CHAPTER 4

NUCLEAR ENERGY AND ELECTRIC POWER

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Prior to the nineteenth century the primary sources of energy were animal and human power, fuel wood and agricultural wastes, and wind and water power. The industrial revolution has been associated with two major transitions in energy use. The first was made possible by the steam engine, the first technology for the conversion of fossil energy resources into work. The second was associated with the introduction of electricity, the first energy carrier that that could be converted into light, heat and work at the point at which it is used (Grubler 1998: 149-251).[1]

These technical changes have been associated with dramatic changes in the relative importance of the several sources of energy.

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[1] In this chapter I draw on a more detailed discussion of the development of the electric light and power industries in Ruttan (2001: 235-285). I am indebted to Richard Fuller, Robert Seidel, and Douglas Tiffany for comments on an earlier draft of this chapter.

In the nineteenth century with the expansion of railroads, the growth of the steel industry, and the growth of the electric power industry, the share of energy accounted for by coal rose dramatically. Oil and natural gas were introduced in the 1870s. Their use has been closely associated with the diffusion of the internal combustion engine and the growth of the petrochemical industry. By the 1970s, each accounted for a larger share of energy than coal. Nuclear power use, which experienced exceptioNolly rapid growth after it introduction in the late 1950s, has experienced slower growth since the early 1980s.

In this chapter my primary objective is to explore the role or the U.S. military and defense related institutions in the scientific and technical development of nuclear power in the United States. Institutional innovation represents an important sub-theme. The Manhattan Project that was organized to produce the atomic bomb was one of the most significant institutional innovations during World War II. It marked the transition from the public armory system to the private contractor system in the development of armaments and in the transition to ”big science” in the mobilization of scientific resources to address mission oriented research and development (Danhof 1968: 93-99).

THE ELECTRIC UTILITY INDUSTRY

The initial development of electric power technology took place entirely in the private sector. In 1876 Thomas A. Edison established the first modern industrial laboratory in United States in Menlo Park, New Jersey. He visualized the laboratory as an “invention factory”—capable of turning out “a minor invention every ten days and a big thing every six months or so.” The invention of the high-resistance incandescent lamp and the development of system for the generation and distribution of electric power by Edison and his research team at his Menlo Park laboratory established the technical foundation for the electric utility industry (Hughes 1983).

Until the advent of nuclear power the technology of electric power generation would have remained familiar to Edison. Each power generation "unit," called a "boiler-turbogenerator" unit, operated independently of other units. It consisted of a boiler to burn the fuel and to generate and expand the steam and a turbo-generator to convert high-pressure steam into electric energy. A condenser converted the steam into hot water to complete the cycle. Until the late 1960s technical change was aimed primarily at increasing the size of generators and boilers and improving thermal efficiency of the generating cycle (Ruttan 3001: 260-62).

A series of equally important institutional innovations were required to realize the economic gains made possible by the advances in technology and the integration of equipment manufacturers into a coherent electric supply (utility) industry. The manager-entrepreneur Samuel Insull, became a pivotal figure in the institutional innovations that gave rise to an integrated publicly regulated electric supply industry in the United States. In 1892 Insull, who had worked with Edison at Menlo Park, moved to Schenectady to become manager of the Edison General Electric Company. When it merged with the Thompson-Huston Company, a leading manufacturer of electrical equipment, to form the General Electric Company Insull moved to Chicago to become president of the Chicago Edison Company, one of the many small electric power companies that served the Chicago area market. Within two decades Insull and his associates succeeded in creating a single “monopolistic, technologically efficient, and economically operated company for all Chicago” (Hughes 1979: 140).

As the Chicago Edison Company expanded to include most of Illinois Insull was able to persuade the state legislature to enact legislation that substituted state regulation of rates and service for local regulation.[2] The Illinois system became the model for regulation in other states. “The utility industry interpreted such developments in Illinois and elsewhere as an implicit social contract in which the utilities undertook to provide reliable and affordable electricity in exchange for a socially determined rate of return,” (Ruttan 2001:246). Innovations in state and federal

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[2] In Chicago and elsewhere in Illinois politics became an essential component of the Insull system. “Methods were found by which politicians obtained wealth from political power without having to steal public money” (Hughes 1983:206)

regulatory regimes in the 1980’s and early 1990s, particularly the Energy Policy Act of 1992, contributed to the deconstruction of the institutional structure that Insull and other leaders of the electrical power industry had erected in the 1920s. These policy reforms enabled independent power producers using natural gas as a primary energy source to walk through the door that energy activists thought they had opened for sustainable energy sources such as biomass, wind and solar-thermal (Hirsh 1999).

NUCLEAR ENERGY

Demonstration of the feasibility of controlled nuclear fission by a team directed by the young Italian physicist Enrico Fermi at the University of Chicago’s Stagg field on December 2, 1942 set the stage for an active role of the U.S. military and defense related institutions in technology development for the power industry.[3]

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[3] I do not in this section attempt to provide a scientific or technical account of the development of atomic power. My purpose is to provide insight into the critical role played by military considerations in the development of atomic power for military and commercial purposes. Throughout this section I draw

From its beginning it has not been possible to understand the nuclear power industry apart from the military application of nuclear energy (Cantelon, Hewlett and Williams 1991: 303-307; Cowan 1990).

