Chapter 5

Fusion as an Energy Program

CONTENTS

Figures

Tables

Chapter 5

Fusion as an Energy Program

The primary long-term goal of U.S. fusion research is to develop a fusion reactor that is an attractive source of electricity.[1] The overall role that fusion might play in the future energy supply of the United States depends on the characteristics of such a fusion reactor and on the characteristics of other energy technologies with which fusion will compete. It is too early to evaluate either of these characteristics: fusion's commercial prospects are not yet known and neither are the prospects of developments in other technologies. However, preliminary analyses can be performed on the basis of fusion system studies conducted to date.

[1]Fusion also may be valuable in a number of non-electric applications, described in app. A.

CHARACTERISTICS OF FUSION ELECTRIC GENERATING STATIONS

Pre-conceptual designs and feasibility studies for fusion generating stations were developed as long ago as 1954.[2] However, it was not until the early 1970s that studies began to simultaneously address the plasma physics, structural materials, operating characteristics, economics, and environmental implications of fusion reactors.[3] During the late 1970s and early 1980s, comprehensive system studies and comparative models were developed to evaluate the interdependence of fusion reactor performance and various scientific and technological parameters.

These studies represent a mix of technological optimism and conservatism. They optimistically assume that the research and development (R&D) effort mapped out in chapter 4 of this assessment will be successfully completed and that it will permit a fusion reactor to be designed and built. At the same time, studies are inherently conservative in that they cannot account for as-yet-unforeseen developments and innovations in fusion and competing technologies.

The studies have been especially valuable in identifying improvements in fusion physics or technology that appear to have the greatest potential for making fusion reactors attractive and competitive. Their value to the fusion program notwithstanding, system studies should not be considered definitive assessments of future fusion reactors. Given that the scientific and technological base for fusion has not yet been established, fusion system studies are inherently based on incomplete information, and the values calculated for reactor parameters such as capital cost and cost-of-electricity must be considered highly uncertain. As a result of the technical progress made in fusion research, system studies today describe reactors that are very different from those envisioned 30 years ago. It is likely that the fusion reactor that eventually enters the marketplace will make today's designs appear just as dated.

The discussion that follows identifies generic features of future fusion reactors as well as factors that depend on particular design choices. The focus is on reactors that produce electricity from fusion alone, called *pure fusion* reactors, as distinguished from fusion reactors that draw part of their energy from fission or that are used to make fissionable fuel.[4] Much of the discussion draws on comparisons of fusion technology to present-generation light-water reactor fission technology, the closest analog to fusion for which significant operational data exists. Fusion and fission plants

[2]L. Spitzer, Jr., et al., *Problems of the Stellarator as a Useful Power Source, NYO 6047* (Princeton, NJ: Princeton University, 1954),

[3]The evolution of fusion reactor studies is discussed in *Fusion Reactor Design: On the Road to Commercialization*, by G. L. Kulcinski, Fusion Engineering Program, Nuclear Engineering Department, University of Wisconsin, UWFDM-529, Madison, WI, May 31, 1983, p. 3.

[4]These devices, called *fission/fusion hybrid* reactors, are discussed in app. A.

are comparable because both are nuclear technologies suited for central-station power generation, and because they share some of the same environmental and safety concerns. However, the further that a technology is extrapolated beyond present experience, the less certain any of its features become. As a result, all characterizations of future systems—including the ones in this chapter—should be treated with extreme caution.

Risk and Severity of Accident

The D-T fusion process has several advantages over fission that should make it easier to assure the safety of a fusion reactor than of a fission reactor. This statement does not imply that existing fission reactors are unsafe, or that fission technology will not continue to develop and improve. However, assuring public safety with fusion technology should be easier for the following reasons:

- **Fusion reactors cannot sustain runaway reactions.** Fuel will be continuously injected, and the amount contained inside the reactor vessel at any given time would only operate the reactor for a short period (probably seconds or less). A fission reactor, on the other hand, contains several years of fuel in its core—a far greater amount of stored energy potentially available for release. Moreover, the conditions necessary to sustain a fusion reaction are difficult to maintain; any significant system malfunction would stop the reaction.
- **Fusion reactors should require simpler post-shutdown or emergency cooling systems than fission reactors, if such systems are needed at all.** Due to the decay of radioactive materials in the reactor, both fusion and fission reactors will continue to generate heat at a small fraction of the full power rate after they have been shut down. In a fission reactor, this decay heat, or *afterheat,* is largely due to fission byproducts that accumulate in the spent fuel rods. In a fusion reactor, afterheat results mostly from radioactivity induced in the reactor structural materials, and the afterheat level is highly dependent on the choice of those materials. With appropriate materials choices, afterheat from fusion reactors should be much less than from fission reactors.
- **potential accidents that could occur in fusion reactors should be less serious than those that could take place in fission reactors.** With suitable materials choices, the radioactive inventory of a fusion reactor should be considerably less hazardous than that of a fission reactor. Fusion reactors would not contain biologically active fission products such as strontium and iodine. Moreover, the radioactive materials in a fusion reactor would generally be less likely to be released in an accident than would those in a fission reactor, since they would largely be bound as metallic structural elements. The only volatile or biologically active radioactive component in a fusion reactor would be the active tritium inventory; gaseous and volatile radioactive products in a fission reactor would be present in amounts orders of magnitude greater.

A recent study of fusion's environmental, safety, and economic attributes quantitatively compares the safety of fusion and fission designs.[5] This study, referred to here as the ESECOM report, sorts various fission and fusion reactor designs into four categories according to the means by which prompt off-site fatalities are prevented in the event of an accident. Some of the designs studied depend on active safety systems to prevent off-site fatalities. These reactors can be safe, but demonstrating their safety involves certifying that the safety systems will work as expected during all conceivable accidents. In other designs,

[5] John Holdren, *et al., Exploring the Competitive Potential of Magnetic Fusion Energy: The Interaction of Economics With Safety and Environmental Characteristics,* excerpts from the Report of the Senior Committee on Economic, Safety, and Environmental Aspects of Magnetic Fusion Energy (ESECOM). Interim results from this study were presented to the Magnetic Fusion Advisory Committee in Princeton, NJ, on May 19, 1987; the full report should be published as a Lawrence Livermore National Laboratory report in September 1987. This study will be cited hereinafter as the ESECOM report.

ESECOM analyzed and compared the environmental, safety, and economic aspects of eight pure fusion reactor designs, two fission/fusion hybrids, and four types of fission reactor. Of the pure fusion reactors, six were tokamaks and two were reversed-tield pinches; both the hybrid reactors were tokamak-based.

and the safety of these systems is much easier to demonstrate.[6]

The levels of safety assurance derived by ESECOM, ordered by increasing ease of demonstrability, are:

- **Level 4: Active Protection.** This level of protection depends on the proper operation of active safety systems to ensure safety.[7] It is extremely difficult to certify that such systems will indeed work as expected in case of accident. These systems must be designed to respond to particular contingencies, and deciding which accident scenarios should be covered is not easy. Furthermore, as the 1986 Chernobyl accident in the Soviet Union showed, active safety systems can be disconnected. At this level of protection, it is impossible to eliminate the risk of operator error.
- **Level 3: Small-Scale Passive Protection.** At this level, safety does not depend on active safety systems. Moreover, failure of components such as relief valves and pump seals—in conjunction with the failure of any active systems—could be tolerated without risking off-site fatalities. However, ensuring safety at this level requires assuming the integrity of key systems such as coolant loops, as well as maintaining the large-scale physical integrity of the overall structure. It would have to be proven that passive design features alone could keep these critical components or systems from being damaged under credible accident scenarios.
- **Level 2: Large-Scale Passive Protection.** A large-scale passively protected reactor would be able to prevent the release of dangerous amounts of hazardous materials as long as certain large-scale structures remained intact. Such a system would not rely on active safety systems and would be able to withstand any combination of small-scale component or system failures. Demonstrating the safety of such a reactor would only require showing that no credible accident could destroy the large-scale geometry of the device.
- **Level 1: Inherent Safety.** A reactor with this degree of safety assurance could be shown to be incapable of causing an immediate, off-site fatality in the event of any conceivable failure, including total system reconfiguration (e.g., it would remain safe even if the entire reactor were somehow crumpled up into a ball). This level of protection is assured by the properties of the reactor materials in one of two ways: either the radioactive inventory must be so small that, if totally released, it could not constitute a lethal dose to the public, or the inventory must consist of materials that could not be melted, converted into volatile oxides, or otherwise dispersed by the sudden release (in an explosion, fire, or power surge) of all the plant's stored energy.

According to the ESECOM report, attributes of the fusion process show that fusion reactors should be able to achieve greater degrees of safety assurance than fission reactors. Of the eight fusion designs that ESECOM evaluated, one was a Level 1 system, three were Level 2, one

[6] The analysis in this study computes "worst-case" radiation exposures to members of the public by calculating the maximum radiation dose deliverable to an individual at the worst possible location at the plant boundary, under weather conditions that keep the radiation from dispersing. Effects that would serve to mitigate the delivered dose, such as buildings, rain, or fallout, were not included (except that the effect of buildings on the wind pattern was included). Absence of prompt fatalities corresponds to limiting the "worst-case" dose to under 200 reins, an amount of radiation exposure generally accepted to be the minimum capable of causing a prompt fatality in the absence of medical treatment. This radiation dose is about 2,000 times the total dosage typically received in one year due to cosmic rays and other naturally occurring sources of radiation.

In addition to prompt radiation dose, the study also considered the long-term dose from ground contamination due to an accident. However, these long-term dosages were not used to define the categories of safety assurance. Long-term effects of radiation release are more difficult to determine than prompt effects because the effects of long-term, low-level exposure to radiation are highly controversial. Estimates of the cancer fatalities resulting from a given long-term, low-level exposure vary by more than a factor of 10.

[7] Under the ESECOM analysis, any system such as an emergency cooling system that would have to be activated or powered at the time of an accident, or any system that would have to be actively turned off, is considered an active system. A containment building is considered an active system under this definition since penetrations such as airlocks, ventilation systems, and plumbing are managed by active systems. Therefore, designs relying significantly on containment buildings to prevent escape of radiation could not achieve a rating higher than Level *4*.

was Level 3, and three were Level 4. Design changes were identified for several of the Level 3 or 4 fusion systems that could raise them to Levels 2 or 3, respectively. ESECOM found that present-generation commercial light-water fission reactors are Level 4 systems, and that two "inherently safe" fission reactor designs now under investigation should be capable of reaching Level 3 on this scale.

