A Plan for the Development of Magnetic Fusion Energy

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The purpose of this plan is to identify a goal and a timely, cost-effective strategy to demonstrate fusion as a viable power source and to enable the US to benefit from its commercialization.

prepared by

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Executive Summary

Fusion energy should be a long-term vital part of the US National Energy Strategy.

Fusion may be the safest and most environmentally acceptable source for meeting future base-load electricity needs.

Fusion fuel supply is widely available and essentially inexhaustible.

Good progress has been made in fusion research towards an energy producing system.

Plasma science advances have improved plasma control and confinement (concept improvement), e.g.:

Plasma pressure limits are well understood; modified configurations of magnetic field are extending these pressure limits.

Non-inductive methods for driving current in the plasma have been developed; agreement between theoretical and experimental efficiency give confidence in extrapolated performance.

Self-controlling properties of magnetoplasmas have been discovered; this allows larger currents to heat the plasma and may eliminate the need for external heating in some magnetic field configurations.

Advances in fusion technology have been made in superconducting magnets, particle beams and radio-frequency energy for plasma heating, control of plasma-wall interactions, tritium processing, development of low-activation radiation-damage resistant materials, etc.

More than a ten-thousand fold improvement of power gain (fusion power output relative to power input to plasma) has been achieved in the past 15 years. Experiments (TFTR and JET) have operated at near-breakeven conditions that would have produced about 10 MW of fusion power if tritium had been used.

A short-pulse burning plasma experiment (CIT) is being designed to study the physics and operational behavior of largely self-heated plasmas producing 100 - 500 megawatts of fusion power.

The International Thermonuclear Experimental Reactor (ITER) conceptual design will be complete by the end of 1990. Designed to produce about 1000 megawatts of fusion power, ITER would test long-pulse (over 200 seconds and ultimately steady-state) burning plasmas and develop the technologies required to handle the heat and utilize the neutrons from fusion reactions to breed tritium.

Goal: **The goal of the US fusion program is to demonstrate early in the 21st century that fusion is a practical, safe, reliable, and environmentally attractive energy source.**

Strategy:

1. Develop plasma-confinement-concept improvements, plasma technologies, and materials needed for practical fusion applications in a core program of science and technology.
2. Construct a burning plasma experiment (CIT) in the US to provide physics information and operating experience for an engineering test reactor, and contribute to the design of a fusion power demonstration facility.
3. Participate in an international engineering test reactor (ITER) to acquire experience with long-pulse burning plasmas and nuclear technologies needed to design a fusion power demonstration facility.
4. Construct a fusion power demonstration facility (DEMO) in the US, which would produce net electric power and provide a basis for fusion commercialization.

This strategy was selected to reduce US cost by use of well-established international collaboration, while retaining for the US the benefits of technological spin-offs and ultimately the commercialization of fusion. To realize these benefits, a strong national program must be maintained with increased involvement of US industry.

Budget and Schedule

The total integrated cost of the US program from its beginning to the operation of a demonstration reactor would be about \$36 billion (in 1990 dollars) according to estimates by ERDA in 1976. By comparison \$29 billion is estimated here, assuming a more focused plan that relies more heavily on international collaboration. Since about \$11 billion (1990 dollars) have been spent by the US through fiscal year 1990, the majority of the investment (\$18 billion) remains to be made to meet the goal of fusion power.

To meet a nominal 2020 operational date for a fusion power demonstration facility, the annual budgets need to be increased to about \$600 million per year by the mid-1990s, and remain at that level (in 1990 dollars) until construction of the DEMO starts.

include extending the power-producing capabilities to longer pulses or steady state, breeding of tritium at adequate rates, and efficiently converting the fusion power into electric power.

D. Advantages of Fusion

The fuel supply for fusion is essentially inexhaustible. Deuterium, one of the basic fusion fuels, is abundant in natural water and is easily extracted. The other component of the "standard" fuel mixture, tritium, does not occur naturally, but it can be produced in the fusion reactor by absorbing the neutrons produced by the fusion reaction in lithium. Abundant domestic supplies of lithium are available.

Compared to fossil and fission, fusion offers the prospect of reduced environmental and safety hazards . The byproducts of the fusion process are helium-4, helium-3, tritium, and energetic neutrons. Tritium is radioactive and, therefore, requires special handling, but it is one of the least hazardous forms of radioactivity. Since tritium is a fuel, it is returned to the reactor to be "burned." Helium is the only by-product that is not retained, and it is both useful and benign.

