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Magnetic Fusion:
The DOE Fusion Energy Sciences Program

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Magnetic Fusion: The DOE Fusion Energy Sciences Program

SUMMARY

For over 45 years, the United States has been trying to tame the energy source of the hydrogen bomb to produce electricity. Harnessing fusion, the nuclear reaction that powers the sun, requires confining and heating deuterium and tritium nuclei so that they will produce sustained, controlled nuclear energy. One path, called magnetic fusion energy, is to use very strong magnetic fields to confine a deuterium and tritium plasma while heating it to fusion temperatures.

The potential benefits from fusion are high. The fuel resources are vast. Radioactive waste would be generated, but the long-term buildup would be orders of magnitude less than that of a comparable fission reactor.

The most successful type of experimental fusion device is the tokamak. Experiments on the JET tokamak in Europe and on the U.S. tokamak TFTR, which was shut down in 1998, have produced substantial amounts of fusion power using deuterium and tritium. The next major scientific milestone is to produce more power through fusion than is used in heating the plasma. A parallel challenge is to develop the technology for a fusion power reactor.

A conceptual design for such a device, the International Thermonuclear Experimental Reactor (ITER), was completed by a consortium of the United States, the European Union, Japan, and Russia. The United States no longer participates in the ITER project, but the other partners are considering a construction decision. Recent efforts in the United States and other countries have focused on development of a burning plasma experiment.

For FY1999, both the House and the Senate directed DOE to undertake a thorough review of all its fusion research activities. A 3-pronged effort to carry out those reviews has been completed, and final reports from the three efforts have been released.

Three reviews of the program carried out over the past three years arrived at a number of common themes: substantial progress in the fusion science has been made and the scientific demonstration of fusion can be accomplished; there should be greater convergence of the magnetic and inertial fusion energy research programs; the United States must step-up its participation in the international fusion research effort; the budget for fusion research needs to grow if a proper balance between inertial and magnetic fusion is to be achieved; and more emphasis is needed on the broader applications of plasma science and technology.

For FY2002, DOE requested $248.5 million for the fusion program, the same amount as the FY2001 appropriation (after rescissions and general reductions). No major new initiatives are planned for FY2002, and the level of effort for the activities within the program is expected to stay close to the level in FY2001. On November 1, 2001, Congress approved the requested amount.

The House energy bill (H.R. 4, passed August 1, 2001) would authorize $335 million for the fusion program for FY2003 and calls on DOE to develop a plan for a burning plasma experiment. The Senate energy bill (S. 1766, introduced December 5, 2001) contains similar language.

MOST RECENT DEVELOPMENTS

The FY2002 energy and water development appropriations act (P.L. 107-66) was passed by the House and Senate on November 1, 2001, and signed by the President on November 12, 2001. It provides $248.5 million for the fusion program, the requested amount. DOE is now considering options for a burning plasma experiment, including proposing to Congress that the United States rejoin the International Thermonuclear Experimental Reactor project. The House energy bill (H.R. 4, passed August 1, 2001) would authorize $335 million for the fusion program for FY2003 and calls on DOE to develop a plan for a burning plasma experiment. The Senate energy bill (S. 1766, introduced December 5, 2001) contains similar language.

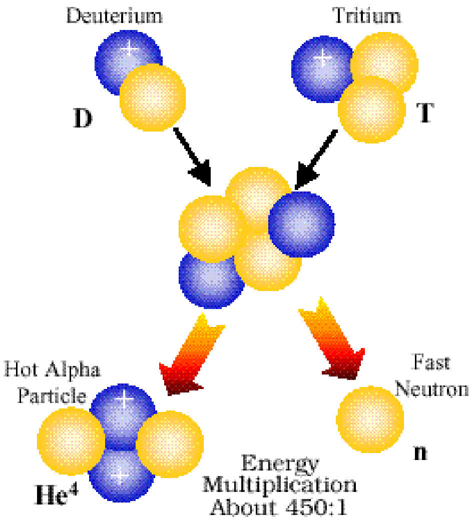
BACKGROUND AND ANALYSIS

Fusion ([http://wwwofe.er.doe.gov/]) is the fundamental mechanism in the universe for producing energy. It is the nuclear reaction that powers the stars. It is also a major contributor to the explosive power in the hydrogen bomb. Controlling this energy source to produce electricity has been sought since before the first hydrogen bomb was exploded. The potential benefits of controlled fusion are great. Successful development of a fusion power plant, however, is proving to be one of the most difficult scientific and technological challenges. Although progress has been steady, it may be at least 35 to 50 years before an operating power plant is built. Fusion is one of a class of nuclear reactions. Another is fission, which involves the splitting of large nuclei, such as uranium, into smaller elements. Fission is the energy source of the atomic bomb, the first nuclear weapon built, and of nuclear power plants currently operating.

Fundamentals of Fusion

Fusion occurs when the nuclei (or core) of light atoms, such as isotopes (or forms) of the element hydrogen (deuterium and tritium), collide with sufficient energy to overcome the natural repulsive forces that exist between such nuclei (see **Figure 1**). When this collision takes place, a D-T reaction is said to have occurred. If the two nuclei fuse, a heavier element, a form of helium (also called an alpha particle), is created, along with a large quantity of energy. For the fusion reaction to take place, the nuclei must be heated to a very high temperature. In a hydrogen bomb, this is done by exploding a fission bomb, uranium or plutonium, forcing the deuterium and tritium together in a violent manner.