Different fusion designs varied significantly in terms of the maximum radiation dose that could be delivered to the public in an accident. Designs using low-activation materials, which do not generate long-lived radioactive byproducts under neutron irradiation, and designs operating on advanced fuel cycles were calculated to have a higher degree of safety assurance than the "reference" design, an updated version of a tokamak reactor study originally published in 1980.[8] However, materials selections and design choices are also possible that yield fusion reactors that require active safety systems.

ESECOM concluded that Level 2 fusion reactors should be possible to design, and that Level 1 designs–although more difficult due to limited materials choices—should also be possible. None of the fission designs ESECOM analyzed could attain these levels of safety assurance. Although fission designs are being developed that appear to have greater degrees of safety assurance than existing fission reactors, fusion appears to have some fundamental advantages. Many of the potentially dangerous substances present in fission reactors are either fuels or fission byproducts that are inherent to the fission reaction. The products of the fusion reaction, on the other hand, are not in themselves hazardous. Tritium fuel does pose a potential hazard, but according to the ESECOM report even the complete release of the active tritium inventory of current reactor designs under adverse meteorological conditions would not produce any prompt fatalities off-site.[9] There is much greater freedom to choose appropriate materials that minimize safety hazards in fusion reactors than in fission reactors. Therefore, a higher degree of safety assurance should be attainable with fusion.

Occupational Safety

Most of the occupational hazards a worker might encounter at a fusion reactor site are already familiar from other occupations. Table 5-1 shows the locations of potential hazards during the operation and maintenance of a D-T fusion reactor.

Of the potential hazards listed, the least is known about the effects of magnetic fields. There is no reason to suppose that the steady or slowly varying magnetic fields associated with fusion reactors could cause adverse health effects. However, little is known definitively about the biological effects of such fields; after many years of research, the technical literature is "extensive and often contradictory."[10] The U.S. Department of Energy (DOE) established interim occupational magnetic field exposure guidelines on an ad hoc basis in 1979, although the committee that developed these guidelines expressed "strong concerns about the lack of data upon which one can construct appropriate exposure criteria,"[11]

[8] Charles C. Baker, et al., *STARFIRE—A Commercial Tokamak Power Plant Study, ANL/FPP-80-l,* Argonne National Laboratory, 1980. The STARFIRE study, conducted by a team of 70 researchers, is one of the most comprehensive fusion reactor design studies completed to date. It presents a conceptual design of a full fusion powerplant, including descriptions of the tokamak reactor as well as all the associated subsystems in the remainder of the facility.

The STARFIRE study has been extensively drawn upon by, and provides a base of comparison for, many subsequent analyses of fusion reactors and system designs. The ESECOM report chose the STARFIRE design, updated with lower activation materials and a more recent blanket design, as its "point-of-departure' reference case.

[9] John Holdren, et al., *ESECOM Report,* op cit. Larger "inactive" tritium supplies would be stored in the plant in addition to the active working inventory, but these could be divided up and extremely well protected.

[10] J.B. Cannon (ed.), *Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy,* DOE/ER-0170, prepared by the Oak Ridge National Laboratory for the U.S. Department of Energy, Office of Fusion Energy, Division of Development and Technology, August 1983, p. 6-2.

This document, hereinafter referred to as *Background Information,* served as the principal reference for a generic Environmental Impact Statement that was prepared for the magnetic fusion program. The generic statement, although completed, has not been reviewed and approved by DOE. DOE has chosen not to file a generic impact statement for the program as a whole but rather to prepare specific statements for individual fusion facilities as needed.

[11] Letter from Dr. Edward Alpen, Director of the Dormer Laboratory, University of California at Berkeley, and Chairman of the committee established to set interim magnetic field exposure standards, to Dr. Kenneth Baker, U.S. Department of Energy, July 23, 1979.

Table 5-1.—Principal Locations of Potential Hazardous Agents in D-T Fusion Reactors

Hazard	Locations of possible exposure during operation	Locations of possible exposure during maintenance
Radiation from tritium	• Tritium recovery systems • Coolant loops	• Reactor hall and structure • Blanket processing • Fuel recycling
Radiation from activation products	• Coolant loops	• Reactor hall and structure • Blanket processing • Steam generator
Radiation from neutrons	• Not present in accessible areas	• Not present
Non-radioactive toxic materials	• Possibly in auxiliary reactor systems	• Chemical processing
Radiofrequency (RF) fields	• Near power sources • Along waveguides	• Not present unless RF components are being tested
Magnetic fields	Environment of reactor hall	• Not present unless magnets are being tested

aHazards are only listed for areas where personnel will be permitted, personnel will not be permitted in the reactor hall during reactor operation, so activation products and neutron radiation present there are not considered occupational hazards in this table.

SOURCE Adapted from J B. Cannon (ed), *Backrground Information and Technical Basis for Assessment of Environmental Implications of Magnetic fusion Energy, DOE/ER-0170,* prepared by Oak Ridge National Laboratory for the U.S. Department of Energy, Office of Fusion Energy, Division of Development and Technology, August 1983, table 6.1, p 6-2

These standards are still being used on a trial basis; although researchers analyzing this issue have flagged uncertainties that call for further research, they have still not found many well-documented studies that show detrimental biological effects of static (non-varying) or slowly varying magnetic fields such as those to be found in fusion reactors. The National Committee on Radiation Protection and Measurement has established a subcommittee on Biological Effects of Magnetic Fields to recommend limits on magnetic field exposure; this subcommittee is in its final stages of document preparation prior to submission to the full committee.[12]

Significant exposure to magnetic fields in or near a fusion reactor probably would be limited to plant workers because magnetic fields extending beyond the site boundary are not expected to be stronger than the earth's field. The interim standards established by DOE were for occupational exposure only, and the committee that developed them stated that it was "not prepared to offer an exposure criteria for general population exposure."[13]

[12] Information provided to OTA staff by Dr. Donald Ross, Acting Director, Occupational Safety and Health Division, Office of Operational Safety, U.S. Department of Energy, Apr. 22, 1987; and by Dr. Dennis Mahlum, chairman of the National Committee on Radiation Protection and Measurement Scientific Committee 67 on Biological Effects of Magnetic Fields, Apr. 28, 1987.

[13] Letter from Allpen to Baker, note 11 above.

Environmental Effects

Radioactive Waste

The main environmental problem with fusion reactors is expected to be radioactive waste. Although the reaction products of the D-T fusion reaction are not radioactive, the fusion reactor itself—particularly the first wall, blanket, shield, and coils—will be. The first wall will be the most severely affected; the cumulative effects of radiation damage will require that the first wall be replaced every 5 to 10 years and disposed of as radioactive waste.

The type and amount of radioactive waste generated by a fusion reactor is highly dependent on the choice of materials. With appropriate materials, fusion reactors can avoid producing the long-lived, intense, and biologically active wastes inherently produced by fission reactors. According to the ESECOM report, although fusion wastes may have greater volume than fission wastes, they will be of shorter half-life and intensity and should be orders of magnitude less hazardous.[14] The wastes from fusion reactors operating with ad-

[14] ESECOM measured radioactive waste hazard by calculating the dosages that future "intruders" could acquire by excavating or farming a radioactive waste site hundreds of years from now. Radioactive waste produced by the fusion designs ESECOM studied were orders of magnitude less hazardous than those produced by fission designs by this measure.

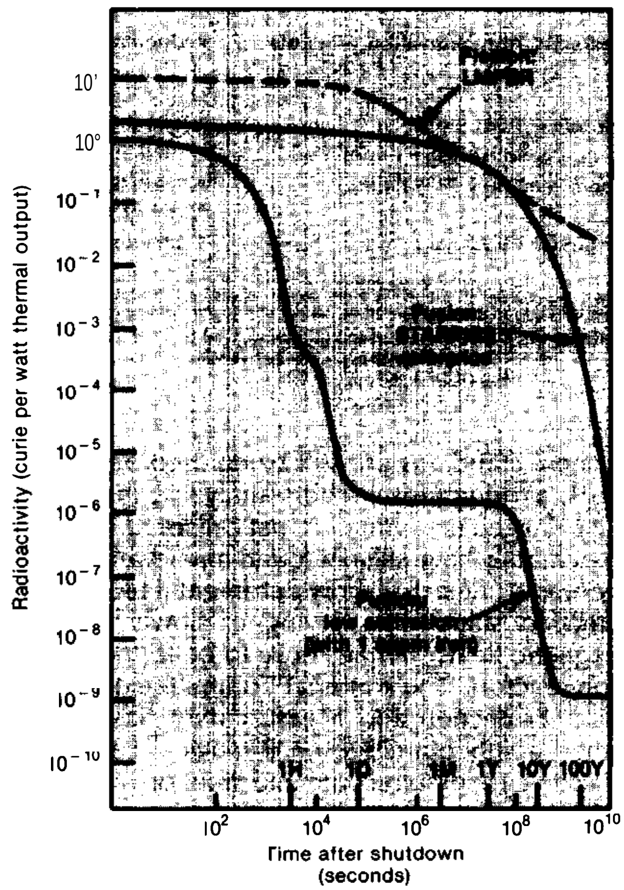
vanced, non-tritium-based fuel cycles would be even less radioactive than those from D-T fusion reactors.

ESECOM's estimates of radioactive waste hazards also indicate that fusion designs differ among themselves by several orders of magnitude. The study found that advanced "low-activation" fusion designs could be tens to hundreds of times better than the fusion reference design, and that other designs could be hundreds or thousands of times worse if the wrong materials are chosen. ESECOM concluded that with proper materials selection, radioactive waste from all of the fusion designs could qualify as low-level waste under existing Nuclear Regulatory Commission regulations.[15]

Figure 5-1 shows the dependence of fusion reactor radioactivity levels on materials selection. Figure 5-2 shows the corresponding dependence for afterheat produced by radioactive decay. For the top curve in each figure, the reactor first wall and blanket are assumed to be made out of a type of steel. The lower curve, having radioactivity and afterheat levels thousands to millions of times lower, assumes that low-activation materials are used in the blanket and first wall.[16]

These figures represent the potential of low-activation materials to reduce radioactive wastes but do not necessarily address the feasibility of using these materials. The source for figures 5-1 and 5-2 was a preliminary conceptual design study that attempted to design credible replacements using low-activation ceramic materials for all reactor structures in the high neutron flux zone of the STARFIRE reactor (footnote 8, above). Engineering feasibility of these materials was considered, and at an initial level of analysis the designs were found to be achievable. However, using ceramics for these components poses engineering issues quite different from those encountered with the metals typically used in engineering applications today. Substantial development of materials and fabrication techniques would be required to use ceramics in a fusion reactor.