While fusion relies on a nuclear process, there is no possibility of a nuclear "runaway" accident. The power plant will require shielding to protect power-plant workers from the energetic fusion neutrons. The neutrons will also induce radioactivity within the fusion reactor structure, leading to after-heat and the need for waste storage. However, the biological hazard from the activated materials would be much smaller than that associated with a fission reactor of comparable output power, and storage requirements would be less stringent. In addition, proper choice of materials and configurations allows the after-heat to be handled passively. With the use of specially developed low-activation materials, the activation can be reduced to even lower levels.[2]

"Advanced" fuels offer potential advantages over the "standard" fuel. None of the advanced fuels require the breeding of tritium. Using pure deuterium as a fuel, for example, simplifies the fuel supply and handling procedures. In addition, the deuterium-helium-3 fuel would significantly reduce the neutron-induced activation and damage. Unfortunately, helium-3 is found naturally in abundance only on the moon. Demonstrating fusion using the standard deuterium-tritium fuel is still the appropriate first goal because achieving the plasma temperature and confinement needed for any advanced fuel is more difficult.

In summary, deuterium-tritium-fueled fusion offers advantages over existing energy technologies in the areas of fuel supply and environmental and safety features. Further improvements in confining plasmas could eventually lead to additional advantages offered by advanced fuels.

E. Progress in Fusion

The initial optimism about fusion in the 1950s was replaced in the early 1960s by serious doubts that net energy could ever be achieved with magnetic confinement. The mechanisms by which heat escapes from the plasma across the magnetic field were much more numerous and complex than originally anticipated. The success in the Soviet Union with the tokamak concept in 1967 rekindled hope, but studies of future reactors initiated in the early 1970s pointed out the enormous advances that would still be required in science and technology to demonstrate a fusion power source.

The continued success with the tokamak and the oil crisis were major factors in the fusion funding increase that began in 1974. This increase enabled the construction of several important facilities that have resulted in dramatic advances over the past 15 years, as shown in Fig. 1.

In 1976, the US Energy Research and Development Administration (ERDA)[3] published a plan to develop fusion. It was estimated at that time that the total cost to progress to demonstration-reactor operation would be, depending on the funding pace, about $36 billion (FY 1990 dollars) including the $3 billion that had been spent through 1976. However, the plan was not funded. Instead of increasing to even the lowest-budget case assumed in the 1976 plan, in which the demonstration reactor was to operate in 2005, the funding has dropped to less than half of the FY 1977 level. Since the beginning of the fusion program, about $11 billion total (in FY 1990 dollars) will have been expended at the end of fiscal year 1990, less than a third of what was projected to be needed to demonstrate fusion power.

A Plan for the Development of Magnetic Fusion Energy

I. MAGNETIC FUSION AND NATIONAL ENERGY POLICY

A. Need for Alternative Sources

Meeting near-term world energy needs will require improvements in energy efficiency and conservation. However, even assuming such improvements, conservative estimates of world population and energy demand growth show the world will soon need new and replacement central-station power plants and increasing amounts of fuel for the transportation sector. Fusion energy is one of only a few potential large sources of energy available to mankind to meet future needs. It may be the central-station power source capable of meeting these needs in the most environmentally acceptable manner.

The role of fusion in national energy policy was reviewed recently by a committee established by the National Research Council. In their report, they state, "The committee concludes that a prudent long-term energy strategy for the United States requires that alternative electric energy supply technologies be researched, developed and demonstrated. A diversified array of alternatives is needed as insurance against the vulnerability of existing alternatives, such as coal and nuclear fission."[1]

Thus, fusion should be seen as a complementary part of an energy policy that recognizes the impending growth in energy demand and the environmental consequences associated with fossil fuels, cost and supply difficulties with oil, public acceptance problems with today's nuclear power, and geographical limitations inherent in large-scale solar energy production.

B. Fusion Power Applications

The main application foreseen for fusion energy is the production of base load electricity. Fusion can also be used in fuel factories for the production of fissile fuel in support of the long-term fission energy supply system. Thus, fusion has a role as an energy source independent of the scale of the fission supply system. In addition, fusion can contribute to the generation of hydrogen and other synfuels.

C. Technical Features and Requirements for Magnetic Fusion

The fusion process combines the nuclei of light atoms (*e.g.* hydrogen or helium), which produces heavier nuclei and releases energy. For this process to proceed at useful rates, the fuel must be heated to about 100 million degrees. At these temperatures, the electrons are stripped from the atoms; the resulting gas of free electrons and nuclei, called a plasma, can be controlled using magnetic fields.

The sun and stars are powered by this fusion process. In these large bodies, gravity confines the hot plasma and allows the fusion process to be sustained. In magnetic fusion, magnetic fields are used to confine the plasma and to provide insulation between the hot plasma and the walls of the surrounding vessel. To allow net power generation, the magnetic fields must provide adequate insulation to ensure that the fusion process heats the plasma faster than the heat can escape.

The fuel that combines or fuses most readily is a 50-50 mixture of two isotopes of hydrogen called deuterium and tritium. This "standard" fuel mixture requires less insulation by the magnetic field and lower plasma temperatures than other possible "advanced" fuels such as pure deuterium or a mixture of deuterium and helium-3.