Figure 1. Fusion Reaction



Fusion reactions are possible between a number of light atoms, including deuterium alone (a D-D reaction); deuterium and helium-3, an isotope of the element helium (a D-^{3}He reaction); and hydrogen and the element lithium, a light metal. All of these reactions occur much less frequently at a given temperature than the D-T reaction. For instance, the fusion energy produced from D-T reactions in a mixture of deuterium and tritium will be about 300 times greater than that from D-D reactions in a mixture of deuterium alone if both mixtures are heated to the same temperature and have the same density. For this reason, research into controlled fusion has concentrated on developing deuterium-tritium fueled reactors.

Potential Benefits of Magnetic Fusion Energy

Fuel Resources

The potential benefits of controlled fusion are many. Foremost is that in principle the fuel for such a plant is essentially inexhaustible. One out of every 6,670 water molecules contains deuterium rather than hydrogen, and there are no significant technical barriers to extracting deuterium from water. Tritium, however, does not occur in nature. It can be produced from the element lithium, which is also very abundant, although much less so than deuterium. To achieve the full resource potential of fusion will require reaching the conditions of plasma density, temperature and confinement time needed for energy production from reactions involving deuterium alone. As described below, these conditions are much more harder to reach than for deuterium and tritium which has proved difficult enough. Fusion researchers, however, note that even if success is reached with the D-T reaction, research will need to continue to reach power production from the D-D reaction.

Environmental and Safety Considerations

There also could be important environmental benefits from fusion. First, a controlled fusion power plant would be inherently safe. A reaction that became "uncontrolled" in such a plant would extinguish itself almost instantly with no part of the system melting and with no significant release of radioactive material. Even major accidents that could occur, such as to the structure of a fusion powerplant would not result in any radiation release. Of course, such an accident could result in significant cost because of severe reactor damage.

A second environmental benefit is that the radioactive waste products produced in a fusion plant would be far less of a problem than those produced in a fission plant. Because of the nature of controlled fusion, it would be possible to reduce the long-term buildup of radioactive waste products by up to a million times below that of a fission system of comparable size while the quantity of radioactive material produced in a power plant of a given size may be comparable for the two types of reactions (at least for the first generation, deuterium-tritium fusion plants), the half-life of the radioactive products from such a fusion plant would be on the order of 100 years or less, compared to tens of thousands of years for those from a fission plant. Radioactive products from fusion plants, therefore, would decay much faster than those from fission plants, resulting in the large differences cited above. More advanced fusion systems using fuel combinations which produce few or no neutrons, such as the D-3He reaction, would result in substantially less radioactive waste.

Paths to Fusion Energy Production

Two paths are being taken in attempts to attain controlled fusion. The first is to confine the light nuclei by a magnetic field and to heat them with an external source of electromagnetic energy. In this case, the deuterium and tritium are in a gas-like condition called a plasma. This process is called magnetic fusion energy (MFE). The other path is to heat very small clusters of solid deuterium and tritium by compressing these clusters with lasers or beams of particles. Such a process is called inertial confinement fusion (ICF) and simulates — on a very small scale — the actions of a hydrogen bomb. Once the reaction starts in either case, it is possible in principle for the heat generated by the fusion reactions to be sufficient to cause other light nuclei to collide, thereby sustaining the reaction without an external energy source. Such a condition, called ignition, has not yet been reached in practice. While substantial progress has been made over the last several years in both ICF and MFE, even the less stringent condition of break-even — the point where power produced by the fusion reactions equals the power supplied by the external energy source — is still to be achieved. A fusion power plant would operate between break-even and ignition. The ratio of power out to heating power supplied would be significantly greater than for break-even, but external energy would still be supplied to control the reaction rate.

By way of comparison, stars operate by using their enormous gravitational force to confine the colliding nuclei. Enough heat is generated by the fusion reactions to force other nuclei to collide and undergo fusion so the reaction is sustained. Because of the large gravitational forces, these nuclei are unable to escape the stellar region before they gain the necessary energy to fuse with one another.

Achieving break-even and power amplification would be only the first steps in the process of producing useful power. The energy from the nuclear reactions would have to be converted into another form that could be used to do work. Energy is carried away from the fusion reactions in the form of neutrons moving at high speed. Because neutrons do not have an electrical charge, they are not confined by the magnetic field and will leave the plasma region. The neutrons will give their energy up if they collide with atoms of another material, causing that substance to heat. A prime candidate for this material for future fusion power plants is the liquid metal lithium. Lithium that is heated by colliding neutrons could then transfer that heat to water, producing steam. The steam, in turn, would drive a steam turbine and generator, producing electricity. While there are no fundamental scientific barriers to this process, putting it into practice will be a complicated engineering task requiring substantial development. A second reason for using lithium is that reaction between the lithium atoms and the neutrons would produce the tritium necessary for the reactor fuel.

