Chapter 2

Introduction and Overview

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FUSION POWER

To geologists and physicists at the turn of the century, the term "energy problem" referred not to finding sources of energy for society, but to identifying the one used by the sun. Most physicists believed that the source of the sun's energy was heat released as the sun slowly shrank under its own gravity, a process that would burn out no more than 20 million years after the sun was formed. Geologists, however, argued that geological and fossil evidence showed that the earth-assumed to be no older than the sun—was in fact many times more than 20 million years old.

Although many hypotheses were developed to reconcile the two positions, it was not until 1938 that one explanation received virtually instantaneous and universal acclaim: the sun's "energy problem" was solved when nuclear fusion was identified as its energy source. Through fusion, the sun has been able to shine for nearly 5 billion years using only about half of its original fuel.

Nuclear fusion is the process by which the nuclei—or central cores—of two atoms combine or *fuse* together. The total mass of the final products is slightly less than the total mass of the original nuclei, and the difference—less than 1 percent of the original mass—is released as energy. Nuclear fusion, in a sense, is the opposite of nuclear *fission,* the process utilized in existing nuclear powerplants. In a fission reaction, energy is released when a heavy nuclei splits into smaller pieces whose total mass is slightly less than that of the original nucleus.

Nuclear fusion may be applicable to the energy needs of humans. If the fusion process can be utilized economically, it has the potential to provide society with an essentially unlimited source of electricity. It may also offer significant environmental and safety advantages over other energy technologies, characteristics that are particularly appealing in a world where no energy technology is perfect. Since the 1950s, the potential payoff of fusion energy has motivated a worldwide research effort.

The previous decades of research have shown that fusion energy is extremely difficult to produce. Experiments planned for the next few years should be able to assess fusion's scientific feasibility as an energy source, but several decades of additional research and development, and billions of additional dollars, will be needed to see whether a marketable fusion reactor can be developed. Researchers in the United States, Western Europe, Japan, and the Soviet Union generally agree on the technical tasks yet to be done to evaluate fusion's potential. Policy makers in these nations must now decide if, when, and how to allocate the resources necessary to accomplish these tasks.

The Allure

In the future, fusion power could bean attractive source of energy because it might offer a combination of benefits unmatched by other fuels. Compared to other energy technologies, fusion could be:

- **Unlimited.** A form of hydrogen found naturally in water is a potential fusion fuel, and every gallon of water on earth contains the fusion energy equivalent of 300 gallons of gasoline.
- **Clean.** Using fusion reactions to generate power may be significantly cleaner than either fossil fuels or nuclear fission. Fusion, unlike coal combustion, does not produce carbon dioxide whose accumulation in the atmosphere may affect world climate. Moreover, fusion will not contribute to acid rain or other potential environmental damage associated with fossil fuels. Although fusion reactors themselves will become radioactive, the products of the fusion reaction are not radioactive. With appropriate choice of struc-

tural materials, fusion reactors will produce far less radioactive waste than fission reactors.

- **Safe.** It may be possible to design fusion reactors in which "safe operation is assured by physical properties, rather than by active safety systems that might fail due to malfunction, operator error, or natural disaster.

Substantial further scientific and technological development is required to see whether these benefits can be attained,

Establishing Fusion's Feasibility

Two requirements must be met before fusion can be an attractive source of energy. First, fusion's technological *feasibility* must be demonstrated by establishing the scientific and engineering understanding necessary to build an operating fusion reactor. Second, fusion's *commercial feasibility* must be demonstrated.

Technological feasibility is usually considered in two stages: *scientific feasibility* and *engineering feasibility.* Scientific feasibility requires generating a fusion reaction that produces at least as much energy as must be input into the plasma to maintain the reaction. This milestone, called *breakeven,* has not yet been reached, but it is expected that breakeven will be accomplished in existing machines by 1990.

Simply breaking even, however, does not show that fusion can serve as a useful source of energy. in addition, a fusion reaction must be created that has *high energy gain,* producing an energy output many times higher than its energy input. No existing experiment has the capability to produce such a reaction, a task that is more significant and more difficult to achieve than breakeven. However, the Department of Energy (DOE) has requested funds in its fiscal year 1988 budget to begin construction of an experiment to generate a reaction with such high-gain that it should become self-sustaining, or ignited. At ignition, reactions will generate enough power to sustain the fusion process even after external heating power has been shut off.