Figure 5-1 .—Post-Shutdown Radioactivity Levels for Fission Breeder Reactor, Reference STARFIRE Fusion Reactor, and Low-Activation Fusion Reactor Design



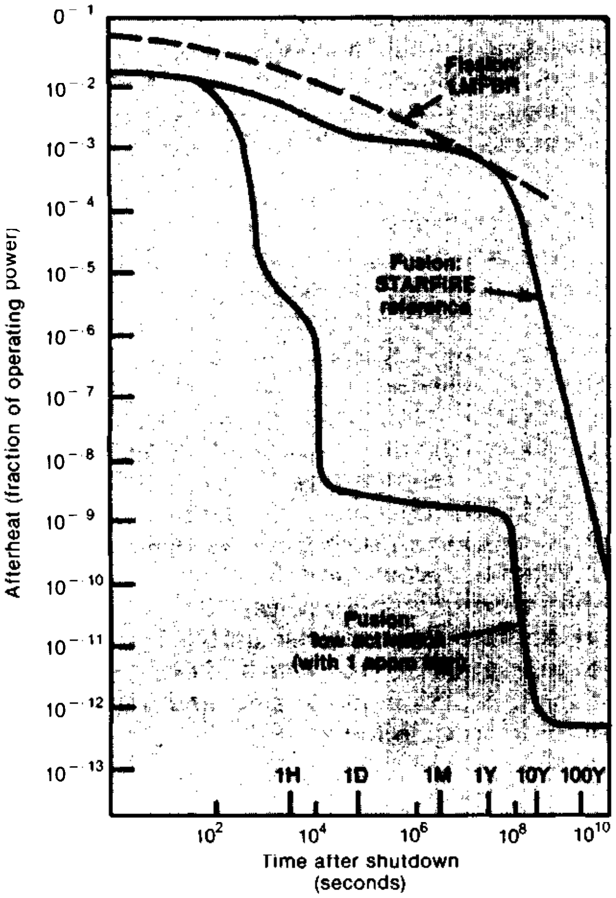
KEY: H = hour
D = day
M = month
Y = year
appm = atomic parts per million (impurity atoms per million atoms of substrate)
LMFBR = Liquid Metal Fast Breeder Reactor

SOURCE: General Atomic Co., *Low Activation Materials Design Study: Annual Report for Fiscal Year 1981*, GA-A16426, UC-20cd, September 1981, p. 5-4.

[15] John Holdren, et al., *ESECOM Report*, op. cit.

[16] The induced radioactivity intrinsic to the low-activation materials themselves is extremely small; the majority of the radioactivity shown by the "low-activation" curve more than one day after shutdown is due to iron impurities. According to Cannon, *Background Information*, op. cit., p. 3-41, realizing impurity levels as low as those assumed in this figure is a "difficult and expensive task at the present time, and may or may not be achievable at the time low-activation/low-impurity structural materials are required in a fusion reactor economy. "

Figure 5-2.— Post-Shutdown Afterheat Levels for Fission Breeder Reactor, Reference STARFIRE Fusion Reactor, and Low-Activation Fusion Reactor Design



KEY: H = hour
D = day
M = month
Y = year
appm = atomic parts per million (impurity atoms per million atoms of substrate)
LMFBR = Liquid Metal Fast Breeder Reactor

SOURCE: General Atomic Co., *Low Activation Materials Design Study: Annual Report for Fiscal Year 1981*, GA-A16426, UC-20cd, September 1981, p. 5-4.

Routine Radioactive Emissions

The total estimated radiation dosages attributable to routine releases from fusion reactors would be a very small fraction of the radiation dose due to naturally occurring background radiation.[17] Two types of radioactive substances may be emitted by fusion reactors: activation products, which are substances made radioactive by neutron irradiation, and tritium, which is produced in the reactor blanket and used as fuel. Activation products would be released either through liquid waste processing systems or plant ventilation systems; most of the tritium releases would be to the atmosphere.

Activation products released by fusion reactors should be no more hazardous than those routinely released by fission reactors. Tritium discharges from fusion reactors, in terms of radioactivity levels, would be much larger than activation product emissions. However, since tritium differs significantly from activation products in the type of radiation emitted and the method of absorption in the body, the total radiation dosages due to tritium releases would not be correspondingly large.

Very preliminary estimates of tritium emissions from fusion reactors are on the order of 5,000 to 10,000 curies per year from a 1,000-megawatt plant.[18] Most of these emissions would occur during major system maintenance, and they might be removable by an atmospheric detritiation system before release to the environment. Tritium releases of this amount are well within the range of routine tritium releases from some existing DOE facilities. By comparison, tritium emissions from an equivalently sized pressurized-water fission reactor—the predominant type of commercial nuclear fission reactor—would be about

[17] Naturally occurring background radiation is due primarily to cosmic rays and to radioactive elements contained in rocks and soils. In the United States, the dosages due to these sources vary by factors of 2 to 4 depending on location; the typical contributions of the two sources are comparable.

Medical X-rays and radiopharmaceuticals provide, on average, a radiation dosage about equal to the natural background. A substantially smaller contribution comes from the sum of other manmade sources such as atmospheric nuclear weapons tests, occupational radiation exposure, nuclear powerplant emissions, and consumer products.

[18] One curie of a radioactive substance is the amount needed to have 3.7 X 10^{10} radioactive disintegrations per second. Ten thousand curies of tritium have a mass of about one gram.

1,400 curies per year.[19] It is estimated that the total dose to the population within 80 kilometers (50 miles) of a routinely operating fusion reactor should be less than 0.01 percent of the dose from natural background sources .20

Routine Nonradioactive Emissions

The energy generated in a fusion reactor that is not converted into electricity would be discharged as heat, primarily into the atmosphere. In this respect, a fusion reactor would resemble fossil fuel and nuclear fission generating stations. Like a fission plant, but unlike a plant that burns fossil fuels, a fusion plant would *not* emit combustion products such as carbon dioxide into the atmosphere. Since carbon dioxide emissions may potentially affect world climate, this aspect of fusion (and fission) technology could prove to be very advantageous. Carbon dioxide emissions are discussed later in this chapter under "Comparisons of Long-Term Electricity Generating Technologies. "

Nuclear Proliferation Potential

A fusion reactor's ability to breed fissionable materials such as uranium or plutonium could possibly increase the risk of nuclear weapons proliferation. A pure fusion reactor would not contain fissionable materials usable in nuclear weapons, and it would be impossible to produce such materials by manipulating the reactor's normal fuel cycle. Therefore, normal operation of a pure fusion reactor poses negligible proliferation risk.zl However, if the blanket of a pure fusion reactor were appropriately modified, fissionable fuel could be bred there. To ensure that fissionable materials were not surreptitiously produced, changes to the reactor blanket would have to be prevented. The difficulty of detecting such changes would depend on the design of the reactor; it is plausible that reactor designs could be developed that would make undesirable modifications easy (or difficult) to monitor.[22]

Proliferation concerns are not unique to fusion reactors; fission reactors also pose this risk. Depending on the fuel cycle used, the proliferation potential of fission can be much greater than that of a pure fusion reactor. After being irradiated in the core of a fission reactor, uranium fuel will be converted into plutonium, which can be extracted from the uranium and other byproducts by chemical reprocessing, Alternatively, plutonium can be produced in breeder reactors (pure fission or fission/fusion hybrid) designed explicitly for plutonium production. If either reprocessing or breeder reactors become used on a wide scale, it is possible that material usable for nuclear weapons could be produced and extracted during the production, processing, and transportation of fissionable fuel.[23]

[19] Fusion reactor radioactive discharge and radiation dosage estimates are from Cannon, *Background Information*, op. cit., chs. 4 and 8, particularly tables 4.19, 8.8, and 8.9. Pressurized water reactor emissions are from Nuclear Regulatory Commission, *Calculation of Releases of Radioactive Materials in Gaseous and Liquid Effluents From Pressurized Water Reactors,* NUREG-0017, Rev. 1, 1985, p. 2-70.

[20] Dosages estimated from tritium releases assume that all the tritium is in the form of tritium oxide, or tritiated water. Tritiated water is water in which one or both of the hydrogen atoms are replaced by tritium atoms, and it is absorbed by and discharged from the human body like ordinary water. These dosages represent conservative upper bounds, and are tens of thousands of times higher than the dosages that would result if the tritium were released in the form of tritium gas. Tritium gas is not readily absorbed by the body.

[21] Pure fusion reactors do contain tritium, which could be used in thermonuclear weapons such as the hydrogen bomb. However, such weapons cannot be built by parties who do not already possess fission weapons, and possession of tritium will not provide any assistance to a party that is trying to develop fission weapons.

[22] A fission/fusion hybrid reactor would incorporate a blanket designed specifically to breed (and/or utilize) fissionable fuel. Proliferation concerns for hybrids are therefore considerably more serious than those for pure fusion reactors.

[23] The Plutonium produced in a fission reactor consists of a mixture of different isotopes whose relative proportions depend on how long the original uranium is irradiated. Any mixture of plutonium isotopes can be used to make a nuclear explosive, but weapons designers prefer to minimize the percentage of the heavier isotopes that are produced when the fuel is irradiated for longer periods of time. Therefore, short fueling cycles are preferable—but not required—for producing plutonium usable in nuclear weapons. Since plutonium can be produced in this manner in existing fission reactors, the International Atomic Energy Agency operates a safeguards program to assure that production and diversion of fissionable fuel would be detected, minimizing the possibility of covert production of nuclear weapons.