Magnetic Fusion Energy Research

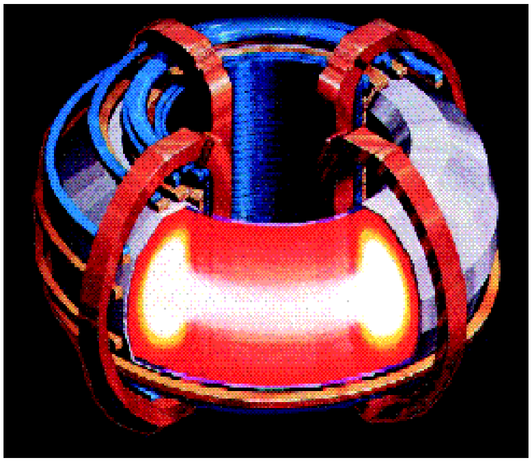
Both the magnetic fusion energy (MFE) and inertial confinement fusion (ICF) research activities are funded by the U.S. Department of Energy ([http://www.doe.gov]). The ICF program currently is primarily oriented to defense applications, for simulation of nuclear weapons, although energy applications are an important part of the research effort. Nearly all of the funds for ICF research come from DOE's Defense Programs ([http://www.dp.doe.gov]). An major initiative of the DOE ICF program is the National Ignition Facility (NIF) ([http://www-lasers.llnl.gov/lasers/nif.html]) at DOE's Lawrence Livermore National Laboratory which is currently entering the detailed engineering design stage. The NIF is primarily for weapons applications, but it will also carry out important research for potential energy production from inertial fusion.

Magnetic fusion energy research is within DOE's civilian programs and is located in the Office of Energy Research. Although funding for ICF research now exceeds that for magnetic fusion, the latter has been and continues to be the major fusion energy focus in the United States.

Developments to Date

Magnetic fusion energy research has been underway for nearly 50 years. The scientific challenges are to develop ways to confine a high-density deuterium and tritium plasma and to heat it so that the combination of temperature, density, and confinement time are sufficient that break-even and beyond are reached. Considerable progress has been made in the last 20 years in meeting these scientific challenges. Since the mid-1970s, the amount of measurable fusion power produced in fusion experiments has increased by a factor of nearly 100 million, or eight orders of magnitude.

Figure 2. Magnetic Fusion Concept



Much of the progress towards achieving those goals has taken place on toroidal (donut-shaped) concepts like that pictured in **Figure 2.** The most successful such concept has been the tokamak (a Russian acronym), first demonstrated in the former Soviet Union in 1968. It is a device in which the plasma is contained in a toroidal chamber surrounded by magnetic field coils. The plasma produces a large electric current by circulating within the chamber, and the combination of the magnetic field produced by that current and by the coils imparts a high degree of stability to the plasma. This stability has made possible much longer confinement times than previous devices. Currently, the largest and most successful tokamak still operating is the Joint European Torus (JET) ([http://www.jet.uk]) which is located in Great Britain and is funded by the European Union. The tokamak fusion test reactor (TFTR) at Princeton Plasma Physics Laboratory ([http://www.pppl.gov]), which was one of the largest, was shutdown in 1998 because of reductions in the U.S. fusion research budget. Other large tokamaks operate in Japan, Italy and France, and in San Diego ([http://fusioned.gat.com]) and at MIT.

In September 1994, the TFTR produced 10.7 MW of fusion power using a mixture of deuterium and tritium (D-T) to form the plasma. A ratio of fusion power produced to power used to heat the plasma — called the gain or Q — of about 0.3 was reached. When Q is greater than one, a condition known as a burning plasma is reached. In this case, heating by the alpha particles (helium-4 nuclei, see figure 1) created by the fusion reaction provides more energy to heat the plasma than is provided by external sources. When alpha particle heating is sufficient to sustain the fusion reaction without any external source of plasma heating, ignition is said to be reached. In this case, Q is infinite. In 1997, JET reached a fusion power output of nearly 16,000 kW under the same conditions. In addition, JET results indicate that alpha particle heating provided about 10% of the total plasma heating. In TFTR, there was evidence of enhanced confinement of the plasma during the heating pulse and some indications of heating of the plasma by alpha particles. It appears that plasma behavior is improved by the addition of tritium. Many in the fusion research community believe these experiments demonstrate conclusively the scientific feasibility of controlled fusion. In Japan, a large tokamak called the JT-60U ([http://www-jt60.naka.jaeri.go.jp]), recently reported reaching conditions in a deuterium only plasma which would be equivalent to break-even conditions, Q=1.05, in a plasma of 50% tritium and 50% deuterium. A value of 20,000 kW is expected to be reached on JET within the next few years.