After high gain or ignition has shown fusion's scientific feasibility, its engineering feasibility must be demonstrated. This accomplishment will entail developing future reactor systems, subsystems, and components that can function reliably under reactor operating conditions. Demonstrating engineering feasibility will require an extensive amount of research and development, and it will be a technical achievement at least as impressive as the scientific accomplishment of harnessing controlled fusion reactions.

Although scientific feasibility and engineering feasibility involve different issues, fusion science and fusion engineering are interdependent: advancing scientific understanding of the fusion process requires improved technological capabilities in experimental facilities, just as solving the engineering problems posed by fusion reactor design requires additional basic understanding in a number of areas. Demonstrating both the scientific and engineering feasibility of fusion power requires advances to be made in basic scientific understanding as well as in technological capability.

The goal of fusion research is to establish fusion's technological feasibility in a manner that makes commercial feasibility likely. If and when it becomes clear that generating electricity in a fusion reactor is possible, such a reactor must prove socially and environmentally acceptable and economically attractive compared to its alternatives. Although dependent on the technical results of fusion research, fusion's commercial feasibility also involves factors unrelated to the technology itself, such as the status of other energy technologies and the regulatory and licensing structure. Commercial feasibility ultimately will be determined by individuals and institutions that are not involved directly in fusion research.

The Fusion Reaction

Only light elements can release energy through fusion. While many different fusion reactions take place in the stars, the one that can be used most easily to generate power on earth involves hydro*gen (H),* the lightest element. Three forms, or iso*topes,* of hydrogen exist: *protium,* which is usually referred to simply as hydrogen, *deuterium (D),* and *tritium (T).* The nuclei of these isotopes consist of a single proton and zero, one, or two neutrons, respectively. Over 99.98 percent of all hydrogen found in nature is the protium isotope. Less than 0.02 percent (one part in 6,700) is composed of deuterium. Tritium is radioactive, with a half-life of 12 1/4 years;[1] it is practically nonexistent in nature, but it can be manufactured.[2]

The easiest fusion reaction to initiate combines deuterium and tritium to form helium and a free neutron, as shown in figure 2-1; a fission reaction is also shown for comparison. The fusion reaction shown—called a D-T reaction—liberates 17.6 million electron volts[3] of energy. By way of comparison, burning a single atom of carbon (the combustible material in coal) releases only about 4 electron volts. Therefore, a single D-T fusion reaction is over 4 million times more energetic.

Four-fifths of the energy released in a D-T fusion reaction is carried off by the neutron as kinetic energy. In a fusion reactor, it is anticipated that neutrons would be captured in the material surrounding the reaction chamber, where their kinetic energy would be converted into heat. One-fifth of the reaction energy, carried off by the helium nucleus, would remain inside the reaction chamber, heating up the fuel and making additional reactions possible.

The primary application of fusion will probably be for electric power generation, using heat from the fusion reaction to boil water to drive a steam turbine that generates electricity. Advanced systems for converting fusion energy more directly into electricity may also be possible. Other applications of fusion might use the neutrons themselves for various purposes, rather than just extracting their energy. It is also possible that, as fusion development progresses, additional uses of the technology might be found. The potential characteristics of fusion reactors used to produce electricity are discussed in chapter 5; other possible applications of fusion are discussed in appendix A.

The D-T reaction is not the only one that can generate fusion energy. One deuterium nucleus can fuse with another in a D-D reaction. It is also possible to use other light elements besides hydrogen as fuel. However, it is much harder to initiate fusion reactions with fuels other than deuterium and tritium, and many of these alternate fuels produce less power for a given amount of fuel than the D-T reaction does. Reactors using alternate fuels would be more difficult to design and build than D-T reactors producing the same amount of energy. On the other hand, these alternate reactions may not require tritium production and/or may not generate as many neutrons as the D-T reaction. Both tritium production and neutron generation increase the amount of radioactive material contained in a reactor, a situation that complicates the reactor's design and can raise environmental and safety issues.

Requirements for Fusion Reactions

Fusion reactions can only occur when the requirements of *temperature, confinement time,* and density are simultaneously met. The minimum temperatures, confinement times, and densities needed to produce fusion power have been known for decades. Achieving these conditions in experiments, however, has proven extremely difficult.

Temperature

Because the nuclei that must fuse have the same electrical charge, they must be heated to extremely high temperatures to overcome their natural repulsion. Temperatures on the order of 100 million degrees Celsius (C) are required. No matter exists in solid form at these temperatures; individual atoms are broken down—ionized—into their constituent electrons and nuclei. With their outside electrons missing, the nuclei have a positive electric charge and are called ions.

