Fifty years of U.S. fusion research— An overview of programs

BY STEPHEN O. DEAN

Fusion has been certified as ready for engineering development for more than 20 years, but a weak-willed government has been unwilling to manage and fund the program to accomplish its avowed practical purpose.

1 FIFTY YEARS AGO, the United States, United Kingdom, and Soviet Union began, independently and in secret, research to harness the energy process of the Sun. Success came quickly, in the form of the hydrogen bomb, but producing controlled thermonuclear reactions, or nuclear fusion, as it is now more commonly called, has remained elusive.

2 Many, if not most, of the basic approaches to achieving fusion were postulated in rudimentary form during the 1950s,[1, 2] based on well-known principles of electromagnetic theory and nuclear physics. Nuclei carry positive charge and can be guided by magnetic fields. Since the repulsive (Coulomb) force between two nuclei increases with the product of the charge on the nuclei, fusion would be most easily achieved, it was reasoned, between singly charged isotopes of hydrogen. Two nuclei approaching each other, however, are about a thousand times more likely to be scattered than to fuse, even when traveling at high speed. Consequently, some means is needed to confine the nuclei for a sufficient time to allow many attempted collisions. Magnetic bottles, of various shapes, seemed the ideal solution.

3 The high-temperature, ionized hydrogen gas (called "plasma") turned out to be much more difficult to contain in the various magnetic bottles than scientists originally hoped would be the case. Consequently, in 1958, at the Second UN Geneva Conference on the Peaceful Uses of Atomic Energy, the United States, United Kingdom, and Soviet Union declassified their research.

4 A variety of methods to heat the nuclei to the high speeds (kinetic energies) required to penetrate the Coulomb barrier have been successfully utilized, including running a high current through an ionized hydrogen gas ("ohmic heating"), accelerating beams of nuclei, and using radio-frequency power. Temperatures well in excess of the 50 million Kelvin needed for fusion are routinely achieved.

The 1960s and 1970s

5 During the decade of the 1960s, and continuing to the present, scientists developed a whole new branch of physics, called plasma physics,[3] to describe the behavior of these plasmas in various magnetic configurations, and sophisticated theories, models, and computer simulation codes for making predictions and for interpreting data.

6 A breakthrough of sorts occurred in the late 1960s when the Russians announced greatly improved confinement in a magnetic configuration called the "tokamak"—from Russian words meaning "toroidal magnetic chamber." Thus began an international stampede to develop this approach. During the next two decades, multimillion-fold improvements in confinement were demonstrated in ever larger, ever more powerful tokamak devices (Fig. 1).

7 Three large tokamak construction projects were begun during the energy crisis days of the mid-1970s: the Tokamak Fusion Test Reactor (TFTR) in the United States, the Joint European Torus (JET) in England, and the Japan Tokamak (JT-60) in Japan. All three have achieved plasma conditions approximating "scientific break-even," defined as a condition where the amount of energy released from fusion reactions approximately equals the amount of energy put in to heat the plasma to fusion conditions. JET and JT-60 are still operating, but TFTR operations were terminated in 1998 by instructions from a budget-cutting Congress.

8 By the mid-1990s, more than 10 MW of fusion power had been produced in TFTR and JET. The facilities were designed to sustain this power for only a few seconds, however. Obviously, for power plants, this power would need to be sustained in steady state. Hence, new facilities are required. ITER (the proposed International Thermonuclear Experimental Reactor) is designed for 1000-second operation, with upgrade potential to steady state.

In 1976, the U.S. Energy Research and

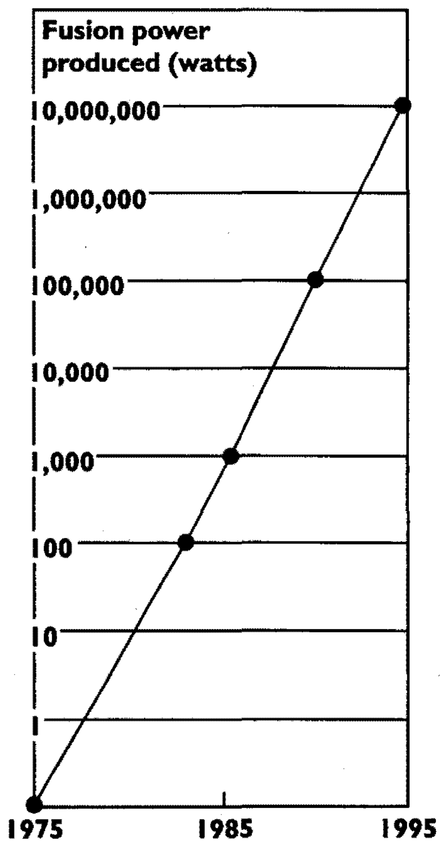

Fig. 1. Fusion power produced in the laboratory has increased 100 million-fold over 20 years to more than 10 million watts.

Stephen O. Dean (<fpa@compuserve.com>) is president of Fusion Power Associates, a nonprofit research and educational foundation. During the 1970s, he was director of the Magnetic Confinement Fusion Systems Division at the U.S. Department of Energy and previously was a laser-plasma research scientist at the U.S. Naval Research Laboratory. He is a Fellow of the American Nuclear Society.

Development Administration (ERDA) published a detailed fusion program plan[4] suggesting that if a sequence of advanced test facilities were constructed in a timely fashion, fusion electricity could be on the grid in a demonstration power plant by the year 2000. This plan was codified by Congress in the Magnetic Fusion Energy Engineering Act of 1980, signed by President Carter on October 7, 1980. The Act was signed just as the U.S. energy crisis was coming to an end, as proclaimed by President Reagan upon his taking office in January 1981.

