Historical Perspective on the United States Fusion Program

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Progress and Policy is traced over the approximately 55 year history of the U. S. Fusion Program. The classified beginnings of the effort in the 1950s ended with declassification in 1958. The effort struggled during the 1960s, but ended on a positive note with the emergence of the tokamak and the promise of laser fusion. The decade of the 1970s was the "Golden Age" of fusion, with large budget increases and the construction of many new facilities, including the Tokamak Fusion Test Reactor (TFTR) and the Shiva laser. The decade ended on a high note with the passage of the Magnetic Fusion Energy Engineering Act of 1980, overwhelming approved by Congress and signed by President Carter. The Act called for a "$20 billion, 20-year" effort aimed at construction of a fusion Demonstration Power Plant around the end of the century. The U. S. Magnetic Fusion Energy program has been on a downhill slide since 1980, both in terms of budgets and the construction of new facilities. The Inertial Confinement Fusion program, funded by Department of Energy Defense Programs, has faired considerably better, with the construction of many new facilities, including the National Ignition Facility (NIF).

I. INTRODUCTION

Fifty years ago, the U.S., Britain and Russia 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.

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. Magnetic bottles, of various shapes, seemed the ideal solution.

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 US, Britain and Russia declassified their research.

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 degrees needed for fusion are now routinely achieved.

II. THE 1960s AND 1970s

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.

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, multi-million-fold improvements in confinement were demonstrated in ever larger, ever more powerful tokamak devices. Three large tokamak construction projects were begun during the energy crisis days of the mid-1970s: the Tokamak Fusion Test Reactor (TFTR) in the US, the Joint European Torus (JET) in England, and the Japan Tokamak (JT-60) in Japan. All three have achieved plasma conditions approximating "scientific breakeven," 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 is still operating, but TFTR operations were terminated in 1997 by instructions from a budget-cutting Congress. By the mid-1990s, over 10 million watts 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 US Energy Research and 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 US "energy crisis" was coming to an end, as proclaimed by President Reagan upon 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, though 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, called the International Thermonuclear Experimental Reactor (ITER), became a major international venture of the European Union, Japan, Russia and the US. A comparison of the funding requirements, as postulated in the 1976 plan, to actual funding received (in $1978) is shown in Figure 1. Also shown are funding levels proposed around 1990 by several review panels.

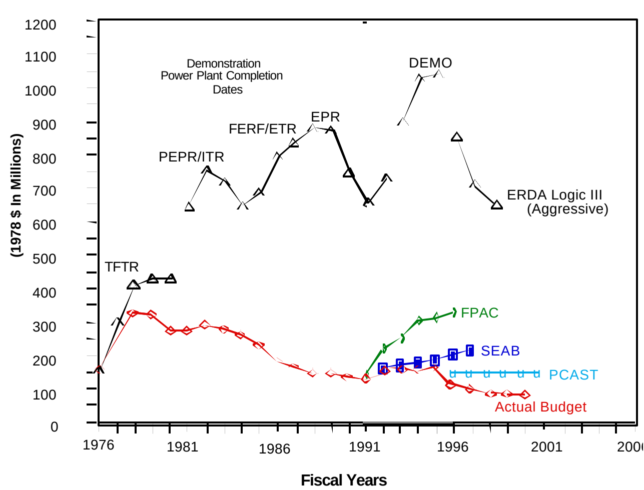

Figure 1. Comparison of projected needs vs. actual budgets (1978 $M)

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 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." If this is repeated frequently in a chamber, power plants can be envisaged and have been designed. Progress in inertial confinement has been systematic. The multi-billion dollar 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 around 2010. Programs are underway to develop repetitively pulsed lasers, particle beams and pulsed X-ray sources for possible power plant applications.

III. THE 1980s AND 1990s

As funding for fusion and other energy programs declined during the 1980s, US fusion program managers attempted to keep the tokamak program vigorous by reducing funding for other magnetic approaches. Though 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 US 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 report 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. If the CIT had been constructed, it is likely that ignition would have been achieved in magnetic fusion by now.

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, the Congress cut the US fusion budget from $365 million in FY1995 to $244 million in FY1996, 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 remaining ITER Parties have continued discussions on project implementation and are still hoping for siting and construction decisions. Japan and France are 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, DOE convened a meeting October 22-24, 1996 of some US fusion personnel in Leesburg, Virginia with the aim of further "restructuring" the US fusion program from an "energy" program into a "science" program [10]. This group, in a letter to DOE dated November 3, 1996, recommended a “three-fold 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, 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 US fusion program is a skeleton of what it once was.

