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The United States Magnetic Fusion Energy Program

August 1978

U.S. Department of Energy
Assistant Secretary for Energy Technology
Office of Fusion Energy
Washington, D.C. 20545

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The United States Magnetic Fusion Energy Program

August 1978

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TABLE OF CONTENTS

	<u>PAGE</u>
SUMMARY	i
I. POLICY	1
II. MAGNETIC FUSION ENERGY PROGRAM	3
A. GOALS	3
B. OBJECTIVES	3
C. STRATEGY	5
D. FUSION ENERGY APPLICATIONS	8
E. ENVIRONMENTAL OVERVIEW	11
F. SOCIO-ECONOMIC OVERVIEW	13
G. COST/BENEFIT CONSIDERATIONS	15
H. STATUS	16
I. PLANNING, COSTS AND SCHEDULES	20
J. MANAGEMENT	26
K. EVALUATIONS	28
L. COORDINATION	28
III. PHYSICS PROOF-OF-PRINCIPLE PROGRAMS	35
A. EXPERIMENTS LEADING TO TOROIDAL REACTOR SYSTEMS	38
B. EXPERIMENTS LEADING TO LINEAR REACTOR SYSTEMS	56
C. BASE PHYSICS PROGRAMS	69
D. BASE TECHNOLOGY	76
IV. MAJOR SCALING EXPERIMENTS	85
A. TOKAMAK FUSION TEST REACTOR	85
B. MIRROR FUSION TEST FACILITY	92
V. ENERGY PRODUCING EXPERIMENTAL REACTORS: DESIGN STUDIES AND LONG LEAD TIME TECHNOLOGY DEVELOPMENT	107
A. EXPERIMENTAL REACTOR DESIGN STUDIES	108
B. LONG LEAD TIME TECHNOLOGY DEVELOPMENT	117
VI. COMMERCIALIZATION: REACTOR DESIGNS AND SYSTEMS STUDIES ..	128
A. COMMERCIAL REACTOR DESIGNS	129
B. SYSTEM STUDIES	135

TABLE OF CONTENTS - continued

	<u>PAGE</u>
VII. ENHANCEMENT PROGRAMS	140
A. ACCELERATION OF PROOF-OF-PRINCIPLE PROGRAMS	140
B. ENHANCEMENT OF ENERGY PRODUCING EXPERIMENTAL REACTORS: R&D REQUIRED PRIOR TO CONSTRUCTION	141
C. ENHANCEMENT OF ENERGY PRODUCING EXPERIMENTAL REACTORS: INITIATION OF CONSTRUCTION	141
APPENDIX A ENHANCEMENT PROGRAMS	142

SUMMARY

The only known candidates for providing the bulk of long-term energy needs are fusion, solar and fission fuel breeders. These are all still in the development stage and, consequently, it is too early to precisely identify their relative advantages and disadvantages.

To assure that fusion will be available as one of the long-term options, continuation of a dedicated, research and development program is required to take fusion from its present state to a point where its commercial viability can be ascertained. This document describes the programs of the Office of Fusion Energy in magnetic confinement systems.

A. GOALS

The goal of the magnetic fusion energy program is to develop the use of fusion energy as a virtually inexhaustible energy resource for a variety of applications. The primary focus of the program towards this goal is to develop systems for the commercial production of central station electric power. A secondary focus of the program is to develop and evaluate other applications of fusion systems. Potential applications include (a) the production of fissile material, to extend uranium and thorium resources and thus to assure fuel supplies for fission reactors, (b) the production of synthetic fuels, such as hydrogen gas to be used directly or indirectly by the conversion of coal into liquid or gaseous fuels, and (c) the production of industrial process heat and heat for other end-use categories, such as residential/commercial space heating.

B. OBJECTIVES

To achieve the above stated goals, the program has established several objectives. The first of these is to develop a solid scientific and technical base so that the viability of various applications can be confidently assessed. A second objective is to construct and operate, when justified, major physics/engineering scaling experiments which will provide the data required for the

design of energy-producing prototype reactors. A third objective is to perform systems and conceptual design studies of energy producing systems. A fourth objective is to perform systems studies to help guide the R&D program towards a final product that will possess characteristics that maximize its beneficial impact on society. A fifth objective is to construct and operate, when justified, energy-producing experimental fusion reactors, which will provide the basis for commercialization.

The programs set forth herein are aimed at the achievement of the above goals and objectives in an expeditious manner, consistent with scientific/technical progress and the availability of funds. Documents such as this one will evolve and change as scientific, engineering/technology and commercial/economic/environmental analyses and progress proceeds.

C. STRATEGY

The program strategy is to proceed systematically through four stages of development, as shown in Figure 1: (1) Proof-of-Principle Programs, (2) Major Scaling Experiments, (3) Energy-Producing Experimental Reactors, and (4) Commercialization. Primary emphasis at this time is on stages (1) and (2) in which a solid scientific and technological base is being developed so that the viability of various applications can be confidently assessed. The stage of development entitled "energy producing experimental reactors" provides the bridge between fusion energy experiments and commercialization. The final stage, "commercialization", involves the design, construction and operation of those demonstration facilities necessary to prove the technical and economic feasibility of commercial fusion energy systems. During this last stage of development, significant private investment is anticipated, although a strong federal role may be necessary to facilitate the transfer of the technology from the public to the private sector.

At present, primary emphasis is placed on performing physics proof-of-principle experiments. In addition, two major physics/engineering scaling experiments are being constructed and operation will be initiated in the early 1980's. Also, design studies and long-lead time engineering activities related to energy-producing experimental fusion reactors and to commercialization

STAGES IN FUSION ENERGY DEVELOPMENT

FIGURE i-1

will be continued at an appropriate level. Although no energy producing reactors have as yet been initiated, the program continues to pursue this objective as funding may permit.

D. STATUS

Progress over the years in fusion has been steady. Fusion research has now reached a stage where both plasma temperatures and quality of confinement ($n\tau$) required for a reactor have been achieved separately in experiments designed for those purposes. The steps required to attain reactor operation can now be described in terms of known plasma behavior and near-term technology.

Scientific progress on the tokamak concept has been especially dramatic. Temperatures (T) up to 6.5 keV (70 million degrees) have been achieved, compared to the 5 to 10 keV predicted to be required respectively for breakeven and for operation of a tokamak fusion reactor. The quality of confinement needed for successful production of net energy from fusion, the product of density and confinement time ($n\tau$), has been raised tenfold during the past several years to the level $3 \times 10^{13} \text{cm}^{-3} \text{sec}$, a value which exceeds the theoretical minimum of $10^{13} \text{cm}^{-3} \text{sec}$ needed for breakeven. (An $n\tau$ -value of slightly in excess of $10^{14} \text{cm}^{-3} \text{sec}$ is estimated for operation of an ignited tokamak reactor.) Values of beta (ratio of plasma pressure to magnetic field pressure, a measure of power density) of 1% have been achieved, compared to a value of about 2% estimated for breakeven and 5-10% for operating reactors. Recently the Princeton Large Tokamak (PLT) achieved an equivalent Gain (ratio of fusion energy released to energy required to heat the plasma) of 0.01. The present status of tokamak research, described above, is summarized in Figure 2. Although the values of $n\tau$ and T required for breakeven have been achieved in separate tokamaks, it is now certain that the required parameter values for breakeven can be realized simultaneously in the same device. This could happen first in Alcator C, Doublet III or in the major scale-up experiment TFTR.

While progress in tokamaks has been dramatic, other confinement concepts show promise as well. Magnetic mirrors have achieved $n\tau$ values of $10^{11} \text{cm}^{-3} \text{sec}$ at temperatures of 13 keV. Two promising new concepts have emerged in the mirror program: the tandem mirror and the field reversed mirror. A proof-of-concept experiment, the Tandem Mirror Experiment, will operate in October 1978 and

Parameter	Highest Achieved	Requirement for Breakeven	Goal for Reactors
$n\tau$ (cm^{-3}sec)	3×10^{13} (Alcator)	1×10^{13}	3×10^{14}
T (keV)	6.5 (PLT)	5	6-10
Beta* (%)	1	2	6-10
Gain**	0.01	1.0	~10-20

* Beta is the ratio of plasma pressure to magnetic field pressure and is a measure of power density; higher power density leads to smaller reactors.

**Gain is the ratio of fusion energy released to energy input to heat the plasma. The gains shown are calculated based on substituting a 50-50 deuterium-tritium mixture for the pure deuterium actually used in the experiments. D-T mixtures have a yield approximately 100 times higher than occurs in pure deuterium.

FIGURE i-2 STATUS OF TOKAMAK PARAMETERS

several different approaches to achieving field reversal are being pursued. These recent results in mirror experiments have resulted in a major scale-up experiment for this concept. This scale-up will take place in the Mirror Fusion Test Facility (MFTF) now under construction at LLL.

E. ENHANCEMENT PROGRAMS

The program discussed in the main sections of this report describes a magnetic fusion energy program in which the physics and technology base for fusion would be systematically developed. The program would be committed to specific target dates only through the major scaling experiments stage. No energy-producing reactors would be initiated and there would be no specific target dates for commercial applications, although the program would continue to pursue these as major goals.

The enhancement programs described in Section VII and Appendix A of this document, would, if adopted in whole or in part, permit (a) acceleration of physics proof-of-principle programs, (b) R&D required prior to construction of energy producing experimental reactors, and (c) initiation of construction of energy producing experimental reactors. The enhancements would permit the program to commit to operation of an energy producing experimental reactor about 1990 and to reinstate the previous goal of operating a commercial demonstration reactor by the year 2000.

I. POLICY

The U.S. is in the process of formulating new energy policies to meet the anticipated shortage of worldwide fuel supplies. Immediate attention must necessarily focus on fuel conservation and on the stretch-out of conventional energy technologies (oil, gas, coal, light water reactors). An underlying concern of national energy policy, however, is to guard against the emergence of a time gap between the exhaustion of conventional fuels and the availability of appropriate inexhaustible energy sources. If this gap is to be bridged successfully, intensive efforts on both sides of the gap -- near-term conservation and production, and long-range development -- are important.

It is national policy that the nation will pursue a vigorous research and development program to provide renewable and other virtually inexhaustible energy resources to meet U.S. energy needs in the next century. The Federal Government intends to support a variety of energy alternatives in their early stages, and continue support through the development and demonstration stage for technologies that are technically, economically, and environmentally most promising.

The only known candidates for providing the bulk of long-term energy needs are fusion, solar and fission fuel breeders. These are all still in the development stage and, consequently, it is too early to precisely identify their relative advantages and disadvantages.

To assure that fusion will be available as one of the long-term options, continuation of a dedicated, research and development program is required to take fusion from its present state to a point where its commercial viability can be ascertained.

Presently, two different approaches are being followed to develop fusion. One, magnetic confinement, involves the confinement by magnetic fields and heating of a deuterium and tritium "plasma" to temperatures at which fusion of the nuclei occurs, releasing energy. The second approach, inertial confinement, involves the use of laser, electron-beam or ion-beam sources to implode and heat small pellets containing deuterium and tritium. At the projected high densities and temperatures which may result, fusion of the nuclei occurs, releasing energy.

Research on inertial confinement systems is administered by the DOE Assistant Secretary for Defense Programs through the Office of Laser Fusion. Research on magnetic confinement systems is administered by the Assistant Secretary for Energy Technology through the Office of Fusion Energy. This document describes activities of the Office of Fusion Energy in magnetic confinement systems.

II. MAGNETIC FUSION ENERGY PROGRAM

A. GOALS

The goal of the magnetic fusion energy program is to develop the use of fusion energy as a virtually inexhaustible energy resource for a variety of applications. The primary focus of the program towards this goal is to develop systems for the commercial production of central station electric power. A secondary focus of the program is to develop and evaluate other applications of fusion systems. Potential applications include (a) the production of fissile material, to extend uranium and thorium resources and thus to assure fuel supplies for fission reactors, (b) the production of synthetic fuels, such as hydrogen gas to be used directly or indirectly by the conversion of coal into liquid or gaseous fuels, and (c) the production of industrial process heat and heat for other end-use categories, such as residential/commercial space heating.

B. OBJECTIVES

To achieve the above stated goals, the program has established several objectives. The first of these is to develop a solid scientific and technical base, so that the viability of various applications can be confidently assessed. A second objective is to construct and operate, when justified, major physics/engineering scaling experiments which will provide the data required for the design of energy-producing prototype reactors. A third objective is to perform conceptual design studies of energy producing systems. A fourth objective is to perform systems studies to help guide the R&D program toward a final product that will possess characteristics that maximize its beneficial impact on society. A fifth objective is to construct and operate, when justified, energy-producing fusion reactors, which will provide the basis for commercialization. The above goals and objectives are summarized in Figure II-1.

The programs described are aimed at the achievement of the above goals and objectives in an expeditious manner, consistent with scientific/technical progress and the availability of funds. Documents such as this one will

GOAL: To develop the use of fusion energy as a virtually inexhaustible energy resource.

PRIMARY FOCUS: To develop systems for the commercial production of electricity.

SECONDARY FOCUS: To evaluate other applications of fusion systems, such as:

- . production of fissile material
- . production of synthetic fuels
- . production of process heat

OBJECTIVES:

- . To develop a solid scientific and technical base.
- . To construct and operate major physics/engineering scaling experiments.
- . To perform conceptual designs of energy-producing systems.
- . To perform systems studies to help guide the R&D program toward a final product that will possess characteristics that maximize its beneficial impact on society.
- . At the appropriate time, to construct and operate energy producing experimental reactors which will provide the basis for commercialization.

FIGURE II-1 GOALS AND OBJECTIVES

evolve and change as scientific, engineering/technology and commercial/economic/environmental analyses and progress proceeds.

At present, primary emphasis is placed on performing physics proof-of-principle experiments. Two major physics/engineering scaling experiments are being constructed and operation will be initiated in the early 1980's. In addition, design studies and long-lead time engineering activities related to energy producing experimental fusion reactors and to commercialization will be continued at an appropriate level.

C. STRATEGY

The strategy of the magnetic fusion energy program is to first develop a solid scientific and technical base, and then to design, construct, and operate experimental reactors leading to an energy resource based on the use of virtually inexhaustible fuels such as deuterium and lithium.

This strategy can be thought of consisting of four stages of development as shown in Figure II-2: (1) Proof-of-Principle Programs, (2) Major Scaling Experiments, (3) Energy-Producing Experimental Reactors, and (4) Commercialization. The goal of the proof-of-principle programs is to develop a solid scientific and technical base so that the viability of various magnetic confinement concepts and their applications can be assessed. These programs result in the understanding and predictive capability necessary for the next stage of development: Major Scaling Experiments. The goal of the Major Scaling Experiments is to provide tests of physics scaling laws to reactor level conditions as well as the demonstration of critical technology developments. Given the successful outcome of the proof-of-principle programs and a high confidence level in the outcome of the major scaling experiments, the program can progress to the next stage of development, namely the initiation of programs leading to the construction of energy-producing experimental reactors.

This latter stage of development provides the bridge between fusion energy experiments and commercialization. It involves the design, construction, and

STAGES IN FUSION ENERGY DEVELOPMENT

FIGURE II-2

operation of those prototype facilities necessary prior to progressing to the final stage of fusion development. The final stage of fusion development is commercialization which involves the design, construction and operation of those demonstration facilities necessary to prove the technical and economic feasibility of commercial fusion energy systems. During this last stage of development, significant private investment is anticipated, although a strong federal role may be necessary to facilitate the transfer of the technology from the public to the private sector.

The major effort at this proof-of-principle stage of development is directed toward achieving magnetic confinement of plasma in the physics regime of a fusion reactor.

Fusion systems of the tokamak type are nearest to producing the required conditions. Other fusion concepts, e.g., magnetic mirrors, also are showing promise and may provide engineering and/or economic advantages. The program strategy calls for maintaining a sufficient R&D program on several concepts until their relative advantages and disadvantages can be assessed.

An important element in the program strategy is the performance of assessments of the relevance of knowledge gained in one subprogram element to other elements so that proper program balance is maintained. These assessments are the responsibility of the line management in DOE, but an openness is maintained that encourages participation of other knowledgeable and responsible groups in the decision making process.