In developments that offer great promise for an eventual fusion power reactor, researchers at Princeton, before the TFTR was shutdown, and at General Atomics in San Diego (on its DIII-D tokamak) have been able to greatly enhance plasma confinement in their tokamak devices. In addition, the loss of heat from the plasma has been reduced by over a factor of 40 and the peak density of the plasma increased over three times. The process used has been explored in the past, but only to a limited extent. These new experiments expanded the region in the plasma over which the process was in effect. Scientists at Princeton were also able to perform experiments on the TFTR prior to its shutdown that demonstrated promising new operating regimes for a tokamak plasma. A preliminary prediction by some fusion researchers is that these developments could reduce the size and cost of an eventual fusion reactor based on the tokamak concept by about 50%. Most recently, researchers at General Atomics have reached plasma densities that exceed the limits previously thought possible given the parameters of the DIII-D facility. Because the power output increases as the square of the density (a doubling of density would increase power output by a factor of four), these results portend the possibility of more power from a given size fusion power plant or a smaller power plant to achieve a given power level.

Future Developments

The ultimate goal of the worldwide effort in controlled fusion research is to develop useful energy — most likely electricity — from a fusion powered reactor. In the central attempt to reach this goal, the major players in the international fusion research — the United States, Japan, Russia, and the European Union — participated in the engineering design of the International Thermonuclear Experimental Reactor (ITER) ([http://www.iter.org]). The project's ultimate objective is to demonstrate extended operation of a fusion plasma after substantial power amplification has been achieved. It also is to serve as an engineering test bed for those systems needed on an operating power plant. The first phase of this project, completed in December 1990, yielded a conceptual design of a reactor. The next phase was the development of a detailed engineering design, called the Engineering Design Activity (EDA), which began in 1992 and was completed in July 1998. The cost of the EDA was about $1 billion.

A decision on whether to build the machine was to be made upon completion of the EDA. The ITER Council, however, proposed a 3-year extension to the agreement. This extension was signed by Japan, the European Union, and Russia, in July 1998. The United States, reacting to concerns by Congress, withdrew from the project. During the extension period, alternatives to the ITER design, including a reduced-cost option, have been considered, and discussions of whether to proceed with construction of some form of ITER has taken place. In October 2000, a revised design of ITER, called ITER-FEAT (fusion energy amplifier tokamak) was announced (see below) although no construction decision has been made at this time.

Currently the international fusion community is considering options for the next step in the development of fusion energy. Most believe that construction of a burning plasma device — one that produces more fusion energy than is needed to heat the plasma — is essential. Many in Europe and Japan hope that ITER-FEAT will be that device. Others believe that a decision on a burning plasma experiment (BPX) should wait for more results on the large facilities currently operating in Europe and Japan, including two large stellarators, and on the advanced tokamaks. Currently, the original partners in the ITER project, including the United States, have formed the International Tokamak Physics Activity (ITPA) to cooperate in the development of a burning plasma experiment. The activity includes the development of databases — including ITER physics, modeling, analysis, and workshops — that will be important for any BPX. An ITPA coordinating committee has been formed, and its first meeting was held in September, 2001. On October 5, 2000, the Director of the DOE Office of Science asked the FESAC to address key scientific issues about a burning plasma physics experiment. The report (DOE/SC-0041) was published in September 2001, and concluded that DOE should take the next step of constructing a burning plasma experiment (see below for more discussion). Whatever the decision, it would likely be followed by a facility capable of producing small amounts of electric power. Finally, a demonstration fusion power reactor would be built that would verify the economics and reliability of an operating power plant. Currently, some fusion researchers speculate that such a demonstration plant could be operating by 2050.

Congressional Considerations

Department of Energy Research Program

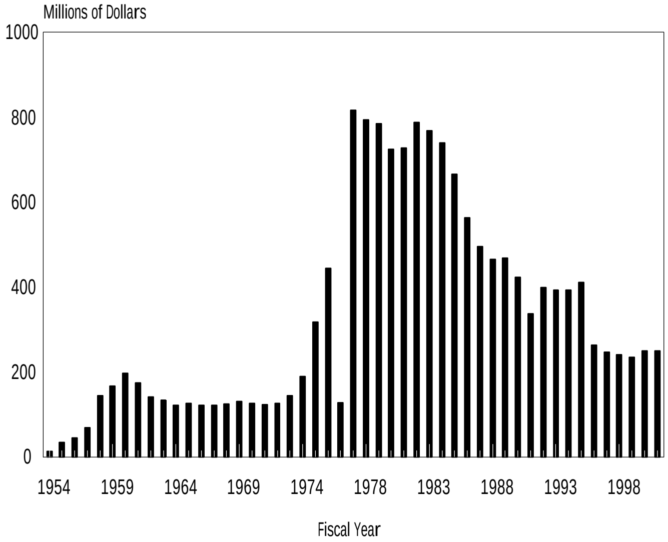
The nation's magnetic fusion energy (MFE) research program began in 1951 under the

Table 1. FES Budget
(millions of dollars)

	FY2001 (Funds)	FY2002 (Request)	FY2002 (House)	FY2002 (Senate)	FY2002 (Conf)
Science	136.31	131.70			131.70
Facilities	77.90	74.55			74.55
Enabling R&D	34.28	42.24			42.24
Total	$248.49	$248.49	$248.49	$248.49	$248.49[a]

[a] The final total will be somewhat smaller after DOE has allocated the congressional directed general reduction of $12.8 million among the various Office of Science programs.