The provisions of the Act were never implemented. Furthermore, fusion and other energy R&D programs experienced major funding reductions during the 1980s and 1990s. No new major fusion "stepping stone" facility beyond TFTR was ever built, although design of a "next-step" tokamak engineering test reactor was initiated in late 1985, following the Reagan-Gorbachev summit. The design of that test reactor (ITER) became a major international venture of the European Union, Japan, Russia, and the United States.

The 1960s and 1970s also saw the emergence of another approach, fundamentally different from magnetic confinement: inertial confinement. It paralleled the development of high-power lasers and high-energy particle beams, undertaken primarily by military programs.

In this approach, a high-energy, high-power beam is focused onto the surface of a spherical pellet containing fusion fuel. The resulting blowoff drives an inward compression of the pellet, by the principle of action/reaction, raising both the temperature and density of the fuel. If the compression remains spherically symmetric, fusion ignition is calculated to occur for a specific input energy, setting off a miniature and containable hydrogen bomb–like "micro-explosion." Power plants using this process, repeated several times a second in a chamber, can be envisaged and, in fact, have been designed.

Progress in inertial confinement has been systematic. The $2.2-billion National Ignition Facility (NIF) laser, currently under construction at the Lawrence Livermore National Laboratory, is aimed at igniting such a pellet in a single shot some time after 2010. Programs are under way to develop repetitively pulsed lasers and particle beams for possible power plant applications.

The 1980s and 1990s

As funding for fusion and other energy programs declined during the 1980s, U.S. fusion program managers attempted to keep the tokamak program vigorous by reducing funding for other magnetic approaches. Although the tokamak was recognized as a potentially successful track to a power plant, many scientists were critical of its complexity and projected economics.

A revolt, of sorts, occurred in the early 1990s, which led to a further slowing of the U.S. tokamak effort and a modest rebirth of other concepts.[5] These concepts included variations on the toroidal geometry (stellarator, reversed-field pinch) and hybrids in which the magnetic configuration had toroidal properties but the mechanical chamber was cylindrical (field-reversed concept, spheromak). Other approaches also emerged, such as the magnetized target plasma (MTF) and inertial electrostatic confinement (IEC). The technical aspects of these approaches have been summarized elsewhere.[6, 7]

As the 1990s began, the Department of Energy, through its Energy Research Advisory Board (ERAB) formed a high-level panel to review its fusion policy. Under the chairmanship of former Presidential science advisor H. Guyford Stever, this Fusion Policy Advisory Committee (FPAC) advised[8] then Secretary of Energy James Watkins that "The fusion energy program should have two distinct and separate approaches, magnetic fusion energy (MFE) and inertial fusion energy (IFE), both aimed at the same goal of fusion energy production. Both should plan for major facilities along the lines of the Committee's conceptual plan in the report."

The report also recommended that "Both MFE and IFE should increase industrial participation to permit an orderly transition to an energy development program with strong emphasis on technology development" and that the DOE should set 2025 as the target date for operation of a Demonstration Power Plant. The document assumed the construction of a "Compact Ignition Tokamak (CIT)" during the early 1990s and budgets rising from the FY 1990 budget of $318 million to $620 million in FY 1996. Neither the CIT nor the required budgets materialized.

For a variety of reasons, mostly financial, the ITER parties were unable, during the 1990s, to go beyond design and into construction. Impatient with the delay, Congress cut the U.S. fusion budget from $365 million in FY 1995 to $244 million in FY 1996, to $225 million in FY 1997, and instructed the DOE to refocus the fusion program away from a schedule-driven development strategy and onto its scientific underpinnings.

Subsequently, the Congress ordered the DOE to shut down TFTR and to withdraw from the ITER collaboration, which it did in 1998. (The United States, however, is currently reviewing the possibility of rejoining ITER.) The remaining ITER parties have continued discussions on project implementation and are still hoping for siting and construction decisions by the end of 2002. Canada has joined the partnership by offering a site on Lake Ontario. Japan and France are also considered possible sites for ITER.

Faced with massive budget cuts and new Congressional policy guidelines, the DOE reconstituted its Fusion Energy Advisory Committee (FEAC), removing most industry members, and renamed it the Fusion Energy Sciences Advisory Committee (FESAC). In its final acts, the FEAC recommended an intensification of "alternate concepts" and inertial fusion energy research, even within the lower budget levels[7] and described in detail a "restructured fusion energy sciences program" with no target date for operation of a demonstration power plant[9].

Following a second round of Congressional budget cuts for FY 1997, the DOE convened a meeting on October 22–24, 1996, of some U.S. fusion personnel in Leesburg, Va., with the aim of further restructuring the U.S. fusion program from an "energy" program into a "science" program.[10] This group, in a November 3, 1996, letter to the DOE, recommended a "threefold vision" for the fusion program: (1) "Understanding the physics of plasmas, the fourth state of matter," (2) "Identifying and exploring innovative and cost-effective development paths to fusion energy," and (3) "Exploring the science and technology of burning plasmas, the next frontier in fusion research, as a partner in an international effort."