Magnetic confinement fusion experiments tend to be capital-intensive since the underlying theories and concepts necessary for constructing reactors can only be tested on increasingly large and technically sophisticated hardware. Consequently major experimental facilities have been constructed and operated at a few key sites -- General Atomic, Los Alamos Scientific Laboratory, Massachusetts Institute of Technology, Oak Ridge National Laboratory, Lawrence Livermore Laboratory, and Princeton Plasma Physics Laboratory. In addition to

research and development activities at these major sites, supporting research and development is funded at universities and in industry. At the present time, the primary direct industrial involvement is with General Atomic; other major industrial participation has been acquired on a subcontract basis for fabrication of major hardware items. Examples of major industrial involvement include Grumman, Westinghouse, United Technologies, Convair, TRW, Varian Associates, and McDonnell-Douglas. As the fusion program progresses, more direct industrial involvement will be required.

D. FUSION ENERGY APPLICATIONS

Fusion energy, once released, potentially can be used for a variety of applications as shown in Figure II-3. The applications may be further grouped as electric and non-electric applications. While the primary focus of the fusion program is aimed at the economic production of electricity based on the pure fusion process, non-electric applications of fusion energy also are being investigated as to their technical and economic attractiveness.

1. Electric Applications

The production of electricity is a straight-forward fusion energy application. The highly energetic fusion products would be absorbed in the reactor blanket and the heat produced used, via a coolant, to drive conventional turbine generators. Fusion is particularly attractive for electricity production because it is based on a virtually inexhaustible and widely distributed fuel supply (water and lithium) and it is expected that fusion will be very attractive from an environmental and safety point of view. Furthermore, it is expected that fusion power plants will be economically competitive with other energy sources in the same time period and that fusion reactors can be built in unit sizes acceptable to most utility systems (500-1000 MWe). Whatever the ultimate proportion between electric and non-electric energy that is eventually desired by the nation, there will always be an irreducible minimum demand for electrical energy. Thus there is a need to assure that a long-term supply of electricity will be available. Fusion could provide such assurance.

FUSION
ENERGY

POTENTIAL USES OF FUSION ENERGY

POTENTIAL
USES

FIGURE II-3

2. Non-Electric Applications

Fusion also could provide industrial process heat and heat for the heating and cooling of buildings. In addition to the production of process heat, two other major potential non-electric applications of fusion energy are production of synthetic fuels and production of fissile fuel for fission reactors. Both of these applications are a result of the fact that, in the fusion of deuterium and tritium, 80% of the energy appears in the form of high energy (14 MeV) neutrons. These neutrons may be used in a number of unique ways. For synthetic fuel production, for example, very high temperatures in refractory blanket materials may be achieved due to the separation of the blanket from the other reactor components. This would permit efficient, high temperature electrolytic and thermochemical synthetic fuel production cycles. Initial studies have indicated that thermal efficiencies exceeding 50% may be achievable.

Fissile fuel production capabilities result from the neutron multiplication advantages offered by the 14 MeV energy of the fusion neutron. The "neutron richness" in a fusion-fission hybrid reactor results in very rapid fissile fuel production capability in the reactor blanket which, depending on the choice and details of the fuel cycle, could be sufficient to provide the make-up fuel for roughly 5 to 20 fission plants.

3. State of Technical Readiness

Each of the aforementioned applications requires different levels of technical achievement in the fusion program. As a result some of the applications may become technically feasible before others. The plasma parameter which most directly indicates the state of technical readiness is the energy gain Q . This is a measure of the ratio of fusion energy produced by the plasma to the energy supplied to the plasma. Values of Q of 2-5 are believed sufficient for fissile fuel

production; whereas values of 10 or more are probably required for the economic production of synthetic fuels or electricity. A value of $Q \geq 1$ is confidently expected in 1982-85 from the Tokamak Fusion Test Reactor, under construction at the Princeton Plasma Physics Laboratory.

E. ENVIRONMENTAL OVERVIEW

1. Environmental Advantages

A major advantage of fusion power is its relatively low potential for producing significant environmental effects. Compared to two of the other potential candidates for major, long term power production -- coal, and fission breeder -- fusion has a number of distinct advantages from the environmental and safety point of view.

Compared with fission breeders the absence of fission products and actinides from the fuel cycle reduces, by orders of magnitude, the potential hazard associated with any accident. Criticality accidents are not possible in fusion reactors and the relatively low power density of the fusion core makes coolant perturbations much less severe. Radioactive waste will be produced only as a result of the activation of structural material and, without fission product and actinides, will require storage for much shorter periods of time. Since the selection of structural materials is a design choice, the potential exists for use of low activation alloys which can be recycled within a few decades. The deuterium-tritium fusion fuel cycle will be almost entirely self-contained within the reactor plant, eliminating fuel milling, enrichment and reprocessing facilities and their associated environmental impacts. Transportation and land useage requirements will be proportionately reduced, as well.

Compared to coal, the transportation and land useage impacts of fusion are small. There are also no chemical or particulate emissions nor ash disposal problems and consequently no adverse effects on air quality in the vicinity of the plant.

Finally, fusion may be able to progress to advanced (non-tritium) fuel cycles having almost no radioactive by-products and thus become an environmentally benign energy source.

2. Environmental Barriers to Commercialization

It must be recognized however that fusion power will have some potential environmental and safety problems which must be solved if wide-spread commercialization is to occur. At least for the early deuterium-tritium systems, substantial inventories of tritium will have to be safely managed. Although tritium is a low radiotoxicity, short half-life isotope, the quantities of tritium which will have to be routinely handled, and its high permeability through most common structural materials, make this a significant technical challenge. A Tritium Systems Test Assembly (TSTA) is being constructed at Los Alamos to address these problems at an early stage.

Similarly, activated structural materials will be produced and development will be required to minimize these quantities and safely manage their handling and eventual disposal. This problem is being addressed in both the fusion systems engineering and fusion reactor materials programs. Some technical developments may also be required to safely manage and contain inventories of other plant materials, such as liquid lithium, which have large chemical and thermal energy associated with them. While none of these problems are negligible, neither are they without potential technical solutions. Provisions are included in the Environmental Development Plan for Magnetic Fusion for their resolution in phase with the overall progress of the program.

Fusion-fission systems would share many of the disadvantages of pure fission systems but to a much lesser degree. Studies to develop quantitative measures of the differences are underway.

F. SOCIO-ECONOMIC OVERVIEW

1. Socio-Economic Advantages

Fusion reactors have a range of possible sizes and applications. Recent conceptual design work indicates that designs carried out in the early 1970's which resulted in large installations (greater than 1500 MWe) are not inevitable and that fusion reactor design sizes can be brought within the range (500-1000 MWe) appropriate to projected utility system capacities. These smaller plants will enhance fusion commercialization potential by both reducing capital cost requirements and total system vulnerability to unscheduled outages. As discussed previously, fusion reactors have a wide range of potential applications, including practically all of the end-use energy forms desired by society: electricity, portable fuels, industrial process heat, and residential/commercial space heating and cooling. Given flexibility in size and allowable variations in specific design choices depending upon applications, there could be fusion reactor designs tailored to suit various potential end-use requirements.

Finally, fusion shares the same economic advantage of any virtually inexhaustible energy resource, namely, once the energy costs from fusion plants become economically competitive with the power costs from exhaustible energy technologies (e.g., coal or nuclear power) they will become increasingly competitive with time due to insensitivity to the rising costs of scarce fuels.

2. Socio-Economic Barriers to Commercialization

In order to maintain flexibility in fusion reactor designs, several trade-offs will have to be made. First there is the trade-off between economy-of-scale and smaller reactor sizes. Reactor design studies are addressing the problem of finding the smallest economical reactor size.

There is, also, the problem of the nature and magnitude of materials requirements for fusion reactors. Due to the multiplicity of potentially conflicting requirements concerning materials performance: mechanical integrity, low activation, resource availability and cost, it is likely that trade-offs will have to be made among these characteristics. Also, due to the different character of fusion reactors compared to other energy sources, it will be necessary to have appropriate licensing procedures and environmental and safety standards. Resolution of this latter problem will involve coordination with those responsible for these problem areas.

While pure fusion reactors do not appear to pose a significant nuclear proliferation risk, hybrid fusion-fission reactors may have proliferation aspects similar in character to those of fission systems. With regard to this potential problem, one non-proliferation advantage of fusion-fission energy systems is that it permits the use of so-called "denatured" fuel cycles, an option not easily achieved by pure fission systems. These issues, as well as others, are being addressed in the current program.

Finally, to ensure that the selected approach to commercial fusion power will prove attractive to the users, a continuing and growing involvement of industry and utilities in the program is necessary. It is difficult to obtain significant financial participation from the private sector at such an early stage of development because of the cost, risk, and lead times involved. However, there is currently several million dollars of utility participation in fusion R&D through direct contracts (primarily through EPRI) and, also, utilities participate by providing advice and consultation to DOE program management.

The establishment of an industrial base for fusion is beginning through the practice of laboratory sub-contracting for the fabrication of components and subsystems for experimental fusion devices, and in some cases (e.g., General Atomic) industry has direct responsibility for major programs. Such industry and utility participation will continue to grow as the program progresses.

G. COST/BENEFIT CONSIDERATIONS

The question of program costs versus program benefits is an extremely difficult one to deal with for the longer term technologies such as the breeder, fusion and solar electric. The obvious benefits that these programs can contribute do not usually occur until much later than the development costs are accrued. As a result the classical application of cost benefit techniques can lead to negative net benefits as the discount rate and market penetration assumptions are varied.

For example, the main problems in applying classical cost/benefit analysis to the long term options comes principally from the arbitrariness in choice of discount rate and an inability to catalogue and collect information on all associated costs and all associated benefits. A recent study by ECON, Inc. has shown, however, that just the possibility of an advanced energy technology being available in the early 21st century can result in billions of dollars of benefits as a result of a strategy to keep down fossil fuel prices which would be followed by the parties controlling that resource.

Other key features which can influence the analysis are the reduction in environmental damages, spin-off technology, and the technology introduction time. All of these must be very carefully examined before a value can be assigned for a particular technology. Hidden costs that may be incurred by not developing advanced energy technologies, such as the maintenance of a large defense organization, the heightened world tension due to energy scarcity, reduced GNP growth rate, etc., must all be factored into the equation in order to obtain a reasonable judgment on the cost/benefit of a technology can be made.

In the end, of course, it will be impossible to account fully for all costs and benefits. The cost/benefit of a long range technology in general and fusion in particular must be viewed as an inexact science which provides useful but not definitive guidance to policy makers.

Fusion is one of only two or three options for supplying a major portion of the world's energy needs for many centuries. In this context it would appear that the benefits to mankind of an inexhaustible energy supply, such as fusion, would far outweigh any reasonable cost to develop it.

H. STATUS

Progress over the years in fusion has been steady. Fusion research has now reached a stage where plasma temperatures and confinement times are within modest factors of the values required for a reactor. The steps required to attain reactor operation can now be described in terms of known plasma behavior and near-term technology development.

Scientific progress on the tokamak concept has been especially dramatic. As shown in Figure II-4, ion temperatures (T) up to 5.5 keV have been achieved, compared to the 5 to 10 keV predicted to be required respectively for breakeven and for operation of a tokamak fusion reactor. The quality of confinement needed (Figure II-5) for successful production of net energy from fusion, the product of density and confinement time ($n\tau$), has been raised tenfold during the past several years to the level $3 \times 10^{13} \text{cm}^{-3} \text{sec}$, a value which exceeds the theoretical minimum of $10^{13} \text{cm}^{-3} \text{sec}$ needed for breakeven. (An $n\tau$ -value of slightly in excess of $10^{14} \text{cm}^{-3} \text{sec}$ is estimated for operation of an ignited tokamak reactor). Values of beta (ratio of plasma pressure to magnetic field pressure, a measure of power density) of 1% have been achieved (Figure II-6), compared to a value of about 2% estimated for breakeven and 5-10% for operating reactors. Recently the Princeton Large Tokamak (PLT) achieved an equivalent Gain (ratio of fusion energy released to energy required to heat the plasma) of 0.01 (Figure II-7). The present status of tokamak research, described

In the end, of course, it will be impossible to account fully for all costs and benefits. The cost/benefit of a long range technology in general and fusion in particular must be viewed as an inexact science which provides useful but not definitive guidance to policy makers.

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H. STATUS

Progress over the years in fusion has been steady. Fusion research has now reached a stage where both plasma temperatures and quality of confinement ($n\tau$) required for a reactor have been achieved separately in experiments designed for those purposes. The steps required to attain reactor operation can now be described in terms of known plasma behavior and near-term technology development.

Scientific progress on the tokamak concept has been especially dramatic. As shown in Figure II-4, ion temperatures (T) up to 6.5 keV (70 million degrees) have been achieved, compared to the 5 to 10 keV predicted to be required respectively for breakeven and for operation of a tokamak fusion reactor. The quality of confinement needed (Figure II-5) for successful production of net energy from fusion, the product of density and confinement time ($n\tau$), has been raised tenfold during the past several years to the level $3 \times 10^{13} \text{cm}^{-3} \text{sec}$, a value which exceeds the theoretical minimum of $10^{13} \text{cm}^{-3} \text{sec}$ needed for breakeven. (An $n\tau$ -value of slightly in excess of $10^{14} \text{cm}^{-3} \text{sec}$ is estimated for operation of an ignited tokamak reactor). Values of beta (ratio of plasma pressure to magnetic field pressure, a measure of power density) of 1% have been achieved (Figure II-6), compared to a value of about 2% estimated for breakeven and 5-10% for operating reactors. Recently the Princeton Large Tokamak (PLT) achieved an equivalent Gain (ratio of fusion energy released to energy required to heat the plasma of 0.01 (Figure II-7). The present status of tokamak research, described

FIGURE II-4

FIGURE II-5

FIGURE II-6.

FIGURE II-7

above, is summarized in Figure II-8. Although the values of $n\tau$ and T required for breakeven have been achieved in separate tokamaks, it is now certain that the parameter values required for breakeven can be realized in the same device.

While progress in tokamaks has been dramatic, other confinement concepts show promise as well. Magnetic mirrors have achieved $n\tau$ values of $10^{11} \text{ cm}^{-3} \text{ sec}$ at temperatures of 13 keV. Two promising new concepts have emerged in the mirror program: the tandem mirror and the field reversed mirror. A proof-of-concept experiment, the Tandem Mirror Experiment, begins operation in October 1978 and several different approaches to achieving field reversal are being pursued. These recent results in mirror experiments have resulted in a major scale-up experiment for this concept. This scale-up will take place in the Mirror Fusion Test Facility (MFTF), now under construction at LLL.

A strong effort is also maintained on other toroidal and linear concepts. Such concepts may have simpler technology, or employ components and materials which could lead to reactors with lower capital and/or maintenance costs. However all of these concepts are at a much earlier stage of development than either tokamaks or mirrors.

I. PLANNING, COSTS AND SCHEDULES

Planning is a dynamic process, involving continuous change. Although the planning process involves the establishment of a schedule, including a set of goals and milestones consistent with projected funding profiles, it is not a roadmap to be followed blindly to the end goal; rather the detailed path must be allowed to emerge as knowledge and perspective is gained along the way. Planning assists program development by stimulating interactions among the participants in the development. However, the details of the plan are more accurate in the near-term than in the longer range. The use of plans in technically complex development programs requires judgment and flexibility as new insights into the nature of the task evolve.

Parameter	Highest Achieved	Requirement for Breakeven	Goal for Reactors
$n\tau$ (cm^{-3}sec)	3×10^{13} (Alcator)	1×10^{13}	3×10^{14}
T (keV)	6.5 (PLT)	5	6-10
Beta* (%)	1	2	6-10
Gain**	0.01	1.0	$\sim 10-20$

* Beta is the ratio of plasma pressure to magnetic field pressure and is a measure of power density; higher power density leads to smaller reactors.

**Gain is the ratio of fusion energy released to energy input to heat the plasma. The gains shown are calculated based on substituting a 50-50 deuterium-tritium mixture for the pure deuterium actually used in the experiments. D-T mixtures have a yield approximately 100 times higher than occurs in pure deuterium.

FIGURE II-8 STATUS OF TOKAMAK PARAMETERS

Planning is done in both the "roll-forward" and "roll-back" modes. "Roll-forward" planning consists of evaluating past and present knowledge and projecting near-term possibilities. "Roll-back" planning consists of examining the range of desired end products to ensure that the R&D programs required to achieve the desired product are in place on a timely basis. The roll-forward and roll-back planning of the magnetic fusion program are described in detail in the five volume set, "Fusion Power by Magnetic Confinement: Program Plan" (ERDA-76/110/0-4) which benefited from major involvement of the fusion scientific and engineering community. In that planning document a multiplicity of possible paths were described called "Program Logics". Although the details depended on both policy variables (what is expected by when) and on technical variables (what is possible by when), the time required to reach a given end product was shown to be primarily describable by the presumed level of funding. The Program Logics were:

- Logic I: Level of Effort Research
- Logic II: Moderately Expanding
- Logic III: Aggressive
- Logic IV: Accelerated
- Logic V: Maximum Effective Effort

The result, shown in Figure II-9, used FY 1976 funding as a base and projected operating budgets in unescalated FY 1978 dollars, exclusive of plant and capital equipment.