Resource Supplies

Much of fusion’s allure stems from the essentially unlimited supply of fuel. D-T fusion reactors will require two elements—deuterium and lithium –for fueling. Deuterium will be used as fuel directly in the reaction chamber and lithium will be used in the blanket to breed tritium fuel. Advanced fuel cycles discussed in chapter 4 that do not use tritium would not require lithium.

It appears that domestic supplies of fusion fuel will not constrain the development and use of fusion power. Deuterium contained in water is readily extractable, with each gallon of water having the energy equivalent of 300 gallons of gasoline. This supply offers billions of years’ worth of energy at present consumption rates. Similarly, domestic lithium supplies probably offer thousands of years’ worth of fuel with vastly greater quantities of lithium contained in the oceans. Although recovering lithium from seawater is not currently economical, it could be in the future; fuel costs are such a small part of the cost of fusion power that lithium could become many times more expensive without substantially affecting the cost of fusion electricity. According to a study of fuel resources for fusion, it appears “unlikely that an absolute shortage of lithium could constrain the prospects of D-T fusion in any time of practical interest.”[24]

Preliminary studies of the materials required to build fusion reactors also do not foresee any important materials constraints, although the preliminary nature of fusion reactor designs makes firm conclusions impossible. In 1983, Oak Ridge National Laboratory conducted a study that estimated a “per reactor” materials demand from a set of fusion reactor design studies completed in the 1970s. These estimates were converted into annual fusion demands by assuming that in the long run, close to 40 fusion reactors would be built per year.[25]

The study compared these estimates to non-fusion demand projections, based on U.S. Bureau of Mines estimates, which were extrapolated over a time span comparable to that assumed for the fusion estimates. The study also compared demand estimates to estimated world supplies.

The study did not find any materials for which total fusion demands exceeded non-fusion demands. Therefore, in those cases for which total demand appeared to exceed available supply when projected over many decades, overall scarcity would not be due solely to fusion. There would be ample motivation other than fusion for either identifying substitutes or finding new sources of Supply.[26]

At this stage of fusion reactor design, substitutes can be found for any of the materials that might be in short supply. However, replacing several materials simultaneously, such as all those that would be in short supply if foreign sources were not available, would be much more difficult than finding substitutes for any one material. **If resource constraints affect fusion reactors, they will concern materials for reactor construction rather than fuel supply.**

cost

Estimating the costs of fusion reactors that cannot yet be designed in detail is difficult. The task is considerably complicated by the fact that economic projections, more than many other features discussed so far, depend critically on parameters that can be little more than guessed at

[24] W. Hafele, J. F. Hold ren, and G. L. Kulcinski, “The Problem of Fuel Resources, ” *Fusion and Fast Breeder Reactors* (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1977), p. 32,

[25] Cannon, *Background Information*, op. cit., ch. 9. The study assumed a worldwide installed electric generating capacity of 1,500 gigawatts, or about 2.4 times the 1986 U.S. installed capacity [given by the North American Electric Reliability Council, “ 1986 Electricity Supply and Demand, ” figure 8, p. 25]. Assuming this capacity to be supplied by generating stations averaging 1 gigawatt each and having an average lifetime of 40 years, an average of 1,500+-40= 37.5 plants would have to be replaced per year. The study assumed that all replacements would eventually be made with fusion reactors.

[26] Ibid., table 9.24, p. 9-36. Although fusion materials demand did not constitute the majority of the total (fusion plus non-fusion) demand for any of the materials studied, fusion requirements constituted between 10 and 50 percent of the total demand for five materials: beryllium, lithium, helium, tungsten, and vanadium. All of these except tungsten were found to be in ample supply.

Fusion demands were calculated from an ensemble of 10 different reactor designs. Such an ensemble represented a diversity of reactor concepts, and using the ensemble kept the analysis from being too dependent on a single design. Any individual reactor design, however, may have materials requirements significantly different from the ensemble average.

today. Many non-technical factors such as interest rates, construction time, and the licensing and regulatory process will have a profound and unpredictable impact on ultimate cost.

Fusion will be a capital-intensive technology. Existing system studies show that most of the cost of electricity will come from building the powerplant. Costs for the deuterium and lithium required to fuel fusion reactors will be a negligible fraction of the total cost. More significant as an effective "fuel" cost will be the expense of periodically replacing the blanket components as they exceed their service lifetimes. Even including these replacements, however, total operational and maintenance expense is projected to constitute less than half of the total cost of fusion-generated electricity.[27]

In analyzing how the costs of fusion electricity depend on various physics and technology parameters, system designers can determine important cost drivers and identify high-payoff areas for further research. Because of overall uncertainties, however, the actual costs estimated in system studies are less dependable than their variation as design assumptions are changed. A National Research Council report on fission/fusion hybrid reactors[28] identifies many sources of uncertainty in present cost estimates, including:

- incomplete design information;
- limited understanding of the required fusion technologies, methods of fabrication, materials, and support systems, including in particular incomplete knowledge of the effects of high-energy neutron irradiation;
- complex requirements for tritium recovery and handling, and the need for remote handling and storage of large, radioactive components;
- the degree of containment facility that will be required for the reactor and for associated tritium handling systems;
- the approach taken towards licensing, including the need for in-service inspection, seismic qualification, redundancy and diversity;
- the costs of waste disposal and decommissioning; and
- the life expectancies and failure modes of plant components, which depend on the combined effects of neutron irradiation, magnetic fields, high temperatures, and corrosion.

Existing information on the costs of fusion experimental facilities does not necessarily provide much guidance for estimating the future costs of commercial reactors. No experiment to date comes close to integrating the various systems that would be required in an operating reactor. Many individuals argue that the proposed costs of future experimental facilities—an engineering test reactor, for example, which will cost at least $1 billion and **very possibly** several times that much—do not bode well for inexpensive powerplants. However, experimental facilities and commercial devices have very different missions and design constraints.

A number of factors would tend to make commercial facilities less expensive than experimental devices that produce comparable amounts of power. Experiments are necessarily based on incomplete knowledge—otherwise there would be no need for them—and their designs must be conservative to ensure that their objectives can be fulfilled. Experiments must be flexible; they must have the ability to operate under a wide range of conditions, since the operating parameters that will be of most interest for future commercial reactors are not yet known. They must be extensively instrumented with diagnostic equipment, since their primary objective would be to produce information, not electricity. The result of this information and the experience with the technology acquired through the research program should make it possible to reduce the cost of subsequent facilities, including commercial ones.

On the other hand, a different set of factors would tend to increase the cost of commercial facilities over that of their experimental counterparts. Expenses may be incurred in ensuring long life, reliability, ease of maintenance, and ease of operation, qualities that are crucial for commer-

[27] J. Sheffield, et al., *Cost Assessment of a Generic Magnetic Fusion Reactor,* Oak Ridge National Laboratory, ORNL/TM-9311, March 1986, table 1.2, p. 7.

[28] National Research Council, *Outlook for the Fusion Hybrid and Tritium-Breeding Fusion Reactors* (Washington, DC: National Academy Press, 1987), p. 90.

cial facilities but that may not be so important for experimental devices. Many of the design features and requirements introduced in the process of licensing, optimizing, and commercializing fusion reactors will also tend to add to the expense of commercial facilities. It is therefore very difficult to draw conclusions about reactor cost from existing experience or from the cost of proposed experiments.

ESECOM has conducted the most extensive analysis to date comparing costs of various fusion designs to one another and to fission reactors. In the ESECOM report, construction cost estimates varied by about a factor of 2 among the fusion designs, and the pure fission costs were similar to or below the low fusion estimates. "Cost-of-electricity' estimates varied over a somewhat smaller range, and the fission designs again were at the low end.

The lowest operating cost of any of the reactors examined by ESECOM was for the "best experience" light-water reactor, representing the lowest cost fission reactors now operating. The highest operating cost of all designs was for the "median experience' light-water reactor, representing a cross-section of present light-water reactor experience. Estimated operating costs for all the fusion designs fell in between these cases. Construction cost (as opposed to operating cost) estimates varied similarly, with some of the pure fusion design construction costs exceeding that of the "median experience" light-water reactor.

One feature of fusion reactor design that could significantly affect economics is its level of safety assurance. The easier it is to demonstrate the safety of a fusion reactor, the easier that reactor will be to license and site. in particular, if the licensing process does not depend on complex and controversial calculations concerning the performance of active safety systems, it might proceed more quickly and with greater consensus. If in turn the construction process were sped up, considerable cost savings could result.

Higher degrees of safety assurance could also have a more direct effect in reducing construction cost. Because safe operation of commercial nuclear reactors today depends on active safety systems, those systems must meet exacting quality assurance standards. Components and systems built to meet these "nuclear-grade" standards are considerably more expensive than similar components in less critical applications. Since the safety of reactor designs with higher levels of safety assurance would not be as dependent on particular components or systems, fewer "nuclear-grade" components would be required. The ESECOM report estimated that up to 30 percent of the "overnight" construction costs (e. g., the total cost if construction could be completed instantaneously, not including interest charges or inflation) could be avoided if nuclear-grade construction were not required. Such a decrease in construction cost would lower the cost of electricity by about 25 percent. This savings is overestimated in that no fusion system is likely to be able to avoid nuclear-grade construction entirely; tritium-handling systems, for example, will always have the potential to release some radioactivity in the event of sufficient component failures. Nevertheless, the ability to relax construction standards through higher levels of safety assurance could lead to cost savings.

Possibly mitigating these cost savings is the price of achieving increased safety assurance in the first place. In the ESECOM report, the costs of the pure fusion designs (before any savings due to safety assurance were taken into account) tended to be higher for those designs with higher levels of safety assurance. The net effect of safety assurance on reactor cost, therefore, depends on whether savings can outweigh the price of additional design constraints.