Concurrently, the DOE, Office of Management and Budget (OMB), and Congress shifted the fusion budget from the "energy account" into the "science account" for federal budget purposes. The OMB at first took that as an opportunity to propose reducing the fusion budget further by eliminating all remaining engineering and technology elements from the fusion budget request, then relented on the basis of arguments that some technology development was necessary for the evolution of the science program. Nevertheless, the current engineering/technology portion of the U.S. fusion program is a skeleton of what it once was.

PCAST report, other plans

In September 1997, the Energy Research and Development Panel of the President's Committee of Advisors on Science and Technology (PCAST) issued a report,[11] "Federal Energy Research and Development for the Challenges of the Twenty-First Century." The panel was chaired by PCAST member John Holdren, a professor at Harvard University, who had previously chaired a 1995 PCAST panel on fusion.[12]

The 1997 panel recommended across-the-board increases for most energy R&D programs, including fusion, over the next five years. It said these increases were necessary "to close the gap between the current energy R&D program and the one that the challenges require."

Continued

For fusion, the panel recommended gradual increases from the $232-million level then, to a level of $328 million in 2003. It said, "Our Panel reaffirms support also for the specific elements of the 1995 PCAST recommendation that the program's budget-constrained strategy be around three key principles: (1) a strong domestic core program in plasma science and fusion technology; (2) a collaboratively funded international fusion experiment focused on the key next-step scientific issue of ignition and moderately sustained burn; and (3) participation in an international program to develop practical low-activation materials for fusion energy systems."

The inertial fusion energy "roadmap" proposal at the meeting stimulated leaders of the magnetic fusion energy community to think in similar fashion, and soon there was a combined "roadmap."

The panel recommended that the U.S. program collaborate with the JET program in Europe and the JT-60 program in Japan, to provide experience for a burning plasma machine, such as ITER. Also, it declared that:

> [ITER's] proposed 3-year transition between completion of the EDA (Engineering Design Activities) and an international decision to construct is reasonable and that the ITER merits continued U.S. involvement. . . . Clearly, one major hurdle to ITER construction is its total project cost, most recently estimated to be $11.4 billion, with the host party expected to fund a substantial share. If the parties agree to move forward to construction, the U.S. should be prepared to determine, with stakeholder input, what the level and nature of its involvement should be. . . . [I]f no party offers to host ITER in the next three years, it will nonetheless be vital to continue without delay the international pursuit of fusion energy. A more modestly scaled and priced device aimed at a mutually agreed upon set of scientific objectives focused on the key next-step issue of burning plasma physics may make it easier for all parties to come to agreement.

The panel also said that the present funding level is "too low" and allows no significant U.S. activity relating to participation in an international program to develop practical low-activation materials; reduces the level of funding for design of the International Thermonuclear Experimental Reactor (ITER); forced an early shutdown for the largest U.S. fusion experiment; canceled the next major U.S. plasma science and fusion experiment; and it also limited resources available to explore alternative fusion concepts.

Despite these recommendations from PCAST, fusion funding remained essentially flat. During 1998, many scientists, within both the magnetic and inertial fusion factions, focused their planning efforts on "next step options" and development pathway roadmaps. In April 1998, leaders of the U.S. inertial confinement fusion program presented a comprehensive plan to develop a commercial fusion energy source to a group of mostly magnetic fusion scientists meeting in Madison, Wis.[13] The event, "Forum for Major Next-Step Fusion Experiments," brought together about 150 members of the U.S. fusion community to "identify a range of options for major next-step experiments in support of fusion energy development with broad community involvement" and to "establish a broad consensus within the community around the pursuit of a few options whose implementation would be contingent on domestic and international budget developments." E. Michael Campbell, then Lawrence Livermore National Laboratory's Associate Director for Lasers (and now a vice president at General Atomics) called for "address[ing] the concerns about the present fusion program—not just the need for good science, but also the need for better end products and lower cost development paths." He emphasized that the inertial fusion path differs from the path of magnetic fusion and thus provides a real alternative. Campbell also noted that an energy path for inertial fusion "can leverage investment by DOE Defense Programs."

The plan discussed at the meeting proposed to further develop the required efficient, repetitively pulsed driver technologies, combined with target design and technology R&D between then and 2002 at a cost of about $35 million–$40 million per year. At that point, a decision would be made to construct an "Integrated Research Experiment" in parallel with continued advanced driver and target R&D and supporting technology R&D at a cost of about $80 million per year. About 2011, a decision would be made to construct an Engineering Test Facility at a total project cost of about $2 billion, followed by a decision about 2023 to construct an IFE demonstration power plant for about $3 billion.

Details were presented on all elements of the plan. As might have been predicted, the funds required to meet this timetable have not been forthcoming, although the general strategy is still in place.

The inertial fusion energy "roadmap" proposal at the meeting stimulated leaders of the magnetic fusion energy community to think in similar fashion, and soon there was a combined "roadmap" being proposed (Fig. 2). This fusion roadmap, notably without a timetable, is still basically guiding long-range, top-level program thinking today.[14]

A "Next Step Options" program was initiated within the U.S. magnetic fusion community, aimed at developing options for studying burning plasmas. Over the next several years, numerous meetings, designs and reviews of these options took place.[15]

The SEAB report

In late 1998, Energy Secretary Bill Richardson requested his Secretary of Energy Advisory Board (SEAB) to form "a new fusion subcommittee to review the department's fusion-related technologies, programs and priorities pertaining to the development of a fusion energy source." This request was stimulated by language contained in a Senate Appropriations Committee report recommending "that the Department, prior to committing to any future magnetic fusion program or facilities, conduct a broader review to determine which fusion technology or technologies the U.S. should pursue to achieve ignition and/or a fusion energy device."