Some of the programs described in the previous plan have been delayed, relative to Logic III reference schedules which were used as a planning baseline, due to funding levels provided in FY 1978 and 1979. The program described in this document, also shown in Figure II-8, is based upon a constant level of effort assumption (Logic I) beginning in FY 1980, using FY 1979 as a base. Optional enhancements are described in Section VII which would accelerate progress toward a practical product at a pace similar to that shown in Logics II and III.

FUSION R&D PROGRAM OPERATING BUDGET AND LOCI OF DEMO OPERATING DATES FOR LOGIC I THRU V

FIGURE II-9

The primary emphasis at present is to establish the scientific and technical base required to assess the viability of the various toroidal and linear fusion systems as candidates for fusion reactors. A firm experimental and theoretical base will be established that will provide a predictive capability for designing energy-producing experimental reactors. The information will be obtained in the proof-of-principle programs and from major scaling experiments. The technology activities required to support these efforts through the development of hardware for major experiments will be continued.

Scoping studies for energy-producing experimental reactors and commercial reactors will be continued at an appropriate level to provide direction and guidance for near-term research and development. The commercial reactor studies include the use of fusion reactors for synthetic fuel production, fissile fuel production, and for electric power generation. In addition, certain long lead time technology development such as for reactor materials will continue.

Possible program path alternatives are shown in Figure II-10 taken from the previous long range plan (ERDA-76/110/0-4). Two stages of energy-producing experimental reactors (designated PEPR/ITR and EPR)* were assumed to be necessary prior to construction of a commercial demonstration reactor. The physics information needed to make a positive decision in FY 1979 to proceed along the shortest (tokamak) path as shown will in fact be available on schedule; however, technology developments have not kept pace due to the FY 1978 and 1979 budget levels. Consequently it is likely that about two years have been lost relative to the shortest path, shown in Figure II-10 (Earliest Demo Operation). Therefore the mirror path (which permits a choice between tokamak and mirror reactors in 1982) is approximately the path and schedule being followed at this time. Of course, projections like these are inexact and it is quite possible that some time can be made up later if a more aggressive program is re-established.

*PEPR/ITR: Prototype Experimental Power Reactor/Ignition Test Reactor
EPR: Experimental Power Reactor

LOGIC III REFERENCE OPTION PROGRAM PATH ALTERNATIVES

FIGURE II-10

J. MANAGEMENT

The fusion program may be considered from several points-of-view. The main points-of-view, or "cross-cuts" of the program are illustrated in Figure II-11 which shows the "technical" viewpoint, the organizational "management" viewpoint and the "stage of development" viewpoint. The "technical" viewpoint consists of "base physics and technology", specific R&D activities that are directed towards toroidal reactor systems, and activities directed towards linear reactor systems. The management structure viewpoint corresponds to the organizational structure of the Office of Fusion Energy and is described in greater detail in other DOE budget documents such as the Presidential Budget, the Magnetic Fusion Energy Program Summary Document - FY 1979 ("Gold Book") and the predecessor 5-year program plan, "Fusion Power by Magnetic Confinement: Program Plan (ERDA-76/110/3). The "stage of development" point-of-view is portrayed on the upper face of the cube in Figure II-11. While the largest portion of the program's activities are necessarily aimed at the "proof-of-principle" and "major scaling experiment" stages, the remaining stages of development are also receiving an appropriate degree of attention by the program.

Subject to review and approval by DOE upper management, the Office of Fusion Energy is responsible for research and development on fusion power by magnetic confinement, including the formulation of strategies and the development of plans encompassing scientific and technical program content, goals and objectives. The Office also develops and defines budget requirements, defends budget requests, interprets policy and monitors programmatic and technical progress. This requires a strong, knowledgeable headquarters staff capable of synthesizing and focusing the views of the fusion community and incorporating guidance and insight from others, both from within DOE and from external organizations such as the electric utilities and other potential user groups.

DOE field offices are responsible for the administrative management of all programs, including the control of management plans for all fabrication and

CROSS-CUTS OF THE MAGNETIC FUSION ENERGY PROGRAM

FIGURE II-11

construction projects. Overall direction is provided from Headquarters with supporting field administrative management but, to the maximum extent possible, responsibility for program implementation is decentralized.

Responsibility for day-to-day management of all research and development programs rests with the management of the performing laboratory or contractor.

K. EVALUATIONS

Decisions to move ahead, mark time, retreat, change approach, etc., are based on evaluations of the status of the physics and engineering technology at a given point in time. These evaluations include a prognosis on the implications of current understanding for future commercial fusion reactors and are called "critical parameter assessments". They are currently scheduled to take place in 1979 for tokamaks, in 1982 for magnetic mirrors and in 1985 for other concepts. In addition, dozens of program subelement assessments are carried out each year using "ad hoc panels" of technical experts. The assessments involve evaluation of the status and prospects for major program elements of fusion energy systems as shown in Figure II-12. The details of the major planning assessments is given in the previous planning document, ERDA-76/110/2, Section III.C.

L. COORDINATION

The Office of Fusion Energy maintains interactions with a variety of other organizations in order to coordinate activities, minimize unnecessary duplication and maximize efficiency. The major coordination activities are with DOE Inertial Confinement Fusion Programs, fusion programs in the U.S.S.R., Europe, and Japan and the Electric Power Research Institute.

1. Inertial Confinement Fusion

A member of the Office of Fusion Energy has served as a member of the Laser Fusion Coordinating Committee, which is an advisory body chaired by the Director of the Office of Laser Fusion. Members of the Office of Fusion Energy attend meetings and receive technical

MAJOR PROGRAM ELEMENTS
FOR ALL CONCEPTS

Physics

- I. Scaling
- II. Impurity Control
- III. Beta Limits
- IV. DT Burn Dynamics

Engineering/Technology

- V. Plasma Maintenance and Control
- VI. Heating Technology
- VII. Superconducting Magnets
- VIII. Pulsed Energy Systems
- IX. Blanket and Shield
- X. Tritium Processing and Control
- XI. Electrical Subsystems
- XII. Power Handling
- XIII. Plant Availability
- XIV. Instrumentation and Control
- XV. Plant Maintenance
- XVI. Vacuum Technology
- XVII. Materials
- XVIII. Balance of Plant
- XIX. Systems Integration
- XX. Environment and Safety
- XXI. Economics

FIGURE II-12

briefings regularly on the status of inertial confinement fusion. A coordinating group has recently been established between the Office of Fusion Energy and Office of Laser Fusion to identify common research elements, primarily in the areas of common technology development, systems studies and applications of fusion energy. Also, the Director of the Office of Fusion Energy participates in the coordination activities of the Office of the DOE Director of Research.

2. Coordination with the U.S.S.R.

Since 1974, the Director of the Office of Fusion Energy, and the Directors of the technical divisions of the Office of Fusion Energy and the Directors of the four principal fusion programs at PPPL, ORNL, LASL, and LLL, have participated as members of the Joint (U.S. - U.S.S.R.) Fusion Power Coordinating Committee (JFPCC). This body was established under the aegis of the Protocol between the U.S. Atomic Energy Commission and the U.S.S.R. State Committee for the Utilization of Atomic Energy on Joint Projects in Controlled Thermonuclear Fusion and Plasma Physics. The JFPCC meets yearly (alternately in the U.S. and the U.S.S.R.) to exchange information and to approve personnel exchanges to conduct joint research. Approximately 150 man-weeks of effort in each direction are exchanged yearly between the U.S. and U.S.S.R. programs.

3. Coordination with IAEA

The IAEA coordinates fusion programs world-wide through the International Fusion Research Council (IFRC). The Director of the Office of Fusion Energy is a member of this Council and through this mechanism conducts formal coordination with European programs.

Extensive cooperation with European programs, however, is conducted directly between European centers and DOE contractors on a less formal basis. Every two years the IAEA conducts a large inter-

national conference on Plasma Physics and Controlled Fusion Research. Meetings have been held in 1958, 1961, 1964, 1968, 1971, 1974 and 1976. The next meeting is scheduled for August 1978 in Innsbruck, Austria.

The Office of Fusion Energy also participates formally in the activities of the International Energy Agency (IEA). Joint programs have been established in the areas of materials research, superconducting magnets, and plasma wall interactions.

4. Coordination with Japan

The Minister of State for Science and Technology of the Japanese Government expressed an interest in forming a formal coordinating activity with the U.S. in fusion on the occasion of his visit to the U.S. in September 1977. Consequently, the Director, Office of Fusion Energy visited Japan in November 1977 for the purpose of gaining a better knowledge of the Japanese fusion program and discussing the possibilities for such an agreement. Further discussions are now in progress.

5. Coordination with the Electric Power Research Institute (EPRI)

Officials of the Office of Fusion Energy meet periodically with their counterparts in EPRI to exchange information and coordinate plans, and both the Office of Fusion Energy and the Office of Laser Fusion are represented on the EPRI Fusion Program Committee. Negotiations are in process to strengthen ties with members of the electric utilities and industry through coordination mechanisms to be established by EPRI.

6. Internal Coordination

For effective program management, as well as to effectively utilize program resources, it is necessary to have a strong coordination function within, as well as external to the program. The organization

chart for the Office of Fusion Energy is shown in Figure II-13. The coordination between the three technical organizational elements (Magnetic Confinement Systems, Applied Plasma Physics, and Development and Technology) is accomplished through their mutually supporting role in fostering and managing activities associated with each stage of fusion development, as shown in Figure II-14. Confinement Systems is responsible for the design, fabrication and operation of tokamak and mirror proof-of-principle experiments and the mirror major scaling experiment (MFTF) and for operation of the tokamak major scaling experiment (TFTR). Applied Plasma Physics is responsible for conducting proof-of-principle programs for other concepts and for all base physics, including theory and computation. Development and Technology is responsible for the development of all component technologies for all stages of development and for conceptual studies of energy-producing systems, applications, environmental issues and commercialization. Planning and Project Management is responsible for planning and for construction of TFTR and other major construction projects such as neutron sources for materials testing. Thus success at each stage of development is dependent upon the degree of success achieved in coordinating these four organizational elements of the Office of Fusion Energy.

FIGURE II-13

COORDINATION OF MAGNETIC FUSION PROGRAM

FIGURE II-14

III. PHYSICS PROOF-OF-PRINCIPLE PROGRAMS

As mentioned previously, the fusion program may be considered from several points-of-view. In this document, the program will be presented from the "stage of development" point of view: (1) Physics Proof of Principle Program, (2) Major Scaling Experiments, (3) Energy-Producing Experimental Reactors, and (4) Commercialization. At the present time, Physics Proof-of-Principle Programs are the primary activities of the magnetic fusion program. These programs, together with the Major Scaling Experiments, should provide the required data base to design and construct, when justified, energy-producing experimental reactors. Within the proof-of-principle programs both toroidal and linear systems are being developed. The leading concepts in these two categories are the tokamak and magnetic mirror devices.

Base physics and technology programs are carried out in support of the physics proof-of-principle programs. The base physics includes theory and small experiments and is important in developing the necessary understanding and predictive capability to progress through various stages of development.

The Base Technology effort provides the necessary hardware developments required for larger, higher energy density plasma production and confinement devices. For example, the development of high power neutral beams that provide nearly one megawatt per beam is essential for pursuing both tokamaks and mirror experiments into near reactor-level plasma regimes.

The goal of the physics proof-of-principle programs is to develop a solid scientific base so that the viability of various fusion applications can be assessed. These programs result in the understanding and predictive capability necessary to design major scaling experiments and energy-producing experimental reactors. Near term objectives of the proof-of-principle programs are to perform experimental tests on key physics questions associated with both toroidal and linear fusion concepts.

Particular emphasis is placed on the study of scaling laws in the plasma physics regime of a fusion reactor to test the key physics questions.

All of the magnetic fusion concepts can be classified into two broad categories: toroidal and linear systems, where the tokamak is the leading example of a toroidal system and the mirror is the leading example of a linear system. Closely related to the categories of toroidal and linear are the categories of closed and open systems as shown. While the toroidal and linear categories are based upon the geometric shape of the physical system, the categories of closed and open refer to whether the magnetic field lines close upon themselves within or outside the core plasma region. It is in terms of these latter categories (shown schematically in Figure III-1) that the relationship among the confinement technologies is most easily discussed.

The tokamak and mirror systems also qualify as the best examples of closed and open systems respectively. However some of the other concepts achieve their particular advantages by employing a magnetic geometry which though primarily based upon one kind of magnetic field shape (i.e., either open or closed) also embodies some of the other kind. For example, the Bumpy Torus concept is built upon the open mirror geometry but, by forming a torus from mirror modules results in a closed magnetic system. Other mirror concepts also accomplish this to a lesser degree as in the case of the (linear) Field Reversed Theta Pinch which reverses the direction of the magnetic field lines deep within the plasma resulting in an effectively closed system. Another example, Tormac, has a toroidal configuration like a tokamak, but has two distinct regions of magnetic fields: an outer sheath region where the magnetic field lines are open and an internal region where the field lines are closed within the plasma. These examples show that there is a close relationship between closed and open systems which makes possible a wealth of technically interesting variations upon them. Such a variety of possibilities increases the likelihood of finding technically attractive configurations upon which to base successful commercial reactor designs.

MAGNETIC CONTAINMENT CONFIGURATIONS

OPEN SYSTEM - SIMPLE MAGNETIC MIRROR

CLOSED SYSTEM - SIMPLE TORUS

A. EXPERIMENTS LEADING TO TOROIDAL REACTOR SYSTEMS

The primary goal of experiments leading to toroidal reactor systems is to establish the physics principles upon which the major scaling experiments and energy-producing experimental reactors are based for all toroidal concepts.

The immediate objective is to use the tokamak concept to perform experimental tests of key physics issues associated with plasma confinement in toroidal devices. Plasma parameters have been extended into the plasma physics regime of a fusion reactor. In these experiments, issues common to several toroidal concepts will be examined for use in optimized systems.

1. Tokamak Systems

a. Strategy and Description

The tokamak is the most successful and, in many ways, the simplest toroidal magnetic confinement system. The tokamak strategy is to emphasize the development and utilization of a main line of devices (moderate magnetic field, circular cross-section and neutral beam heated), while concurrently developing and testing variants of the design, the results of which should answer the major remaining physics questions and could change the design of the next mainline device. Thus, a strong thrust towards achieving reactor level confinement is maintained, while flexibility is allowed to ensure an optimized final reactor design.

The tokamak effort is focused on five critical areas: plasma heating, plasma transport and scaling, plasma shape optimization, impurity control, and long pulse operation. Plasma heating refers to techniques for transferring enough energy to the plasma to attain required plasma temperatures (e.g., ignition temperature). Plasma transport and scaling determines relationships between device parameters (e.g., plasma radius, heating power) and performance parameters (e.g., temperature, Lawson Product, $n\tau$, and power balance Q) that allow prediction of plasma behavior

in more advanced devices. Shape optimization implies the determination of the best cross-sectional shape for the plasma. Impurity control refers to the development of techniques to prevent plasma cooling by particles scattered from the vacuum chamber wall. Long pulse operation refers to problems such as fueling, maintaining the magnetic field configuration, power supplies, remote handling, etc., which must eventually be solved for energy producing systems. These five critical problem areas are addressed in a series of major tokamak facilities.

b. Status

During the recent past, the tokamak program has advanced considerably toward the goal of a viable reactor system. Tokamak progress, which is generally measured in terms of $n\tau$ has increased from 10^{12} to $3 \times 10^{13} \text{cm}^{-3} \text{sec}$; ion temperature has increased from less than 500 eV to over 6000 eV; and gain (Q) has increased by several orders of magnitude to 1%.

Of equal importance are the engineering accomplishments over the past five years. These accomplishments include the fabrication of a new generation of tokamaks, the Princeton Large Torus (PLT) and the Poloidal Divertor Experiment (PDX) at Princeton; Doublet III at General Atomic, Alcator C at MIT, and ISX-B at Oak Ridge. These tokamaks will provide the facilities to address the major remaining tokamak physics issues during the next few years and will lead naturally into the operation of TFTR in 1982. The engineering accomplishments also include the development of auxiliary heating devices including neutral beams with megawatt capability and powerful radiofrequency heating equipment.