Figure 3. MFE Budget History (2000 Dollars)



auspices of the former United States Atomic Energy Commission. Since that time, the United States has spent over $16.6 billion, in constant 2000 dollars, on research into MFE. **Figure 3** (next page) shows the budget history since 1954 in constant 1994 dollars. The MFE appropriations for FY2000 and FY2001, the FY2002 request, and the FY2002 House and Senate appropriations are shown in **Table 1**. These amounts will be discussed in more detail below. The breakdown according to activities is shown in the table. Under **science**, DOE funds research into the tokamak and alternate confinement concepts, plasma theory, and general plasma science. Within this activity, DOE is funding research on two large tokamak efforts, the DIII-D at General Atomics in San Diego, and the Alcator C-Mod at the Massachusetts of Technology, and the National Spherical Tokamak Experiment (NSTX). Under **facilities operations**, DOE funds operations and maintenance for the two major tokamak facilities and the NSTX, and decommission of the TFTR. Funding within **enabling R&D** is for basic research in fusion technology and the development of technologies needed to facilitate plasma science research and ultimate development of a fusion energy source.

Budget. For FY2002, DOE requested the same amount as approved for FY2001, $248.49 million. According to the justification, funding for **science** category is currently scheduled to decline by 2.1% from the FY2001 level. Programs in this category include tokamak experimental research, alternative concept experimental research, theory, and general plasma science. Funding for **facility operations** is currently scheduled to decline by 7.6% from the FY2001 level. Programs within this category include TFTR decontamination and decommissioning (D&D), and operations and maintenance for the DIII-D, Alcator C-Mod, and NSTX facilities. Funding for **enabling technologies** is now scheduled to decline by 1.0% from the comparable FY2001 level. Programs within this category include engineering research and materials research.

Within the **science** category for FY2002, tokamak-related efforts will focus on increasing plasma heating and stability on the DIII-D device, on exploration of advanced confinement modes in Alcator C-Mod, and on understanding other plasma phenomena in the tokamaks at UCLA and Columbia University. Collaborative research on several large foreign tokamaks is planned for FY2002 focusing on important magnetic fusion energy issues. Under alternative concepts, efforts on the NSTX will focus on increasing plasma current and demonstrating new concepts for initiating and maintaining that current, and on the study of intense heavy ion source drivers and technical assessment of IFE concepts. In addition, funding is planned for 12 small alternative concept experiments, one proof-of-principle experiment, and a design for a compact stellarator proof-of-principle experiment. Theoretical research for FY2002 will continue to focus on the application of advanced computing to solve complex plasma and fusion science problems. The general plasma science program plans to continue funding peer reviewed proposals addressing basic plasma physics and engineering research.

Within the **facility operations** category, funding for FY2002 is planned for completion of the decommissioning and decontamination of the TFTR. In addition, funds are to be provided for operation and maintenance of the DIII-D, C-Mod, and NSTX facilities. The latter is expected to include upgrades to the diagnostics. Funds for 14 weeks of operation of the DIII-D, 8 weeks for the C-Mod, and 11 weeks of the NSTX are included in this portion of the request. In the **enabling R&D** category, funding for FY2002 is planned for plasma technology development critical for domestic experiments including high power microwave generators and plasma-facing technologies; for technical assessment of critical IFE technologies; and for design studies of the next steps in fusion experiments for achieving fusion energy production. In addition, funding in this category is planned for continued experimental and modeling research on the behavior of materials properties when subjected to fusion plasma particle and heat fluxes.

On June 28, 2001, the House approved its version of the Energy and Water Development Appropriations Bill, 2002 (H.R. 2311, H.Rept. 107-112). In that bill, $248.49 million was appropriated for Fusion Energy Science. In the accompanying report (H.Rept. 107-112), the House expressed its agreement with the finding of the National Energy Policy about the potential for fusion energy, but stated that it could not provide any more research funds than requested because of funding constraints. The House noted that it had also provided an additional $25 million for research on high average power lasers in the inertial confinement fusion budget within the DOE defense programs. On July 19, 2001, the Senate approved its version of the Energy and Water Development Appropriations Bill, 2002 (H.R. 1171, S.Rept. 107-39). The Senate also approved $248.49 million for FY2002. On November 11, 2001, Congress approved the conference report (H.Rept.107-258), which provided $248.49 million for FES for FY2002.

In a related action, legislation was introduced on May 9, 2001, sponsored by Representative Zoe Lofgren and 18 cosponsors (H.R. 1781), that would accelerate “the scientific understanding and development of fusion as a long term energy source.” As part of this effort, the legislation would direct the Secretary of Energy to develop a plan by July 1, 2004, for domestic construction of a burning plasma experiment. The legislation would also allow the Secretary to submit a plan based on U.S. participation in an international burning plasma experiment if such actions were cost effective and provided the United States with the same scientific benefits as a domestic facility. The legislation also would require the

Secretary of Energy do submit a plan within 6 months of enactment that would ensure "a strong scientific base of the [FES] Program" and make possible the burning plasma experiment. While the legislation would not authorize the experiment itself, it would authorize $320 million for the program in FY2002 and $345 million in FY2003. The bill has been incorporated in H.R. 4, a bill to enhance energy conservation, research and development and to provide for security and diversity in the energy supply for the American people, and for other purposes. On August 2, 2001, the House passed H.R. 4. On June 28, 2001, a Senate version (S. 1130) of H.R. 1781, sponsored by Senators Craig and Feinstein, was introduced. This bill has been incorporated in S. 1766, the comprehensive energy bill in the Senate.