The SEAB fusion Task Force, chaired by Richard Meserve (currently chairman of the Nuclear Regulatory Commission), made its report on August 9, 1999.[16] In a cover letter transmitting the report to Richardson, SEAB Chairman Andrew Athy said that "the fusion energy program must be led by strong management, capable of directing the program towards its goals at a reasonable pace," and with a sufficient budget, "on the order of $300 million per year." Some excerpts of the report:

> [I]t is the Task Force's view that the threshold scientific question—namely, whether a fusion reaction producing sufficient net energy gain to be attractive as a commercial power source can be sustained and controlled—can and will be solved. The time when this achievement will be accomplished is dependent, among other factors, on the creativity of scientists and engineers, skill in management, the adequacy of funding, and the effectiveness of international cooperation.
>
> Nonetheless, there remain significant barriers to the realization of fusion as a sig-

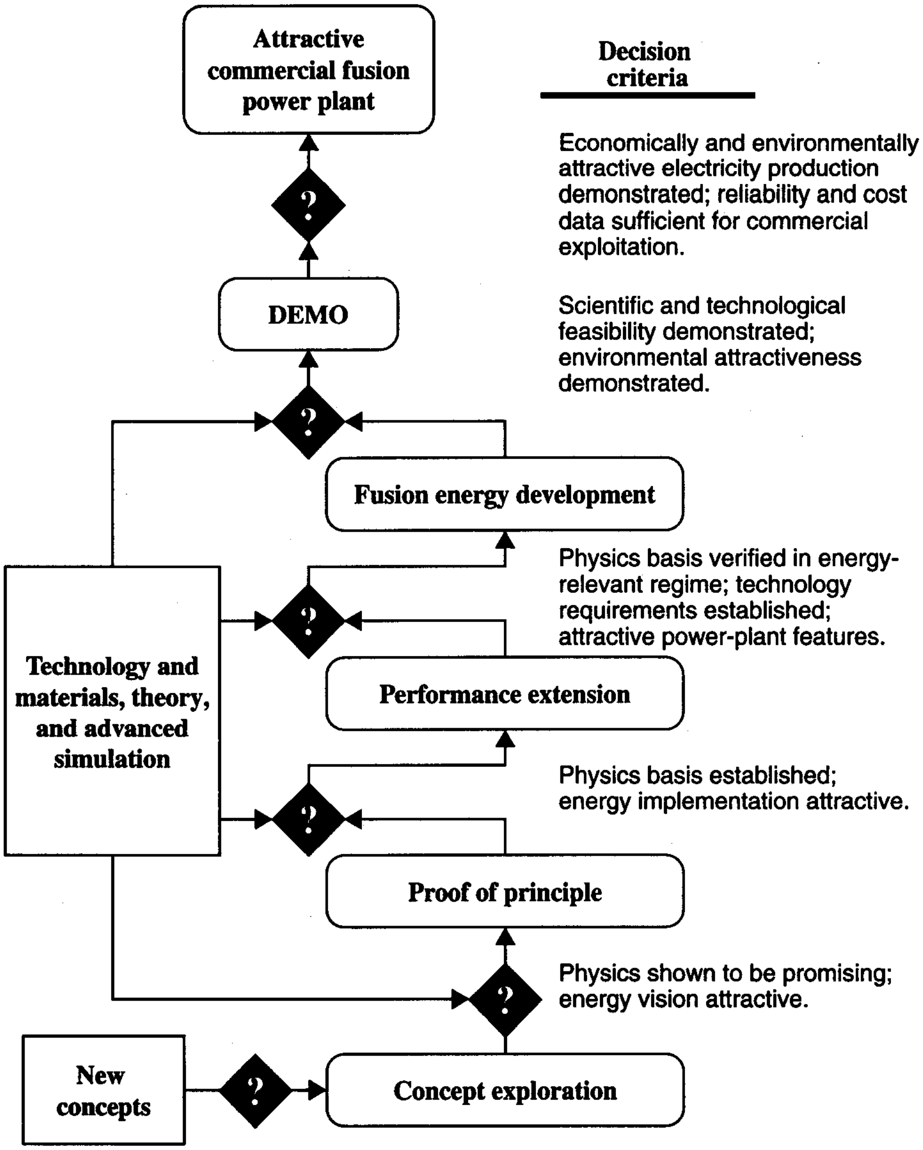

Fig. 2. Logic framework for stages of fusion energy development

nificant contributor to the world's energy supply. Progress requires advancing fundamental scientific knowledge (from controlling turbulence, to optimizing the magnetic-field configuration, to enhancing the fusion power gain), resolving very difficult materials issues (e.g., developing a vessel that can withstand high temperatures and intense neutron flux while exhibiting favorable activation characteristics), finding answers to difficult engineering challenges (e.g., constructing a reliable and repairable system), and proving economic feasibility (solving these problems in a manner that does not make fusion prohibitively expensive). Many years of persistent effort will be required to overcome these challenges. In spite of the extended effort and expense that will be required, the fusion program deserves continued support because of its unique energy potential. Constraints on supply and limits on the atmospheric loading of combustion products will eventually require that we diminish our reliance on fossil fuels. Because of this reality, the Department is wisely advancing a portfolio of energy technologies to meet future energy needs. Indeed, in light of fusion's potential and the risks arising from increasing worldwide energy demand and from eventually declining fossil energy supply, it is our view that we should pursue fusion energy aggressively.