Finally, an impressive array of diagnostics supported by a highly sophisticated computerized data handling capability has been developed. It is now possible to follow the detailed particle and energy flows within a plasma and thereby identify the responsible physics mechanisms. This kind of detailed information is essential for furthering our understanding of the behavior of plasmas in a tokamak and for optimizing the heating and confinement properties of a tokamak.

c. Plans

The tokamak proof-of-principle program, during the next five years, will center about the major tokamaks PLT, PDX, Doublet III, Alcator C, and ISX. The problem areas principally addressed by each tokamak are summarized in Figure III-2. Prime contractors for and operational status of each experiment are also presented. A description of the plans for each device follows the table.

Princeton Large Torus (PLT)

The PLT is a major tokamak device that is a critical intermediate step between the initial small tokamak devices and a machine that will possess a number of reactor characteristics (Tokamak Fusion Test Reactor). In fulfillment of this role, the primary PLT project objective is to determine how plasma parameters (e.g., density, temperature, and confinement time) vary as machine size and heating power increase. In addition, PLT will be used as a test bed for high power neutral beam and radio frequency heating experiments, as well as numerous technology and instrumentation development experiments which directly support the next important step in the tokamak program -- the Tokamak Fusion Test Reactor (TFTR).

In its first year of operation, PLT demonstrated the theoretically-predicted increase in confinement time with increased density and

<u>Problem Areas</u>	<u>PLT (PPPL) FY 76*</u>	<u>ISX (ORNL) FY 77</u>	<u>DIII (GA) FY 78</u>	<u>ALC-C (MIT) FY 78</u>	<u>PDX (PPPL) FY 79</u>
Heating	1	-	2	4	3
Transport and Scaling	1,2	-	2	3	-
Shape Optimization	-	3	2	-	3
Impurity Control	-	1	-	-	3
Long Pulse Operation	-	2	-	-	-

- 1 - Operational, Applicable Experiments in Progress
 2 - Operational, Applicable Experiments in Preparation
 3 - Under Design, Construction or Major Modification
 4 - Proposed

*Dates give beginning of operations

FIGURE III-2 RELATIONSHIP BETWEEN TOKAMAK EXPERIMENTS AND
CRITICAL PROBLEM AREAS

PRINCETON LARGE TORUS (PLT).

size. Then, in 1977, PLT operated with 1 MW of injected neutral beam power and achieved a world record peak ion temperature in excess of 2 keV. During the Summer of 1978, PLT operated with over 2 MW of beam power and attained a temperature of over 6 keV. At these temperatures the plasma has entered into the plasma physics regime of a fusion reactor, and the experiment addressed the basic issues of plasma transport and impurities under reactor-relevant conditions. In addition to the neutral beam experiments, 2.5 MW of radio frequency heating (ICRF) power will be installed to study in FY 1979 the effect of massive radio frequency heating. The radio frequency heating experiments will continue into FY 1980 after which PLT could perform a number of experiments, such as impurity control studies, in preparation for the start-up of TFTR.

Poloidal Divertor Experiment (PDX)

The primary objective of PDX is to control plasma impurities via the use of special magnetic field coils. These coils produce open magnetic field lines that lead from the edge of the plasma to a collection chamber. Charged particles are therefore diverted to the collection chamber before they can sputter impurities from the wall, and wall impurities are diverted to the chamber before they can enter the plasma. A second objective of PDX is in the area of configurational optimization and is to evaluate the stability of a D-shaped plasma configuration which could lead to a significant reduction in the toroidal magnetic field strength needed for confinement.

PDX will initially operate in November 1978 with ohmic heating alone. Neutral beam heating will be added in stages with 6 MW of neutral beam power available in FY 1980 and 10 MW in FY 1982. This beam capability will allow PDX to investigate impurity problems at plasma temperature in excess of 5 keV. In addition it will allow the investigation of the limits of plasma pressure in a tokamak, and permit equivalent Gains* of 0.1 to 0.5 to be achieved.

*Gain is the ratio of fusion energy released to input power to the plasma.

POLOIDAL DIVERTOR EXPERIMENT (PDX)

Doublet III

The primary objective of the Doublet program is to optimize the cross-sectional shape of the tokamak. Cross-sectional optimization is motivated by the theoretical prediction that the ratio of plasma pressure to magnetic field pressure, or beta, is higher for non-circular than for circular tokamaks. A higher value of beta implies a greater magnetic field utilization which in turn implies that reactors can be built with higher power density and therefore in smaller sizes and at lower costs.

Doublet II-A, a small scale tokamak, has demonstrated that plasmas with different cross-sections, elliptical, D-shaped, or doublet (peanut shaped) can be obtained and controlled through use of coils deployed around the plasma chamber. Doublet III, a much larger device, is now in operation and will study the characteristics of non-circular cross-section in the confinement of plasmas under reactor conditions. During the initial ohmically heated phase (through 1979), Doublet III will investigate the confinement properties of non-circular cross-section plasmas.

In 1980, 7 MWatts of neutral beam heating is scheduled for injection into Doublet III. This heating capability should raise the plasma temperature to close to 3 keV and provide an initial test of beta limits in the elliptical, D-shaped, and Doublet configurations.

Alcator

The Alcator concept provides the basis for smaller fusion reactor designs. By using high magnetic fields and a small plasma cross-section, high density (with correspondingly large values for Lawson's Product) reactor-grade plasmas can be obtained.

DOUBLET III (DIII)

ALCATOR C

The Alcator C device operated initially in the spring of 1978 and will operate at full field in early 1979. The device will build upon the success of the compact high field, high density tokamak, Alcator A, which has obtained world record values for confinement. In particular, Alcator C, with a toroidal field 50% greater and a minor radius twice Alcator A, is predicted to achieve in 1979 a quality of confinement $n_T \approx 10^{14}$. This quality of confinement will, however, initially be achieved at an ion temperature 20% of the value needed for ignition. Future efforts will therefore be focused upon auxiliary heating to raise the ion temperature.

In 1980, one megawatt of very high frequency (lower hybrid) electromagnetic radiation is planned with the goal of raising the temperature in Alcator to 3 keV. Depending upon the success of these experiments, further ion heating is planned for Alcator C during 1981 and 1982 with the ultimate objective of raising the ion temperature to 5-6 keV.

ISX

The Impurity Studies Experiment, ISX, at Oak Ridge is a small and versatile tokamak that was initially operated in early 1977. Its original purpose was to investigate techniques for impurity control and study the interaction between the plasma and wall. Very clean plasma conditions with correspondingly high levels of energy confinement were observed. The device has recently undergone an upgrade and is operating now with 1.8 megawatts of neutral beam power. This experiment will provide an early test of the limits of plasma pressure at high (2 keV) temperatures. In particular, the projected value of beta (the ratio of plasma to magnetic field pressure, is 5% and, with upgraded beams, is 10%). Following these experiments a number of different experiments are planned including very high frequency (electron cyclotron resonance) heating; testing of a compact, inexpensive divertor (bundle divertor); and studies of new techniques for neutral beam injection (ripple injection).

ISX - B

Future Directions

The tokamaks discussed thus far have been primarily concerned with developing the scaling laws for extrapolation to energy producing systems. In addition, in the transition from short pulsed (~ 1 second) experiments to a long pulsed (~ 30 minutes) reactor, a number of engineering questions arise. These include power supplies, material problems, remote handling, fueling problems, maintenance of the magnetic field configuration, impurity build-up over long times, etc. Also it may be possible to develop a steady-state tokamak by driving the current with neutral beams, radio frequency waves, or by adjustment of plasma transport, etc. True steady state operation would reduce the need for transfer of large amounts of power associated with frequent start-up and result in significant engineering simplification and cost savings for the tokamak. Studies of these issues are underway.

d. Milestones

The key device milestones are shown in Table III-1.

2. Other Toroidal Programs

There are several other toroidal confinement concepts which have not been explored as extensively as tokamaks. Each of these concepts has special attractive physics and technology features which may be incorporated into an optimized toroidal reactor system. While there are differences among the toroidal concepts, there are also many similarities in physics and technology. The physical models and many of the device components developed for one are useful for the others. Consequently, non-tokamak toroidal systems could progress rapidly and their features quickly incorporated into scaled-up closed systems once their physics principles are appropriately tested.

Among the leading alternate toroidal systems are Elmo Bumpy Torus, Tormac, reversed field pinches (RFP), multipoles, and stellarators. Other types of toroidal systems have also been proposed.

TABLE 1

Elmo Bumpy Torus

EBT is a torus formed by linking of a number of simple mirror cells. The well known MHD instability of a simple mirror cell is overcome by using r.f. heating techniques to produce a high beta plasma region which suitably modifies the magnetic field. The EBT concept may lead to attractive fusion reactor designs, featuring steady state operation, plasma ignition, low magnetic fields, relatively simple technology, ease of access and maintenance, and modular design and construction. The goal of the EBT program is to develop the physics basis for designing such a fusion reactor.

Present understanding of the equilibrium, stability and transport in EBT leads to a sequence of research devices aimed at a full-scale reactor. The implementation of the steps in this sequence hinges on favorable scaling of plasma confinement into the collisionless plasma regime and the concomitant development of advanced microwave power sources having high specific power levels at millimeter wavelengths. The EBT program thus encompasses an aggressive high power millimeter CW microwave tube development effort based on the Cyclotron Resonant Maser principle. This effort is presently concerned with the development of a 28 GHz, 200 kW CW gyrokystron, which is itself a scale version of the 120 GHz tube required for heating and stabilizing an EBT reactor.

Typical EBT-I parameters are $B_{min} \sim 4$ kG, mirror ratio 2:1, $n \sim 2 \times 10^{13} \text{cm}^{-3}$, $T_e \sim 300$ eV, $T_i \sim 100$ eV, $\beta < 1\%$ (these values all refer to the toroidal component, in the annulus, for example, $\beta \sim 40\%$). In addition to achieving its primary experimental objectives, EBT-I has generated a considerable amount of interesting and supportive plasma information.

Experimental observations include density decay times of 10's of milliseconds, extremely high plasma purity, increased plasma temperature with increased microwave power, and the fact that magnetic field errors apparently do not present a practical problem.

In mid-1978, EBT-S, an upgraded version of EBT will begin operation to investigate scaling of plasma parameters through the use of significantly increased microwave heating power and higher magnetic fields. The primary objective is to confirm theoretical parametric relationships that can be used to design the next step device (EBT-II) discussed in the enhancement package. An upgrade of EBT-S (EBT-SA) is scheduled to operate in FY 1979 to test additional EBT design principles, such as aspect ratio enhancement (ARE) coils.

Reversed Field Pinch

The Reversed Field Pinch (RFP) configuration is much like a tokamak except that stable confinement is achieved for higher toroidal currents and higher betas by tailoring the plasma pressure and magnetic field as a function of radius, with the toroidal field reversing direction near the wall. Some of the advantages of the RFP reactor are high beta operation, normal conducting magnets, large aspect ratio for simplified construction and maintenance, and little or no need for auxiliary heating.

The RFP program includes two devices, ZT-40, and ZT-S, which are both located at the Los Alamos Scientific Laboratory (LASL).

The fabrication of the ZT-40 device was initiated in December 1976 and it will begin research operations in July 1979. The smaller device, ZT-S, has been in operation since January 1976, and has already demonstrated the a^2 scaling of confinement time (a is the minor radius of the vacuum vessel).

Methods of reducing impurities are under intensive investigation on this device.

TORMAC

The TORMAC configuration utilizes poloidal cusp magnetic fields to support the plasma and provide MHD stability in conjunction with a toroidal magnetic field to reduce radial energy transport. Some of the advantages of TORMAC are possible steady state operation, ignited operation, moderate beta, built-in divertors to remove impurities, low magnetic fields, and modest technology requirements.

The experimental program is conducted at the Lawrence Berkeley Laboratory (LBL). Experiments on TORMAC to date have been performed on small devices, in modest but meaningful parameter regimes.

Current plans call for initiation of research on TORMAC P-1 during FY 1978 in order to study the issues of plasma and magnetic field injection into a TORMAC configuration in order to demonstrate a steady-state capability. Success in that activity coupled with demonstrations of heating and sheath stability in TORMAC IV could lead to a program decision on initiating a proof-of-concept experiment, TORMAC VI.

Stellarators (Torsatrons)

Stellarators, like tokamaks, achieve plasma confinement by a combination of toroidal and poloidal magnetic fields. The primary difference is that in stellarators these fields are provided by current carrying conductors usually placed outside the plasma chamber in the plasma. One of the main

advantages of stellarator reactors is that this conductor arrangement permits steady state operation. The primary disadvantage of these systems is the difficulty of fabricating and supporting the field windings.

Research on stellarators is vigorously pursued in Europe, Japan, the U.K., and the U.S.S.R. Altogether, there are 22 stellarator devices that are currently operating (or in design or construction phases) abroad. The only stellarator experiment in the U.S. is at the University of Wisconsin which is supported by NSF. A small scale reactor study is being supported by DOE at MIT to assess the reactor possibilities of this concept. In addition, a stellarator advisory committee has been formed to review research progress, and to promote international cooperation on stellarators by participation of two or three U.S. scientists in the stellarator experiments at foreign laboratories.

Multipoles

Toroidal multipole devices utilize current carrying internal rings to provide poloidal magnetic fields that form stable magnetic wells for plasma confinement. In multipole confinement configurations, such as SURMAC at UCLA, that have their magnetic fields localized near the outer edge of the plasma, radiation losses due to synchrotron emission are low. This makes such concepts potentially advantageous for use as advanced fuel reactor systems where the requirements for very high temperatures lead to significant energy losses by synchrotron radiation for only modestly magnetized plasma.

The objectives of multipole, toroidal reactor system development include demonstrations of the extrapolation of present favorable confinement results to higher energy density parameter regimes, the demonstration of adequate stability at beta levels

necessary for economic reactor systems, the suppression of refluxing neutrals and impurities from internal conductors, and adequate means of energy extraction from the confined plasma.

B. EXPERIMENTS LEADING TO LINEAR REACTOR SYSTEMS

Linear reactor systems are generally simpler than toroidal systems to design, construct, and maintain, and they offer the possibility of direct electrical conversion with its concomitant higher thermal efficiencies. Magnetic field line curvature can be made neutral or stabilizing over most of the system, allowing high beta (~ 1) operation. The price they pay in return is the existence of open magnetic field lines, which, in the simplest form, allow plasma particles to escape out the ends on the time scale of a single scattering event, leading to low energy gain. Thus, it is necessary to find efficient ways of reducing the end losses in linear systems.

The goal of research leading to linear reactor systems is, therefore, to propose, develop, and demonstrate the elements of physics and technology which are required for the successful operation of an economically attractive fusion machine based on one of several possible linear or open ended magnetic confinement geometries.

In pursuit of the above goal, experiments leading to linear reactor systems have the following near-term objectives:

- . Demonstration of stable, high beta plasma confinement in geometries scaleable to a reactor.
- . Demonstration of satisfactory means to produce, heat and fuel the high energy plasmas.
- . Demonstration of end loss reduction techniques which lead to high Q (i.e., high power gain) reactor system designs.

TABLE 2

1. Mirror Systems

a. Strategy and Description

As a consequence of the successful 2X-IIB experiments at LLL during the past several years, the basic physics and technology of the mirror program is more or less in place. 2X-IIB answered most of the outstanding questions by demonstrating plasma start-up in a steady magnetic field, heating and refueling by means of neutral beam injection, high beta macrostability (MHD) confinement, and understanding and control of high frequency turbulence -- the drift cyclotron loss cone (DCLC) mode -- will diminish to insignificance as the size of mirror devices is increased into the regime of reactor interest, and the leakage of plasma from mirror machines will be governed by classical diffusion rates across field lines. Thus encouraged, the mirror program strategy is to devote major attention to means of reducing classical end losses and thereby achieving higher Q. The leading candidates are field reversal and the tandem mirror, for which experimental tests are planned in the FY 79-82 time frame. Further technology advances in the key areas of superconducting magnets, neutral beams, cryovacuum systems, and operation of large mirror facilities by means of computer control will be addressed in FY 1981 in the Mirror Fusion Test Facility (MFTF) at LLL. Also, confirmation of the basic physics scaling laws needed to design next generation mirror machines will be obtained from the operation of MFTF and TMX.

The mirror program strategy is to test different combinations and variations of the proven mirror technologies to arrive at an optimum reactor candidate.