Atoms for War

The steps that lead to Fermi's demonstration of the possibility of controlled nuclear fission, and a few years later to the construction of the nuclear bomb, were set in motion in 1938 when two German chemists, Otto Hahn and Fritz Strassman, of the Kaiser Wilhelm Institute in Berlin, found that they could split uranium atoms by bombarding their nuclei with neutrons. The neutron bombardment causes the uranium to "fission" into smaller pieces that fly apart with a great deal of energy.[4]

It was immediately recognized in the physics community, in both Europe and the United States, that if the energy liberated by the splitting of the uranium atom could be controlled and directed

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heavily on the exceedingly useful official histories by Hewlett and Anderson (1962) and Hewlett and Duncan (1969). See also Lawrence (1959), Hughes (1989: 353-44), and Pool (1997). For excellent technical accounts of nuclear fission, nuclear fusion, nuclear reactor, and nuclear weapons see *Encyclopedia Britannica* (1974, Vol. 13: 301-328).

[4] For a useful introduction to the process of nuclear fission see Leachman 1965.

it might be possible to construct a nuclear weapon far more powerful than anything that was currently available (Hewlett and Anderson 1962: 10-14). This possibility led Leo Szilard, a Hungarian physicist who had immigrated to the United States and was then employed at Columbia University, to attempt to bring the implications of the discovery to the attention of the United States government. Szilard contacted Albert Einstein about his concern. On August 2, 1939, Einstein signed a letter, prepared by Szliad and addressed to President Roosevelt. In the letter Einstein urged that everything possible be done to prevent Germany from being first to develop an atomic bomb. Szilard then arranged to have the letter delivered to President Roosevelt by Alexander Sachs, a Lehman Corporation economist who had access to the White House.[5] On November 1 the Presidents Advisory Committee on Uranium urged that the United States initiate a crash program to study the physics of uranium fission. By early 1941 the Committee

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[5] For Einstein's letter and Roosevelt's reply see Stoff, Fanton and Williams (1991: 18-20). The Einstein letter to Roosevelt did not have the immediate impact on policy that its sponsors had hoped. It was not until the end of 1941, over two years after the letter had been presented to Roosevelt, that a decision to build the atomic bomb was finally taken. For a personal account see Lawrence (1959: 37-66).

concluded that it was theoretically possible to build an atomic bomb many thousands time more powerful than the largest bomb that had ever been made (Hewlett and Anderson 1962: 20; Pool 1997: 31-33).[6]

Responsibility for the construction of an atomic bomb was assigned by President Roosevelt to the Army, which in turn assigned the project to the Army Corps of Engineers. The Corps was the only agency in the federal government, with the possible exception of the Tennessee Valley Authority, that had sufficient large-scale construction experience to undertake the project. In June of 1942 the Corps formed a special District, the Manhattan District, to oversee and construct what would come to be termed the Manhattan Project. It soon became apparent that lines of authority between the scientific community, represented by

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[6] Institutional arrangements for providing advice to the president on issues of science and technology on military affairs evolved in two steps in the early 1940's. Ono June 27, 1940 President Roosevelt issued an executive order establishing the National Defense Research Council (NDRC) to be chaired by Vannevar Bush, dean of engineering at Massachusetts Institute of Technology and chairman of the National Advisory Committee for Aeronautics. In June of 1941 Roosevelt issued a second executive order establishing an Office of Scientific Research and Development also to be headed by Bush. The OSRD had substantially greater resources and authority than the NDRC. Bush and the OSRD played a key role in initiating the institutional arrangements for the development of both radar and the atomic bomb. The mobilization of these and other wartime projects set the stage for a prominent role for physicists in science and technology policy during World War II and during the initial years of the Cold War (Dawson 1976: 11-13; Kelves 1979: 287-348).

Vannevar Bush, who directed the Presidents Office of Scientific Research and Development, and the Army would have to be clarified. General Brehon Sommervelle, Commanding General of the Army Services of Supply (in which the Corps of Engineers was then located) selected Colonel (later Brigadier General) Leslie Groves, Deputy Chief of Construction in the Corps of Engineers, to direct the Manhattan Project. Groves brought the energy, direction and decisiveness to the project that was necessary to assure its success.

The task that faced Groves was not only to find a workable design for the bomb but to create an entirely new scientific, technical and industrial infrastructure for its production and testing. By the time the bomb was completed and tested on July 16, 1945 the complex included a series of university based scientific laboratories, plutonium production facilities, uranium separation laboratories, and test reactors. Three entirely new cities, Oak Ridge (Tennessee), Los Alamos (New Mexico), and Hanford (Washington) were constructed to support the project (Fig. 4.1).

Research on gaseous diffusion was initially conducted at Colombia University and on the electromagnetic separation process at the University of California Radiation Laboratory Development and production facilities were constructed at Oak Ridge for uranium enrichment, at Hanford for plutonium production. The Los Alamos facility, directed by Robert Openheimer was given responsibility for the actual design and production of the uranium and plutonium bombs.[7] "The manufacturing complex created by the Manhattan Project was approximately the same size as the U.S. automobile industry at that time," (Poole 1997: 40).