While reactor-level temperatures and energy confinement have been achieved separately, progress towards simultaneously achieving the needed conditions for net power continues to depend on both improved scientific understanding and technological development. Scientific and technological expertise is essential to design and operate systems that can produce the appropriate magnetic fields, heat and fuel the plasma, handle the heat load on the vessel walls, *etc.*

In addition to demonstrating that a magnetically confined plasma can produce net fusion power, other developments will be required to demonstrate a practical fusion power source. These developments

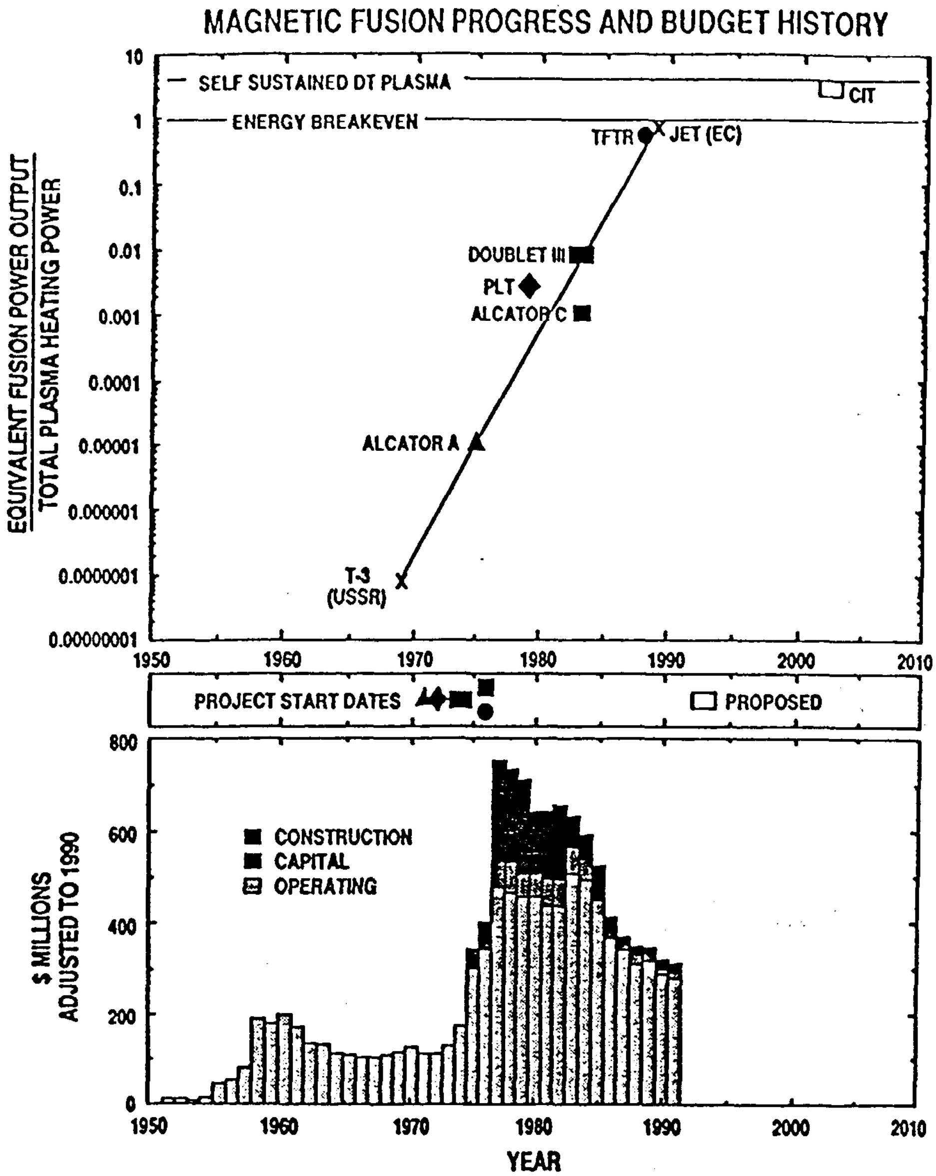


Fig. 1. Comparison of progress in equivalent-fusion-power gain[4] with the US magnetic fusion budget profile estimated in 1990 dollars. The progress in the 1980s was made possible by the investment in new facilities made during the peak funding years.

The technical progress has been remarkable during the past 15 years. This progress has largely been achieved in facilities that were initiated over a decade ago, before the funding began to drop. For example, in 1988, the TFTR experiment at Princeton produced an equivalent fusion power gain of about 0.5. This means that if a 50-50 deuterium-tritium mixture had been used instead of pure deuterium, the fusion power produced by the plasma would have been half of the power used to heat the plasma. More recently, the JET experiment in Europe achieved an equivalent fusion power gain of about 0.8. As shown in Fig. 1, this power gain has been increased by a factor of more than 10,000 since that ERDA planning document and cost estimates were made fourteen years ago. Using deuterium fuel, TFTR and JET experiments have produced up to 50 kilowatts of fusion power. JET has produced 100 kilowatts using deuterium and helium-3. If the deuterium-tritium mixture were used instead, these experiments would produce tens of megawatts of fusion power.