Future technological developments could also decrease the cost of fusion power. For example, the recent discovery of new superconducting materials that do not require liquid helium temperatures could affect fusion design and economics if these materials can be used in fusion magnets. Cheaper magnets, by themselves, will not dramatically alter the price of a fusion reactor. Even if the magnets in the STARFIRE design were free, the total capital cost would only be reduced by about 12 percent.[29] However, if new magnet capabilities in turn make possible the use of sign if-

[29] J. Sheffield, et al., *Cost Assessment of a Generic Magnetic Fusion Reactor,* op. cit., tables A.4. 1 and A.4.2, pp. 84-85,

icantly different designs—e.g., the use of substantially higher magnetic fields, which could ease the requirements on other systems or permit the use of advanced fuels—then significantly different economic estimates might result. JO

If reactors running on advanced fuel cycles were developed that had substantially lower levels of neutron irradiation, blanket components would not have to be changed as often, reducing operating costs, However, in the case of the D-^{3}He cycle, the costs of the actual fuel would no longer be negligible due to the expense of generating or recovering ^{3}He, which is not found in nature. Capital cost for the fusion core of a reactor using advanced fuels might be higher than that of a D-T reactor since the advanced reactor technology would be considerably more challenging. On the other hand, if an advanced reactor were able to generate electricity directly, without the use of steam generators and turbines, it might be able to bypass some of the balance-of-plant costs.

Given all the uncertainties, OTA finds that the economic evidence to date concerning fusion's cost-effectiveness is inconclusive. No factors yet identified in the fusion research program conclusively demonstrate that fusion will be either much more or much less expensive than possible competitors, including nuclear fission. Fusion appears to have the potential to be economically competitive, but making reliable cost comparisons will require additional technical research and a better understanding of non-technical factors, such as ease of licensing and construction, that can have a profound influence on the bottom line.

[30] Possible applications of high field superconducting magnets to fusion reactor design are discussed in *Tokamak Reactor Concepts Using High Temperature, High Field Superconductors,* by D.R. Cohn, et al., Massachusetts Institute of Technology Plasma Fusion Center, PFC/RR-87-5, Apr. 14, 1987.

THE SUPPLY OF AND DEMAND FOR FUSION POWER

The factors that influence how successfully fusion technology will serve as a source of energy include how well fusion's characteristics meet the requirements of potential customers and how well fusion compares to alternate electricity-generating technologies. How well fusion will meet the needs of its users, primarily electric utilities, depends in turn both on when it can become commercially available and on what its users want. These issues are discussed first below. Next is a brief summary of competing energy supply technologies that provides some context for fusion power. Finally, the implications of estimates of future electricity demand are analyzed.

The Availability of Fusion Power

Financial resources permitting, the research program outlined by the Technical Planning Activity (TPA)[31] and described in chapter 4 is targeted toward enabling a decision on fusion's overall potential to be made by 2005. According to TPA, if the decision is made to proceed with fusion at that time, an "Integrated Fusion Facility" (IFF) based on "commercially relevant fusion technology" could be built that would mark the "beginning of the commercialization phase of fusion."[32] TPA did not specify the nature of the IFF. It could be a demonstration or prototype reactor, although the IFF parameters TPA presented in an example show it to be well short of commercial performance (see ch. 4, footnote 28). Thus, the technical steps that might follow the research phase, in terms of the necessary facilities that would lead to a prototype commercial fusion reactor, have not yet been determined.

The institutional process by which any demonstration fusion reactor might be built and operated is also highly uncertain. Under present Fed-

[31] The Technical Planning Activity was a fusion communitywide effort to identify the technical issues, tasks, and milestones that characterize the remaining fusion research effort. Its primary output was *Technical Planning Activity: Final Report,* prepared by the Argonne National Laboratory, Fusion Power Program, for the U.S. Department of Energy, Office of Energy Research, AN L/FPP-87- 1, January 1987. The Technical Planning Activity is described in the section of ch. 4 titled "The Technical Planning Activity. "

[32] *Technical planning Activity: Final Report,* op. cit., pp. 9 and 26.

eral policy, building and operating a demonstration reactor is the responsibility of the private sector, which has certainly proven capable of demonstrating major new technologies in the past. However, involving the private sector in an effort of this scale may not be straightforward. According to one utility executive:

> . . . there is a certain level of concern for the enormous gap in perception that exists between industry and government concerning private sector commercialization. It may be unrealistic to assume that once a scientific and related technology data base is established in the program, the stage will be set for private sector commercialization of attractive fusion energy sources.[33]

Unless the Federal Government becomes responsible for owning and operating fusion generating stations—a change whose ramifications would extend far beyond fusion's development—some mechanism for easing the transition from government to private responsibility will be required.[34]

The timing of the commercialization process is difficult to predict for both technical and institutional reasons. Conceivably, if the research program provides the information necessary to design and build a reactor prototype, such a device could be started early in the next century. After several years of construction and several more years of qualification and operation, a base of operating experience could be acquired that would be sufficient for the design and construction of subsequent reactors. If the regulatory and licensing processes proceeded concurrently, vendors could begin to consider the manufacture and sale, and utilities could consider the purchase, of commercial fusion reactors midway through the first half of the next century.

The subsequent penetration of fusion reactors into the energy market would take time because existing electrical generating capacity will not be replaced overnight. If early fusion plants can be built and operated without undue delays or surprises, they may begin to develop a satisfactory track record that will stimulate further construction; if early plants show unfavorable operating experience, commercialization will be delayed. At any rate, it will take decades from their first successful demonstration for fusion reactors to generate a considerable fraction of the Nation's electricity. **Even under the most favorable circumstances it does not appear likely that fusion will be able to satisfy a significant fraction of the Nation's electricity demand before the middle of the 21st century.**

The Desirability of Fusion Power

Ultimately, fusion's commercial potential will be determined by its ability to meet societal needs more effectively than its alternatives. This determination will be made by the eventual purchasers of fusion technology, most likely electric utilities. However, given the long-term nature of the fusion program, it is difficult to predict what characteristics will be important to future customers. The best that can be done is to identify those attributes that are important to utilities today, recognizing that utilities and their requirements may evolve with time.

Certainly one of the most important factors will be the capital cost of fusion plants and the cost of fusion-generated electricity. Although fusion may be economically competitive with other energy technologies, it is not likely to be substantially less expensive. Nevertheless, without a demonstrable economic advantage, it might be difficult to convince potential purchasers to risk substantial investments in what would be an unknown and unproven technology.

Even if fusion cannot beat its competitors economically, it still may be judged preferable on environmental, safety, and resource security grounds. If the potential of fusion technology in these areas is achieved, and if these attributes are important enough to compensate for an economic penalty, explicit policy decisions could be made to promote fusion through legislation or regulation. Barring such direct intervention, how-

[33] Kenneth L. Matson, Vice President, PSE&G [Public Service Electric & Gas Co.] Research Corp., Newark, NJ; quoted in "Panel Discussion on Industry and Utility Perspectives on Future Directions in Fusion Energy Development," *Journal of Fusion Energy,* vol. 5, No. 2, June 1986, pp. 144-145. This issue of the *Journal of Fusion Energy* presents an edited transcript of a symposium sponsored by Fusion Power Associates titled "The Search for Attractive Fusion Concepts."

[34] For more discussion of the role of the private sector in fusion's development, see the section in ch. 6 on "Private Industry."

ever, the primary determinant of fusion's market penetration probably will be cost.

In addition to purely economic factors, a number of additional factors–most of them indirectly influencing the cost of energy—are also important to present utilities. The Electric Power Research Institute (EPRI) surveyed a number of electric utilities in 1981 to determine how important factors other than the cost of energy would be to their acceptance of fusion. The results of the survey are shown in table 5-2.

EPRI found that utilities identified four factors as "vital" and ten as "very important" for future fusion reactors. Although it is too early to evaluate how well fusion will be able to satisfy these requirements, the potential of the technology in some areas can be noted. For example, successfully designing fusion reactors with high levels of safety assurance could satisfy *plant safety* requirements, lessen *financial liability*[35], and improve plant licensability. In addition, if fusion reactors could be convincingly demonstrated to be safe, siting *flexibility* might be increased; reactors could be located close to population centers on sites that would not be considered for fission reactors.

Table 5-2.—Utility Requirements Summary (in addition to cost of energy)

Requirement	Weighting
A. Utility planning and finance	
1. Plant capital cost .,	Vital
2. Plant O&M[a] and fuel cost	Important
3. Outage rates	Very important
4. Plant life	Important
5. Plant construction time	Very important
6. Financial liability , . .	Vital
7. Unit rating ~ ~	Moderately important
B. Safety, siting, and licensing	
1, Plant safety	Vital
2. Flexibility of siting ~ ~	Very important
3. Waste handling and disposal .	Very important
4. Decommissioning .,	Important
5. Licensability.	Vital
6. Weapons proliferation	Important
C. Utility operations	
1. Plant operating requirements	Very important
2. Plant maintenance requirements	Very important
3. Electrical performance .	Very important
4. Capability for load change	Moderately important
5. Part load efficiency . .	Moderately important
6. Minimum load . . .	Moderately important
7. Startup power requirements	Important
D. Manufacturing and resources	
1, Hardware materials availability	Very Important
2. Industrial base.	Very Important
3. Fuel and fertile material availability	Very important

Order of significance
1. Vital
2. Very important
3. Important
4. Moderately important

No factors were judged "slightly important'; factors judged "unimportant' have been deleted from the list.)

aOperations and maintenance

SOURCE Electric Power Research Institute Utility *Requirements for Fusion* EPRI AP-2254 February 1982 table 2-1 p 2-3

potential advantages for fusion reactors also emerge with respect to other utility requirements. Due to its virtually limitless fuel supply, fusion should be able to satisfy the *fuel availability* criteria. Moreover, it appears that the *waste handling and disposal* should be better addressed by fusion than by fission.

A number of uncertainties remain for other factors of importance to utilities. At present, there is virtually no *industrial base* for fusion, although existing fission, aerospace, and materials industries all have capabilities relevant to fusion's needs. Developing fusion's industrial base is essential if the commercialization process is to succeed. Moreover, due to uncertainties in economic studies, how well fusion will be able to minimize *plant capital cost* cannot yet be determined. In addition to affecting the cost of energy through life-cycle capital amortization, large capital expenditures can complicate corporate financial management in areas such as debt-to-equity ratios and capital flexibility. It is clear that fusion reactors will be capital-intensive, but at this stage of development their costs cannot be accurately determined.

Hardware availability, which measures the cost, scarcity, and supply dependability of materials required for plant construction, cannot be determined at this stage of design. Factors such as *outage rates, plant construction times, plant operating requirements, plant maintenance requirements,* and *electrical performance,* also viewed as very important by utilities, probably cannot be evaluated until fusion reactors are well into the commercialization process. Experience

[35] Financial liability measures the maximum potential financial losses due to death, injury, property damage, loss of revenue, and other costs in the event of an accident.

with construction, operation, and maintenance of the reactors will be necessary to fully understand these aspects of fusion technology.