2X-IIB

This experiment achieved or exceeded, during FY 1975-76, all of its original goals (assigned in 1972). Typical parameters are:

$$n\tau \sim 10^{11} \text{ cm}^{-3} \text{ sec}$$

$$n \sim 10^{14} \text{ cm}^{-3}$$

$$E_i \sim 13 \text{ keV}$$

$$I_{\text{beam}} \sim 300\text{-}500 \text{ Amp}$$

$$\beta \sim 0.5\text{-}1.5$$

$$R_p/\rho_i \sim 2.4$$

Here, n is the particle number density, τ is the energy confinement time, E_i is the average ion energy, I_{beam} is the injected neutral particle current, β (beta) is the ratio of the plasma kinetic pressure to the confining magnetic pressure, R_p is the plasma radius, and ρ_i is the ion gyroradius.

Most recently, 2X-IIB has been used in field reversal attempts. The beam current was increased to 500 amperes (from 20 keV injectors) and the beams were focused to give the best conditions for field reversal. Although β on axis increased to about 2.0, and the field on axis was reduced by over 90% by this procedure, actual reversal of the field has yet to be achieved. The present theoretical understanding indicates that either the injection current or the energy confinement time must be increased by a factor of ~ 3 to start-up the reversed field configuration. This does not seem possible in the present 2X-IIB experiment.

2XII B

Tandem Mirror Experiment (TMX)

The tandem mirror concept was first conceived during 1976. The idea was invented independently by both the Soviets (Dimov at Novosibirsk) and in this country (Fowler and Logan at LLL). LLL submitted a proposal for TMX which was favorably reviewed. TMX was approved, and fabrication begun in 1977, at an estimated cost of \$11.4M. The installation of the mirror plug tanks began in April 1978, and some equipment was transferred from 2X-IIB (also at LLL) in June 1978. The experiment became operational in October 1978. The near-term experimental plan is aimed at the following objectives.

1. Demonstrating the existence of a potential magnetic well between the two mirror plasmas.
2. Developing a scaleable magnetic geometry to confine a high temperature, high density reactor grade plasma.
3. Investigating the microstability of the plug-solenoid combination in order to maximize the system energy gain Q .

FRX

The Field Reversal Experiment (FRX) at the Los Alamos Scientific Laboratory involves two separate machines, FRX-A and FRX-B. During FY 1977, FRX-A has generated field reversed configurations using theta pinch techniques and has demonstrated the importance of vacuum cleanliness in achieving stable plasmas. FRX-A has produced plasmas of remarkable MHD stability.

PHAEDRUS

The Phaedrus device at the University of Wisconsin is a small tandem mirror machine being constructed during FY 1978-79.

TANDEM MIRROR EXPERIMENT (TMX)

PHAEDRUS

The basic goal of Phaedrus is to develop radio frequency heating, which, if successful, could lead to a significant reduction in the projected reactor neutral beam energies required for the large TMX and TMR experiments that are planned parts of the mirror program. In addition, Phaedrus will explore the trapping of plasmas by radio frequency techniques in a tandem mirror configuration. In design, Phaedrus will be similar to TMX, but smaller.

Initial results of radio frequency heating in a single end cell will be evaluated in December 1978. This review will directly precede a commitment of funds to complete the Phaedrus tandem mirror device. Initial operation of radio frequency heating in the full tandem mirror device is expected to begin in September 1979.

Stabilization - MIT

Electron beam-plasma interactions in a small mirror machine have been shown to produce a very high energy tail of electrons trapped in the mirror. These electrons trap a corresponding number of cold ions and effectively fill the ion loss cone to stabilize the DCLC mode. This technique decouples the confined plasma from the end walls and reduces the associated electron energy losses.

The present effort at MIT involves rf stabilization methods and is closely coupled with the warm-plasma stream stabilization program being conducted on 2X-IIB at LLL.

b. Mirror Program Plans

The plans for the mirror program are summarized as follows:

- . To operate TMX in FY 1979, confirming the basic premise of the tandem mirror concept.

KEY: ▽ TASK INITIATION △ TASK COMPLETION ○ DECISION OR EVALUATION POINT

TABLE 4

- . To demonstrate field reversal in the period FY 79-81, by using various combinations of slow and fast, neutral beam and charged particle injectors.
- . To operate MFTF in FY 1982 to confirm the requisite technology and physics scaling laws required to design the mirror next step.

2. Other Linear Programs

In addition to mirror systems, there are other linear magnetic fusion concepts that have some physics and reactor technology features similar to those of mirror systems. While there are differences among the linear concepts, there are also many similarities in physics and technology. The physical models and many of the device components developed for one are useful to the others. Consequently, alternate linear systems could progress rapidly and their features quickly be incorporated into scaled-up linear systems once their physics principles are appropriately tested.

Long solenoid confinement systems generally consist of long, small diameter plasma columns confined by an axial magnetic field with several variations for reducing axial energy loss. Options for reducing end losses include multiple-mirrors, material or gaseous end plugs, cusps, and the introduction of turbulence to reduce electron thermal conductivity. Most proposals for linear reactors utilize staged heating in which the plasma temperature is raised by a preheater to approximately 1 kilovolt and then further increased to ignition temperature by adiabatic compression. Preheaters under study include implosion heating, CO₂ laser heating, rf heating, and electron beam heating. Advantages of this type of linear system as a reactor include high beta operation, simple geometry for modular construction and easier maintenance, and favorable physics for equilibrium and stability.

Implosion-heated Linear Theta Pinches have been under investigation for the past two decades. Plasma with ~ 3 keV ion temperature, $\sim 10^{16}$ cm^{-3} densities, and beta of unity are routinely produced in these devices. The confinement time, however, has been limited to 10-20 μsec in ~ 5 m long systems due to end-loss of the plasma along the open field liners. The primary focus of the near-term research on linear theta pinches, therefore, is to develop a suitable end-stoppering method. Material end-plugging techniques are being investigated currently on the Scyllac IV-P theta pinch at LASL, on laser heated solenoid at PPPL, and at other small installations at the Pennsylvania State University and the University of Washington. The confinement time on the S-IV-P device has been increased by 300% by using LiD material end-plug. The multiple mirror method of end-stoppering is being investigated at the University of California at Berkeley. The other types of end-stoppering are in the planning stages.

The end-stoppering studies on the existing facilities will be followed with experiments on longer systems (~ 25 m) to study stability and radial diffusion problems. Since the confinement time increases with the length of the device and with the utilization of the promising end-stoppering methods, the confinement time on the long system is expected to be a few hundred microseconds which is sufficiently long to investigate radial diffusion and to provide reactor-grade plasma for some parameters for a proof-of-concept test of linear systems. This experiment might also incorporate high magnetic fields (~ 100 -150 kG) in order to reduce the length of linear reactor systems.

The CO_2 heating of linear solenoids is being investigated at Mathematical Sciences North West, Inc., and the University of Washington. Kilojoule CO_2 laser beams are used to irradiate plasma confined in very high magnetic field (250 kG) solenoids. Stable propagation of laser beams for distances up to 100 cm has been demonstrated in these experiments.

C. BASE PHYSICS PROGRAMS

The base physics activities are divided into three elements: Fusion Plasma Theory, Computer Services and Technology, and Experimental Plasma Research. The fusion theory and computer service activities provide all essential theoretical and major computational studies that advance the goals of the physics Proof-of-Principle and Major Scaling Experiments program. The experimental plasma research activities provide data on plasma properties and atomic physics, and the development of advanced diagnostics and new experimental techniques which are required for design and operation of the major confinement experiments.

1. Fusion Plasma Theory

a. Strategy and Description

The objective of fusion plasma theory research is to provide the physics understanding necessary for interpreting present and past experiments and to formulate the appropriate scaling laws needed for meaningful experimental planning and prediction of the performance of future devices. Both analytical and computational studies are performed and the data obtained on experimental devices operating at different temperatures, densities, and magnetic field intensities are evaluated to test and possibly modify existing theories of plasma behavior as well as to formulate new theories.

b. Status

Recent Achievements

Many recent dramatic advances in the fusion energy program are based on corresponding advances in the theoretical formulation of new ideas and concepts. We summarize here recent achievements in fusion theory that impact the fusion energy program.

- . Development of a self-consistent model for internal disruptions in tokamaks, including demonstration of its benign nature.

- . Demonstration of high beta tokamak equilibrium for application in economically attractive reactor configurations.
- . Determination of finite beta effects on energy and particle loss rates (transport phenomena).
- . Initiation of studies of high field compact tokamaks utilizing alpha-particle heating.
- . Determination of conditions required for field reversal in neutral beam driven mirrors.

c. Plans

A summary of selected fusion theory milestones through FY 1983 is shown in Table 5.

2. Computer Services and Technology

a. Strategy and Description

The National MFE Computer Center (NMFECC), which opened in October 1975, was planned to meet most of the large-scale computer needs of the MFE program. The associated Network was carefully designed to balance requirements for local computing and access to the major facilities at the Center. This led to medium-scale computers in User Service Centers (USCs) at five major laboratories, linked by high-bandwidth communications lines to the NMFECC. The plan also provided for dial-up access to the NMFECC for all other MFE contractors.

The motivation for a single computer center dedicated to fusion research is that it is the most cost-effective way to provide access to the largest computers to all segments of the program.

The aggregate requirements of the program at the various geographical sites justify the large computers needed to solve problems in plasma physics, engineering and systems studies.

STAGE OF DEVELOPMENT IMPLEMENTING ACTIVITY TASK	PROOF-OF-PRINCIPLE BASE PHYSICS FUSION PLASMA THEORY											
	CY 1979		CY 1980	CY 1981	CY 1982	CY 1983	CY 1984					
	FY 1979	FY 1980	FY 1981	FY 1982	FY 1983	FY 1984						
BUDGET LINE ITEMS												
FIELD TESTING OF MHD STABILITY CODES				CONTINUE USAGE & IMPROVEMENT								
	DD III	ISX-B	TFTR		PDX							
INCORPORATION OF HEAVY IMPURITIES IN TRANSPORT CODES		COMPLETE		CONTINUE USAGE & IMPROVEMENT								
			PDX									
STARTUP AND SKIN-PHASE DYNAMICS IN 2-D TRANSPORT CODES			CONTINUE USAGE & IMPROVEMENT									
PLASMA-LIMITERS INTER-ACTION	COMPLETE INITIAL STUDIES		COMPLETE MODEL	CONTINUE USAGE & IMPROVEMENT								
ALPHA PARTICLE STABILITY AND DYNAMICS	COMPLETE INITIAL STUDIES											
COUPLED EQUILIBRIUM STABILITY TRANSPORT CODE		COMPLETE		CONTINUE USAGE & IMPROVEMENT								
THEORY OF RESISTIVE DRIFT MODE INSTABILITIES		COMPLETE		CONTINUE USAGE & IMPROVEMENT								
COMPARISON WITH EXPERIMENT AND REASSESSMENT OF TRANSPORT THEORY	BEGIN											
FOUNDATION OF THE THEORY OF BURNING PLASMA	BEGIN											
CONTROL SYSTEM THEORY FOR FUSION DEVICES	BEGIN											

KEY: ▽ TASK INITIATION △ TASK COMPLETION ○ DECISION OR EVALUATION POINT

TABLE 5

By tailoring service to special classes of large computational problems, it is possible to absorb communications costs and to provide service at a rate comparable to that charged for local computing at similar installations. This approach permits service to small groups at universities and private laboratories that would not be available otherwise. Such groups have a total requirement much smaller than the major laboratories, but individual problems require the largest computer.

b. Status

The original computer at the NMFEC (a Class IV CDC7600) was quickly saturated. During the two and a half years of its existence, there have been continuing incremental improvements to the efficiency of the computer system and the Network, and additional time has been purchased at other DOE installations. The figure below indicates the distribution of time used on the CDC 7600 by the major laboratories and all other contractors during the last fiscal year.

The capabilities of the CDC 7600 have been well utilized and the use of a single dedicated center has fostered code-sharing and cooperation. However, the one major computer has not met program needs, and it has been necessary to buy time at other installations to carry out essential calculations. Even more important, the Class IV computer has imposed limitations on the problems that could be addressed. As confinement devices have increased in size and complexity, the computers that support them must also increase in capability. The ability to attempt realistic simulations of plasma behavior has fallen behind the increasing number and the complexity of recent confinement devices.

NSUs (CDC 7600 hours)

c. Plans

To redress this imbalance, a Class VI (a CRAY-1) computer was leased at the NMFECC in late spring of 1978. Its larger memory and greater speed are needed for more realistic analyses and it will be heavily utilized. This computer will be leased through FY 1979, but a concern for total costs suggests that it should be purchased as soon as possible, since it will be used for a number of years.

Plans for the Network for the next few years include an upgrade of the central processing units in the USCs. The load on the USCs has grown with the increased computing power of the NMFECC, but another significant component of the USC workload arises from the processing of experimental data. As data acquisition minicomputers linked to fusion devices communicate with the USC computer, the latter has a need for substantially more archival storage and computing capability. Data rates dictate local processing and storage, and for a modest cost, the necessary capability can be obtained. Additional equipment is planned for the NMFECC in the mass storage and file management areas. Some smaller contractors that are not included in the existing leased line network will receive improved terminal equipment, and improved access to the central facilities.

3. Experimental Plasma Research

a. Strategy and Description

The experimental research program supports studies complementary to large confinement devices that develop techniques and provide data for improved design, operation, and understanding of confinement experiments and commercial reactors.

Specific objectives to be accomplished in each case by 1983 are the following:

- . Develop techniques and instrumentation that provide spatial and time resolution for all critical plasma parameters (densities, temperatures, current, potential, magnetic field, impurity concentrations, fluctuations).
- . Obtain rates for all radiative and collisional processes of impurity ions in confinement experiments.
- . Provide quantitative tests of analytical and computer models of plasma properties including trapped particle effects, plasma turbulence, convective transport, divertor and boundary effects, and effects on transport of strong rf and neutral beam heating.
- . Test rf, microwave, and shock heating of plasmas and develop improved positive and negative ion sources for neutral beam heating.
- . Develop superconducting materials with significantly improved mechanical and electromagnetic properties for use in large high field magnets needed by commercial fusion reactors.

Individual projects are supported at more than 25 universities throughout the country, at the National Bureau of Standards and the Naval Research Laboratory, and at five DOE Laboratories (PPPL, LLL, ORNL, LASL, LBL). Projects include low cost special purpose tokamak research devices (low beta) and several toroidal high beta devices.

b. Plans

Significant progress has been made in all areas. This progress has been closely coupled to both improved performance of large fusion devices and much better understanding of the physics responsible for observed phenomena.

The program plan in experimental plasma research is to focus upon fundamental issues which must be understood or resolved to permit substantive advancement of the fusion effort. The next generation of fusion experiments will move closer to the plasma regime for reactors. Stability at higher temperatures must be studied in controlled research experiments as well as investigations of the influence of high plasma beta on confinement properties. To attain the necessary higher temperatures, auxiliary heating methods must be employed and optimized. Increased operating parameters and plasma volume make new diagnostics necessary, e.g., for ion temperatures, and create additional impurity problems, for example, higher ionization states of heavy atoms. A vital component of this effort will be the Fusion Plasma Research Facility at the University of Texas which will provide a vehicle for testing and refining new instrumentation, diagnostic techniques, and rf heating methods as well as providing detailed measurements of impurity properties and other plasma properties in tokamaks. Finally, development of superconducting materials for magnets suitable for future mirrors and possibly tokamaks is needed.

Milestones

The following table summarizes selected experimental plasma research milestones through FY 1983.

D. BASE TECHNOLOGY

The base technology effort supporting the proof-of-principle programs are divided into two major elements: Plasma Engineering and Plasma Materials Interaction. The plasma engineering activity provides all the base technology necessary to operate the plasma experiments. There are four major areas within plasma engineering -- heating, plasma maintenance and control, vacuum component and direct energy conversion. The plasma materials interaction program is aimed at identifying the magnitude of the plasma/material interaction problems and developing solutions for dealing with these problems.

KEY: ▽ TASK INITIATION ▲ TASK COMPLETION ○ DECISION OR EVALUATION POINT

TABLE 6

1. Plasma Engineering

a. Strategy and Description

The primary effort in plasma heating has been neutral beam development involving the formation and injection of streams of high energy neutral deuterium atoms into a confined plasma. The injected neutrals interact with the plasma via ionization or charge exchange and the resultant trapped energetic ions slow down gradually by collisions with the plasma electrons and ions, thus heating the plasma.

Essentially all of the present generation of tokamak and mirror devices incorporate neutral beam heating, and the success of these experimental devices is directly related to the ability of neutral beam systems to deliver the power and energy necessary to achieve the design plasma parameters. In major scaling experiments like the Tokamak Fusion Test Reactor (TFTR), the energetic particle beams will be used directly to induce fusion reactions as well as to heat the plasma.

b. Status and Plans

Neutral beam sources have been developed and are operating on PLT. Activities are in place developing and producing prototype neutral beam sources for PDX, ISX, MFTF, Doublet III and TFTR.