Technological advances have been essential to the progress of fusion. As a specific example, new plasma heating and fueling technologies enabled TFTR to achieve a 300 million degrees peak plasma temperature, an entirely acceptable temperature for a power plant. More generally, advances in fusion technology have been made in superconducting magnets, particle beams and rf energy for plasma heating, control of plasma-wall interactions, tritium processing, development of low-activation radiation-damage-resistant materials, *etc.*

Along with the advances in technologies and plasma performance scientific understanding has improved through an iterative process involving theory, computations, and experimental data. This understanding is important in advancing plasma conditions toward those of a practical power source. For example, a large plasma pressure is desirable to maximize the fusion power for a given strength of magnetic field. Progress in theory now allows pressure limits to be predicted quantitatively, and modified configurations of magnetic field (stellarators and variations of the tokamak geometry) have been studied and have shown increased plasma pressure.

Another scientific success is the development of methods for driving currents in the plasma that do not depend on magnetic induction. The inductive technique, used to drive currents in tokamaks and reversed field pinches (stellarators do not require driven currents), cannot be extended to steady state as desired in a reactor. Both neutral beams and radio-frequency power have been used to provide non-inductive current drive in tokamaks, and the data are in good agreement with the theoretically predicted efficiencies. The understanding of these current drive processes allows the prediction of performance in other devices.

A third example of progress in plasma science is the discovery that some magnetic configurations have intrinsic self-controlling properties that permit large current in the plasma for a given confining magnetic field. Heating by the current may be adequate to produce fusion temperatures without the need for external heating. These self-controlling properties may also allow more efficient non-inductive techniques for driving currents. This motivates preliminary studies on both reversed-field pinches and tokamaks.

These are only three examples of scientific progress, but they illustrate that studying variations of the basic toroidal magnetic field configuration, *e.g.*, tokamaks, stellarator, and reversed field pinches, yields new understanding that is mutually beneficial. This diversity enhances progress in the fusion program and is important in achieving the goal of a practical power source.

F. Assessment of the Current Status of Fusion

Based on this scientific and technical progress, a burning plasma experiment (CIT) is being designed to produce over 100 megawatts of fusion power (for a few seconds) from a largely self-heated plasma. The improvements required to progress beyond this experiment to a practical power system include the ability to sustain the self-heated plasma, to extract the heat from the plasma while controlling plasma impurities and minimizing vessel damage, to breed tritium, and to do it with a reliable cost-effective design that encourages public and utility acceptance. The issues of economics, safety, and environmental impact are not just engineering questions; scientific understanding and improved approaches to plasma confinement can significantly improve the fusion product. Therefore, integrated progress in science, engineering, and materials is needed in order to achieve the goal of practical fusion power.

In summary, excellent progress has been made with the funds that have been provided, and the prospects for a practical fusion power source are more soundly based than ever before. However, continued progress is hampered because construction funds were not invested in starting new major[5] facilities over the past decade, as indicated in Fig. 1. New facilities are needed to capitalize on past progress and enter into the burning-plasma[6] regime, the plasma physics regime required in a fusion reactor.

G. Cost of Development

The total cost estimated for the plan presented in Section III of this document (about $29 billion) is less than the 1976 estimate, because the present plan is more focused and relies much more on international collaboration. However, even with this lower-cost plan, a majority of the investment (about $18 billion) remains to be made.

The capital investment required for new power-plant construction in the US alone during the first half of the 21st century is about $4 trillion.[7] The total cost projected for fusion development is less than 1% of this figure and represents an important investment for the future. Government funding is appropriate, at least to the power demonstration facility stage, because industry cannot provide the capital investment necessary for the long-term development of fusion.

H. National Policy

Fusion has long been recognized as a major energy candidate for the future. At the 1985 Geneva Summit Meeting, President Reagan and General Secretary Gorbachev "emphasized the potential of the work aimed at utilizing controlled thermonuclear fusion for peaceful purposes and, in this connection, advocated the widest practical development of international cooperation in obtaining this source of energy, which is essentially inexhaustible, for the benefit of mankind." The policy has been reconfirmed at subsequent summit meetings, and has resulted in the establishment of a joint, multi-national effort, under the auspices of the IAEA, to design the world's first fusion engineering test reactor. The conceptual design activity for this International Thermonuclear Experimental Reactor (ITER) was committed to in early 1988 and is being carried out by the USSR, Japan, the European Community, and the US. This activity will be completed at the end of 1990. The next step is the engineering design. To maintain continuity a decision by the US and other parties to commit to the engineering design phase must be made soon. Assuming success in the engineering design activity, the mid-1990s will be appropriate for deciding whether or not to commit to construct ITER.

If ITER operates soon after the turn of the century, and if the US participates in ITER as a complement to a strengthened national fusion science and technology program, a fusion power demonstration plant can be operational in the US in the first quarter of the next century.