The Administration's National Energy Policy, released May 2001, recommended the development of "next-generation" energy technology including fusion. The report described the promise of fusion energy and noted the progress fusion research has made over the last 30 years. Also, FESAC is currently preparing a report at the request of the Director of the DOE Office of Science that considers a number of issues including the ability of the FES program to meet its five-year goals. A draft of that report suggests that insufficient funding is hindering the program's ability to maintain an adequate rate of technological advance towards fusion energy development. FESAC argues that program goals were predicated on annual appropriations of about $300 million, which has not been met any year since the goals were set. In particular, operating time on the program's major user facilities has been insufficient and decisions about the development of new facilities are being delayed.

Program Reviews. Primarily as a result of congressional direction, DOE set in motion three major reviews of its fusion research activities from 1998 to early 1999. One was carried out by FESAC and consisted of two parts. The first summarized "the opportunities and requirements of a fusion energy science program" while the second provided recommendations for proof-of-principle experiments and program balance between tokamak and alternative options, and between inertial and magnetic fusion. The second review — of the magnetic (MFE) and inertial confinement energy (ICF) programs — was done by a task force on fusion energy of the Secretary of Energy Advisory Board (SEAB) (see below). That review was in response to the Senate Appropriations Committee in its report accompanying its version of the FY1999 DOE appropriations bill.

The third review was carried out by the National Research Council (NRC) to assess the scientific quality of the fusion energy science program. The NRC issued its final report (see below) on October 23, 2000. A major motivation for these studies was for DOE to reexamine how it approaches fusion research by considering all of the options its supports in a comprehensive manner. In addition to the three reviews, a two-week summer workshop on MFE and ICF was held at Snowmass, CO in July, 1999, with the findings of that workshop reported to FESAC for consideration during its program review. A followup meeting at Snowmass is scheduled for 2002.

Program Issues

Restructuring. The magnetic fusion program is completing the congressionally directed restructuring it began in 1996. The first phase resulted in a significant shift in program focus from primarily being concerned about fusion energy technology development to one concentrating on plasma and fusion science and technology research. This second phase resulted in the ending of U.S. participation in the ITER project and a review the entire DOE fusion effort.

Formal participation in the ITER project by the United States ended in FY1999. The other partners are continuing with the program, however, and currently developing plans for the next step in the project. In October 2000, the outline of the new ITER design, called ITER-FEAT, was announced. The revised design is for a machine significantly smaller than the one that emerged from the Engineering Design Activity that was completed in July 1998. At that time, the partners decided not to proceed with construction because of financial constraints including the U.S. withdrawal from the program. See below for more details.

With the end of the ITER project, Congress directed DOE to reconsider its entire fusion effort. These studies were to focus on a number of issues about the future of the MFE program. All of these studies are now complete and are summarized next.

SEAB Fusion Task Force. The Task Force found that progress in fusion science has been substantial and that the basic scientific feasibility of fusion can be demonstrated [http://fire.pppl.gov/SEAB_final_Aug99.pdf]. The Task Force also endorsed the broader focus of the MFE program on fusion and plasma science and engineering with greater attention to alternate confinement concepts. The Task Force also recommended "stable and meaningful" participation in international fusion research, particularly in view of the large cost requirements of future burning plasma experiments including, possibly, ITER. In this connection, early discussions with Congress were deemed important so that any participation could coexist with the current broad-based domestic program. The Task Force noted that any new large international project will require clear understanding of its goals and broad political support.

FESAC Report on Priorities and Balance. The FESAC panel endorsed the findings and recommendations of the SEAB Task Force. In addition, the panel considers the current MFE program to be reasonably well in balance but did urge more emphasis on pulsed concepts [http://fire.pppl.gov/FESAC_Priorities_Final99.pdf]. It noted that restructuring was not yet complete and the program could be strengthened with "moderate" budget growth. The panel recommended four areas as targets for any budget increases:

- Strengthen theory and computation
- Pursue a number of confinement concepts in the proof-of-principle program
- Focus the advanced tokamak program to a 5-year assessment point, and
- Revitalize the technology program.

FESAC Report on Criteria, Goals, and Metrics. This report was prepared by a special panel for consideration by FESAC during preparation of its report on Priorities and Balance. The panel recommended that DOE continue with the stages of development first described by the FESAC Alternate Concept Review Panel in 1996. Progress through these stages -- concept evaluation (CE), proof-of-principle (PoP), performance extension (PE), fusion energy development, and demonstration -- would be governed by peer and expert review. A set of criteria to make the evaluation was presented by the panel.

The panel also noted that the international magnetic fusion effort is about 5-6 times greater than the U.S. effort, and the U.S. should participate as appropriate in order to leverage its research program. In IFE, the U.S. is by far the leader and OFES should supplement the DP effort. The panel developed metrics for each of the nine program elements within IFE/MFE research.