A factor that is interesting due to its relatively low weighting is *unit rating,* or the electrical capacity of a particular generating station. In the early 1970s, fusion reactor conceptual designs had electrical outputs considerably higher than those of existing generating stations. Subsequent designs have lowered electrical capacities to 1,000 megawatts of electricity or less, more in line with existing stations; some recent studies have even considered fusion plants generating as little as 300 megawatts of electricity, although at a higher projected cost of electricity.[36] Now that fusion reactor designs are sized within the range of utility experience—together with the relative unimportance of this parameter —fusion reactors should have little trouble meeting unit rating requirements.

Comparisons of Long-Term Electricity Generating Technologies

This section summarizes the long-range potential of various electricity generating technologies in the 21st century and discusses possible problems associated with their use and/or further development. A detailed examination of the characteristics of these energy technologies, however, is beyond the scope of this report .1'

The role of demand modification, such as conservation and improvement in the efficiency of energy use, is critical in determining future energy requirements. However, as shown in the following section on "Fusion's Energy Context, " the level of electricity demand does not strongly affect the relative demand for fusion power compared to its alternatives. Therefore, improved efficiency of energy use is not specifically discussed here as a generating technology.

Fossil Fuel Technologies

Coal.–Coal is the most abundant energy source in the United States and is currently used to generate over half of the Nation's electricity .38 According to the Energy Research Advisory Board:

> Coal supply for the 1985-2020 period does not seem to require any special attention at this time . . . It has been the conventional wisdom that the U.S. coal resource base is of such magnitude that it can be safely relied upon to supply any demand for the foreseeable future. This would be true even if nuclear generation does not grow and if a major demand for coal-based synthetics should arise,[39]

Many coal technologies are highly developed and well understood, and they are economically attractive. Proven domestic reserves of coal are adequate to maintain present rates of use for several hundred years. However, there are serious environmental impacts associated with or anticipated from the combustion of coal. Mitigating these adverse environmental impacts increases the cost of coal combustion and may reduce the efficiency of conversion to electricity. Furthermore, coal combustion inherently produces carbon dioxide gas, which may affect world climate and make the use of coal undesirable.

The main near-term problem associated with the use of coal appears to be emissions of combustion byproducts such as sulfur and nitrogen oxides and particulate. These emissions are a major contributing factor to acid deposition, also called "acid rain. " Air pollution from coal and other fossil fuel combustion can harm natural

[36]One study presenting cost of electricity as a function Of electrical output is J. Sheffield, et al., Cost *Assessment of a Generic Magnetic Fusion Reactor,* op. cit., figure 4.17, p. 48.

[37]Selected OTA studies that have examined other energy technologies i n more detail include New *Electric Power Technologies: Problems and Prospects for the 1990s,* OTA-E-246 (Washington, DC: U.S. Government Printing Office, July 1985); *Nuclear Power in an Age of* Uncertainty, OTA-E-216 (Washington, DC: U.S. Government Printing Office, February 1984); and *Industrial and Commercial Cogeneration,* OTA-E-192 (Springfield, VA: National Technical Information Service, February 1983).

[38]In 1985, coal generated 1,401 billion of the 2,469 billion kilowatt-hours of electricity generated in the United States, according to *Annual Energy Review 1985,* published by the U.S. Department of Energy, Energy Information Administration, DOE/EIA-0384(85), table 81, p. 185.

[39]Energy Research Advisory Board, "Appendix D: Coal Research and Development, " by Eric H. Reichl, *Guidelines for DOE Long Term Civilian Research and Development, vol.* VI, Report of ERAB Supply Subpanel, Long-Range Energy Research and Development Strategy Study, A Report of the Energy Research Advisory Board to the U.S. Department of Energy, DOE/S-9944, December 1985, p. 65.

ecosystems, damage economically important materials, impair visibility, and may affect human health.@

The near-term environmental problems associated with coal and fossil fuel combustion, though serious, can be controlled. The release of combustion byproducts can be mitigated by using cleaner fuels, attaining more complete combustion, or cleaning ("scrubbing") the combustion exhaust. Several technologies to reduce undesirable combustion byproducts are currently available, and more are being developed.[41] Such pollution abatement systems make coal-fired electricity somewhat more expensive, but they do not eliminate coal as a major source of future electricity supply. With the exception of carbon dioxide buildup, discussed below, issues concerning the environmental acceptability of coal combustion are resolvable by burning cleaner fuels or by using "clean coal" technologies.

Oil and Gas.–Oil and gas today generate substantially less electricity in the United States than coal.[42] The domestic resource bases for oil and gas are considerably smaller than coal's, and for this reason oil and gas technologies are not generally included in discussions of long-range electricity supply over the periods in which fusion may make a major contribution.

In the nearer term, however, these fuels—particularly gas—may have an increasing role in electricity generation and may very well form part of the mix of generating technologies at the time that fusion reactors are first introduced. Advanced gas turbines now under development may be highly efficient sources of electricity emitting far less combustion byproducts than current coal plants. Furthermore, such turbines would produce only about one-third as much carbon dioxide per kilowatt-hour as a coal generation plant, reducing (but not eliminating) carbon dioxide emissions as well.[43] Near-term electricity generating technologies are discussed in a separate OTA assessment .[44]

Carbon Dioxide Buildup.–Carbon dioxide ($C0_2$) is formed as a byproduct of the combustion of fossil fuels–coal, oil, and gas. in the past several decades, the amount of CO_2 in the atmosphere has increased about 10 percent, largely as a result of fossil fuel combustion. Atmospheric carbon dioxide gas can trap some of the heat radiated from the earth instead of allowing it to escape into space. Therefore, the buildup of $C0_2$ is associated with a global warming effect, sometimes called the "greenhouse effect. "

Increased use of fossil fuels is only one potential contributor to global warming. Other gases released into the atmosphere, such as methane, nitrous oxide, and chlorofluorocarbons, have similar heat-retaining properties and may, in aggregate, contribute as much as $C0_2$ to global warming. Moreover, the connection between fossil fuel use and global warming is influenced by factors such as the production and use of CO, by green plants, its absorption by the oceans, and vegetative decomposition. Global warming is potentially a very serious problem, and the consensus within the scientific community studying the issue is that such a warming appears inevitable if emission of $C0_2$ and other "greenhouse gases" continues to increase. However, there is no certainty to date about the timing and magnitude of the effect, nor about what its climatic implications might be.

The use of fossil fuels will always produce CO_2; there is no way to eliminate $C0_2$ as a product of the combustion process. As noted above, however, different fossil fuels and combustion technologies produce different amounts of CO_2 per unit of generated energy. Techniques to capture the $C0_2$ from fossil fuel combustion emissions have been proposed, but they are generally considered to be impractical for either economic or technological reasons. Neither is there a practical way to recover $C0_2$ and other greenhouse

[40] U.S. Congress, Office of Technology Assessment, *Acid Rain and Transported Air Pollutants: Implications for Public Policy,* OTA-O-204 (Washington, DC: U.S. Government Printing Office, June 1984), pp. 9-13.

[41] Ibid., Appendix A.2: "Control Technologies for Reducing Sulfur and Nitrogen Oxide Emissions, " p, 152.

[42] Total use of oil and gas, however, including uses other than electricity generation, is greater than that of coal.

[43] Part of the reduction is due to the higher efficiency of these turbines; part is due to the lower carbon content of the fuel.

[44] *New Electric Power Technologies: Problems and Prospects for the 1990s,* op. cit., chs. 4 and 5.

gases that are already in the atmosphere. The only way to reduce CO_2 emissions from fossil fuel combustion is to curtail the combustion of fossil fuels.

Limiting the use of fossil fuels will not be easy. The simplest way, up to a point, would be to increase the efficiency of energy use, lessening the growth of energy demand. Displacing fossil fuel usage with other energy technologies will be more difficult. Coal will continue to be a major source of electricity for the early 21st century, and deemphasizing its use would foreclose a substantial resource base. Oil and gas currently generate more CO_2 annually than coal due to their heavier use; much of their use is in decentralized applications such as transportation and space heating where they will be difficult and expensive to replace.

Without government intervention, technologies developed to reduce fossil fuel usage must be economically preferable to succeed. Because CO_2 buildup would be a global problem, fossil fuel combustion would have to be reduced on a global scale. It is not clear that developing nations would be willing or able to shift from fossil fuels to other energy sources if doing so would impose serious economic hardship. Furthermore, those regions of the world that might benefit from CO_2-induced climatic change would have no incentive to reduce CO_2 emissions unless they were otherwise compensated.

Possible global warming due to carbon dioxide buildup is a complex problem with a number of contributing causes. It provides an incentive to develop new technologies that can substitute for or otherwise curtail the use of fossil fuels. However, the degree to which these new technologies reduce fossil fuel use will depend heavily on their economic advantages, and any reductions they contribute to fossil fuel use will occur gradually.

Nuclear Fission Technologies

Nuclear fission currently appears to be the main alternative to the widespread future use of coal. The technology is well developed and relatively well understood, and it is supported by a substantial research and development infrastructure. In 1985, 95 nuclear powerplants produced 16 percent of U.S. electricity supply,[45] and nuclear power is likely to remain the second largest source of domestic electricity generation (after coal) into the 21st century. Nuclear fission may become a more important source of electricity if CO_2 or other environmental problems require constraint of coal combustion. The main impediments to increased use of nuclear fission appear to be its unfavorable economics and concern about health and safety. In the long run, many decades from now, fuel constraints may affect the potential of nuclear fission unless more efficient technology, fuel reprocessing, or fuel breeding is instituted.

Public Acceptance.–The long-term feasibility of nuclear fission technologies will require resolution of health and safety concerns. Nuclear power is currently the target of widespread opposition for several reasons. Members of the public feel that mechanisms to dispose of radioactive wastes are inadequate to prevent the ultimate release of dangerous radioactive effluents. Moreover, there is concern about the safety of nuclear reactors, particularly in the aftermath of the Three Mile Island (U. S.) and Chernobyl (U. S. S. R.) accidents. The potential for mechanical failure and operator error casts doubt on the integrity of reactor safety systems.