(Insert Fig 4.1 about here)

The first atomic test explosion, of a plutonium bomb, was conducted at Jornada del Mexico, New Mexico (designated Trinity by Robert Openheimer) on July 16 1945. The first uranium bomb, "Little Boy" was detonated over Hiroshima on August 6-

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[7] When the Manhattan Project began it was not possible to predict whether a uranium bomb or a plutonium bomb would be faster to build. In view of this uncertainty it was decided to try both. The Oak Ridge facility would focus on separating fissionable U-235 from natural uranium. The Hanford facilities would focus on plutonium production. Plutonium was a recently discovered new element not found in nature. It is obtained by bombarding uranium with deuterons – the neuclei of heavy hydrogen atoms. The potential advantage of plutonium is that a fissionable substance could be obtained without building isotope separation plants (Hewlett and Anderson 1962: 22-23, 88-91, 308-310).

and the plutonium bomb, "Fat Man" was detonated over Nagasaki on August 9, 1945. [8]

In retrospect it seems evident that Germany did not have the scientific, technical and financial resources to construct an atomic bomb. "The German effort gained momentum slowly, made no real headway in solving the technical problems of building or testing a bomb, and largely petered out by the end of 1943 (Stoff, Fanton and Williams 1991: 16). It has also been asserted that the Japanese government had decided to surrender before the atomic bombs were dropped on Hiroshima and Nagasaki. "Japan would have surrendered even if the atomic bombs had not been dropped, even if Russia had not entered the war, and even if no invasion had been planned or contemplated" (*U.S. Strategic Bombing Survey Report 1945.* In Stoff, Fanton and Williams 1991: 272). It is possible that both statements are correct. But neither answer was available at the time the decision was made.

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[8] For a graphic description of the physical and human devastation of the bombing of Hiroshima see Hersey (1946).

In 1942 it had been estimated that the development of the atomic bomb would cost in the neighborhood of $100 million. In the three years between September 17, 1942, when Groves appointed to head the Manhattan Project, and July 16 1945, when the test explosion was conducted at Trinity, the total cost of the Manhattan project had risen to approximately $2 billion (approximately $20 billion in 2000 dollars). It is hard to believe the U.S. political system would have supported the mobilization of resources of anything like this magnitude except during war or threat of war.

Atoms for Peace

In 1946 authority to promote and regulate the development of nuclear technology for both military and non-military purposes was transferred to the newly established United States Atomic Energy Commission (AEC). The laboratories and other facilities that had been initially established to support of the work of the Manhattan Project were placed under the jurisdiction of the Commission.

Initially, neither the Atomic Energy Commission nor the power industry evidenced a great deal of enthusiasm about the prospect for nuclear power development. The Atomic Energy Commission focused much of the effort of its laboratory system on weapons development. The private sector found the secrecy constrains imposed by the AEC cumbersome and was concerned about the long run prospect for an adequate uranium supply. "Because of the requirements for uranium in the weapons program dual use breeder reactors were considered necessary. The AEC initiated a uranium exploration and procurement program to alleviate this material shortage and by the early 1950s the availability of uranium appeared to no longer be a constraint," (Dawson 1976: 234)[9]

President Eisenhower's "Atoms for Peace" speech in December 1953 had the effect of committing the U.S. to a much more active commercial nuclear power program. The 1954 Atomic Energy Act provided a statutory basis for private sector

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[9] For another early cautious evaluation see Schurr and Marschak (1950).

development of nuclear technology and for cooperation in the development of "peaceful uses" of nuclear technology with other countries (Hewlett and Hall 1989).[10]

In December 1954 the Atomic Energy Commission, under pressure from the Congress and the power industry, announced a Power Demonstration Reactor Program. Detroit Edison proposed a fast breeder reactor; Yankee Atomic, a consortium of New England utilities, proposed a boiling water reactor; a group headed by Commonwealth Edison of Chicago proposed a heavy water reactor; Consolidated Edison of New York submitted an application to build a pressurized water reactor; the Consumers Power District of Nebraska submitted plans for a sodium-graphite

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[10] The 1954 Atomic energy Act "represented a compromise among those in the administration, Congress and industry who preferred that private enterprise develop atomic energy, others who wanted a cooperative arrangement between government and private industry, and some who wished the industry to be nationalized. It allowed private corporations to build and own nuclear –power plants, but government continued to own and control the fuel (Hughes 1989: 438). Prior to 1954 the debate about the future of atomic energy was largely confined to the Office of the President, the military and the scientists who had been active in the development of the bomb. Private power interests had not yet acquired sufficient technical capacity to participate effectively in the debate. Industry representatives were, however insistent that they did not want the AEC to become a "nuclear TVA"—owning and operating nuclear power generating facilities. To the extent that public interests were involved they were represented by the scientific community whose major concern was that the development of nuclear energy for military and commercial use not be monopolized by the military ((Dawson 1976: 222-276).

reactor.[11] By 1962 there were 7 commercial nuclear power prototypes in operation in the United States (Table 4.1) The effect of these actions was to generate considerable enthusiasm within the general public, the power industry and in the congress. It was frequently asserted that nuclear energy would make electric power so inexpensive that it would be "too cheap to meter (Pool 1997: 71).

