of course, the only scientific contribution to the arms race. Von Braun and his teams built on the achievements of the V-2 to found a rocket program that made possible a new delivery system, the intercontinental ballistic missile, but also laid the foundations of the American space program. The latter was, in fact, stirred into action by the rivalry of the cold war and the Russians' early achievements in this area, most notably the launching of the *Sputnik* satellite in October 1957. Soon the missiles were being launched from nuclear-powered submarines that could stay submerged for months in the hope of escaping detection. Navies wanted new methods of locating those submarines and demanded a better knowledge of the deep-sea bed where they might be hiding—one spin-off from this was better information about the sea floor that provided crucial evidence for the theory of plate tectonics. Studies of how the radiation from atomic bombs might increase the mutation rate in humans and other species represented an important source of funding for biologists (Beatty 1991). The interaction between science and the military thus began to flourish in many different ways, and the flow of information has not always been one way. What starts as applied science in one area sometimes provides evidence for new insights in an entirely different area.

Conclusions

The twentieth century saw a massive expansion in the relationship between science and the military. The early phases were tentative in nature: patriotic scientists suggested ways of improving weapons (or devising new ones) under pressure of national emergency, often to be greeted with hostility or derision by the military authorities. World War I saw the emergence of the first attempts to streamline the interaction, though none of the new weapons turned out to be decisive. During the interwar years, several nations built on these early efforts and began the integrated programs linking scientists, industry, and the military that generated genuinely new systems such as radar, capable of transforming the way navies and air forces (especially) would fight. World War II laid the foundations for scientists' involvement with the military-industrial conflict during the cold war. As a consequence of these developments, theoretical science acquired a new degree of involvement with industry, the military, and the government. The line between pure and applied science became increasingly blurred, especially in those areas where enormous amounts of funding were needed for equipment. Scientists also realized that technical problems could sometimes generate fascinating theoretical issues. Leading scientists now managed large projects absorbing vast amounts of industrial and government money and needed the managerial skills necessary to interact with those who provided the funds.

The emergence of a close relationship between science and the military had been delayed by the mutual suspicion inevitable between two professions with such different origins. But once that relationship was established, it is hardly surprising that scientists should be attracted by the funding it made available—especially if it allowed them to work on projects in which they were genuinely interested. By the 1950s, 90% of the funding provided for research in physics at American universities came from the Atomic Energy Commission, much of it for work on military projects (Hoch 1988, 95; see also Forman 1987). Small wonder that many scientists were willing to slant their research in this direction and to acquire the managerial skills needed to interact with the world of government and industry. More serious, for those concerned with the moral consequences of the relationship, was the temptation to promote the development of new weapons systems simply because this would open up the government's coffers to fund new areas of research. Teller almost certainly wanted the H-bomb because he feared the threat from the Soviet Union—but the more recent proposal of the Star Wars missile defense system has raised suspicions that the weapons designers have moved into the driving seat. Those scientists who actually work in defense industries are controlled by engineers and managers with commercial priorities.

After World War II, there were some efforts in the West to reestablish the ideal of pure science carried out solely to gain knowledge, partly because the Soviet system encouraged the rival view that scientists, like everyone, else, should work for the common good (invariably identified with the state). The leading American science adviser Vannevar Bush wrote a report in 1945 titled "Science: The Endless Frontier" in an attempt to re-create the image of the disinterested search for an understanding of nature. A firm foundation in pure research was necessary to ensure that technological spin-offs would subsequently emerge. This is still the orthodox notion of science promoted by many academic scientists, but it fails to acknowledge the extent to which much apparently pure research is now done with finance provided by industry and the military. Those scientists who most effectively confronted the moral dilemmas posed by the new situation were not those who retreated into isolationism, but those who accepted the engagement with the practical world and argued that scientists must use their influence to control the ways in which their work was exploited. This might involve active campaigning against the temptation to promote a new military technology just because it offered opportunities for research, but it might also involve constructive engagement with the military and political realities, as with Bethe's contribution to the signing of a treaty that would limit, at least, the dangers from the testing of nuclear weapons.

References and Further Reading

Alperowitz, Gar. 1996. *The Decision to Use the Atomic Bomb.* London: Fontana.

Beatty, John. 1991. "Genetics in the Atomic Age: The Atomic Bomb Casualty Commission, 1947–1956." In *The Expansion of American Biology,* edited by Keith R. Benson, Jane Maienschein, and Ronald Rainger. New Brunswick, NJ: Rutgers University Press, 284–324.

Boyer, Paul. 1994. *By the Bomb's Early Light: American Thought and Culture at the Dawn of the Atomic Age.* New ed. Chapel Hill: University of North Carolina Press.

Brown, L. 1999. *A Radar History of World War II.* Philadelphia: Institute of Physics.