Industrialization activities are in place to competitively select and qualify manufacturers of neutral beam sources.

In support of the prototype effort, activities are in place leading to:

- . improved atomic yield
- . more efficient extraction
- . better beam focus

- . more reliable operation
- . longer pulse length and cw operation
- . direct energy recovery
- . generation, acceleration and transport of negative ion beams

This development work is not only required for next generation systems such as for the TFTR and Mirror Fusion Test Facility (MFTF) but also is necessary now to lay the foundation for net energy producing reactors or beam driven hybrid fusion systems.

Radiofrequency heating component development is focused on development of 28, 90, and 120 GHz 200 kilowatt cw tubes and the associated system components. While this program was motivated by the Elmo Bumpy Torus program, it is now apparent that spinoff applications to tokamak and mirror applications alone will make the program cost effective.

The direct energy conversion program is aimed at the development of workable methods and hardware for direct energy recovery of ion beams and plasma exhaust. Beam direct conversion is essential in higher energy, long pulse systems not only to recover otherwise lost power, but to reduce equipment and operating costs of power supplies and beam dump systems. In addition, plasma direct conversion will allow efficient and economic mirror fusion reactors and will be applied as well to direct recovery for tokamak divertor exhaust.

The vacuum component development and demonstration program is providing the engineering data and technology base for vacuum components and systems. Near-term emphasis is on selecting and qualifying the more viable pumps (cryosorption, cryopanel, gettering, etc.) for fusion vacuum applications and understanding the subtleties of large scale helium and tritium pumping.

The plasma maintenance and control program plan is to develop fueling and divertor techniques and hardware for longer pulsed fusion reactor systems. Near-term emphasis is on development of a solid hydrogen pellet injector for testing on PLT, Doublet III, PDX, and, if successful, on TFTR. It is expected that 1-2 km/sec 1-10mm diameter pellets will be produced within the next eighteen months.

c. Milestones

The following table summarizes selected plasma engineering milestones through FY 1983.

2. Plasma Materials Interaction

a. Strategy and Description

The dominant materials problem area in fusion is that associated with the influence of radiation from plasma on the first wall and related structural materials, and the attendant influence of those materials (as impurity sources) on the plasma. These factors may well dictate the integrity of the plasma in the short term.

One of the primary objectives associated with proof-of-principle activities of the Materials and Radiation Effects Program therefore deals with the interaction of structural materials with the plasma in terms of impurities injected into the plasma.

This concern forms the basis for the Plasma Materials Interaction program element which is aimed towards the determination of the magnitude of the plasma materials interaction with respect to impurity and surface effects and the development of a material solution to minimize these effects.

TABLE 7

The goals are to provide a quantitative data base for the plasma impurity problem and fuel recycling, to minimize detrimental near-surface alteration of first wall materials, and to provide designers of confinement experiments and fusion reactors innovative concepts for walls and other components involving plasma interactions.

b. Status and Plans

It is generally recognized that radiation losses from impurities introduced through sputtering, blistering, desorption, or other processes, may impose very difficult conditions on ignition. The impurities may accumulate in the core of the plasmas, distorting temperature and density profiles, and may lead to undesirable attenuation conditions for neutral beams. Also, burn times for fusion power reactors, which should be many times longer than one energy confinement time, may be seriously limited by the accumulation of impurities and resultant energy losses.

Thus, the plasma materials interaction problem is unique in that it affects not only long term considerations for the economic production of fusion power, but has immediate impact on near-term confinement devices which are designed to prove the scientific principles upon which fusion power is based. Plasma contamination by impurities may limit the operation of confinement devices built and operated over the next five years. Phenomena such as impurity influx, H isotope recycling, and limiter and first wall modification, will assume even greater importance in future confinement devices and reactors which require hotter plasmas, longer confinement times and higher heating power levels.

The program is coordinated with the entire schedule for fusion power development including the major scaling confinement experiments,

energy-producing prototype and demonstration reactors and commercial power plants. Ongoing studies include single component (e.g., photons, ions, hydrogen, helium) irradiations, multi-component irradiations, plasma irradiation, analyses of walls in confinement devices, and protective wall coating development.

STAGE OF DEVELOPMENT PHYSICS PROOF-OF-PRINCIPLE																															
IMPLEMENTING ACTIVITY BASE TECHNOLOGY ACTIVITIES																															
TASK PLASMA MATERIALS INTERACTION																															
BUDGET LINE ITEMS (NO.)				CY 1979				CY 1980				CY 1981				CY 1982				CY 1983				CY 1984							
				FY 1979				FY 1980				FY 1981				FY 1982				FY 1983				FY 1984							
<ul style="list-style-type: none">• COMPLETE COMPREHENSIVE DATA BASE FOR IMPURITY INJECTION MECHANISMS FOR EARLY D-T DEVICES• SELECT SURFACE COATING RESEARCH REFERENCE MATERIALS• COMPLETE DATA BASE FOR HYDROGEN ISOTOPE HOLDUP AND RECYCLING• DEVELOP HYDROGEN ISOTOPE RECYCLING CONTROL BY TAILORED SURFACES OR ACTIVE CONTROLS FOR EARLY D-T DEVICES																															

KEY: ▽ TASK INITIATION △ TASK COMPLETION ⬡ DECISION ON EVALUATION POINT

TABLE 8

IV. MAJOR SCALING EXPERIMENTS

The goal of the Major Scaling Experiment stage in fusion reactor development is to provide tests of physics scaling laws to reactor level conditions and the demonstration of critical technology developments required for plasma confinement and heating in a large scale device. This represents the final large experimental testing before construction of an energy-producing experimental reactor.

Near-term objectives are to construct and operate the Tokamak Fusion Test Reactor and the Mirror Fusion Test Facility. The Tokamak Fusion Test Reactor will provide the physics scaling data for large toroidal systems and will, for the first time in magnetic fusion systems, enter the regime of burning plasmas.

The Mirror Fusion Test Facility (MFTF) will provide physics scaling data and technology tests needed to design energy-producing mirror fusion machines.

The strategy for the major scaling experiments is to design, construct and operate these experiments. Definition of the specific objectives and methods for resolving design issues will require assistance from many contractors as appropriate to ensure that the experiments are proceeding on the proper course. Industrial subcontractors will be used extensively.

Each of these projects is presently underway. The plans and milestones are summarized on Table 9.

A. TOKAMAK FUSION TEST REACTOR

1. Goals

The Tokamak Fusion Test Reactor (TFTR) will be the nation's first magnetic confinement fusion device to demonstrate experimentally the release of fusion energy from the deuterium-tritium reaction under conditions relevant to fusion power reactors. It is currently the

STAGE OF DEVELOPMENT		MAJOR SCALING EXPERIMENTS											
IMPLEMENTING ACTIVITY		TFTR/MFTF											
TASK													
BUDGET LINE ITEMS		CY 1979		CY 1980		CY 1981		CY 1982		CY 1983		CY 1984	
		FY 1979	FY 1980	FY 1981	FY 1982	FY 1983	FY 1984						
TFTR													
MFTF													

KEY: ▽ TASK INITIATION △ TASK COMPLETION ○ DECISION OR EVALUATION POINT

TABLE 9

TOKAMAK FUSION TEST REACTOR (TFTR)

the largest project in the magnetic fusion program and represents a major step forward in the physics and technology toward the development of commercial fusion power reactors. The TFTR is now being constructed at the Princeton Plasma Physics Laboratory (PPPL) near Princeton, New Jersey.

The TFTR project will proceed in two phases - basic TFTR and TFTR Improvements Project. The basic TFTR is a currently authorized project and is expected to be completed in mid-1982 at a total construction cost of \$239M. The TFTR Improvements Project could be an FY 80 line item request (\$75M TEC), leading to operation in early FY 84.

2. Near-Term Objectives

The TFTR facilities will make major contributions to the fusion program in both physics and engineering. The principal objectives are:

- . To demonstrate fusion energy production from the burning of deuterium and tritium (DT) in a toroidal plasma system.
- . To provide a flexible plasma physics research tool with a large plasma volume, high magnetic field and high power neutral beams to study the start-up, heating, confinement and shutdown of hydrogen, deuterium and DT plasmas.
- . To advance the engineering and technology of hardware systems and component generic to fusion reactors.

It is expected that with the basic TFTR, for the first time, energy breakeven will be achieved in a magnetic fusion device; that is, the fusion power produced will be comparable to the neutral beam energy input. With the TFTR Improvements Project, the plasma parameters will be extended further to the point where entry into the temperature excursion regime of a commercial reactor will be achieved.

The TFTR will serve as an intermediate step to help bridge the gap between current, relatively small, hydrogen proof-of-principle experiments and energy-producing experimental reactors. The

experience being gained in design and construction and in future operation and the information to be gathered in physics and engineering will provide a sound foundation for design and construction of the succeeding generation of fusion reactor experiments.

3. Program Implementation - Basic TFTR

The specific objectives of the basic TFTR project are:

- . Attain reasonably pure hydrogenic plasma conditions at 5-10 keV temperature, approximately 10^{14}cm^{-3} density, and provide stable confinement with $n\tau_E$ equal to or greater than $10^{13} \text{cm}^{-3} \text{sec}$.
- . Provide a neutral beam injection system capable of injecting into the plasma 20 MW of 120 keV neutral deuterium (D^0) beam, for at least 0.5 sec.
- . Provide a toroidal magnetic field of about 5 tesla (on vacuum chamber axis), for at least 3 sec. flattop time, with a 5 min. repetition rate.
- . Develop plasma handling techniques and provide hardware capable of initiation, control (including feedback control and major radius compression), and dissipation of tokamak discharges up to 2.5 MA.
- . Provide a vacuum chamber with 2.7m major radius and 1.1m minor radius, equipped for high-power discharge cleaning in situ bake-out, and capable of achieving base pressures of 10^{-8}Torr .
- . Provide capability for routine pulsed operation with H-H; D-D; D- He^3 ; or DT plasmas, with safe and reliable gas handling and support systems.

TFTR is currently well into the construction phase. Contracts for all the conventional facilities have been signed and site construction is underway.

TABLE 10

4. Program Implementation - TFTR Improvements

The encouraging results obtained recently in the operation of PLT and Alcator have provided a basis for extending the objectives of TFTR further toward the plasma regime of fusion reactors. The choice can now be made to produce fusion reactions throughout the bulk of the confined plasma, as will be done in fusion reactors, rather than merely using the confined plasma as a fusion target for the highly energetic neutral atom beams. Bulk "burning" of the plasma will so change the nature of the plasma that the α -particles, generated in the fusion reactions, will deposit their energy back into the plasma, tending to raise the temperature toward the point at which the process becomes self-sustaining -- the ignition point.

The TFTR Improvements Project (TIP) provides the additions to the basic TFTR facility to enable reaching this regime. These include:

- . Providing additional neutral beam lines and improving their performance either in species mix or pulse length,
- . Augmenting the magnet power supplies,
- . Providing facilities for the above,
- . Adding supplementary features for impurity control,
- . Modifying the tokamak structure and shielding for higher power operation.

With the increase in neutral injection power to around 45 MW and EF level of .5-.5 Tesla, the central ion temperature is expected to rise to 15-20 keV with beta in the 3% range. Q-values of around 2 should be attained. Other modes of operation will also be possible with the TIP, including local ignition -- in which an alpha-heated central region, assisted by beam heating at the plasma edge, reaches n , τ , T conditions exceeding those required for ignition.

The TFTR Improvements Project could be initiated in FY 80. Construction activities would be carried out in parallel with basic TFTR operations during FY 82 and FY 83, including a six-month shutdown for completion of

completion of the initial scaling experiments with H_2 and D_2 plasmas and perhaps limited D-T testing, but not so much that activation levels would impede installation of TIP. TFTR/TIP could begin with full scale D-T testing to study the physics of burning plasmas, achievement of breakeven conditions and temperature excursion regime plasmas as described above.

B. MIRROR FUSION TEST FACILITY (MFTF)

1. Goals

The goal of the Mirror Fusion Test Facility is to provide sufficient understanding of the physics and technology of large volume, high beta, steady state, reactor-grade plasmas to allow the subsequent development and design of a mirror fusion reactor.

The key parameter goals of MFTF are:

- . $n\tau(\text{cm}^{-3}\text{-sec}) \geq 10^{12}$
- . $T_i(\text{keV}) \geq 50$
- . $T_e(\text{keV}) \geq 1$
- . $R_p/\rho_i(\text{cm/cm}) = 13$ (ratio of plasma radius to ion gyroradius)
- . $L/\rho_i(\text{cm/cm}) = 100$ (ratio of plasma length to ion gyroradius)
- . $\beta = 0.5$
- . $n(\text{cm}^{-3}) = 10^{14}$

The experience that will be gained in the design, construction, operation and management of this facility, as well as the information to be gathered in the physics and engineering, will place the mirror program in a position to proceed with the design and construction of the next generation of fusion reactor machines.

TABLE 11

ESTIMATED PLASMA PERFORMANCE OF TFTR DEVICES

	TFTR Basic	TFTR Improvements Projects Mod 1	Mod 2*	Tokamak Ignition
Lawson Product ($n \tau$) ($\text{cm}^{-3} \text{sec}$)	$\geq 10^{13}$	10^{14}	3×10^{14}	3×10^{14}
Temperature (Kev)	5-10	15-20	20	7-10
Beta (%)	1	3	3	6-10
Gain	1	2	2-10	10-20

*These Conditions May Be Possible Within Very Local Regions of the Plasma

MFTF

12 METER OVERALL HEIGHT

2. Near-Term Objectives

The objectives of the MFTF for the period covered are:

- . To bridge the gap between present smaller mirror experiments and future experimental fusion reactors based on magnetic mirror systems.
- . To test size scaling, temperature scaling, and confinement scaling of magnetic mirror systems.
- . To test stability theory for large volume plasmas in magnetic mirrors.
- . To test ways of improving power balance (Q-enhancement) in mirror fusion systems.
- . To explore steady-state operation of a large plasma facility.
- . To achieve the key parameter goals given in Section 1 above.

3. Program Implementation

MFTF was authorized for start of construction in FY 1978. The project management system is in place, and specifications, RFP's and contracts for the various parts of the Facility are in preparation. The coil winder for winding the superconducting magnet has been constructed and installed at LLL. All parts of the project are moving head aggressively.

The Facility is designed to be flexible and to have an operating life-time of ten years, allowing a wide variety of plasma and technology experiments to be performed over the lifetime of the facility. Initial experiments will be performed in the large volume plasmas to test size scaling, temperature scaling and confinement scaling, as well as the stability for large volume, high β plasmas in magnetic mirrors.

After completion of the scaling experiments, field reversal experiments will be initiated to demonstrate field reversal in a large volume reactor-grade plasma.

Investigation, as required, relevant to a large tandem mirror reactor system will also be carried out in MFTF.

Finally, depending on program needs and funding during the period covered by this plan, two additional areas might be explored: First, the ion source, beam, and plasma dump could be upgraded to 30 second operation capability in order to examine wall equilibrium and steady state or long time operation. Second, high energy ion beams (up to 200 keV) could be added to the facility to investigate confinement, as the confinement parameter is a strong function of ion energy.

4. Strategy

These goals and objectives will be achieved by constructing and operating a facility having the following characteristics:

- . NbTi Yin-Yang Magnet (Superconducting)
 - a. $B = 2T$
 - b. mirror length = 3.4m
 - c. mirror ratio = 2
- . Sustaining Neutral Beam System
 - a. source voltage = 80 kV
 - b. beam current = 750A of neutral deuterium atoms (D^0)
- . Startup Neutral Beam System
 - a. source voltage = 20 kV
 - b. beam current $\geq 100A$ (D^0)
- . Operating Times
 - a. sustaining neutral beam sources = 0.5 sec
 - b. sustaining neutral beam supply = 30 sec
 - c. magnet - steady state
- . Control System
 - a. automated computer control and diagnostics system.

The MFTF facility represents a major step forward in both size and technology as noted by some of its components:

- . A cylindrical vacuum vessel 10.8m (36 feet) in diameter and 18.0m (60 feet) high.
- . A cryopumping system of 1500 square meters area.
- . A superconducting (NbTi) Yin-Yang mirror coil system (2 Tesla in the center, with a 2:1 minor ratio, a 3.4m mirror-to-mirror separation distance, and weighing over 200 tons).
- . 24 sustaining neutral beam power supplies capable of 80 kV, 83A, 30 second pulse width operation.
- . A utility electrical transmission line for the neutral beam power supplies rated at 250 megawatts.
- . A hierarchical computer control and diagnostics system for near automatic operation of a large experimental plasma facility.