Considering fusions potential and the demonstrated progress, fusion should be a vital element in the National Energy Strategy. A long-term commitment is needed in light of the estimated timescale and cost. In the near term, the magnetic fusion program, with its sophisticated scientific and technological activities, will continue to foster technical education and technological spin offs that benefit this nation.

II. GOAL AND STRATEGY

The goal of the US fusion program is to demonstrate early in the 21st century that fusion is a practical, safe, reliable, and environmentally attractive energy source.

Strong national commitment and management will be required to accomplish this goal. The strategy (see Fig. 2.) has the following elements:

1. Develop plasma-confinement-concept improvements, plasma technologies, and materials needed for practical fusion applications in a core program of science and technology.
2. Construct a burning plasma[6] experiment (CIT) in the US to provide physics information and operating experience for an engineering test reactor, and contribute to the design for a fusion power demonstration facility.
3. Participate in an international engineering test reactor (ITER) to acquire experience with long-pulse burning plasmas and nuclear technologies needed to design a fusion power demonstration facility.
4. Construct a fusion power demonstration facility (DEMO) in the US, which will produce net electric power and provide a basis for fusion commercialization.

These elements address the essential issues required to achieve the goal, but they are not unique. The details of the strategy, such as the sequence of facilities leading to the DEMO, location, schedules, and funding profiles could be changed. This particular strategy has been selected to reduce the total US program costs by utilizing international collaboration, while retaining appropriate benefits for the US.

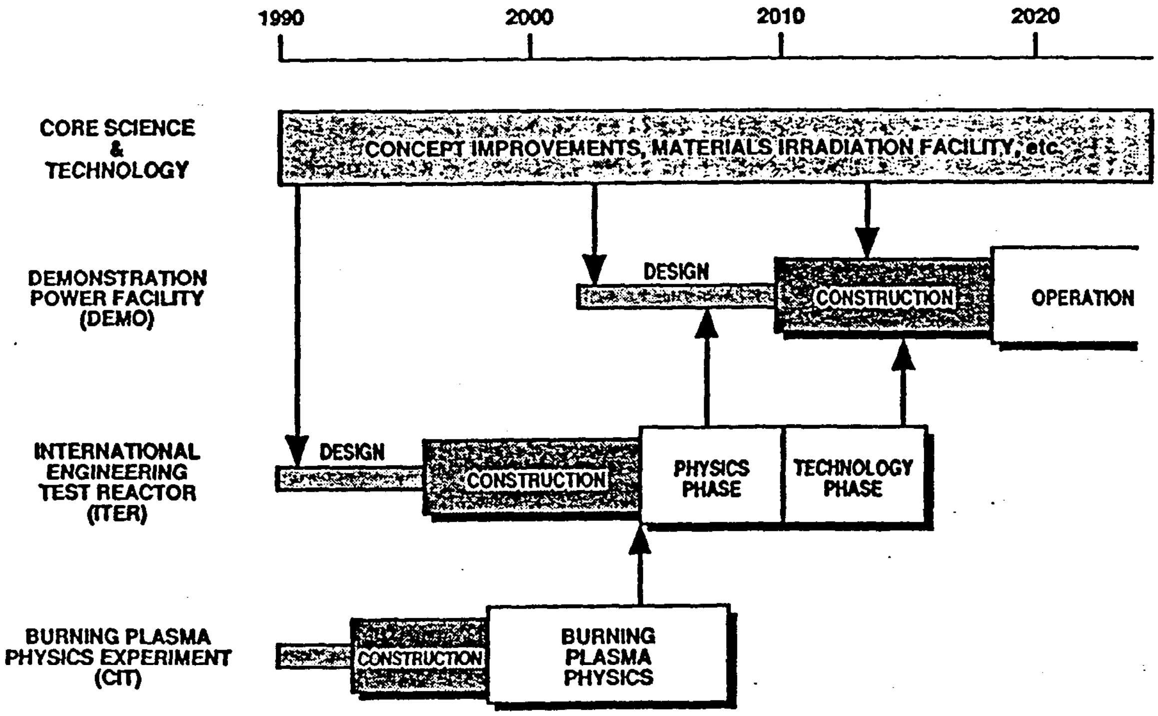


Fig. 2. Major elements of the program strategy.

This strategy builds on the major, well-established international collaborations between the US and Japan, the Soviet Union, and the European Community. To date, these collaborations have yielded numerous examples of mutual benefit, including joint planning and task sharing, joint construction and operation of facilities, expansion and confirmation of data bases, and flow of ideas and techniques. These benefits enhance the progress in fusion per dollar invested by the US.