Economics.–The economics of nuclear power are currently uncertain for several reasons, not all of which are related to characteristics of the technology. The technology is complex and demands strict quality control; nuclear plant construction requires longer lead times and greater capital investment than coal plants. Changing regulations, inadequate management at some plants, and time-consuming litigation add to its cost. The combination of these factors with the soaring interest rates of the late 1970s resulted in costs much higher than expected. Although some plants–even in recent years–have been built on schedule and within budget, the more common experience has been so traumatic that utilities will continue to be extremely cautious about undertaking new nuclear construction. Furthermore, large-scale plants–the only type available at present for nuclear fission–are unattractive in the

[45] *Annual Energy Review 1985*, op. cit., pp. 185, 205.

situation of uncertain demand growth that utilities now face. Smaller scale, modular plants that track load growth more flexibly are preferred in these circumstances.

Fuel.–The light-water reactor technology currently used in fission reactors is capable of extracting only a small fraction of the energy potentially available from uranium fuel rods. In the "once-through" fuel cycle currently in use, the fuel rods are withdrawn from the reactor and stored or disposed of once they become unusable. With greatly expanded use of fission reactors of this type, the demand for uranium would increase and the supply of inexpensive uranium would eventually be depleted. At some point, the price of uranium would rise high enough to make light-water reactor technology economically prohibitive, although current projections indicate that such a point is not likely to be reached before the middle of the next century. Advanced convertor reactors, which extract much more energy from the uranium fuel, are being developed and could extend uranium supply still further.

If the price of uranium rises too high for even advanced convertor reactors to be economical on a once-through fuel cycle, other fuel cycles may be possible. These fuel cycles are sufficient to give fission technology a very long-term resource base. However, since these cycles involve the production, separation, and transportation of fissionable fuel, they could increase the risk of nuclear proliferation over that of a once-through fission economy. (See the discussion of "Nuclear Proliferation Potential" earlier in this chapter).

Research and Development.– It does not appear that nuclear fission technology is unusable or necessarily uneconomical. Extensive research is currently directed at developing advanced fission reactors that will be more acceptable to the public and more attractive to utilities; the intent of this research is to demonstrate that future nuclear fission reactors with very different characteristics than current plants can be a viable source of electricity. in particular, the nuclear industry is attempting to develop passively safe reactors that could not release large amounts of radioactivity due to operator error or mechanical malfunction.[46] Research and development are also focusing on making modular reactor systems, which could be constructed with shorter lead-times and less financial risk to the utilities, and on developing systems that use fuel more efficiently.

The nuclear industry appears to have the potential to develop a superior advanced reactor, and a number of designs for such powerplants exist. However, it is less certain that public confidence in the nuclear industry will improve significantly, particularly in the near term. Without restoring public confidence, the long-term nuclear option may be unattainable.

Renewable Energy Technologies

In addition to coal-fired and nuclear fission powerplants, there are several renewable energy technologies. Two well-developed renewable technologies currently contribute significantly to world energy supply: hydroelectric power and conventional biomass (wood), although only the former is used significantly to generate electricity, Several other technologies, such as wind, unconventional biofuels, solar photovoltaics, geothermal, solar thermal, and ocean energy, may offer significant contributions during the 21st century.[47]

Renewable energy sources are attractive because many of them do not require construction of large facilities for optimal economic operation and because their fuel supplies are continually replenished. Other attractive features of some, but not all, of these technologies, according to an OTA report, "include fewer siting and regulatory barriers, reduced environmental impact, and increased fuel flexibility and diversity."[48]

46Such designs have been called "inherently safe. ' However, inherent safety in this sense differs from the usage adopted by the ESECOM report and discussed earlier in this chapter in the section on "Risk and Severity of Accident" under "Characteristics of Fusion Electric Generating Station s." The ESECOM report found that passively safe fission reactors–although having greater safety assurance than existing nuclear plants—would not attain the highest levels of safety assurance, including the level ESECOM labeled "inherent safety. "

47 Energy Research Advisory Board, "Appendix D," op. cit., P. 11.

48*New Electric* Power *Technologies,* Op. cit., p.19.

Problems associated with renewable energy sources, however, may limit their role as major sources of electricity. Few of the technologies are currently economically competitive in other than highly specialized applications. Many renewable resources are only available intermittently, and their availability depends on factors like the weather and the time of day. Moreover, the availability of renewable technologies depends on geography and climate. The average amount of available solar energy varies significantly across the United States, largely as a result of differing weather conditions. Wind energy is most effectively recovered in California and Hawaii. Finally, most renewable energy sources are diffuse, requiring central-station powerplants to occupy more land than those using technologies such as coal and fission. On the other hand, the diffuse nature of renewable also makes them well-suited for decentralized applications, which may offset the need for large centralized facilities.

In general, both technical and economic improvements are needed to make renewable energy technologies competitive i n the 21st century. Research is being conducted on a wide variety of approaches for harnessing these energy sources, and significant improvements are likely. Nevertheless, it is not expected that renewable technologies will eliminate the need for central-station generating technologies such as coal and nuclear fission.

Nuclear Fusion Technology

Unlike the other supply options, nuclear fusion is still in a pre-development stage. Much of the technology required for generating electricity from magnetic fusion has not been demonstrated, and the commercial potential of fusion cannot yet be determined.

Nuclear fusion appears to have attractive features. First, it could have significant environmental advantages with respect to other central-station generating technologies. The fusion process does not produce CO_2, nor—with appropriate choice of materials—does it appear that radioactive waste will be as high-level or as biologically hazardous as waste produced by nuclear fission. Second, it appears possible to design fusion reactors that will not depend on active safety systems to prevent serious accidents; such reactors could have a higher degree of safety assurance than fission reactors. Finally, high levels of safety assurance, environmental advantages, and independence from geographical constraints could make siting a nuclear fusion powerplant considerably easier than siting a plant based on another energy technology.

The ultimate feasibility of nuclear fusion will not be known until the technology is developed and can be compared with the other energy options that exist at that time. At this point, it is only possible to make projections based on the characteristics of the technology and the research necessary to overcome problems identified to date.

Table 5-3 compares various future electricity supply options, based on extrapolations of current technologies. On this basis, magnetic fusion has the potential to be a very attractive energy source. Obviously, unanticipated developments in any of the technologies described in this table could significantly alter their future role.

Fusion's Energy Context

The anticipated need for energy over the period in which fusion would undergo commercialization will influence the urgency of fusion research and the pace of its entry into the energy supply marketplace. OTA convened a workshop in November 1986 to examine the factors that would determine demand for electricity in general and fusion in particular. Several points became clear during the discussion:[49]

- **The overall size and composition of electricity demand, by itself, should neither require nor eliminate fusion as a supply option.** Economics and acceptability, rather than total demand, will determine the mix of energy technologies. If fusion technology is preferable to its alternatives, it will be used

[49] Fusion Energy Context Workshop, Office of "[ethnology Assessment, Washington, DC, Nov. 20, 1986. A list of participants is given at the front of this report.

Table 5-3.—Comparison of Prospective Long-Range Electricity Supply Options

Energy source	Advantages	Disadvantages and research needs
Coal	• Plentiful • Technology exists today • Safe	• Near-term environmental implications require development of "clean coal technologies" or fuel substitutions that may increase the cost of energy • CO_2 buildup may make increased dependence on fossil fuels undesirable
Oil and gas	• Technology exists today • Fewer combustion byproducts emitted than coal • Less CO_2 emitted per unit energy than coal	• Questionable long-term resource base • Does not avoid CO_2 emission
Fission	• Plentiful • No emission of CO_2 • No emission of combustion byproducts • Technology exists today	• Unfavorable economics and safety concerns suggest development of advanced reactor designs that are smaller and passively safe • Nuclear waste disposal not yet resolved • Public confidence must be improved and may or may not result from technical improvements
Renewable	• Unlimited fuel supply • No net CO_2 emission • Technologically simple • Modular design	• Uncertain economics and technical problems require more R&D • Intermittence and diffuseness may make renewable inadequate substitute for central-station power generation in arbitrary locations
Fusion	• Unlimited fuel supply • Potential for higher degree of safety assurance than fission • No CO_2 production or combustion byproduct emission • Substantially less hazardous nuclear waste than fission"	• Significant R&D effort required to establish technical feasibility • Environmental and safety potential highly dependent on design, especially on materials choice • Economic potential unknown

SOURCE" Office of Technology Assessment, 1987.

to replace retired generating capacity even if overall demand is low. If fusion proves inferior to its competitors, it may not be used even at very high demand levels. Fuel supplies for both coal and nuclear fission are adequate to meet high levels of demand for at least a few hundred years without fusion. However, late in the next century, fission may require the use of breeder reactors.

Should fusion technology prove favorable, rapid growth in demand would facilitate its introduction because the opportunities for new powerplant construction would be greater. Nevertheless, demand alone cannot turn an unattractive technology into an attractive one.

- **It is unlikely that any one technology will take over the electricity supply market, barring major difficulties with the others.** At **present, a number of supply technologies have roughly equivalent marginal costs of production, and all participate in the supply mix.**
- **Given that technologies such as coal combustion and nuclear fission are already commercialized, fusion will have to prove better-not only comparable—before it can start to displace them.** The criteria on which fusion will be judged include economic, safety and environmental issues as well as resource security. Advantages in one area may, but will not necessarily, compensate for shortcomings in another.
- **Potential problems with the major technologies currently viewed as supplying electricity in the future provide incentives to develop alternate energy technologies and/or substantially improve the efficiency of energy use. Considerable expansion of coal use** may prove undesirable due to the "greenhouse effect"; safety or proliferation concerns may similarly impair expansion of the nuclear fission option. Over the long run, fusion could provide a substitute for these technologies. The urgency for developing fusion, therefore, depends on assumptions of

the likelihood that existing energy technologies will prove undesirable in the future.

- **There is little to be gained and a great deal to be lost if fusion is prematurely introduced without attaining its potential economic, environmental, and safety capabilities.** Even in a situation where problems with other energy technologies urgently call for development of an alternative source of supply, that alternative must be preferable in order to be accepted. It would be unwise to emphasize one fusion feature—economics or safety or environmental advantages—over the others before we know which aspect will be most important for fusion's eventual acceptance.
- New **energy technologies take a long time to develop and gain wide use.** It currently appears that it will be many decades before fusion will be able to supply a significant fraction of U.S. electricity even under optimistic assumptions concerning its technological development.