The construction project will have a total cost of \$92.4M, and the facility will be located at Lawrence Livermore Laboratory. When completed in 1981, this facility will be the largest mirror facility in the world, and a focus of mirror research work for the next 5-10 years.

C. BASE TECHNOLOGY: MAGNETICS AND TRITIUM SYSTEMS

1. Goals

As magnetic fusion experiments scale toward reactor size, both technical and economic considerations force a departure from conventional copper magnets and their enormous power supplies. Superconductors offer the potential for meeting all necessary requirements, but the materials, magnets, and energy storage devices must be substantially improved, made larger and industrialized. In addition, containment and reprocessing technology for tritium fuel must be developed and demonstrated.

KEY: ▽ TASK INITIATION ▲ TASK COMPLETION ⬡ DECISION OR EVALUATION POINT

TABLE 12

2. Near-Term Objectives

The purpose of the Development and Technology efforts for major scaling experiments has been the engineering design and component development of large superconducting magnets and energy storage systems. In particular superconductors are being developed for the Mirror Fusion Test Facility, Elmo Bumpy Torus II and long-pulse tokamaks. In addition, the Tritium Systems Test Assembly will provide valuable experience for TFTR and for future tritium-burning fusion experiments.

3. Program Implementation

a. Magnetic Systems

1. Strategy

Superconducting magnet activities have been oriented toward the goal of developing appropriate superconductors, magnet construction techniques and an industrial production capability for large confinement systems experiments and future power reactors. This effort is focused largely on the Large Coil Program at Oak Ridge National Laboratory which entails fabrication of 2.5m x 3.5m size superconducting coils by industry and the construction of a Large Coil Test Facility (LCTF) for these magnets as well as future large magnets. The LCTF consists of a large vacuum chamber with supporting vacuum, cryogenic, and instrumentation and control systems to test a six-coil superconducting compact array. The general configuration of the LCTF as shown below will be jointly used through the International Energy Agency collaboration with other participants in superconducting magnet development for fusion.

In addition to superconducting toroidal fields, work is required to produce efficient poloidal field systems capable of transferring up to one gigajoule of energy in a few seconds, repeatedly and reliably. Accordingly, a

superconducting poloidal field system development program is proposed at LASL with superconducting pulsed coil development and the associated switching and energy storage systems development.

Mirror and some tokamak experiments will require higher magnetic fields, so that a High Field Test Facility and niobium tin superconductor development were authorized at LLL. Also, other laboratories such as BNL, Ames, BCL and ORNL have been supported to improve basic superconductor properties.

2. Status

In the Large Coil Program both preliminary and detailed coil designs have been completed, and advance procurements started for coil construction by three industrial subcontractors: Westinghouse, General Dynamics and General Electric. Preliminary evaluation of both niobium-titanium and niobium-tin superconductors has produced encouraging results, and new stabilization methods for force-cooled coils have been developed at MIT and ORNL. The helium liquefier for the Large Coil Test Facility is complete and installed, and the central test chamber is being completed.

At LLL the High Field Test Facility is partially complete and used for final testing of the MFTF superconductor. Large monolithic niobium-tin superconductors have been developed and tested with enhanced strain capability for use in large mirror experiments.

At LASL several small 300 kilojoule energy storage coils have been tested. The most successful, constructed by Westinghouse, stored 500 kilojoules and was discharged in one second without losing its superconductivity.

KEY: ▽ TASK INITIATION ▲ TASK COMPLETION ○ DECISION OR EVALUATION POINT

TABLE 13

However, large extrapolations of this technology will be required for alternate applications experiments or tokamak ohmic heating.

3. Plans

For the Large Coil Program, three superconducting test coils will be developed and fabricated by U.S. industry with delivery to the LCTF in 1981-82. Three additional coils built to a common U.S. designed interface are planned to be supplied by Euratom, Switzerland, and Japan through an International Energy Agency collaboration.

Initial operation of the Large Coil Test Facility with a capability of testing three coils is scheduled for 1981. The facility will be fully operational in 1982 and will be utilized for at least three years for testing of six coils in a toroidal array. This torus test is the pacing item in design and fabrication of the large superconducting magnets that will be needed for the next major step in fusion research.

The High Field Test Facility at LLL will be completed by 1981 and a 12 Tesla niobium-tin coil inserted.

b. Tritium Systems Test Assembly

1. Strategy

Tritium processing and control efforts have the objective of the timely demonstration of all tritium processing and control subsystems required for each major fusion facility. Efforts are focused on the Tritium Systems Test Assembly (TSTA) which will be dedicated to the development, demonstration, and interfacing of technologies related to the deuterium-tritium fuel cycle for fusion reactor systems.

It will serve as a test bed for demonstrating the tritium processing and containment system technology for large scale fusion experiments.

2. Status

In May 1976, the Development and Technology Program concluded that consolidation and acceleration of tritium development were essential to provide adequate input to design of any major fusion experiment in the 1980's. Proposals for design of TSTA to demonstrate tritium fuel cycle and containment/cleanup technology were requested from seven ERDA laboratories with tritium handling experience. In January of 1977, LASL was selected to proceed with conceptual design and to prepare a formal proposal for MFE review as a Major Device Fabrication project. The LASL proposal was completed and submitted to MFE in June, and authorized for construction in July of 1977 with an estimated total cost of \$13.2M.

3. Plans

The TSTA will consist of a large gas loop which can simulate the proposed fuel cycle for a fusion facility. The loop does not include any specific fuel injection system, but will be sufficiently versatile so that such systems can be added as the design requirements are better defined. The gas loop will be designed to handle up to ~500 moles per day DT. This flow will provide cycle operating experience on a scale that is equal to or greater than the full-scale fuel cycle currently being addressed for TNS and EPR systems. To accomplish this at TSTA will require an on-site tritium inventory of approximately 200 g. A conceptual view of the completed facility is shown.

Tritium Systems Test Assembly (TSTA)

TABLE 14

V. ENERGY PRODUCING EXPERIMENTAL REACTORS: DESIGN STUDIES AND LONG LEAD TIME TECHNOLOGY DEVELOPMENT

This stage of the Magnetic Fusion Energy Program provides the bridge between fusion energy experiments and commercialization. There are currently several activities looking ahead toward this stage of development: Experimental Reactor Design Studies, Alternate Applications Studies, and Long Lead Time Technology Developments. The design studies cover a spectrum of machines from devices demonstrating key technical objectives to demonstrating electrical power generation or some other specific applications of fusion power.

The objectives of this program segment are as follows:

1. Develop and document program plans for proceeding from current experimental programs to the demonstrated commercial feasibility of fusion power. This objective will include both toroidal and linear concepts.
2. Identify and characterize the nature of experimental reactors leading to commercial applications.
3. Provide conceptual designs for the class of experimental machines which are potential candidates for initiation in the 1980's.
4. Strengthen the user and vendor involvement in the program design, review and evaluation process.
5. Provide the technology research and development base to support the experimental reactor requirements in plasma engineering, magnetic systems, materials and systems engineering.

The achievement of these near-term objectives for each of the program elements is described below. Particular emphasis is given to designing devices which maximize the production and evaluation of critical data and minimizes redundancies. Careful attention is given to schedule, cost and technical features and these factors are carefully weighed against criteria established by the commercialization element of the program.

A. EXPERIMENTAL REACTOR DESIGN STUDIES

The goal of the experimental reactor design studies for the next five years is to bring to fruition reactor studies on the most promising confinement systems concepts in order to outline and guide the major program decisions that must be made on the path to fusion energy commercialization. A second goal is to provide a focus for the physics and technology programs. A third goal is to develop conceptual designs for the major D-T burning experiments which are candidates for construction in the 1980's and beyond.

The near-term objectives for this program element are as follows:

1. Complete the conceptual design for a post-TFTR tokamak device.
2. Initiate and complete conceptual design for a post-MFTF mirror device.
3. Complete studies for other confinement concepts consistent with experimental and theoretical results.
4. Complete Tandem Mirror Reactor and Field Reversed Mirror Reactor Design.
5. Update tokamak EPR and Demonstration Reactor Studies consistent with advances in theoretical and experimental programs.
6. Define major technology requirements for other candidate confinement concepts.

1. Machine Options for the 1980's

a. Strategy and Description

This task established in early 1976, has two principal objectives:

- (1) to define the reasonable next step in the tokamak and mirror tasks; and (2) to provide a near-term focus for the physics and technology subtasks of the national magnetic fusion activity.

TABLE 15

The design of the next major devices will require carefully weighed trade-offs between cost and the contribution to the entire body of knowledge needed to make fusion useful, between risk and the need to confidently demonstrate a significant level of technical advance, and between time and the need to consider carefully all the input variables. The decision will be crucial for all fusion activities in the 1980's.

The task strategy is to prepare competitive designs for a class of experimental machines which are significant advances toward fusion power; and to evaluate these designs in terms of technical risk, schedule and cost. In principle, such a device could be built for each of the confinement systems; in practice, it is anticipated that perhaps as much as 60 percent of the system and component design and operation for a tokamak device will be generically useful for any other confinement system as well. For example, the construction of a prototype tokamak reactor with its generic tritium, cryogenics, modular blanket, instrumentation and control systems, etc., may remove the necessity of constructing a mirror device next step as well.

The options in the mirror program have not been as clearly defined as in the tokamak program, although two options are known to exist. These are the tandem mirror and field reversed mirror options. A program will be initiated in FY 79 to develop plans and subsequently designs of various options in the mirror programs. Similarly, major D-T steps may be considered for the other concepts if there is sufficient promise from the reactor studies and sufficient progress in the experimental/theoretical program.

b. Status and Plans

The tokamak design and engineering studies were initiated in FY 1976 at ORNL as an outgrowth of the earlier experimental

reactor (EPR) design studies at that laboratory. Similarly, in FY 1977, General Atomic redirected an effort on EPR design supported by EPRI to evaluate that design as part of a government-funded effort. Finally, in FY 1978, PPPL and MIT initiated studies as an evolution of a TFTR upgrade study that had been completed in FY 1977. There are now three competitive teams, General Atomic, Oak Ridge National Laboratory, and MIT/PPPL, evaluating the various options.

2. Experimental Power Reactors

The experimental power reactor is a class of device which operates with net electrical power production but with less than optimum power density, availability and associated auxiliary systems. These devices are necessary precursors to commercial reactors, and provide the basis for maintaining continuity in understanding between the near-term facilities and the commercial reactors.

During the next five-year period, studies will be maintained on the Tokamak Experimental Power Reactor. Additional studies on a Mirror Experimental Power Reactor will be initiated as the results become available from Q-enhancement work on TMX and field reversal.

Additionally, power reactor studies may be started on other concepts as initial reactor studies and experimental results dictate.

3. Commercial Demonstration Reactors

This effort involves assessment of ongoing and near-term future programs, as well as projections of the eventual nature of fusion power production. Reactor studies of potential commercial tokamak fusion power plants are underway at the University of Wisconsin and at the Massachusetts Institute of Technology. Parametric analysis of tokamak power plants and the potential Elmo Bumpy Torus (EBT) alternate fusion power reactor are underway at Argonne National Laboratory (ANL) and Oak Ridge National Laboratory (ORNL), respectively. A detailed design of a stainless steel first wall and blanket is also underway at ORNL.

TABLE 16

TABLE 17

Lawrence Livermore Laboratory (LLL) is studying techniques for making the neutral beams for mirror reactors more radiation resistant and techniques of achieving higher Q and power density in tandem mirror reactors. Finally, an assessment of the reactor plant prospects of alternate confinement techniques is being conducted by LASL as a backup to the main line tokamak and associated mirror and EBT concepts.

As a result of this evaluation, it is anticipated that several confinement schemes will be chosen as candidates for mature point reactor designs. These reactor embodiments will then be evaluated relative to commercialization criteria which grow out of the studies in VI.B. and the relative program priority from an experimental/theoretical viewpoint will be adjusted accordingly.

FY 1978 activities include completing the first round of detailed design studies for tokamak and mirror reactor subsystems (e.g., blankets and neutral beams), definition of the reactor implications of several alternate confinement concept approaches, and continuation of studies to define viable approaches to fusion reactor maintenance and control. A study will be concluded on an evaluation of a single committed site with support facilities for future major fusion experimental devices.

4. Alternate Applications Reactors

a. Strategy and Description

The goal of the Alternate Applications activity is to investigate the feasibility of non-electric applications of fusion energy. This investigation departs somewhat from similar efforts directed at fusion electric power development because of differing technical objectives. In addition, fusion energy applications may require less demanding performance from the fusion driver than for electric power production. Consequently,

TABLE 18

fusion reactor concepts alternative to the mainline tokamaks and mirrors may offer attractive advantages. The types of energy producing experimental reactors discussed in the previous three sections also apply to Alternate Applications Reactors. The objectives and timing of these machines could differ somewhat depending on the specific applications selected and the choice of the fusion driver.

The first element of the basic strategy of Alternative Applications Reactor design activities is to "piggy back" on similar efforts directed at fusion electric power reactors and to initiate design efforts based on alternative fusion drivers. This makes maximum use of the studies performed to date and provides sufficient resources for new design initiatives. In addition, it is expected that the relaxed fusion driver requirements for selected applications may revive design concepts that were set aside as too aggressive and risky.

The second element of the strategy is to make maximum use of completed and ongoing efforts supported by other DOE programs. There is a considerable amount of work underway, particularly in fissile fuel production and synthetic chemical production, that is directly adaptable for use in Alternate Applications Reactor designs. In addition, encouragement will be provided to other DOE organizations to initiate or increase efforts relevant to fusion energy applications objectives.

b. Status and Plans

Because the non-electric fusion energy activity is a new element in the fusion program, no Alternative Applications Reactor designs have been produced leading to a demonstration reactor. Only very preliminary fusion-fission hybrid "commercial" reactor designs have been prepared and these for the

production of plutonium and not a more proliferation resistant nuclear fuel. No reactor designs for the production of synthetic fuels and process heat have yet been prepared because of the uncertainty of the fusion driver requirements at this time.

Early in the next five year period experimental Alternative Applications Reactors will emphasize tokamaks and mirrors because of their relatively advanced state of development. However, it is planned that other concepts will receive increasing emphasis in the future.

c. Milestones

Milestones for the experimental Alternative Applications Reactor design program are shown in Table 22.

B. LONG LEAD TIME TECHNOLOGY DEVELOPMENT

The goal of the supporting technology development for the next five years is to establish a strong technology base in materials research and in reactor systems. This data base would allow an expanded program in energy producing reactors to be initiated in FY 85 or earlier if an enhancement package is approved. This program is responsive to the reactor studies discussed in V.A. above.

The near-term objectives for this program element are as follows:

- . To select optimum alloys and coating first wall application in fusion power reactors and to initiate a development program to proof test the alloys.
- . To construct and operate a high flux high neutron energy irradiation facility.
- . To complete blanket and shield conceptual designs for a broad range of fusion confinement concepts.
- . To analyze and diagnose instrumentation and control requirements for fusion power systems incorporating tritium, cryogenic magnets, electromagnetic coil/plasma interface and balance of plant systems.
- . To develop and evaluate neutron-hardened systems for use in D-T reactors.

- . To complete a neutron streaming experimental program.

This program element is accomplished by a constant interaction between design studies (which establish goals and general reactor configuration) and the on-going experimental program (which incorporates many of the technologies in an embryonic sense). The two major elements of this work, materials and systems engineering, are discussed in the following sections.

1. Reactor Materials

a. Strategy and Description

Successful economic operation of commercial fusion reactors depends on the development of materials capable of withstanding the severe radiation environment resulting from the deuterium-tritium (DT) fusion reaction. Material performance must be sustained for long periods of time, at elevated temperatures, under repeated thermal cycling and nonuniform loading, perhaps in the presence of a corrosive primary coolant. Other material problem areas include an array of special purpose materials including superconductors, insulators and special structural alloys. Heat extraction and tritium breeding impose additional requirements in regard to compatibility and mass transfer.

The primary objectives of the Materials and Radiation Effects program which relate to energy-producing experimental reactors are the (a) development of materials and the understanding of materials behavior that will assure the structural and plasma integrity of the first wall; (b) development of special purpose materials that are required for magnetic confinement, heat transport, energy conversion and storage, and other functions of specific fusion systems; and (c) materials engineering support for the continuing development programs.