IV. 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 Prof. John Holdren, Harvard University, who had previously chaired a 1995 PCAST panel on fusion [12].

For fusion, the panel recommended gradual increases from the then $232 million level to a level of $328 million in 2003. They 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 Panel said, "The present funding level of $230 million is too low in the view of the PCAST Energy R&D Panel; it 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; and canceled the next major U. S. plasma science and fusion experiment. It also limited resources available to explore alternative fusion concepts."

Despite these recommendations from PCAST, fusion funding remained essentially flat. Many scientists, both within the magnetic and inertial fusion factions, focused their planning efforts on "next step options" and development pathway roadmaps during 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, Wisconsin, during the week of April 27, 1998 [13]. The meeting, "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." Lawrence Livermore Lab Associate Director for Lasers Mike Campbell said we must "address 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. He also noted that an energy path for inertial fusion "can leverage investment by DOE Defense Programs."

The plan 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 - 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. Around 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 around 2023 to construct an IFE demonstration power plant at a total project cost of about $3 billion.

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

The inertial fusion energy "roadmap" proposal stimulated leaders of the magnetic fusion energy community to think in similar fashion and soon there was a combined "roadmap" being proposed. 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 US 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].

V. 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."

The SEAB Fusion Task Force, chaired by Richard Meserve, made its report on August 9, 1999 [16]. The Task Force stated, "It 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."

The DOE, through its FESAC, subsequently produced several comprehensive program descriptions and "integrated planning" documents [17, 18, 19]. The “Priorities and Balance Report [17]” established a series of five, ten and fifteen year goals, and a set of associated objectives, for the fusion program.

In July of 1999, more than 300 physicists from across the United States and eleven other countries met for two weeks in Snowmass Village, Colorado, to discuss the present state of the U.S. fusion energy sciences research 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." Importantly, 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; however, the work accomplished has had a significant effect on the directions of the US fusion program. A second "Snowmass Meeting," focused on Burning Plasmas, was held in July 2002 [21].

Despite the obvious interest in fusion energy applications by both the SEAB, PCAST and most members of the US fusion community, fusion continued to be viewed as a "science program" at the Office of Management and Budget. Speaking at Fusion Power Associates annual meeting on October 19,1999 [22], OMB fusion budget examiner Dr. 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."

In response to questions, Dr. Holland made the following additional comments: "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 above view remains the basis for Executive Branch fusion policy, though high level policy statements would lead one (erroneously) to conclude that a serious effort is underway to develop both the science and technology for fusion electric power applications.

VI. NATIONAL RESEARCH COUNCIL STUDY

In April 2001, the National Research Council (NRC) of the National Academies finished a study on the quality of the U. S. fusion science program [23]. The DOE had requested the study four years earlier. The study was performed by a panel chaired by Dr. Charles Kennel, Director of the Scripps Institute of Oceanography, a highly respected plasma scientist in his own right and 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 aimed at strengthening 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 states, "Fusion research carried out in the United States under the sponsorship of the Office of Fusion Energy Sciences (OFES) has made remarkable strides over the years and recently passed several important milestones." It states, "The Committee concludes, therefore, 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 committee report states, "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," though nowhere in the report do they provide arguments to support that assertion.

The Committee acknowledged that "Consonant with its charge, the committee has 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."

VII. NEDP REPORT

Early in his new administration, which began in late January 2001, 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, issued on May 17, 2001, focuses primarily on near- and mid- term energy sources, conservation and efficiency [24]. However, the report 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, 2002, Senator Larry Craig (R-ID) and Senator Dianne Feinstein (D-CA) introduced S. 1130 [25], "The Fusion Energy Sciences Act of 2001" in the Senate. The bill was virtually identical to a bill introduced in the House on May 9th by Congresspersons Zoe Lofgren (D-CA) and George Nethercutt (R-WA) [26]. The latter subsequently passed the House as part of a broader energy bill but has not passed both houses of Congress. The bill calls 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 US 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 to higher values have chosen to try to convince policymakers 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, some scientists have looked at other, less expensive experimental facilities that might address the science of burning plasmas.

VIII. BURNING PLASMA

A series of "burning plasma physics" workshops were held during 2000-2002 [27] and a FESAC panel completed a study of these issues and options [28].