To be a strong partner in international collaborations and to benefit from the results of the research, the US must maintain a strong domestic program. Integrated involvement by US industry, national laboratories, and universities is needed to ensure the US has the trained people and industrial capability in place for the ultimate purpose of commercializing fusion power. Particularly important is a stronger involvement by US industry. The declining budgets over the past decade and the absence of any new construction of major facilities has all but eliminated industry from the US fusion program. In contrast, the Japanese and European programs have stronger industrial involvement. The burning plasma experiment, appropriately funded and managed, will begin the process of attracting industry back to the fusion program. Industrial involvement during the ITER collaboration will further the process and provide an opportunity for US industries to become competitive with those in Europe and Japan. Since the mission of the DEMO will be to prepare for commercialization, its success will hinge upon leadership and expertise in US industry. The proposed strategy promotes the orderly transfer of fusion technology from national laboratories and universities into an industrial setting. This is essential both for the US to commercialize fusion power and to take advantage of the technological spin-offs that result from fusion research.

A. Core Program

The multifaceted core program addresses several issues that are essential for the development of fusion. These include the development of low-activation materials, the development of reliable plasma heating, fueling and impurity control technologies that are capable of steady-state operation, and the development of a variety of improvements in the control and confinement of the plasma. These improvements include the simultaneous achievement of increased plasma power density, reduced plasma transport, disruption control, and plasma sustainment (*e.g.* efficient non-inductive current drive). This collection of improvements will be referred to as "confinement-concept improvement," or in abbreviated form "concept improvement," in this document.

Low-activation materials, plasma technologies, and confinement-concept improvements are being developed on a variety of existing facilities in the world program. A few facilities now under construction will allow continued progress in some areas. However, three new larger facilities are needed over the next decade to develop data that will be helpful to the international engineering test reactor and essential for the DEMO. These facilities, in order of their anticipated start dates, are:

1. A 14-MeV neutron source to develop radiation-resistant low-activation materials.
2. A steady-state (or long-pulse high-duty-factor) non-burning-plasma facility to make an integrated test of technologies and associated physics in a tokamak with advanced features, including efficient current drive and impurity control.
3. A confinement-concept-improvement facility to make an integrated test of the most promising magnetic field configuration and all required technologies at reactor-level performance.

As indicated in Fig. 3, these facilities will be constructed within an essentially flat core-program budget as existing facilities and activities provide the required data and complete their missions. The materials development made possible by the neutron source will contribute to an engineering test reactor, and will give necessary data for the DEMO mission of demonstrating the durability and low-activation features essential for practicality and environmental attractiveness.

The steady-state (or long-pulse) facility will test the physics and technology needed to achieve sustained, high-quality plasma performance important to both an engineering test reactor and to the DEMO. The magnetic configuration will most likely be a moderate-scale superconducting tokamak with some advanced design features. The testing of these features will allow their incorporation into the DEMO design.

The concept-improvement facility will allow a major test of the most promising variation of the magnetic field configuration selected from the more advanced types of tokamaks and alternate concepts (*e.g.* stellarators and reversed-field pinches). The decision to proceed at that time (about 2000) with the construction of the facility will depend on the projected improvement in reactor performance compared with that projected from the tokamak design being tested in the steady-state device. If warranted, the concept-improvement facility could be extended to a full deuterium-tritium burn test and the DEMO could be delayed by about five years to take advantage of the improvements. If the DEMO construction were not delayed, the results of the improved confinement-concept test could still form the basis of a second generation reactor.

B. Burning Plasma Experiment

The next step for fusion development is a burning plasma experiment in which the physics behavior of self-heated plasmas will be studied and the production of substantial amounts of fusion power will be demonstrated. Present fusion experiments will not elucidate the physics of plasma self-heating by the alpha particles (helium-4) generated by fusion reactions. The attainment of this knowledge as soon as possible is an important factor in optimizing the fusion development program and confirming the design and operating characteristics of the ensuing steps in the program. Scientific understanding of the tokamak concept is sufficient at this time to allow commitment to a burning plasma experiment, and the US fusion community has consistently recommended this as the next major fusion experiment in this country.

The proposed CIT experiment is being designed to meet the goals of a burning plasma experiment. The CIT objective is to demonstrate a high fusion power gain at reactor power densities while producing more than 100 MW of fusion power. It will have sufficient fusion power gain and pulse length (about 5 seconds) to extend the science of burning plasmas well beyond that possible in TFTR and JET. It will determine the confinement physics, operational limits, and alpha-particle dynamics in the self-heated regime. The CIT experiment will also demonstrate heating, fueling, and plasma handling techniques necessary to produce self-heated fusion plasmas. Results from the experiment will be important for efficiently achieving full operation of a larger, more complex engineering test reactor.

The national scope of the CIT project and the significance of its mission will make it an important element for maintaining a strong US program during the next decade of extensive international collaboration. With appropriate funding and management, CIT will be a vehicle for meaningful industrial involvement, a step towards ensuring that this nation benefits from the world-wide effort to develop fusion.