At the time the Power Demonstration Project was announced the Atomic Energy Commission had already made a decision to cooperate with Duquesene Light and Power and Westinghouse to build a pressurized water reactor at Shippingport, Pennsylvania. That decision was a direct consequence of a 1950 decision by the Navy to develop a water-cooled nuclear reactor to propel its first nuclear powered submarine. President Eisenhower's "atoms for

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[11] "Nuclear reactors are classified by two of the materials used in their construction: the coolant used to transfer heat from the reactor core and the moderator used to control the energy level of the neutrons in the reactor core. In a light water reactor both the coolant and moderator are light water—H2O. In a heavy water reactor both are heavy water—D2O. In a gas graphite reactor the coolant is a gas, usually helium or carbon dioxide, the moderator is graphite" (Cowan 1990: 545). In 1955 at the first international conference on nuclear power about 100 types of reactor piles were discussed. Three years later the number was down to about 12. When the U.S. Navy decided to produce a nuclear-powered submarine, after initial experiments by the AEC with six technical variants, two variants were considered, and after a single experiment with each, the light waster reactor was selected. This variant was intensively explored and developed of the following decades (Cowan 1990: 547-548.)

peace" speech in December 1953 had the effect of committing the U.S. to a civilian nuclear power program. The reactor technology that was most readily available was the pressurized water technology that had been initially developed for use in nuclear powered submarine and aircraft carriers.

The Navy nuclear power program was directed by then Captain (later Admiral) Hyman Rickover, who simultaneously held responsibility for Nuclear Propulsion in the Navy and headed the Naval Reactors Branch of the AEC. In 1946 the Navy Bureau of Ships assigned Rickover and a small contingent of civil and uniformed staff to Oak Ridge National Laboratory to evaluate the possible application of nuclear power for naval propulsion. It was recognized that nuclear powered submarines would have clear advantages relative to diesel in term of quieter operation, cruse range and speed, and ability to remain submerged over a longer period. From 1946 through the launching of the Nautilus nuclear submarine in 1955 and to 1957 when the Shippingport power plant began operations the development of nuclear power for both military and commercial use was almost completely dominated by Rickover's powerful engineering skills and personality (Hewlett and Duncan 1974; Hewlett and Hall 1989; Duncan 2001).

The Shippingport reactor began producing electricity for commercial use in 1957. By 1962 seven experimental nuclear electric power plants were in operation in the United States (Table 4.1). "By the mid-1960s experimentation over power reactors was over. The pressurized water reactor, by Westinghouse, and the boiling water reactor, built by General Electric, became the industry standards," (Cantelon, Hewlett and Williams 1991: 305).

In the United States and later in Germany and Japan, large public R&D programs were complemented by substantial private research investment by firms such as Westinghouse, General Electric, Babcock and Wilcox, Siemens, AEG, and Mitsubishi. In the United Kingdom, France and the USSR, the research was conducted almost exclusively by the public sector. Nowhere were electric utility firms heavily involved in nuclear research. They assumed that replacing a fossil fired boiler with a nuclear reactor to produce steam would be a relatively simple process—“a nuclear reactor was just another way to boil water.”

A number of different reactor designs had been advanced in the late 1950s and early 1960s. As noted above the U.S. elected to use the light-water cooling and enriched uranium fuel technologies. The British and French initially used a gas graphite reactor. Canada used heavy water and natural uranium. By the mid 1960s all of the major industrial countries—the United States, Canada, the United Kingdom, the USSR, France, Germany, Sweden and Japan—were making significant investments in nuclear power generation. Improvements in reactor design and construction experience had locked the industry into the light-water enriched uranium path of nuclear energy development. Whether other designs would in fact have been superior in the long run is open to question, although some of the engineering literature suggests that high-temperature gas-cooled reactors would have been superior.

Brian Arthur (1990: 99) and Robin Cowan (1990: 541-567) have interpreted this history as an example of politically inspired “path dependence.” Before other technologies became technical and economically viable it was too late. The “path dependence” was forced by strategic rather than technical or economic considerations. Without the uranium enrichment facilities built by the Atomic Energy Committee for weapons purposes, the commercial reactors built at least through the mid-1970’s would not have been economically feasible (Dawson 1976: 268). And Poole has insisted that without an atomic weapons program no country would have built enriched uranium facilities (Poole 1997: 43).[12]

Cost Inflation

As late as the mid-1970s the U.S. nuclear power industry seemed poised for even more rapid expansion. Restrictions by the atomic

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[12] From the late 1960’s until the early 1980’s the Atomic Energy Commission devoted very large resources to development of the Liquid Metal Fast Breeder Reactor (LMFBR). The technical argument for the breeder reactor was its potential ability to produce more fuel than it consumes. By 1980 it became clear that the prospects for developing a commercially viable breeder would not be realized until 2025 or beyond. In 1984 appropriations for the Clinch River demonstration project were discontinued (Cohen and Noll 1991: 217-257).

energy Commission on ownership of nuclear fuel had been relaxed since the mid 1960s. By 1975 government ownership of uranium enrichment facilities was the only major exception to private ownership of the nuclear energy supply system.[13] A petroleum supply crisis that began in the early 1970s was expected to increase demand for nuclear power. It was completely unanticipated that a combination of public safety, health and environmental concerns would bring expansion to a halt by the end of the decade.