With respect to the magnetic fusion energy (MFE) program, the Task Force endorsed the "revised focus of the program" away from a "nearly exclusive focus on the achievement of fusion energy in tokamaks to a broader program that would also explore scientific foundations and other confinement approaches." It observed that the DOE Office of Fusion Energy Sciences (OFES) should be encouraged to continue expanding the fusion portfolio. It said that "the Department must participate in international activities that enhance our fusion effort."

The Task Force noted the "remarkable" progress in the inertial fusion energy (IFE) program. "The scientific basis of inertial fusion has progressed to the point where the driver and pellet requirements to achieve ignition are known to high confidence and are within reach," it observed. The Task Force noted that "Some considerations favor heavy ion beams as the driver technology for IFE." But, it said, "Given the immature state of the technology, it is not appropriate at this time to select only one driver technology for continued exploration." The panel recommended that reactor studies "should continue to be used as guides in establishing the direction and balance of research efforts, as well as to establish goals that constitute thresholds for further investment."

The DOE, through its FESAC, subsequently produced several comprehensive program descriptions and "integrated planning" documents[17, 18, 19] but "strong program management" never emerged. The Priorities and Balance Report[17] did, however, establish a series of five-, 10- and 15-year goals, and a set of associated objectives, for the fusion program. These are still currently in use for establishing program priorities.

In July 1999, more than 300 physicists from across the United States and 11 other countries met for two weeks in Snowmass Village, Colo., to discuss the present state of the U.S. fusion program and its future direction.[20] The long, formal title of this meeting was *1999 Fusion Summer Study: Opportunities and Directions in Fusion Energy Science for the Next Decade.* It is important to note that the magnetic confinement effort and the inertial confinement effort were both broadly represented. Making specific decisions about program management was not in the charter of the meeting; the work accomplished, however, has had a significant effect on the directions of the U.S. fusion program. A second meeting, *Snowmass 2002: Fusion energy Sciences Summer Study,* is planned for July 8–19, 2002.[21]

Despite the obvious interest in fusion energy applications by the SEAB, PCAST, and most members of the U.S. fusion community, fusion continued to be viewed as a "science program" at OMB. Speaking at the Fusion Power Associates annual meeting on October 19, 1999,[22] OMB fusion budget examiner Michael Holland said: "From OMB's view, I'd like to emphasize that we see fusion as a science program and not an energy technology program. And that means that we judge you according to the criteria that we judge the other programs in the science portfolio: high-energy physics, nuclear physics, basic energy sciences. Scientific excellence is the critical performance measure that we look for. Part of the reason why we look at fusion sciences as a science program and not an energy technology program is due to some of the recent actions that Congress took, particularly moving fusion out of the energy supply budget account and into the science account."

Continued

In response to questions, Holland commented: "My personal feeling is that the technology aspects of the fusion sciences program ought to be considered in the same way that the technology aspects of high-energy physics are considered. We invest a lot in accelerator R&D, but we do that to advance science in high-energy physics. And accelerator R&D is not an end to itself. So, if the technology aspects of the fusion sciences program are connected to the science that you're trying to advance, then I think that's a wise investment. I guess that's the only way I would imagine doing that part of the budget."

The purpose of the assessment was to evaluate the quality of the fusion research program and to provide guidance for future program strategy.

Research Council study

In April 2001, the National Research Council of the National Academies finished a study (requested four years earlier by the DOE) on the quality of the U.S. fusion science program.[23] It was done by a panel—the 19-member Fusion Science Assessment Committee—chaired by Charles Kennel, director of the Scripps Institute of Oceanography, a highly respected plasma scientist in his own right and a former deputy administrator of NASA.

The purpose of the assessment was to evaluate the quality of the fusion research program and to provide guidance for future program strategy to strengthen the research component of the program. For the most part, the committee restricted its review to the magnetic confinement plasma science portion of the program and did not assess either the DOE Defense Program's inertial confinement fusion program or the technology portion of the program.

The report stated that the U.S. fusion research sponsored by the DOE's OFES "has made remarkable strides over the years and recently passed several important milestones." It concluded that "the quality of the science funded by the United States fusion research program in pursuit of a practical source of power from fusion (the fusion energy goal) is easily on a par with the quality in other leading areas of contemporary physical science." The document declared that "A strong case can also be made that a program organized around critical science goals will also maximize progress toward a practical fusion power source," although nowhere in the report do they provide arguments to support that assertion.

The panel addressed fusion issues under three topics: (1) assessment of quality: scientific progress and the development of predictive capability; (2) program development: plasma confinement configurations; and (3) institutional considerations: interactions of the fusion program with allied areas of science and technology.

The Committee made seven "primary recommendations:"

1. Increasing scientific understanding of fusion-relevant plasmas should become a central goal of the U.S. fusion energy program on a par with the goal of developing fusion energy technology, and decision-making should reflect these dual and related goals.
2. A systematic effort to reduce the scientific isolation of the fusion research community from the rest of the scientific community is urgently needed.
3. The fusion science program should be broadened in terms of both its institutional base and its reach into the wider scientific community; it should also be open to evolution in its content and structure as it strengthens its research portfolio.
4. Several new centers, selected through a competitive, peer-review process and devoted to exploring the frontiers of fusion science, are needed for both scientific and institutional reasons.
5. Solid support should be developed within the broad scientific community for U.S. investment in a fusion burning experiment.
6. The National Science Foundation should play a role in extending the reach of fusion science and in sponsoring general plasma science.
7. There should be continuing broad assessments of the outlook for fusion energy and periodic reviews of fusion energy science.