NAS - Fusion Science Assessment Committee (FuSAC) Final Report. The NAS study, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program* [http://fire.pppl.gov/FuSAC_Prepub_Draft_Fig.pdf] was carried out to examine the quality of research being supported by the OFES. The FuSAC concluded that U.S. fusion research has made significant advances over the past several years and is now in a position to make critical contributions to guide new scientific discovery in the program. The committee also concluded that the quality of magnetic fusion science is at least as good as that from other major physical science fields within the United States. At the same time, however, the Committee found that the concentration of fusion research on energy production has led to growing "intellectual" isolation between the magnetic fusion research and other scientific fields. As a result, there is insufficient appreciation by other scientists of the quality of magnetic fusion science and a stagnation of the interchange of ideas between fusion and the rest of science. This, according to the Committee, has led to a "negative view of fusion science" and a decline of new entrants into the field. The Committee stated that a more outward looking program, focusing on important scientific goals, would both alter this view and enhance progress towards practical fusion power.

Snowmass Meeting. This meeting brought together IFE and MFE researchers to develop a consensus on the key science and technology issues for plasma science, technology and fusion energy development The participants also identified opportunities for existing and future facilities and programs to contribute to making fusion an attractive energy source [http://www.ap.columbia.edu/fusion/snowmass/WG_Summaries.html]. The workshop divided into six groups – magnetic fusion concepts, inertial fusion concepts, emerging concepts, plasma science, technology, and energy issues. A number of overlapping issues were identified for the various concepts.

Discussion. Several themes emerge from these reports. First, there is general agreement that progress in fusion science has been substantial and that the basic scientific feasibility of fusion will be successful. Such an event, of course, will still leave a number of major scientific and technical issues that must be resolved before an economically attractive fusion power plant can be built. Nevertheless, it appears to be only a matter of time before the fundamental scientific issues are resolved and the participants in these studies urge continued and aggressive pursuit of that goal.

A second theme is that strong international participation is essential. As mentioned, the international magnetic fusion research effort is about 5 to 6 times larger than the U.S. effort. Further, there are currently several large one billion dollar plus machines, at the performance extension (PE) stage, either operating or under construction in Japan and Europe in which some level of U.S. participation would be desirable. While the United States has three such PE machines -- the Alcator C-MOD, DIII-D, and NIF -- it is unlikely that any additional fusion machines of that size will be constructed in the United States in the foreseeable future. Therefore, construction of additional PE-size and fusion energy development facilities will undoubtedly require an international effort.

Third, the reviews strongly urged a budget increase for OFES to about $300 million per year for the next 5 years. The balance between MFE and IFE research recommended in the reviews would not be possible at current budget levels. It was noted at the time that a funding level of $250 million for OFES and an additional $10 million for laser development within the ICF program (amounts approved for FY2000), would go a long way toward achieving a more desirable balance if most of the increment for OFES went to IFE research. For FY2001, $252.4 million was appropriated for OFES and an additional $25 million was approved for high average power laser development in the ICF program.

A fourth theme was that more emphasis should be placed on general plasma science and technology research for applications beyond fusion. Several examples were given of such applications in microelectronics, lasers, environmental control, and other areas. In addition, the relation between plasma science and astrophysics, space physics, and materials science was noted. In all cases, the contribution of the plasma science developed in the pursuit of fusion was considered substantial to the entire U.S. science and technology base. In this context, a greater emphasis on plasma science research was considered very important for the program to enhance both the scientific interchange between fusion researchers and the rest of the scientific community and the development of fusion energy.

Next Step. In 1983, the DOE magnetic fusion energy program recommended the construction of a high magnetic field tokamak that would be capable of reaching fusion ignition. That device, known as the compact ignition tokamak (CIT), would be the first U.S. attempt at a burning plasma experiment (BPX). In 1991, DOE terminated the program when it became clear that Congress would not fund the estimated $1.4 billion for its construction. At that point, DOE concentrated its efforts towards a BPX on ITER. When the DOE withdrew from the ITER project in 1998, however, the U.S. magnetic fusion effort was left without the prospect of participating in a BPX of any kind.

At present, there is a renewed interest in the U.S. fusion community in a BPX. As noted above, the U.S. program has undergone a major transition in recent years towards more of a science-based program. Yet it is clear that such a program retains an important energy focus and progress in both fusion science and towards a fusion energy system cannot continue without a BPX of some kind. Indeed, several of the studies described above about the future of the U.S. program note the need to be considering the next steps in the U.S. fusion effort, both magnetic and inertial confinement. In addition, as noted, legislation (H.R.4) has passed the House calling for DOE to begin design of a BPX or to enter into an international agreement to participate in such a project.

At present there are two major proposals for a BPX. One is ITER-FEAT and the other is the Fusion Ignition Research Experiment (FIRE). As noted above, ITER-FEAT is a scaled-down version of the ITER resulting from the Engineering Design Activity (ITER-EDA). Its goal is to provide the scientific and technical knowledge needed to build a prototype fusion power plant. The aim of ITER-FEAT is to reach a fusion energy gain of $Q \geq 10$ for a plasma operated in the pulsed mode and a $Q \geq 5$ for a steady-state plasma. Projected power output is about 400 MW. As such, ITER-FEAT would not reach ignition, but that does not appear to be necessary because a power plant would operate with a Q of about 30. These gain targets, however, are significantly less than those of ITER-EDA. In addition, ITER-FEAT would have a reduced ability to study long-term effects of radiation on the walls surrounding the plasma from that expected for the ITER-EDA. The estimated cost of ITER-FEAT is $4.3 billion compared to about $7.8 billion for ITER-EDA. Also, ITER-FEAT will operate with superconducting magnets and the new design will accommodate advances in plasma physics made since the ITER-EDA design was completed. Potential sites for the ITER-FEAT project include Canada, Japan, and France.