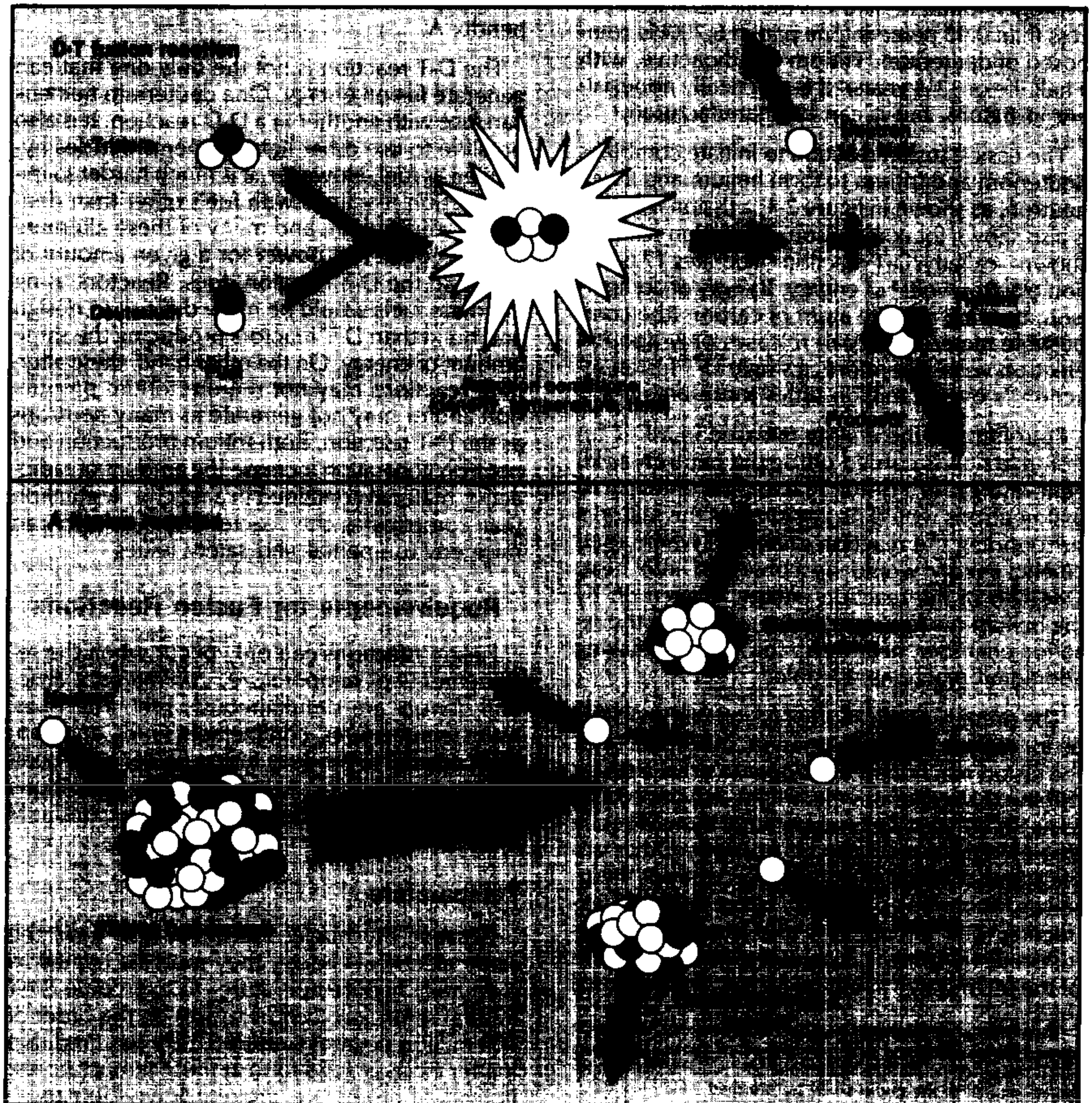
Matter in this state is called *plasrna* (figure 2-2). Plasma is considered a fourth state of matter

[1] Radioactive materials decay over time as the nuclei of radioactive atoms emit radiation and transform into other nuclei. The decay rate is measured by the substance's *half-life,* which is the time required for half of the nuclei to be transformed.

[2] Trace amounts of tritium are continually produced by cosmic rays in the upper atmosphere. Most of the tritium now in the environment, however, was produced by atmospheric nuclear weapons tests in the 1950s.