C. Engineering Test Reactor

The engineering test reactor and its supporting R&D will provide the capability to demonstrate the integration of a fusion burning plasma core and the nuclear technologies required to breed tritium and handle the neutrons and heat from a repetitive-long-pulse or steady-state burning plasma operation. It will be the first device in which the intensity and duration of the fusion-produced neutron flux will be in a reactor relevant regime. Such an experimental reactor is an important step between a burning plasma experiment and a DEMO. The program for this facility permits an assessment of engineering, cost, and maintenance issues essential to the design and operation of a fusion power demonstration facility.

The International Thermonuclear Experimental Reactor (ITER), which will have a completed conceptual design by the end of 1990, is intended to serve as the world's fusion engineering test reactor. It is being designed to produce at least 1,000 megawatts of fusion power. It has a large size to ensure high fusion power gain and long pulse length. Two operating phases are planned. The first phase will focus on the physics of high-fusion-power-gain plasmas with pulse lengths greater than 200 seconds. The second phase will focus on technology testing of systems to breed tritium, extract heat, etc. This phase requires high-duty-factor operation with much longer pulses. The ultimate goal is steady-state operation but at lower fusion power gains.

The confluence of two factors provides a unique opportunity for the US to commit to the ITER engineering design activity. First, a consensus exists in the world fusion community that an engineering test reactor is needed, and as the ITER conceptual design activity comes to completion, a consensus is building that the engineering design activity of ITER should be initiated and be aimed toward construction. Second, the ITER process has been developed through unique political leadership at the Summit level. If the US delays its commitment too long, the opportunity could be lost. Making such a commitment will be an important step in implementing the strategy advocated in this plan.

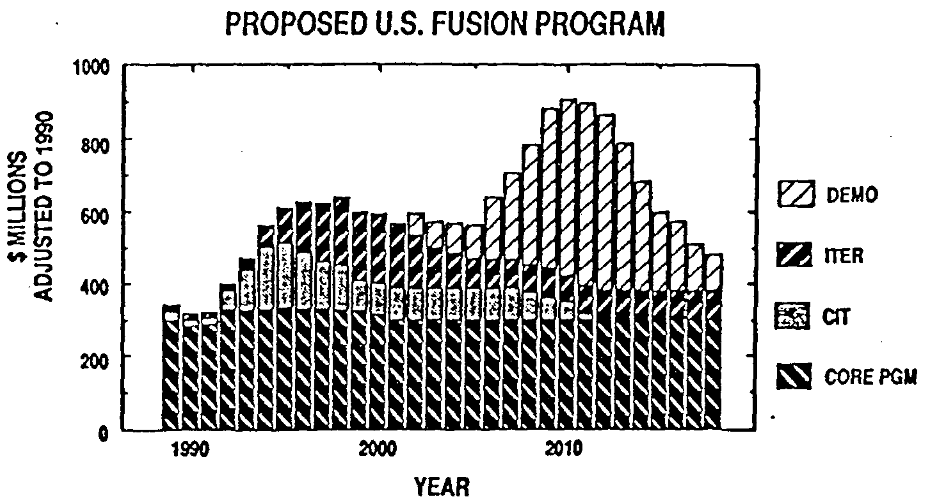
As already noted, strong involvement by US industry in the ITER process is an important step in preparation for the design and construction of a DEMO. Of course, if the US were to fund ITER unilaterally, then the US would have more control over the scope, design, and schedule of the project, and our industry would derive even greater benefit. Such an approach would require greater total cost for the US; the strategy of relying on international collaboration for the engineering test reactor step is advocated as the best balance between cost and benefit to the US.

D. Fusion Power Demonstration Facility

The fusion power demonstration facility (DEMO) will be a prototype power plant producing significant amounts of electricity from fusion reactions for the first time. Reasonable reliability and availability will be important in this prototype for commercial power production. Its purpose is to provide the basis for the subsequent commercialization of fusion by the private sector. Although the DEMO will not provide electricity at a cost that is competitive with existing power sources, such as coal and fission, it will provide the data and experience necessary to design a competitive plant. The DEMO will also demonstrate the safety and environmental features necessary to establish licensing procedures.

III. BUDGET SCHEDULE AND ASSUMPTIONS

A number of detailed studies have been performed that indicate the approximate budgets and schedules necessary to develop fusion. They show that a fusion power demonstration facility can be operational as early as the first quarter of the 21st century, depending on the budgets available and the timing of commitments to the needed facilities. To meet a nominal 2020 operational date, the approximate annual budgets need to be increased to about $600 M per year by the mid-1990s. Budgets remain at that level (in 1990 dollars) for about 10 years, until construction of the DEMO starts as shown in Fig. 3.