Cost estimates by the Atomic Energy Commission (AEC) in the 1960s indicated that nuclear power capital costs would be substantially greater than those of electricity generated by large coal fired plants. It was expected, however that this would be compensated for by low operating costs due to the limited quantities of uranium fuel required (Weinberg 1972: 28). However, the anticipated economies of scale and cost reductions from "learning by doing" and "learning by using" were not realized. They were more than offset by increases in the complexity of

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[13] Government retention of uranium enrichment facilities was justified by the continuing concern over the ownership of the natural uranium essential to the military weapons program (Dawson 1976: 259).

reactors, due partly to initial design errors, but largely to increasingly stringent safety standards. In many cases, final costs exceeded initial estimates by over 100 percent. It became apparent by the mid-1970s that the simple and comparatively inexpensive light water reactors of the late 1960s were, partly on engineering grounds and partly due to safety concern, no longer commercially viable (MacKerron 1992).

Since the early 1970s, safety requirements for nuclear plants in the United States have been continually tightened by the Nuclear Regulatory Commission (NRC) in response to public risk perception. Although it is not clear that the changes in those requirements resulted in substantial safety improvements, the frequent design changes in the course of construction did result in higher construction costs. Average construction time in the United States rose to 12 years. The costs of nuclear plants of comparable size, corrected for inflation, quadrupled in little more than a decade. These higher capital costs pushed the cost of producing electricity from nuclear-fueled plants even higher relative to coal burning plants. In the United States no new nuclear power plants have been ordered since 1978. Plants ordered after 1974 have been cancelled. Strategic considerations continued to weigh heavily in decisions to sustain or expand nuclear power capacity.[14] In many developing countries nuclear power programs have absorbed a far larger share of public resources than could be justified in terms of any potential economic benefits (Marcus 1993: 394-395; Abelson 1996: 463-465; Solingen 1996: 188).

Since the late 1970's operational experience and advances in reactor technologies have led to renewed interest in the role of nuclear power in meeting future electric power demand (Taylor 2004).This economic interest has been reinforced by the potential role that nuclear power might play in reducing greenhouse gas emissions.. The authors of a MIT Nuclear Energy Study (2003) have argued that a nuclear energy option should be included, along with increased efficiency in electricity generation and use and

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[14] In spite of the fact that no new plants were being constructed nuclear power production in the United States increased by about 40 percent between 1990 and 2000. This increase has largely been the result of improvements in plant operation (Meserve 2002).

renewable energy sources in any comprehensive effort to reduce carbon dioxide emissions from energy generation. They suggested that if nuclear energy is to play an important role in meeting the rapidly growing global demand for electricity three unresolved problems, in addition to cost, must be successfully addressed. These include concerns about safety and health, proliferation of nuclear weapons, and disposal of nuclear wastes. The MIT study group is cautiously optimistic that these concerns can be successfully resolved over the next several decades.

Power based on nuclear fission is still viewed by many scientists and engineers as a potentially environmentally benign technology capable of replacing fossil fuels on a large-scale basis (Rhoades and Beller 2000). Physicists and engineers continue to be intrigued by the possibility of producing controlled fusion reactions in a power plant to capture the large amounts of energy that are theoretically available. Fusion has two potentially important advantages. The first is that the fuel, hydrogen and its isotopes, is much less expensive and more abundant than the heavy metals, such as uranium, used in fission. The second is that although the fusion process would create some radioactive waste, due to irradiation of the plant construction materials, it would not generate the huge amount of waste produced by fission. Fusion's major disadvantage, even should it become technically feasible, is one it shares with existing nuclear fission plants—high capital cost of initial investment that would remain an obstacle to commercial viability.[15]

(Insert Box 4.1 about here)

ALTERNATIVE ENERGY

Concern about the environmental and health implications of fossil fuel and nuclear technology, combined with the oil price shocks of the 1970s, induced an intense debate about energy futures. From the end of World War II through the early 1970s, United State energy research and development effort had focused almost entirely on nuclear energy. In 1973, for example, 67% of federal

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[15] In November 2003 the U.S. Department of Energy announced that a $5.0 billion contribution to the International Thermonuclear Experimental Reactor (ITER) fusion energy project ranked first among its list of scientific priorities (Malakoff and Cho 2003: 1126-27).

energy R&D expenditures were on nuclear power. Smaller amounts were spent on coal, petroleum, and natural gas. Renewable energy sources and conservation were largely ignored (Tilton 1974: 8-15).[16]

By the mid-1970s, it was widely assumed that energy conservation could slow the rate of growth in energy use and that by the end of the century renewable energy sources could account for a substantial share of incremental growth in energy production. It was recognized, however, that the substitution of renewable energy for fossil fuel and nuclear sources and the slowing of energy use could be achieved only by changes in the technology of electric power generation, in the technology of energy use, in the incentives facing both producers and consumers.

There have been a series of government interventions, beginning with the Clean Air Act of 1970 and the Public Utility Regulatory Policies Act (PURPA) of 1978, designed to address the environmental health implications of electric power production.

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[16] Hirsh 1999: 72-117. I have discussed the issues of alternative renewable and non-renewable energy options in greater detail in Ruttan (2001: 270-279).

There have also been a series of interventions designed to encourage the development and adoption of energy conserving technologies and practices. By the mid 1990s it was clear that the changes in technology and organization were quite different than the changes that had been anticipated by reform advocates in the 1970's and 1980s. Design improvements have lead to rapid improvements in the efficiency of gas turbines for the generation of electricity and to rapid increase in the use of natural gas as a primary energy source for the production of electricity (Martin 1996; Alic, Mowery and Rubin 2003: 13-14). The changes in energy technology and policy since the early 1970's, particularly the substitution of natural gas for coal in electricity generation, have been associated with continuation of the long term trend toward energy sources with lower carbon content.