The committee acknowledged that consonant with its charge, it had "not taken up the many critical-path issues associated with basic technology development for fusion, nor has it looked at the engineering of fusion energy devices and power plants, yet it is the combined progress made in science and engineering that will determine the pace of advancement toward the energy goal."

NEPD report

Early in his new administration, President George W. Bush announced that energy policy would be a priority. He set up a National Energy Policy Development Group (NEPD) under the direction of Vice President Dick Cheney. The NEPD report, released on May 17, 2001, focused primarily on near- and mid-term energy sources, conservation, and efficiency.[24] The report, however, also addresses fusion, saying, "The NEPD Group recommends that the President direct the Secretary of Energy to develop next generation technology—including hydrogen and fusion." The group also recommended that the Secretary of Energy be directed to "develop an education campaign that communicates the benefits of alternative forms of energy, including hydrogen and fusion." The full statement on fusion contained in the text is:

> Fusion—the energy source of the sun—has the long-range potential to serve as an abundant and clean source of energy. The basic fuels, deuterium (a heavy form of hydrogen) and lithium, are abundantly available to all nations for thousands of years. There are no emissions from fusion, and the radioactive wastes from fusion are short-lived, only requiring burial and oversight for about 100 years. In addition, there is no risk of a meltdown accident because only a small amount of fuel is present in the system at any time. Finally, there is little risk of nuclear proliferation because special nuclear materials, such as uranium and plutonium, are not required for fusion energy. Fusion systems could power an energy supply chain based on hydrogen and fuel cells, as well as provide electricity directly.
>
> Although still in its early stages of development, fusion research has made some advances. In the early 1970s, fusion research achieved the milestone of producing 1/10 watt of fusion power, for 1/100 of a second. Today the energy produced from fusion is 10 billion times greater, and has been demonstrated in the laboratory at powers over 10 million watts in the range of a second.
>
> Internationally, an effort is underway in Europe, Japan and Russia to develop plans for constructing a large-scale fusion science and engineering test facility. This test facility may someday be capable of steady operation with fusion power in the range of hundreds of megawatts.
>
> Both hydrogen and fusion must make significant progress before they can become viable sources of energy. However, the technological advances experienced over the last decade and the advances yet to come will hopefully transform the energy sources of the distant future.

On June 28, 2001, Sen. Larry Craig (R., Idaho) and Sen. Dianne Feinstein (D., Calif.) introduced S. 1130,[25] "The Fusion Energy Sciences Act of 2001" in the U.S. Senate. The bill was virtually identical to a bill introduced in the House on May 9 by Reps. Zoe Lofgren (D., Calif.) and George

Nethercutt (R., Wash.).[26] The latter subsequently passed the House as part of a broader energy bill but was not taken up in the Senate. At this writing, the Senate is currently debating energy legislation. The bills call on the Secretary of Energy to provide a plan for proceeding to the study of "burning plasmas."

In spite of the new science focus, most U.S. fusion scientists and new students coming into the field remain primarily motivated by the energy goal. Those most interested in moving the demonstrated fusion performance parameters shown in Fig. 1 to higher values have chosen to try to convince policy-makers of the importance of the "science of burning plasma physics." Although ITER is recognized as an integrated test of burning plasma physics and some elements of power plant engineering and technology, these scientists have looked at other, less expensive experimental facilities that might address the science of burning plasmas.

Burning plasma

A series of "burning plasma physics" workshops have been held during 2000–2002[27] and a FESAC "Burning Plasma Panel Report" studied these issues and options.[28]

FESAC endorsed the report's recommendations: "In particular, we agree with the Panel recommendation that a burning plasma experiment would bring enormous scientific and technical rewards. We also agree that present scientific understanding and technical expertise allow confidence that such an experiment, however challenging, would succeed." Jeffrey P. Freidberg, professor and head of the Nuclear Engineering Department at MIT, chaired the Burning Plasma Panel. Richard D. Hazeltine, professor at the University of Texas at Austin, chairs the FESAC.

The Panel observed that:

- "A burning plasma experiment is the crucial next step in establishing the credibility of magnetic fusion as a source of commercial electricity."
- "The next frontier in the quest for magnetic fusion energy is the development of a basic understanding of plasma behavior in the regime of strong self-heating, the burning plasma regime."
- "A burning plasma experiment in a tokamak configuration is relevant to other toroidal magnetic configurations," and "Much of the scientific understanding gained will be transferable."
- "A burning plasma experiment, either international or solely within the U.S., will require substantial funding—likely more than $100 million per year," and these funds "should arise as an addition to the base Fusion Energy Sciences budget."
- The United States "should establish a proactive U.S. plan on burning plasma experiments and should not assume a default position of waiting to see what the international community may or may not do regarding the construction of a burning plasma experiment."

The panel stated that there is now sufficient scientific information to determine the most suitable burning plasma experiment for the U.S. program, and that "*Now* is the time for the U.S. Fusion Energy Sciences Program to take the steps leading to the expeditious construction of a burning plasma experiment." It nonetheless recommended that the U.S fusion community hold a Snowmass workshop in summer 2002, "for critical scientific and technological examination of proposed burning plasma experimental designs," followed by a FESAC review and recommendation on the "selected option" by January 2003, a National Research Council panel review to be completed by fall 2003, and a DOE recommendation to Congress in July 2004. This (not surprisingly) is the same schedule called for in the House-passed legislation.