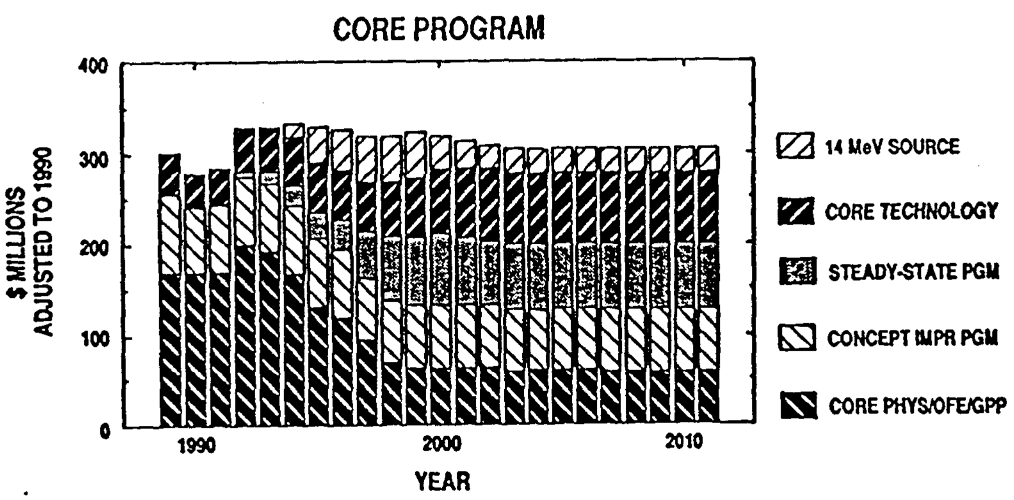


Fig. 3 (a). Budget profiles for the four elements shown in Fig. 2. (b) Evolution of the major core program activities. The three devices described in Section IIA are covered in the following budget categories: the 14-MeV source, the steady-state program, and the concept improvement program.

The budget profiles in Fig. 3 are consistent with the schedule shown in Fig. 2. The projected cost, from 1990 to DEMO operation, is about $18 billion in 1990 dollars. If the approximately $11 billion spent up through 1990 are added, the projection is less than the nominal 36 billion dollars estimated in 1976. The basis and assumptions for the major elements of this cost estimate are given below. These estimates are preliminary and are expected to evolve as the elements are better defined.

The budget profile and schedule for the burning plasma experiment construction and operation shown in Figs. 2 and 3 are the present estimates for CIT. The total construction cost is about $0.8 billion (excluding preconstruction costs) in 1990 dollars. Some foreign contributions might be anticipated but should not be depended on and are not assumed here.

The capital cost for ITER is $4.9 billion (in 1989 dollars) according to the estimate given in the October 1989 ITER Conceptual Design Report. Assuming that ITER is not sited in the US, and that all four parties participate and share the additional costs for design, project management, R&D, and diagnostics, the US would contribute an estimated $1.6 billion of the total construction costs.

The construction of the DEMO is estimated to be $4 billion (1990 dollars). This rough estimate assumes that cost-saving improvements will come from the core program as well as the R&D from ITER. The construction cost is assumed to be supplied by the government with the utility supplying the developed site. A larger cost sharing by the utility would be desirable, but is not assumed here.

The three facilities identified in the core program are estimated to cost in the neighborhood of $0.3 billion each. The funding is assumed to be supplied entirely by the US, but international collaboration could be pursued, particularly with regard to the 14 MeV neutron source. Cost sharing of both construction and operation is very appropriate for this user facility.

The essential task of educating the scientists and engineers needed to implement this fusion plan will largely be carried out in the core program, particularly the core physics and core technology components. While this need will persist, the profiles in Fig. 3 indicate that over the next decade the funding going to industry should increase dramatically, including a significant fraction of the core program and the majority of the program funding increase for CIT and ITER.

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2. J. P. Holdren, et al., "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy," Lawrence Livermore National Laboratory report UCRL-53766 (June 1989).

3. "Fusion Power by Magnetic Confinement Program Plan," ERDA-76/110, July 1976.

4. The power ratio Q* plotted in Fig. 1 is different from the usual power-gain ratio Q. The denominator of Q* includes the self-heating from the fusion-produced alpha particles while the denominator of Q is only the externally supplied heating power. The value of Q* is essentially identical to Q for ratios less than 1 (breakeven). However, above breakeven, Q goes to infinity as the plotted ratio Q* approaches 5. $Q^* = Q/(1+Q/5)$. The plot gives a more realistic impression of the improved performance required to achieve high gain.

5. A few moderate-scale facilities have been initiated during the past decade. For example the Alcator C-Mod and MTX are devices that were initiated to study issues important to next generation tokamaks such as CIT. Other facilities were initiated to advance the understanding of toroidal confinement concepts that have the potential of improved properties. These facilities include PBX-M (advanced tokamak), ATF (stellarator), and CPRF (reversed-field pinch).

6. A "burning plasma" is one that is self heated significantly by the fusion process.

7. The required investment depends upon the rate of growth for electricity demand. Assuming a growth of 2% per annum (see Chap. 3 of Ref. 1) the present US electrical capacity of 670 GW would grow to 2200 GW by 2050, which would cost $4.4 trillion to install for an estimated $2 billion/GW. These assumed values for growth and cost per GW are rough estimates, but the conclusion drawn does not depend critically upon the values assumed within factors of 2.

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