The FIRE proposal is being developed by the Princeton Plasma Physics Lab as part of its Next Step Options study. That study was launched in 1998 to examine where the United States should head in investigating burning plasmas in the wake of U.S. withdrawal from the ITER project. Like ITER-FEAT, FIRE is to be a tokamak facility. It is considerably smaller than ITER-FEAT, however, and would operate with conventional magnetic field coils cooled with liquid nitrogen. The FIRE target for gain is a Q of about 10 with a fusion power production of about 150 MW. The total estimated cost of the project is about $1.2 billion with about $375 million required for construction. If built, FIRE would test plasma confinement projections closer to reactor conditions than any existing machine. According to its proponents, the FIRE approach would be part of a modular strategy where at least three different facilities would be built to develop the science and technology needed to construct a demonstration fusion power reactor. This would be in contrast to the ITER-FEAT approach where nearly all of that research would be carried out on one machine.

Two other projects have been proposed to study burning plasmas. The first is an upgrade to JET that would permit a Q between one and two to be reached. Such an upgrade would be relatively “modest” and could reduce uncertainties in the ITER-FEAT design. The second proposal is Ignitor, which is an Italian design. According to its sponsors, Ignitor is designed to reach ignition but at relatively low fusion power production, about 40 MW. The machine is an extrapolation of the Alcator C-MOD at MIT, and, as such, is a compact, high field, low-power device. It is designed to use conventional magnetic field coils.

The principal issue before Congress is whether the United States should commit to a BPX at this time, and if so, which path. It is clear that continued progress in fusion science and engineering towards a power reactor will require at some point operation of a burning plasma. While much effort, however, has been made to reduce the cost of such a device, it is still substantial. For example, the cost to the United States of rejoining the ITER project is estimated to be about $50 million per year. Without additional funding, this would be about 20% of the current budget, a sum the program could not afford without serious consequences for the other research activities. It is possible that more funding will be made available for a BPX. Indeed, H.R. 4 authorizes a program budget of $320 million for FY2003 for the FES program, $70 million above the current appropriation. Translating that authorization into an appropriation, however, is another matter.

The cost of the FIRE project may be less, but the longer term cost to the program may be greater because of the limitations of that device compared to ITER-FEAT in moving towards a power reactor. Proponents of ITER-FEAT argue that the separate facility approach as proposed by the FIRE sponsors would delay the construction of the demonstration reactor by 10 years or more. The FIRE proponents, on the other hand, note that their approach would significantly reduce risk in moving to the demonstration phase. While it may take longer if all goes well, they assert that a failure or significant problems with ITER-FEAT could substantially lengthen the time to a demonstration reactor.

Another issue concerns the confinement concept used for the BPX. Currently, all of the proposals are tokamaks. This concept is much further advanced than any other at this time, and results on other large tokamaks suggest a high probability of success in achieving a burning plasma. Yet there is concern that a tokamak may not make the most attractive fusion power plant. Congress has long urged DOE to pursue a broader program, and the Office of Fusion Energy Science is funding a number of such projects as noted above. The proponents of a tokamak BPX argue that much of the science and technology learned in such an experiment will be applicable to any magnetic confinement concept. It is not clear, however, whether that knowledge will be sufficient to bypass the burning plasma phase for an alternative concept should it turn out to be a better power plant candidate. Indeed, it may not be possible to determine what is the best candidate without constructing a BPX, although the knowledge gained from operating a tokamak BPX may still be essential. It appears important that such possibilities be carefully considered before deciding whether to proceed.

With the conclusion of its program reassessment, DOE's Office of Fusion Energy Science must now decide how to proceed. It has established a sound, relatively broad-based research effort within the confines of available resources that promises to advance plasma and fusion science and engineering. To achieve the goal of fusion energy production, however, does not appear likely under these conditions. Such an effort will probably require an expanded program and the construction of larger machines either domestically or as a partner in an international effort. While there are signs that Congress may be willing to support an expansion of some size, that is by no means certain. To some degree that will depend on how DOE presents those options.

LEGISLATION

H.R. 4

The Securing America's Future Energy (SAFE) Act of 2001 was passed by the House on August 1, 2001. The Fusion Energy Sciences Act of 2001 (H.R. 1781, introduced on May 9, 2001) was incorporated into H.R. 4 as Sections 2501-2505.

S. 1766

The Energy Policy Act of 2002 was introduced on December 5, 2001. The Fusion Energy Sciences Act of 2001 (S. 1130, introduced on Jun 28, 2001) was incorporated into S. 1766 as Section 1254.

FOR ADDITIONAL READING

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