[3] One electron volt (eV) is the energy that a single electron can pick up from a 1 -volt battery. It is equal to 1.6×10^{-19} joules, 1.52×10^{-22} Btu, or 4.45×10^{-26} kilowatt-hours. One thousand electron volts is called a kiloelectron volt, or keV.

Figure 2-1.—The D-T Fusion Reaction and a Fission Reaction

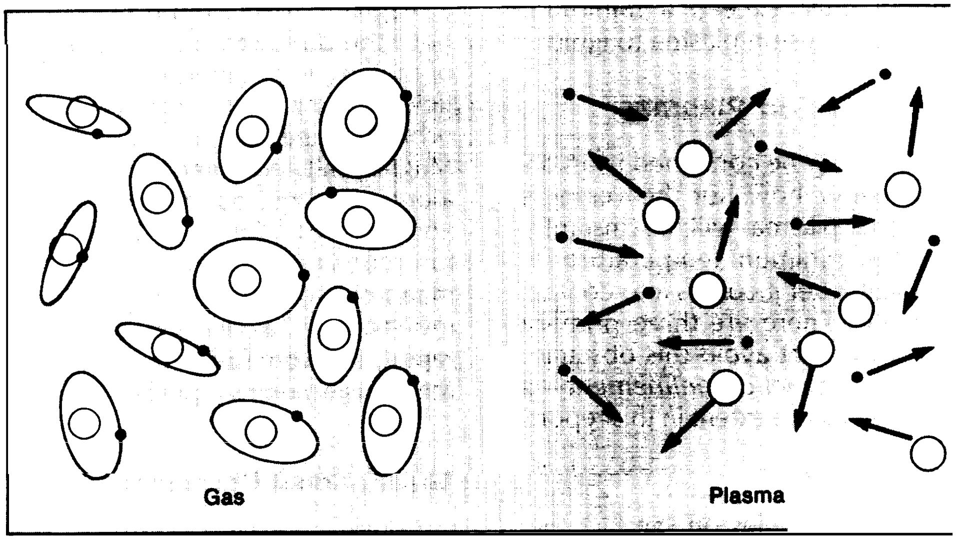


Key: ● Proton
O Neutron

MeV: million electron volts

SOURCE: Adapted from Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 2 (fusion); Office of Technology Assessment (fission), 1987,

Figure 2-2.—Gas and Plasma



SOURCE: Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 3.

because it has properties unlike solids, liquids, or gases. Fusion research, critically dependent on understanding plasmas, has led to the development of a new field of science called *plasrna physics.*

The temperature of a plasma is a measure of the average energy of the plasma particles and is usually expressed in units of electron volts. A plasma temperature of 1 electron volt, which is about 11 ,600° C, corresponds roughly to each particle in the plasma having an average energy of 1 electron volt. In a plasma, the ions and the electrons can have different temperatures; ion temperature is most important and must exceed about 10,000 electron volts for enough of the ions to overcome their mutual repulsion to produce appreciable amounts of fusion power.

Confinement Time

The goal of fusion research is not only to create a hot plasma but also to keep it hot long enough to produce fusion power. [t is not sufficient simply to heat the fuel, because any substance that is hotter than its surroundings will cool off. The rate at which the substance cools depends on its physical characteristics, its surroundings, and the temperature difference between the two. The ability of a plasma to stay hot is represented by its confinement time, which is a measure of the time it would take to cool down to a certain fraction of its initial temperature if no additional heat were added.

With an insufficient confinement time, it is impossible to reach breakeven or ignition. Even if the plasma is heated hot enough for fusion reactions to start, heat would be lost faster than it would be generated in those reactions, and the reactions would not produce any net power. Confinement times on the order of one second are generally considered necessary for an ignited plasma.

Density

The exact confinement time requirement depends on plasma density. The fusion reaction rate, and therefore the amount of fusion power produced by the plasma, goes down rapidly as density drops. A plasma that is not dense enough will not be able to generate power even if it is very hot and retains its heat very well. The density required to reach breakeven or ignition increases as confinement time decreases. The product of density and confinement time (called the *Lawson parameter)* must exceed a minimum threshold in order for a fusion plasma to ignite.[4]

Confining Fusion Plasmas

A fusion plasma cannot be contained in an ordinary vessel no matter how hot the vessel is heated, because the plasma will be instantly cooled far below the minimum temperature required for fusion whenever it comes into contact with the vessel walls. There are three primary ways to hold a plasma that avoid this obstacle. Only one of these–magnetic *confinement-is* discussed to any appreciable extent in this report.