If the trend toward decarbonization is to continue into the middle of the twenty-first century and beyond it may require the use of pure hydrogen as a fuel. This will require the development of an economically viable technology for electrolizing water

(Ausubel 1991; Grubler and Nackicenovic 1996). Water (H_2O) can be split into hydrogen and oxygen by passing an electric current through it. In the 1950s and 1960s it was anticipated that the cost of electricity produced by nuclear power would be low enough to make electrolytic hydrogen production economically viable. In the 1980s and the1990s advances in photoelectric cell technology again created considerable optimism that hydrogen would become an economically viable fuel (Ogden and Williams 1989). The Bush administration announced in January 2003 a commitment to a $1.2 billion research initiative to replace carbon with hydrogen based fuels in the field of transportation. The prospect that a "hydrogen economy" will be successfully implemented during the first half of this century, however, remains controversial (Romm 2004; Sperling and Ogden 2004).

PERSPECTIVE

Nuclear power is the most clear cut example discussed in this book of an important general purpose technology that, in the absence of military and defense related procurement, would not have been developed at all—it would not have been developed "anyway". It is exceedingly difficult to imagine circumstances, in the absence of the threat that Germany might develop nuclear weapons capacity during World War II, that would have induced the U.S. federal government to mobilize the scientific, technical and fiscal resources of the Manhattan Project. It is equally difficult to imagine circumstances, other than the Cold War with the USSR, that would have enabled the U.S. federal government to sustain its investment in nuclear energy into the 1980s.

What if there had been no Manhattan Project? Pool has argued that in the absence of an atomic weapons program the United States would not have built nuclear enrichment facilities. And without the enriched uranium supplied by the postwar weapons program it is unlikely that a nuclear Navy program would have been implemented or that a nuclear power program would have been developed (Pool 1997: 43).

Chauncey Starr, one of the more experienced and thoughtful observers of the nuclear power industry, speculated in the mid 1990's that in the absence of the threat of war the Hahn and Strassman's work would have been written up in the scientific journals and treated as a subject of mostly academic interest. Because of the high cost research and development of atomic reactors would have proceeded at a modest pace. Low-power nuclear reactors would have been developed to produce isotopes primarily for medical and industrial applications (Pool 1997:41).

During the last quarter of the 19th century the electric light and power industry emerged as the most dynamic general purpose technology in the United States economy. During the first half of the 20th century it was a major source of productivity and economic growth in the United States and other industrial economies (Ruttan 2001: 247-266). At mid century there were great expectations that the exploitation of nuclear energy would enable the electric power industry to renew its role as a dynamic source of economic growth by making electricity available to industry and consumers on increasingly favorable terms--:too cheap to meter." These expectations have not been realized. It is possible that during the first half of the 21st century nuclear power will be able to make a significant contribution to meeting the growth in demand for electric power and, by substituting for carbon based fuels, contribute to slowing the accumulation of greenhouse gases in the atmosphere. In retrospect it seems quite possible that if the United States had proceeded at a more measured pace in the development and introduction of nuclear power in the 1950s and 1960s it would today be in a stronger position to bring nuclear technology to bear in meeting the demands of the 21st century.

Box 4.1

THE NATIONAL ENERGY LABORATORIES

The national energy laboratories operated by the U.S. Department of Energy are perhaps the least well understood components of the United States national innovation system (Crow and Bozeman 1998). The 1946 legislation that established the Atomic Energy Commission (AEC) transferred to the Commission the plants, laboratories equipment and personnel that had been assembled to build the atomic bomb.[17] A major consideration in the establishment of the AEC was to avoid military control of nuclear technology (Hewlett and Anderson 1962: 1-8).

At the time the AEC was established it "was intended to serve two main purposes: provision of large scale equipment for

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[17] A major consideration in the establishment of the AEC was to avoid military control of nuclear technology. The AEC was governed by a five man board. The Board was chaired by David Lilienthat, formerly Chairman of the Tennessee Valley Authority

basic research and secure facilities for developing technologies for national security," (Westwick 2003: 8). It was given responsibility for governing the use of radioactive materials and for the development of nuclear technology for both military and civilian use. It maintained and expanded many of the weapons laboratories that it had inherited from the Manhattan Project including the major multi-program national laboratories.[18] Each of these facilities was among the largest scientific research facilities in the world. The AEC employed thousands of scientists and engineers across many disciplines, focusing chiefly on designing, testing, and manufacturing of nuclear weapons systems. It provided the military with laboratory access and services (Crow and Bozeman 1998: 54-55).

In the early 1950's the AEC and the laboratories were confronted with major administrative problems such as how to maintain sufficient program autonomy to assure scientific viability

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[18] Initially the term "national laboratory" was reserved for a limited number of multiprogram- laboratories that were engaged in basic research such as Argonne, Berkeley, Brookhaven Los Alamos and Oak Ridge. Others sites such as Hanford and Sandia that were initially focused on the production of nuclear weapons and weapons material were not covered by the term. As their scope of research broadened over time the term became more inclusive (Westwick 2003: 9).

and sufficient secrecy to meet the national security mission.[19] During the 1950,s laboratory budgets expanded rapidly as the laboratories acquired the increasingly expensive equipment necessary to conduct basic research in sub- atomic and high-energy physics (Seidel 1986). Some o these developments were controversial even within the laboratory system. In 1961 Alvin Weinberg, director of Oak Ridge National Laboratory raised three questions: "First, is Big Science ruining science?; second, is Big Science ruining us financially?; and third, should we divert a larger part of our effort toward scientific issues which bear more directly on human well being?" (Weinberg 1961: 161).