Bud, Robert, and Phillip Gummett, eds. 1999. *Cold War, Hot Science: Applied Research in Britain's Defence Laboratories, 1945–1990.* Amsterdam: Harwood Academic Publishers.

Buderi, Robert. 1997. *The Invention That Changed the World: The Story of Radar from War to Peace.* Boston: Little, Brown.

Forman, Paul. 1987. "Behind Quantum Electronics: National Security as a Basis for Physical Research in the United States, 1940–1960." *Historical Studies in the Physical and Biological Sciences* 18:149–229.

Frayn, Michael. 1998. *Copenhagen.* London: Methuen Drama.

Giovannitti, Len, and Fred Freud. 1965. *The Decision to Drop the Bomb.* New York: Coward-McCann.

Goodchild, Peter. 1980. *J. Robert Oppenheimer, "Shatterer of Worlds."* London: BBC.

Gowing, Margaret. 1965. *Britain and Atomic Energy, 1939–1945.* London: Methuen; New York: St. Martin's Press.

Haber, L. F. 1986. *The Poisonous Cloud: Chemical Warfare in the First World War.* Oxford: Clarendon Press.

Hackmann, Willem. 1984. *Seek and Strike: Sonar Anti-Submarine Warfare and the Royal Navy, 1914–1954.* London: HMSO.

Hartcup, Guy. 1988. *The War of Invention: Scientific Developments, 1914–1918.* London: Brassey's Defence Publishers.

———. 2000. *The Effects of Science on the Second World War.* London: Palgrave.

Hoch, Paul K. 1988. "The Crystallization of a Strategic Alliance: The American Physics Elite and the Military in the 1940s." In *Science, Technology and the Military,* edited by Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart. Dordrecht: Kluwer, 1:87–116.

Hoddeson, Lillian, Paul W. Henrickson, Roger A. Meade, and Catherine Westfall. 1993. *Critical Assembly: A Technical History of Los Alamos during the Oppenheimer Years, 1943–1945.* Cambridge: Cambridge University Press.

Hogan, Michael J., ed. 1996. *Hiroshima in History and Memory.* Cambridge: Cambridge University Press.

Holloway, David. 1975. *Stalin and the Bomb: The Soviet Union and Atomic Energy, 1939–1956.* New Haven, CT: Yale University Press.

Hughes, Jeff. 2002. *Manhattan Project: Big Science and the Atom Bomb.* Cambridge: Icon Books.

Johnson, Brian. 1978. *The Secret War.* London: BBC.

Jones, R. V. 1978. *Most Secret War.* London: Hamish Hamilton.

Kevles, Daniel. 1995. *The Physicists: The History of a Scientific Community in America.* New ed. Cambridge, MA: Harvard University Press.

Mendelsohn, Everett, Merritt Roe Smith, and Peter Weingart, eds. 1988. *Science, Technology and the Military.* 2 vols. Dordrecht: Kluwer.

Neufeld, Michael J. 1995. *The Rocket and the Reich: Peenemünde and the Coming of the Ballistic Missile Era.* New York: Free Press.

Peyton, John. 2001. *Solly Zuckerman: A Scientist out of the Ordinary.* London: John Murray.

Powers, Thomas. 1993. *Heisenberg's War: The Secret History of the German Bomb.* London: Jonanthan Cape.

Price, Alfred. 1977. *Instruments of Darkness: The History of Electronic Warfare.* New ed. London: Macdonalds & Jane's.

Rose, Paul Lawrence. 1998. *Heisenberg and the Nazi Atomic Bomb Project: A Study in German Culture.* Berkeley: University of California Press.

Schweber, Sylvan S. 2000. *In the Shadow of the Bomb: Bethe, Oppenheimer, and the Moral Responsibility of the Scientist.* Princeton, NJ: Princeton University Press.
Swann, Brenda, and Francis Aprahamian, eds. 1999. *J. D. Bernal: A Life in Science and Politics.* London: Verso.
Walker, J. Samuel. 1996. "The Decision to Use the Bomb: A Historiographical Update." In *Hiroshima in History and Memory,* edited by Michael J. Hogan. Cambridge: Cambridge University Press, 11–37.
York, Herbert F. 1976. *The Advisers: Oppenheimer, Teller, and the Superbomb.* San Francisco: W. H. Freeman.
Zachary, G. Pascal. 1999. *Endless Frontier: Vannevar Bush, Engineer of the American Century.* Cambridge, MA: MIT Press.
Zuckerman, Solly. 1978. *From Apes to Warlords: The Autobiography (1904–1946).* London: Hamish Hamilton.
———. 1988. *Monkeys, Men and Missiles: An Autobiography, 1946–1988.* Reprint. New York: Norton.