Magnetic Confinement

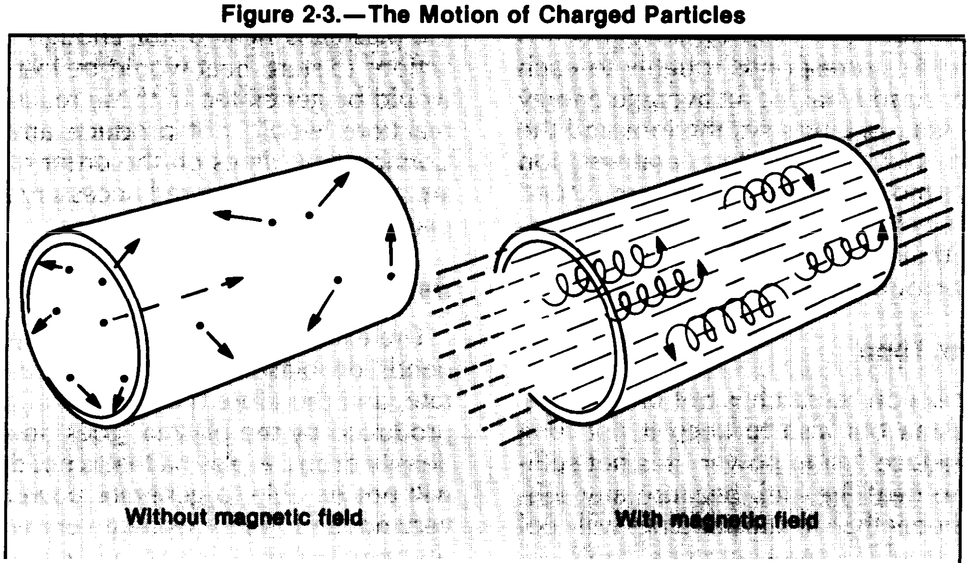
Magnetic confinement relies on the fact that because individual particles in a plasma are electrically charged, their motion is strongly affected by magnetic fields. A charged particle moving in a magnetic field will be bent at right angles to both the direction of the field and its direction of motion, with the result that the energetic particles making up a fusion plasma will trace spiral orbits around magnetic field lines (figure *2-3).* Magnetically confined plasmas will tend to flow along field lines but not across them, and a suitable configuration of magnetic fields can therefore confine a plasma. Many different kinds of magnetic-confinement configurations are u rider investigation, as described in chapter 4. **In this report, the word fusion refers to magnetic confinement fusion unless specifically noted otherwise.**

Gravitational Confinement

A sufficiently large plasma can produce fusion power while holding itself together with its own gravitational field. This process, called *gravitational confinement,* permits fusion to take place in the sun and other stars. It is impossible, however, to utilize gravitational confinement for fusion processes on earth. Even the planet Jupiter, which is over 300 times more massive than earth, does not have sufficient mass to produce gravitationally confined fusion.

[4]The minimum threshold for ignition, as defined **by** the Lawson parameter, is 3×10^{14} second-particles per cubic centimeter. This means that a plasma with a density of 3×10^{14} particles per cubic centimeter must be confined for one second in order to ignite. As mentioned above, if the density were increased to 3×10^{15} particles per cubic centimeter, then the confinement time requirement would decrease to one-tenth (O. 1) of a second.

Figure 2-3.—The Motion of Charged Particles



SOURCE: Princeton Plasma Physics Laboratory, Information Bulletin NT-1: Fusion Power, 1984, p. 3,

Inertial Confinement

In a hydrogen bomb, fusion fuel is heated and compressed to such high densities that it need be confined only for a very short time in order to generate fusion power. The fuel's own inertia keeps it confined long enough for fusion reactions to occur. A research effort is now underway to study this inertial *confinement* process in a controlled manner on a laboratory scale. This program has near-term military applications, due to its close connection with weapons physics, and may have longer term energy applications as well. The energy applications of inertial confinement fusion are generally considered less developed than those of the magnetic confinement process. Because of the direct links between this approach and hydrogen bomb design, much of the research in inertial confinement fusion is classified. The inertial confinement approach is discussed in appendix B.