By the early 1970s events had conspired to force a number of Weinberg's concerns onto the AEC agenda. These included the budgetary pressures associated with the war in Vietnam, the slowing of productivity growth in the United States economy beginning in the late 1960s, and the energy shock of the early 1970's. "Even at the birthplace of AEC high energy physics,

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[19] For a very thorough discussion of the program, administrative and political issues that confronted the national energy laboratory system between the late 1940s and the early 1970s see Westwick (2003).

Lawrence Radiation Laboratory (LRC), scientists adapted to the new realities. New divisions—Energy and Environment, Earth Sciences, Materials, and Molecular Research emerged in the late 1960s and early 1970s to spur the laboratory to renewed growth," (Seidel 1986: 174). Oak Ridge National Laboratory expanded its large scale biology program and initiated new programs, drawing on external resources, in desalinization, civil defense, natural resources, and alternative energy research (Teich and Lambright 1976).

In 1975 the AEC was disbanded and its staff, laboratories and other facilities were transferred to the newly formed Energy Research and Development Administration (ERDA) which was in turn consolidated into a new Department of Energy.[20] As the Cold War was winding down in the 1980s the research effort of the Department of Energy national laboratories embraced four broad missions. (1) *A national security mission* with a primary goal of

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[20] In the two decades since the incorporation of the Atomic Energy Commission into the Department of Energy more than twenty major commissions of task forces were chartered to address the question of just what the United States should expect from its system of national energy laboratories. For a critique of these efforts see Crow and Bozeman 1998).

maintaining the reliability and safety of the nations nuclear deterrent. A second goal was to reduce the risk of nuclear proliferation. (2) *A science mission* that provides university and industry with world class, large scale scientific facilities such as synchraton light sources, neutron sources, and particle accelerators. It supports the nations largest federally funded research program in the physical sciences and contributes importantly to national programs in the environmental sciences, life sciences and mathematics and computing. (3) *An energy mission* directed to the development of new technologies needed to produce energy that is affordable, environmentally acceptable and secure. The objectives include reducing dependence on the Persian Gulf region for energy supplies and reducing the risk of climate change associated with carbon based energy sources. (4) *An environmental mission* including action to clean up the DOE nuclear weapons legacy; to stabilize, safely store, or dispose of nuclear waste; to deactivate, decontaminate, and decommission support facilities, and to remediation of environmental contamination resulting from the nuclear weapons and energy programs.

During the 1980's an economic growth mission was superimposed on the other missions of the DOE national energy laboratories, and on all other federally funded laboratories. It was implemented by a series of institutional innovations governing property rights in the new knowledge and technology generated by federally funded R&D (Ruttan 2001: 576-581). The 1980 Stevenson-Wydler Technology Innovation Act made technology transfer a mission of all federal laboratories. The Bayh-Dole Act, passed the same year gave title to inventions resulting from federal funding to the performers of the R&D. The Federal Technology Transfer Act of 1986 gave incentives to government owned and operated laboratories (GOGOs) to commercialize their inventions and the National Competitiveness Technology Transfer Act of 1989 extended similar rules to government owned and contractor operated laboratories (GOCOs). The later two acts encouraged the laboratories to enter into cooperative R&D agreements (CRADAs) with industrial partners.

Initially there was substantial skepticism on the part of many students of S&T policy as to the effectiveness of these institutional innovations (U.S. Secretary of Energy Advisory Board 1994). Over time, however, careful empirical studies demonstrated that CRADA's have been much more effective than anticipated in stimulating both industrial patents and company financed R&D (Cohen and Noll 1996; Jaffe and Lerner 2001: Adams, Chaing and Jensen 2003). In spite of this accumulating evidence a sharp reaction had emerged by the mid 1990s against the dual use and cooperative programs that had been directed to enhancing technology transfer from the national laboratories to the private sector. The argument was not that the programs were ineffective but that in an era of budget stringency they were diverting effort from traditional defense and energy related missions (Secretary of Energy Advisory Board, 1994: Bozeman and Dietz 2001).

It is doubtful that the new industrial innovation policies introduced in the 1980swill lead to the development of new general purpose technologies. They have generated incremental rather than radical technical innovations. They have had great difficulty in achieving institutional viability within the national energy laboratory system and in achieving sustained political support. It is possible, though unlikely, that a national commitment to the development of an alternative to carbon based energy sources could focus the research and development of the national energy laboratory system, the successor to the Manhattan Project laboratories, to emerge as the source of new environmentally compatible general purpose technologies.

In this Box I draw primarily on the following references listed below. I have found Crow and Bozeam (1998) and Westwick (2003) particularly useful.