In spite of the new science focus, most U.S. fusion scientists and new students coming into the field remain primarily motivated by the energy goal.

Officials of the fusion programs in Europe and Japan expressed surprise and dismay at the slow U.S. decision-making schedule proposed. Europe, Japan, and Russia are proposing to proceed with an international burning plasma experiment by the end of 2002 and have been pressing U.S. officials to rejoin the international effort.

Another look at ITER

On November 3, 2001, fearful that the United States may be left behind, the House Science Committee leadership (which has changed since 1998) asked Energy Secretary Spencer Abraham to consider sending U.S. observers to the ITER meetings and to consider what role, if any, the United States should seek to play in ITER construction.[29]

Delegations from Canada, the European Union, Japan, and the Russian Federation met in Toronto during the week of November 5 to begin formal negotiations on the joint implementation of the ITER project. The United States is not currently a party to the negotiations. The Toronto negotiations were the first in a series that is expected to lead, by the end of 2002, to an agreement on the joint implementation of ITER.[30]

Canada, Europe, and Japan are all offering sites for construction of the estimated $5-billion project. This agreement would govern, under international law, the construction, operation, and decommissioning of ITER.

Matters covered in the discussions also included the site-selection criteria and process, the cost-sharing, and procurement allocation schemes. This first round of negotiations followed preparation meetings in Vienna and in Moscow. During the week there was also a series of discussions by experts supporting the negotiations, including international workshops on aspects of the Canadian site offer to host ITER. The participants in the negotiations took important first steps on a variety of issues, and held a second round of negotiations in Japan in January 2002.

In a January 3, 2002, letter,[31] Secretary Abraham told House Science Committee chair Sherwood Boehlert (R., N.Y.), "I have agreed to explore the current ITER option before us to determine if it is appropriate for the Department—and for the Nation—in the light of the President's National Energy Policy. We will proceed carefully and deliberately since a U.S. commitment to ITER could imply commitment beyond this Administration. I anticipate completing our initial review in the next few months."

The Secretary's letter was in response to the November 3, 2001, letter from Boehlert and ranking minority member Ralph Hall (D., Tex.) urging him to send representatives to ITER planning meetings.

Abraham noted in his letter, "Representatives of other governments have asked that the Department review its current policy toward ITER," and "We have been following closely the progress by the ITER Parties in developing a more attractive, lower cost design for the proposed facility, and most recently, the movements toward concrete site proposals and detailed preparations to begin construction."

In the January 17, 2002, issue of the British science journal *Nature,* science writer Geoff Brumfiel quoted new Bush science advisor John Marburger as saying, "I definitely think that our participation [in ITER] should be reconsidered." The article also quoted FESAC chair Richard Hazeltine as saying, "I think the [U.S.] community is very excited about the possibility of rejoining ITER," but also quoted DOE fusion director N. Anne Davies as declaring, "We're just at the beginning stages of considering what our position should be." Brumfiel reported that Davies said that

Congress and the administration must pledge their full support before U.S. fusion researchers could resume participation.

The big picture

There is little disagreement among fusion researchers that the most assured path to net fusion energy, based on currently demonstrated magnetic confinement physics, is through the tokamak path. If science were the only criterion for setting fusion policy, then the fastest way to fusion power by magnetic confinement is by following the tokamak development strategy—i.e., build a sequence of higher performance tokamak facilities, including a demonstration power plant. Studies have shown that tokamak power plants could be competitive with other sources at some time in the future, depending on fuel availability, pricing, and environmental constraint assumptions.[32]

A significant number of fusion researchers, however, believe that we can do better than the tokamak. The tokamak is indeed a cumbersome configuration from the viewpoint of power plant design. It is mechanically donut-shaped, which presents difficult materials damage, construction, and maintenance challenges. Most would agree that a cylindrical configuration in which all the mechanical equipment surrounds the plasma (rather than threading it, as is the case for tokamak and tokamak-like geometries) would be preferable. A number of such configurations exist, but have very modest funding. As indicated earlier, a series of Innovative Confinement Concept workshops have been held during 2000–2002 to explore these concepts.[27]

Inertial confinement fusion is receiving significant funding from the DOE's weapons program as part of its stockpile stewardship program. As indicated previously, a large laser facility, the NIF, is under construction. Congress has provided additional funds, not asked for by the DOE, to develop high average power lasers capable of pulsing several times per second, as required for power plant operations. Nevertheless, a new, major repetitively pulsed facility would still be required before an IFE power plant could be built.

Fusion research has been under way for a little more than 50 years. Some believe that commercial fusion power is still another 50 years away.[30] Under present U.S. government policy, there is no timetable for fusion. If, however, timely commitment is made to engineering development—admittedly not a likely scenario—fusion power could still be on the grid in a demonstration power plant far sooner.[4, 33] As former Grumman Corporation President and CEO Joe Gavin once said to me, "If you try to develop fusion in 20 years, it may still take you 25 or 30 years, but if you try to develop it in 50 years, it will take at least 50 years." Fusion has been certified as ready for engineering development for more than 20 years,[34] but a weak-willed government has been unwilling to manage and fund the program to accomplish its avowed practical purpose.