THE PURPOSE OF THIS STUDY

Increasing budgetary pressures, along with a decreasing sense of urgency regarding energy supply, have sharpened the competition for funding between one research program and another and, perhaps more significantly, between energy research programs and other components of the Federal budget. At the same time, issues such as the implications of increased fossil fuel usage on the global climate and the long-term acceptability of nuclear power have raised serious concerns about future energy supply.

In balancing the long-term potential of fusion energy against shorter term, more immediate pressures, the congressional committees with jurisdiction over DOE's magnetic fusion program requested this study. In 1986, the House Committee on Science and Technology requested that OTA review the magnetic fusion energy program, citing that “. . . a number of factors have served to decrease the sense of urgency with which the DOE management and many members of the Congress view the development of fusion power.” Shortly afterward, the Senate Committee on Energy and Natural Resources endorsed this request. These committees are faced with setting policy for the fusion program, and they were interested in an independent analysis of the fusion program as input to their budget authorization deliberations.

in response, OTA undertook this assessment of the magnetic fusion research and development program in March 1986. The assessment examines the technical and scientific achievements and objectives of the fusion program. It also analyzes the program from three different, but related, perspectives:

1. It considers the issues related to fusion's role as an energy research and development program, in particular those related to developing an attractive energy supply technology.
2. It analyzes the near-term, non-energy benefits of the fusion program and the financial and personnel resources necessary to support the program.
3. It examines the increasing role of international collaboration in magnetic fusion research.

OTA's assessment was carried out with the assistance of a large number of experts reflecting different perspectives on the fusion program –fusion scientists and engineers, nuclear engineers, environmental scientists, international relations experts, industry and utility executives, consumer groups, economists, financial planners, and energy policy analysts. As with all OTA studies, an advisory panel representing these interests and fields of expertise met periodically throughout the course of the assessment to review and critique interim products and proposals, to discuss fundamental issues affecting the analyses, and to review drafts of the report. Contractors and consultants also provided material in support of the assessment.[5]

[5]Advisory panel members, workshop participants, contractors, and other contributors to this assessment are listed in the front of this report.

Finally, OTA convened three workshops to clarify important issues considered in the assessment and to review and expand upon contractors' analysis. The first workshop dealt with general issues involved in fusion research. It focused on the nature of the fusion research program, the implications of current funding cuts on the program, and the main issues involved in decisions about future courses of action.

The second workshop addressed issues in international collaboration in fusion research. Three contractor reports, detailing the characteristics of the major non-U.S. fusion programs and their views of collaboration, were reviewed at the workshop. The principal issues addressed were the motivations and goals of foreign fusion programs, national security and competitiveness risks of technology transfer through collaboration, and other potential obstacles to collaboration,

The final workshop addressed fusion's energy context. Projections of electricity demand in the 21st century and their relevance to fusion were presented by OTA consultants and reviewed. In addition, the uncertainties inherent in forecasting supply and demand over times relevant to fusion were discussed. Alternative energy supply technologies that might compete with fusion were addressed, as were the implications of potential difficulties such as global climate change and nuclear fission safety or environmental issues.

The material in this report is based on OTA staff research, site visits, workshop discussions, advisory panel recommendations, and contractor and consultant reports. The report is organized as follows:

- Chapter 3 provides a brief history of the U.S. fusion program, which, since its inception in the 195os, has been almost entirely funded by the U.S. Government.
- Chapter 4 explains the technical underpinnings of fusion research and sets out the requirements for demonstrating fusion's technological feasibility. Fusion research is one of the Federal Government's most futuristic and technically complex undertakings. Physical theory and experimentation must advance the present state of the art if the goal is to be reached; forefront technology must be developed not only in the long-run, to harness fusion, but in the short-run to construct each successive experiment.
- Chapter 5 addresses the long-range energy applications of fusion research. The anticipated characteristics of future fusion reactors are discussed, including projected plant economic, safety, and environmental features. Issues involved in commercializing the technology are also examined. In addition, factors that will be important in determining whether and when fusion will penetrate energy markets as a source of electricity are discussed.
- Chapter 6 discusses the character of current fusion research and analyzes the value of the fusion program in terms of its near-term, non-energy benefits. Data on program participants, funding levels, and personnel levels are summarized.
- Chapter 7 examines the extremely important role that international cooperation in fusion research has had in the past and may have in the future. Motivations for and obstacles to future large-scale collaboration are assessed, as well as possible models for such collaboration.
- Finally, chapter 8 summarizes the critical issues facing the fusion program and presents a series of policy paths for Congress to consider as it makes decisions on funding fusion research. The implications of pursuing the different paths are discussed.