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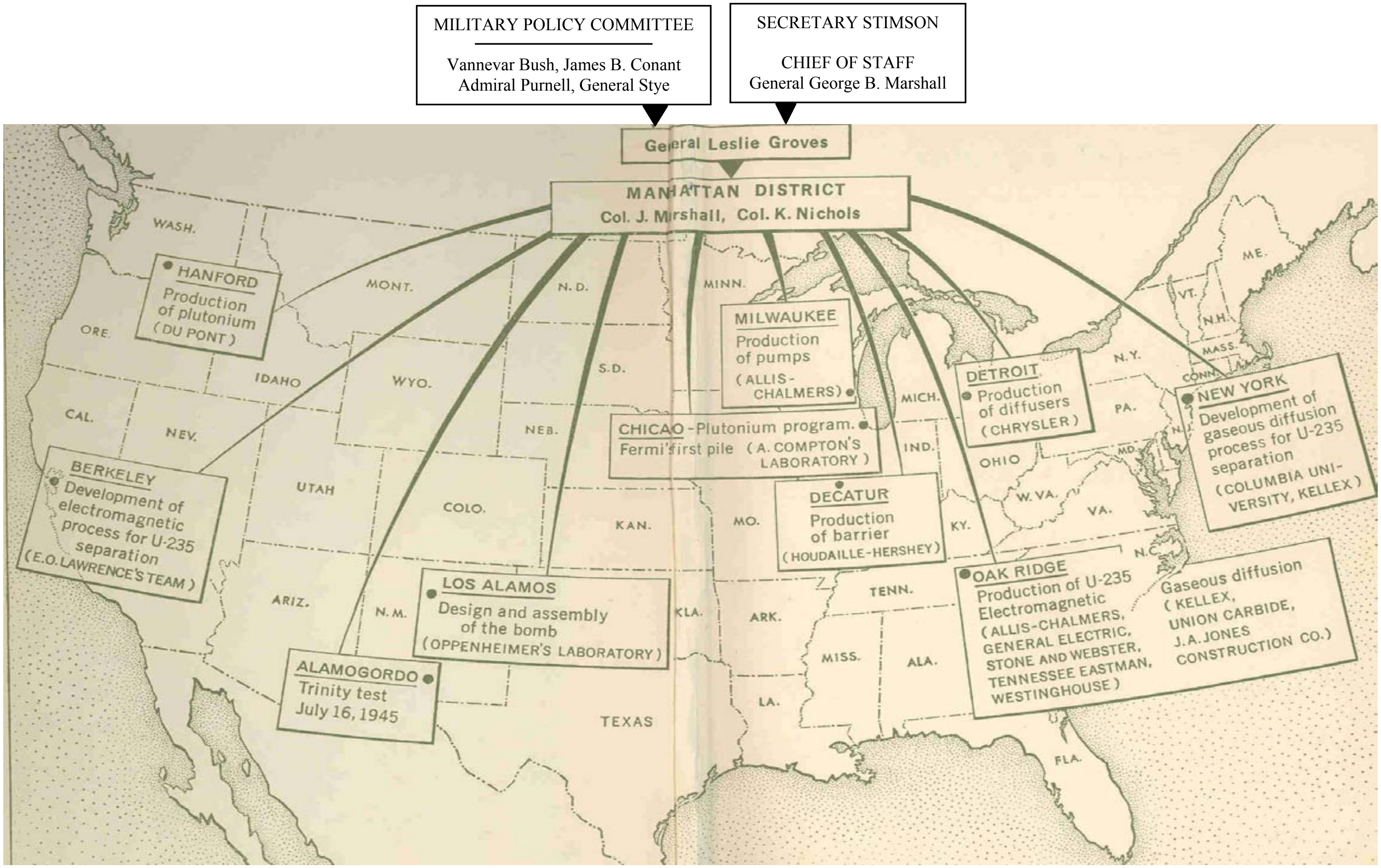
Table 4.1 U.S. Nuclear Electric Power Plant Prototypes in 1962.

			Power		
Name and owner	Location	Type	Plant kw (*) net	Reactor kw (†)	Start-up
Shippingport Atomic Power Station (AEC and Duquesne Light Company)	Shippingport, Pa.	pressurized water	60,000	231,000	1957
Dresden Nuclear Power Station (Commonwealth Edison Company)	Morris, Ill.	boiling water	208,000	700,000	1959
Yankee Nuclear Power Station (Yankee Atomic Electric Company)	Rowe, Mass.	pressurized water	161,000	540,000	1960
Indian Point Unit No. 1 (Consolidated Edison Co. of New York, Inc.)	Indian Point, N.Y.	pressurized water	255,000	585,000	1962
Hallam Nuclear Power Facility, Sheldon Station (AEC and Consumers Public Power District)	Hallam, Neb.	sodium-graphite	75,000	240,000	1962
Big Rock Nuclear Power Plant (Consumers Power Company)	Big Rock Point, Mich.	boiling water	47,800	157,000	1962
Elk River Reactor (AEC and Rural Cooperative Power Association)	Elk River, Minn.	boiling water	20,000	58,200	1962

* Electric output. † Thermal output.

Source: “Nuclear Reactor.” In *The New Encyclopedia Britannica*, Vol. 13: 318. Chicago, IL: Encyclopedia Britannica, Inc.

Figure 4.1 Major United States Atomic Energy Facilities, 1942-46



Source: Stephane Groueff. 1967. *Manhattan Project: The Untold Story of the Making of the Atomic Bomb*. Boston, MA: Little, Brown and Co. (frontspiece).