With respect to global energy demand, in particular, as a motivation for fusion, workshop participants discussed various estimates of future energy demand. Models attempting to chart the evolution of global energy demand over many decades have been developed in the last few years. Because the time periods of interest are much too long for projections of recent experience to be valid, these models must instead simulate the future world economy and use of energy. These models start with a number of assumptions concerning world economic and population growth; the relationship between economic growth, technological development, and energy use; and the resource bases and costs of various energy technologies. The models calculate the evolution of those parameters assumed to be determinants of energy use and then determine desired outputs such as the supply and price of various types of energy.

These models are most useful for parametric analysis: What might be the consequences of some set of actions? Which parameters appear to be the most sensitive determinants of future demand? The models are, however, much less able to project future behavior in any absolute sense. They are inherently simplified, and even if they accurately reflect the behavior of the system they represent, the input data they act on are in many cases highly uncertain.

A recent review of a number of world energy models discusses their respective methodologies and compares some of their results, finding that there is more than an order of magnitude variation in their respective estimates for energy demand in the year 2050 (figure 5-3).[50] The variation results largely from differing input assumptions, as is shown by the fact that, for several of the models, a number of different projections are plotted based on different assumptions or different sets of input data. Nevertheless, unless it is known which assumptions are correct, even a model known to be valid cannot produce valid predictions.

The relative contributions of different forms of energy supply are no better determined than the total energy demands calculated by these models. The costs of different supply technologies cannot be known over the periods of interest and must be assumed. The mix of supply technologies computed by these models therefore depends primarily on the corresponding input assumptions. Furthermore, a detailed sensitivity analysis using one global energy model shows that overall energy consumption figures appear to be much more sensitive to parameters relating to demand–e.g., relative rates of economic development and productivity growth-than to parameters describing supply technologies and costs.[51]

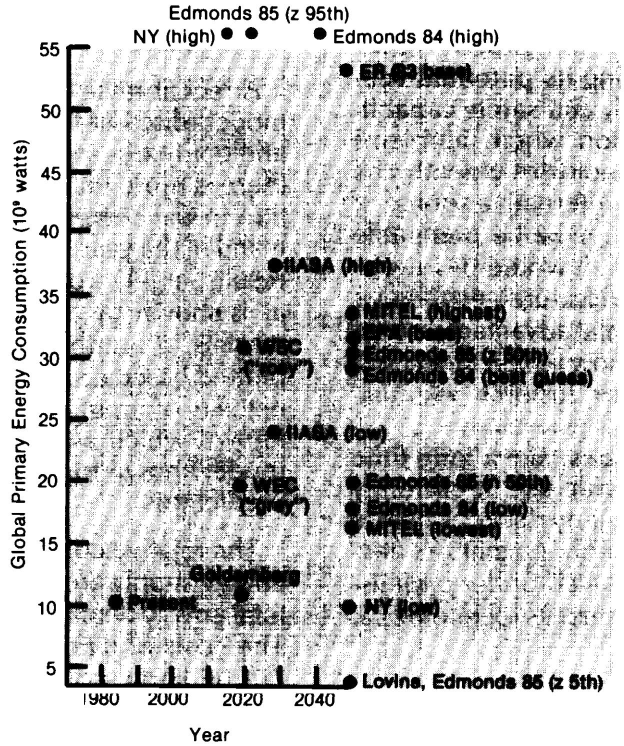
This finding further reinforces the conclusion that predictions of future energy use provide little information about the demand for any particular supply technology. **The urgency for developing fusion technology, therefore, depends on one's assumptions as to the likelihood that existing sources of energy supply cannot be counted on in the future. Little justification can be provided from demand estimates alone.**

---

[50] Bill Keepin, "Review of Global Energy and Carbon Dioxide Projections," *Annual Review of Energy,* Jack Hollander, Harvey Brooks, and David Sternlight (eds.), vol. 11 (Palo Alto, CA: Annual Reviews Inc., 1986), p. 357.

[51] J.M. Reilly, J.A. Edmonds, R. H. Gardner, and A. L. Brenkert, "~' ncertainty Analysis of the IEA/ORAU CO_2 Emissions Model" *Energy Journal, vol. 8, No. 3,* July 1987, pp. 1-30.

Figure 5-3.—Projections of Global Primary Energy Consumption to 2050



KEY: IIASA: International Institute for Applied Systems Analysis, *Energy in a Finite World: A Global Systems Analysis* (Cambridge, MA: Ballinger, 1981).

Lovins: Lovins, A.B., Lovins, L.H., Krause, F., and Bach, W., *Least Cost Energy: Solving the CO_2 Problem* (Andover, MA: Brick House, 1982).

WEC: World Energy Conference, *Energy 2000-2020: World Prospects and Regions Stresses*, J.R. Frisch (ed.), World Energy Conference Conservation Commission (London: Graham & Trotman, 1983).

NY: Nordhaus, W.D., and Yohe, G., "Future Paths of Energy and Carbon Dioxide Emissions, *Changing Climate* (Washington, DC: National Academy of Sciences, 1983).

MITEL: Rose, D.J., Miller, M.M., and Agnew, C., *Global Energy Futures and CO_2-Induced Climate Change*, MITEL 83-015 (Cambridge, MA: MIT Energy Laboratory, 1983).

EPA: U.S. Environmental Protection Agency, *Warning: Can We Delay a Greenhouse Warming?* S. Seidel and D. Keyes (eds.) Washington, DC: U.S. Environmental Protection Agency, 1983).

ER: Edmonds, J., and Reilly, J., "Global Energy and CO_2 to the Year 2050," *Energy Journal* 4(3):21-27, 1983.

Edmonds 84: Edmonds, J., Reilly, J., Trabalka, J.R., and Reichle, D.E., *An Analysis of Possible Future Atmospheric Retention of Fossil Fuel CO_2*, Report No. DOE/OR/21400-1 (Washington, DC: U.S. Department of Energy, 1984).

Edmonds 85: Edmonds, J., Reilly, J., Gardner, R., and Brenkert, A., *Uncertainty in Carbon Emissions, 1975-2075*, Report of the Carbon Dioxide Emissions Project (Oak Ridge, TN: Institute for Energy Analysis, 1985).

Goldemberg: Goldemberg, J., Johansson, T.B., Reddy, A.K.N., and Williams, R.H., "An End-Use Oriented Global Energy Strategy," *Annual Review of Energy*, Jack Hollander, Harvey Brooks, and David Sternlight (eds.), vol. 10 (Palo Alto, CA: Annual Reviews Inc., 1985), pp. 613-88.

SOURCE: Bill Keepin, "Review of Global Energy and Carbon Dioxide Projections," *Annual Review of Energy*, vol. 11, 1986, figure 2, p. 364. Data points are keyed to different models analyzed in that paper.

CONCLUSIONS

Characteristics of Fusion Reactors

Fusion reactors appear to have the potential, using only passive systems, to assure safe operation and shutdown in the event of accident, malfunction, or operator error. If this potential for a high degree of safety assurance is realized, a fusion reactor would be easier to certify as safe than a reactor that depends on active safety systems, such as today's fission reactors. Moreover, fusion reactors do not appear likely to pose new types of occupational hazards.

With proper choice of materials, the environmental characteristics of fusion reactors would likely be preferable to other energy technologies. Unlike fossil fuel combustion, fusion does not produce carbon dioxide that could contribute to overall global warming. Fusion reactors will produce radioactive waste, but these wastes should be less radioactive, less hazardous, and easier to dispose of than those from nuclear fission reactors. However, fusion reactor designs can differ by orders of magnitude in the amount of radioactive waste to be generated. In principle, waste generation can be greatly minimized by the use of materials that would not generate long-lived radioactive isotopes inside a fusion reactor; such materials must still be developed and tested. Routine radioactive emissions from fusion reactors are expected to be insignificant.

One of the most attractive features of fusion is its essentially unlimited fuel supply. Sufficient deuterium is available and recoverable at low cost from water to provide energy for billions of years at present rates of use. The lithium needed to breed tritium in D-T reactors is not as plentiful as deuterium, but it is nevertheless present in sufficient quantity that supply of adequately priced fuel is very unlikely to constrain the prospects of D-T fusion over any time of conceivable interest. Pending detailed fusion reactor designs, other resource requirements are harder to estimate; however, there is no reason to believe that other resource requirements will constrain fusion's development.

Projections of the economics of fusion reactors are inconclusive at this stage of fusion's development. Existing studies tend to show the cost of electricity from present fusion designs would be somewhat more expensive than that of existing energy supplies. However, these studies cannot be considered definitive for a number of reasons. First, any comparisons between prospective technologies and existing ones are highly uncertain, considering the disparate levels of development. Second, fusion's costs are difficult to estimate because substantial research and development remains to be done. Technical features that may lead to decreased fusion costs are being explored, and the ultimate success of these features is uncertain. Alternatively, technical problems that drive up the cost maybe encountered. More significantly, fusion's economics will be profoundly affected by non-technical factors— e.g., the ease and length of the construction and licensing processes—whose impact on fusion costs is not well understood at present. Finally, the costs for fusion's potential competitors are uncertain.

Timetable for Fusion Power

Considering the remaining technical research to be done and the time period needed for the commercialization process to result in substantial market penetration, it does not appear likely that fusion will be able to satisfy a significant fraction of the Nation's electricity demand before the middle of the 21st century. The degree to which fusion is indeed able to penetrate the energy market depends on how effectively it meets the needs of its customers in comparison with other energy technologies. Although the needs of 21st century utilities cannot be predicted with confidence, a number of features desirable to utilities today can be identified. Economic competitiveness is certainly one of the most important; other crucially important attributes are plant capital cost, safety, licensability, and maximum financial liability in case of accident. Developing fusion reactors with high degrees of safety assurance would make fusion attractive in many of these respects.

Competitors with fusion have the potential to supply most or all of the electricity required by the United States in the first half of the next century; the overall size of future electricity demand should neither require nor eliminate fusion as a supply option. However, there are potentially fundamental problems involving the alternate suppliers of electricity that could make fusion the technology of choice. The degree to which fusion will replace its competitors is impossible to predict today.