References

1. Amasa S. Bishop, *Project Sherwood,* Addison-Wesley Publishing Company (Reading, Mass.), 1958.
2. Samuel Glasstone and Ralph H. Lovberg, *Controlled Thermonuclear Reactions,* D. Van Nostrand Company, Inc. (Princeton, N.J.), 1960.
3. Nicholas A. Krall and Alvin W. Trivelpiece, *Principles of Plasma Physics,* McGraw-Hill Book Company (New York), 1973.
4. Stephen O. Dean, "Fusion Power by Magnetic Confinement Program Plan," ERDA-76/110/1-5 (July 1976); summary volume published in *J. Fusion Energy* (Kluwer Academic/Plenum Press), December 1998.
5. Stephen O. Dean, et al., "Report of FEAC Panel 3: Concept Improvement," *J. Fusion Energy* (Kluwer Academic/Plenum Press), December 1992.
6. D. C. Barnes, et al., "Fusion Energy Science Opportunities in Emerging Concepts," *J. Fusion Energy* (Kluwer Academic/Plenum Press), March 1999.
7. Farrokh Najmabadi, et al., "The Report of the Subpanel to FESAC Concerning Alternative Concepts (March 1996)," *J. Fusion Energy* (Kluwer Academic/Plenum Press), September 1999.
8. "Report of the Technical Panel on Magnetic Fusion of the Department of Energy Energy Research Advisory Board," DOE/S-0081, September 1990.
9. "A Restructured Fusion Energy Sciences Program," Advisory Report by the Fusion Energy Advisory Committee, January 27, 1996; posted at <wwwofe.er.doe.gov/more_html/PDFfiles/FEACREPORT.pdf>.
10. Stewart Prager, et al., "Report from the Planning Workshop for the Fusion Energy Sciences Program," *J. Fusion Energy,* December 1997.
11. "Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-first Century," November 1997. Posted at <www.ostp.gov/Energy/index.html>.
12. John P. Holdren, et al., "The U.S. Program of Fusion Energy Research and Development: Report of the Fusion Review Panel of the President's Council of Advisors on Science and Technology," *J. Fusion Energy,* June 1995.
13. "Inertial Fusion Leaders Present Energy Plan," FPN98-11, Fusion Power Associates. Posted at <michelle.ucsd.edu/FPA/ARC98/fpn98-11.shtml>.
14. "Opportunities in the Fusion Energy Sciences Program," report prepared by the Fusion Energy Sciences Advisory Committee, June 1999. Posted at <wwwofe.er.doe.gov/more_html/FESAC/FES_all.pdf>.
15. See material posted at <fire.pppl.gov>.
16. Richard A. Meserve, et al., "Realizing the Promise of Fusion Energy: Final Report of the Task Force on Fusion Energy," *J. Fusion Energy* (Kluwer Academic/Plenum Press), June 1999. Posted at <fire.pppl.gov/SEAB_final_Nov99.PDF>.
17. Charles Baker, et al., "Report of the Fusion Energy Sciences Advisory Committee Panel on Priorities and Balance," *J. Fusion Energy,* June 1999. Posted at <fire.pppl.gov/FESAC_FinalRpt.pdf>.
18. George H. Neilson, Jr., et al., "The Fusion Science Research Plan for the Major U.S. Tokamaks," *J. Fusion Energy,* September 1999.
19. Charles Baker, et al., "Report of the Integrated Program Planning Activity for the DOE Fusion Energy Sciences Program," *J. Fusion Energy* (Kluwer Academic/Plenum Press), December 2000. Posted at <vlt.ucsd.edu/IPPAFinaLDEC00.PDF>.
20. Information posted at <www.pppl.gov/snowmass>.
21. Information posted at <web.gat.com/snowmass>.
22. Stephen O. Dean, "Fusion Science and Technology for the New Millennium," *J. Fusion Energy,* March 1999.
23. Posted at <fire.pppl.gov/fusac_2001_color.pdf>.
24. Report of the National Energy Policy Development Group. Posted at <fire.pppl.gov/National_Energy_Policy.pdf>.
25. Posted at <fire.pppl.gov/fusion_bill_s1130.pdf>.
26. Posted at <fire.pppl.gov/fusion_science_bill_2001.pdf>.
27. Posted at <fire.pppl.gov/ufa_bp_wkshp.html>.
28. Posted at <www.ofes.science.doe.gov/More_HTML/FESAC/BurningPlasma.pdf>.
29. "House Leaders Urge ITER Action Soon," FPN01-82, Fusion Power Associates. Posted at <michelle.ucsd.edu/FPA/ARC01/fpn01-82.shtml>.
30. "Critical Negotiations Set for Fusion's Future," *Nuclear News,* American Nuclear Society, October 2002, pp. 60–61.
31. "US Reconsiders ITER Stance," FPN02-04, Fusion Power Associates. Posted at <aries.ucsd.edu/fpa/fpn01-04.shtml>.
32. I. Cook, R. L. Miller, and D. F. Ward, "Prospects for Economic Fusion Electricity," *Proc. Sixth Int. Symp. On Fusion Nuclear Technology* (April 7–12, 2002), which was to be published in *Fusion Engineering and Design.* Contact: <miller@fusion.ucsd.edu>.
33. Stephen O. Dean, et al., "An Accelerated Fusion Power Development Plan," *J. Fusion Energy* (Plenum Press), June 1991.
34. Solomon J. Buchsbaum, "Report of the Fusion Review Panel of the (DOE) Energy Research Advisory Board," June 1980, stating, in part, "As a result of this progress, the U.S. is now ready to embark on the next step toward the goal of achieving economic fusion power: exploration of the engineering feasibility of fusion. The engineering program should augment the continuing basic work in fusion research and related technology. Such work is indispensable to the success of the fusion program."

NN