In transmitting the panel's report to DOE, the FESAC said, "FESAC fully endorses the recommendations of the Burning Plasma Panel. 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." Prof. Richard D. Hazeltine (University of Texas at Austin) chairs the FESAC. Prof. Jeffrey P. Freidberg (MIT) chaired the Burning Plasma Panel. The Panel found that "a burning plasma experiment is the crucial next step in establishing the credibility of magnetic fusion as a source of commercial electricity," and that "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."

The Panel claimed that "a burning plasma experiment in a tokamak configuration is relevant to other toroidal magnetic configurations," and that "much of the scientific understanding gained will be transferable."

The Panel stated that "a burning plasma experiment, either international or solely within the U.S., will require substantial funding -- likely more than $100 million per year," and recommended that these funds "should arise as an addition to the base Fusion Energy Sciences budget." The Panel recommended that the U.S. "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 construction of a burning plasma experiment."

Although the Panel stated that "sufficient scientific information is now in hand 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," the Panel recommended that the U.S fusion community hold a "Snowmass" workshop in the summer of 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, followed by a National Research Council panel review to be completed by Fall 2003, followed by a DOE recommendation to Congress in July 2004. This (not surprisingly) is the same schedule called for in the House-passed legislation.

IX. ANOTHER LOOK AT ITER

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

Delegations from Canada, the European Union, Japan and the Russian Federation met in Toronto the week of November 5 to begin formal negotiations on the joint implementation of the ITER project. The Toronto negotiations were the first in a series that was expected to lead, by the end of 2002, to an agreement on the joint implementation of ITER [30]. 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] from US Energy Secretary Spencer Abraham to House Science Committee chair Sherwood Boehlert, the Secretary stated, "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 to him from Boehlert and ranking minority member Ralph Hall 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 towards ITER." He said, "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." The U. S. rejoined ITER on January 30, 2003.

X. 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 criteria 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 power plant design viewpoint. 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 (ICC)" workshops have been held during 2000-2002 to explore these concepts [27].

Inertial confinement fusion is receiving significant funding from DOE's weapons program as part of its "Stockpile Stewardship" program. As indicated previously, a large laser facility, the "National Ignition Facility (NIF)" is under construction. Congress has added additional funds, not asked for by DOE, to develop "high average power" lasers capable of pulsing several times per second, and z-pinch technology 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.

The budgetary history of the U. S. fusion program (in $2003) is shown in Figure 2. The budget and policy “high point” for magnetic fusion (OFES) came around 1980, with the construction of TFTR and the passage of the Magnetic Fusion Energy Engineering Act of 1980; the “low point” came in the late 1990s with the termination of TFTR and the U. S. withdrawal from ITER. The budget and policy for inertial confinement is currently at a high point, with construction of NIF and with Congressional add-ons for driver development.

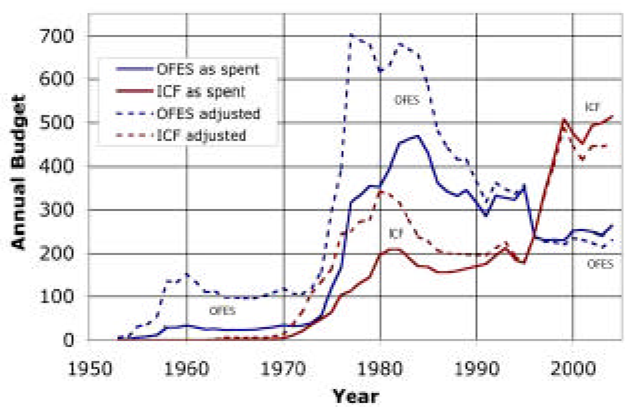

Figure 2. History of the U. S. fusion budget.

XI. CONCLUSIONS

Fusion research has been underway for a little over fifty years. Some believe that commercial fusion power is still another fifty years away [30]. Under present US government policy, there is no timetable for fusion. However, if 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].

Since 2000, the USDOE budget and policy for fusion has been inconsistent with the recommendations of its Fusion Energy Sciences Advisory Committee, which recommended a program in which science and technology were in balance, as also were the efforts on magnetic and inertial fusion energy. Current policy needs to change to bring these program elements back into balance.

The prospects for both magnetic fusion energy and inertial fusion energy would be markedly improved if the Executive Branch recognized (in its budget allocations and not just in its rhetoric) that engineering sciences, technology development , systems analysis and plasma science are all essential elements of a balanced fusion effort.

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