The first of these objectives, materials development for the first wall, deals with the effects of the DT plasma radiation on the structural integrity of the wall. This concern forms

the basis of a program element to develop radiation resistant alloys to satisfy the structural requirements of commercial fusion power. This element is called Alloy Development for Irradiation Performance. Development of special purpose materials will be pursued in the program element Special Purpose Materials which encompasses those materials other than the first wall and structure.

Supporting these activities are two other program elements: Damage Analysis and Dosimetry and Radiation Facilities Development and Operation.

Parametric systems studies provide a basis for specifying the broad requirements which materials must satisfy to function reliably in the fusion environment. The recognition of these requirements allows for the establishment of preliminary long term goals for the fusion materials program. We have established an upper limit of 40 MW-years/m² as the goal for the long range materials development program. This limit is much higher than materials requirements based on most presently available fusion reactor systems; furthermore, it is not expected to be reached by conventional materials. However, in view of rapidly changing design philosophies, this goal must be set as high as practicable.

The temperature goals for the materials development program are related to the heat conversion system under consideration.
(Na:H₂O heat conversion system - 550°C, He/H₂O steam generator - 730°C, helium driven turbine - 900°C.)

b. Status and Plans

1. Alloy Development

Initial surveys suggest that the stainless steel, nickel base, and refractory or reactive metal alloy systems all offer attractive properties for fusion reactor applications.

The Alloy Development Program is Focused on Commercial Power Applications

FIGURE V-1

The alloy development program is, therefore, based on a parallel path approach. Our objective is to develop a program which, although necessarily broad in its early stages, may be sharply focused along a particular path at any time, to allow that path to become the principal direction of an advanced materials development program. A direct outgrowth of the parallel path approach is the development of data for intermediate fusion devices. Materials requirements for such systems are not considered as primary alloy development performance goals, but as timed output of data along the several paths leading to alloys for commercial fusion power.

The four paths included in the program represent materials which have not only different basic characteristics in terms of probable fusion reactor performance but also different levels of technology development and different degrees of risk or potential for performance and success:

Path A: Austenitic Alloys

Path A is directed toward the development of austenitic alloys. These represent the most established technology, including both fabrication and irradiation experience. The present development of austenitic alloys is such that program activities can move immediately in the direction of optimization of composition and microstructure for use in the fusion environment. Austenitic alloys show promise for early fusion power systems, but it is uncertain that they will have either the temperature capability or radiation resistance to meet the requirements for commercial fusion power. In addition to the direct utility of austenitic alloys, compositions in this alloy class will serve as model materials for comparison studies between damage produced by fission and fusion environments and will lead to the understanding necessary for extrapolation from one to the other.

Path B: Higher Strength Fe-Ni-Cr Alloys

Path B is aimed at the optimization of the higher strength-higher temperature capability Fe-Ni-Cr Superalloys. The irradiation performance of a large range of nickel base alloys has indicated a possibility for significant reduction of void swelling and the higher strength levels of this alloy class suggest superior fatigue properties.

Path C: Reactive and Refractory Metals and Alloys

Path C will address the reactive and refractory metals option. These alloys must be considered as the most promising candidates for reaching the long range materials goals for economic fusion power. Preliminary estimates indicate that it may be possible to obtain irradiation resistance greater than 20 MW-years/m². The principal advantages of the refractory metal alloys are high temperature strength, resistance to cyclic thermal fatigue and the possibility of reasonable irradiation resistance.

Path D: Innovative Concepts

Path D will address innovative and composite material options. This path is included in the program in recognition that the conventional concepts of metallurgical development that are implicit in Paths A, B, and C may not be adequate for fusion reactor applications.

2. Damage Analysis and Dosimetry

The Damage Analysis and Dosimetry Program element encompasses establishment of the radiation (primarily neutron) spectra in various materials testing facilities, establishment of damage parameters and measurement of damage in materials, analysis of radiation damage from several spectra, and extrapolation to predict effects of the fusion power spectrum.

3. Radiation Facilities Development and Operation

The complexity of the fusion radiation environment leads to the inevitable conclusion that fully prototypic engineering testing can be achieved only in an actual fusion test reactor. Such a facility, however, will not be available for the next 10-15 years and, even when available, may provide "real time" testing rather than the accelerated testing conditions required for long range materials development. Radiation Facilities Development and Operations, therefore, includes the operation of existing radiation facilities and the development of neutron and plasma sources to simulate the fusion reactor environment for materials testing. Current strategy includes the use of fission reactors, D-T neutron sources, broad spectrum high energy neutron sources, and ion simulation.

4. Special Purpose Materials

The Special Purpose Materials Program element deals with the development of fusion reactor materials other than first wall structural materials. Long-range research efforts are underway on insulators, radiation resistant superconductors, and materials for heat transfer and conversion systems.

Accomplishments

- . Alloy development of irradiation resistant materials initiated. Four paths to be pursued include austenitic alloys, iron-chrome-nickel alloys, refractory metals and innovative concepts.
- . Initiation of EBR-II and ORR irradiation experiments to support alloy development program.
- . Low Z coatings program initiated.
- . Draft of Fusion Materials Program Plan completed.
- . Five position papers (Fusion Materials Program bulletins) distributed. Included are "Overview", "First Wall Structural Goals for Economic Fusion Power", "Alloy Development to Meet First Wall Structural Goals for Economic Fusion

Power", "Plasma-Materials Interaction", and "Radiation Facilities".

- . Creation of US-USSR Joint Working Group on Fusion Materials.
- . Simulation of neutron creep by proton bombardment. First creep data on titanium alloys.
- . HFIR experiments have shown useful ductility in stainless steels containing several thousand PPM of helium. Titanium-modified steels maintain this advantage to higher temperatures.
- . High energy neutron irradiations in RTNS-I and in a D-Be source have shown changes in mechanical properties at fluences of 5×10^{17} n/cm². Data from the same material irradiated in both facilities indicates similar damage is produced at low fluence by 14 MeV and by high energy spectrum sources.
- . Hydrogen permeability was lowered by a factor of 40 in stainless steels containing 2-5% aluminum. Further decreases were obtained by preoxidizing at 600°C.

c. Milestones

Milestones are shown in Table 19.

2. Systems Engineering

a. Strategy and Description

The objectives of the Systems Engineering Activity in this program element is to provide the basic research and engineering for the reactor systems such as blanket and shield, plasma engineering plant system and tritium systems technology.

Blanket and Shield Engineering involves development efforts oriented mainly toward the Prototype Experimental Power Reactors (PEPR). Neutronic mockup experiments are underway at ORNL. Additional shielding code work and blanket and shield engineering assessment are underway at LASL, ANL, and Brookhaven National Laboratory (BNL).

STAGE OF DEVELOPMENT		ENERGY-PRODUCING EXPERIMENTAL REACTORS																	
IMPLEMENTING ACTIVITY		LONG LEAD-TIME TECHNOLOGY									DEVELOPMENT								
TASK		REACTOR MATERIALS																	
BUDGET LINE ITEMS		CY 1979			CY 1980			CY 1981			CY 1982			CY 1983			CY 1984		
		FY 1979			FY 1980			FY 1981			FY 1982			FY 1983			FY 1984		
• SELECT OPTIMUM SURFACE COATING MATERIALS																			△
• SELECT PATH D CONCEPTS FOR SCOPING STUDIES							◻												
• IDENTIFY OPTIMUM PATH A ALLOY										△									
• SELECT PATH C BASE RE-SEARCH ALLOYS										◻									
• COMPLETE DATA BASE FOR ORGANIC MAGNET INSULATORS										△									
• DETERMINE TRITIUM PERMEA-TION MECHANICS AND IDENTIFY BARRIERS													△						
• ASSESS EFFECTS OF PRIMARY RECOIL SPECTRUM AND DAMAGE RATE AND FLOW AND MICRO-STRUCTURE													△						
• SELECT PATH B PRIME CANDIDATE ALLOYS																	△		
• ESTABLISH NEUTRON DOSIME-TRY METHODOLOGY FOR HIGH FLUX LI(D,N) FACILITY																	◻		
• ESTABLISH QUANTITATIVE MODELS FOR EFFECTS OF HELIUM AND DISPLACEMENTS ON FLOW																	△		
• SELECT PATH D BASE RESEARCH MATERIALS																			◻
• DEVELOP PREDICTIVE MODELS FOR IMPURITY INJECTION MECHANISMS FOR LONG TERM DEVICES																			△
• ESTABLISH COMPOSITE MODEL FOR FRACTURE IN AN IRRADI-ATION ENVIRONMENT																			△

KEY: ▽ TASK INITIATION

△ TASK COMPLETION

○ DECISION OR EVALUATION POINT

TABLE 19

b. Status and Plans

Tritium Processing and Control efforts have the objective of the timely demonstration of all tritium processing and control subsystems required for each major fusion facility. Efforts are focused on the Tritium Systems Test Assembly (TSTA), discussed previously, which will be dedicated to the development, demonstration, and interfacing of technologies related to the deuterium-tritium fuel cycle for fusion reactor systems.

Plasma Systems Analysis provides for studies of radio-frequency heating systems, data requirements for pellet fueling analysis, and trade-off studies between divertors and/or gas blankets. Further investigations of startup and shutdown control technology requirements in tokamaks will be undertaken to analyze radiation and charged particle loading of the first wall and system requirements for reverse field plasma configurations. These studies will aid in assessing experimental research and technology development requirements for the PEPR and subsequent reactors.

Plant Systems include hardware-related control system development and detailed assessment of balance of plant R&D requirements. These tasks are largely directed toward support of the PEPR and form the basis for Experimental Power Reactor plant systems.

TABLE 20

VI. COMMERCIALIZATION: REACTOR DESIGNS AND SYSTEMS STUDIES

The fusion program is aimed at deployment as a major energy resource as soon as possible. The process leading to this deployment is called commercialization -- the path leading to and including the successful adoption of a product or technology by the private sector. Because of the long-term nature of the fusion program, commercialization has only recently begun to be considered in planning activities. By and large, recognition of this need has resulted from recent technical progress and the emergence of potentially attractive fusion energy applications.

The near-term objectives of the fusion energy commercialization program include the following elements:

- . Identification of the most attractive evolutionary paths from the point of view of economic pull. This responds to the need to consider market demand and includes both careful analysis of fusion energy applications and specification of physics and technology development programs.
- . Maximize use of data from current and planned physics and technology experiments to provide guidance.
- . Involvement of the users (utilities and others) and vendors in the best fashion to help guide the near and middle term program.
- . Continued utilization of opportunities to improve the perception of fusion energy by the population at large.

The discussion on the commercialization of fusion energy is divided into two basic subprogram activities: commercial reactor designs and systems studies. In essence the commercial reactor designs serve as references against which systems studies are performed.

A. COMMERCIAL REACTOR DESIGNS

The goal of the commercial reactor design activity is to establish a framework within which technological requirements, economic objectives, and environmental and safety constraints are evaluated. In the longer term, of course, commercial reactor design activity will be the design of commercial fusion reactors.

During the next five years, the commercial reactor design activity will emphasize designs of fusion reactors and other concepts, and fusion energy applications using several different confinement concepts.

The following paragraphs explain the strategy, status and milestones for each of the commercial reactor design activities.

1. Pure Fusion Reactor Design

a. Strategy and Description

Pure Fusion Reactor Design is an effort to begin to consider the possible forms of future fusion reactors. The strategy is to do sufficient conceptual design to identify those areas which are critical to eventual success so that R&D can be addressed to finding appropriate solutions.

The commercial reactor designs are used to measure individual power systems against "commercial" criteria such as unit size, power cost, unit cost, reliability, availability, environmental impact, construction lead times, etc. This measurement is done with the involvement of the user, vendor and developer communities to assure reasonable guidance to the program.

b. Status and Plans

During the next five years, commercial reactor designs will be completed for the mirror program and for some other concepts. Tokamak commercial plant designs will be updated as significant physics from PLT, D-III, PDX and Alcator C become available.

TABLE 21

2. Alternate Applications Reactor Designs

a. Strategy and Description

At the present time the Office of Fusion Energy is focusing on two major non-electrical energy applications. These are fusion-fission energy systems and synthetic chemical fuel production reactors, selected because of the high degree of relevance of their resulting energy products to ours, as well as other, industrial societies. In the case of fusion-fission energy, it is expected that this application may offer significant relief to the barriers facing the utilization of nuclear fission energy in the middle to longer terms. Specific emphasis is on proliferation resistant nuclear fuel cycle production, in a fashion that is both economically sound and environmentally safe. While not as well developed as fusion-fission energy sources, synthetic chemical fuel production utilizing the unique features of the fusion neutron source has the potential to reach a far larger market for transportable liquid and gaseous fuels. Specific emphasis in this area is on the high efficiency conversion concepts that are available only to the fusion neutron source because of either its radiative or thermal advantages.

The strategy adopted for the assessment of all fusion energy applications is to roll backward from the commercial requirements and to roll forward from the present status of the fusion energy program to establish the best plan consistent with the aforementioned commercialization criteria. The basic ground rules are to observe the principles of "economic pull" and "evolutionary transition" in the commercial reactor design efforts.

b. Status

Since the fusion energy applications subactivity is a relatively new effort, no detailed commercial reactor designs have yet been produced. Early conceptualization studies suggest that fusion-

fission hybrid reactors would be economically attractive. Synthetic chemical fuel production from fusion reactors is also a relatively new effort. In 1977 it was determined that high temperature electrolysis and thermochemical radiochemical/electrochemical processes offered the greatest promise. Design efforts now are underway to assess the technical prospects for these particular approaches to synthetic chemical fuel production using the unique radiative/thermal environment of fusion reactors. Initial results indicate that thermal efficiencies in excess of 50% may be expected from at least one of these approaches.

c. Plans

Over the next five years, "commercial" designs for the leading fusion energy applications concepts will be generated. Hybrid reactor design activity will principally emphasize fissile fuel production and economically attractive approaches to use the considerable quantities of reject heat that is generated in the process. This objective is consistent with the view that fusion-fission energy may only be a milestone on the path to pure fusion power. Associated nuclear fuel cycle activities will emphasize proliferation resistant nuclear fuel and high conversion ratio fission reactors capable of utilizing this form of fuel. Synthetic chemical fuel production fusion reactor designs also will be performed from the point of view of eventual commercialization. For example, it is envisioned that first generation commercial synfuel fusion reactors would generate hydrogen to be used as a basic feedstock for upgrading coal to liquid and gases. This selection of first generation objectives is consistent with the high probability that a coal-based synthetic chemical fuel economy will emerge over the next two to three decades. Such synfuel fusion plants are expected to evolve into stand-alone facilities in the longer term.

Table 22 presents the milestones for the fusion energy applications activity over the next five years. These milestones were developed

according to the funding expectations of the base case. They present a "Logic I" conservative program.

The Enhancement Programs presented in Section VII permit strategies and objectives that could result from the decision to more seriously consider the prospects for non-electric fusion energy application.

b. Status and Plans

The primary responsibility for achieving the stated Environment and Safety objectives of the Magnetic Fusion Program is vested with the program itself. However, the scope of these objectives is sufficiently broad that DOE has given major, parallel responsibilities to the Assistant Secretary for Environment (ASEV). These responsibilities include supportive biomedical and environmental research and general overview of environment and safety development activities.

To clearly identify these parallel responsibilities and to establish a specific plan for resolution of environment and safety issues related to magnetic fusion, a Magnetic Fusion Program Environmental Development Plan has been jointly prepared and approved by the Assistant Secretaries for Environment and Safety Technology. This plan identifies the major environment and safety issues associated with development of magnetic fusion energy and lays out a schedule for accomplishment of important milestones related to their resolution. It is incorporated in this plan by reference. The Environment and Safety subactivity within the Office of Fusion Energy is divided into two funding categories: Environmental Assessment and Reactor Safety Research.

Environmental Assessment

Formal analysis of environmental impact is required for all major federal activities, including broadly based R&D programs as well

TABLE 22

as specific projects. Activities in this category are aimed at developing information required to assess the environmental impacts of major fusion facilities, the magnetic fusion R&D program as a whole, and the ultimate commercialization of fusion power. Milestones have been established for publication of Environmental Impact Assessments or Statements, as appropriate, in each of these areas. Currently, efforts are being focused on the development of alternate approaches to preparation of the generic program statements to be consistent with new regulations being prepared by the Council on Environmental Quality.

B. SYSTEM STUDIES

The goal of this system studies activity is to address the socio-economic aspects of the commercialization process. This includes evaluation of economic competitiveness, of market demand and penetration, of costs versus benefits for various fusion power deployment schemes, of institutional factors which may influence vendor/customer decisions and of political social constraints such as environment and safety. The near term goal for this activity is to establish a strong and broad base for evaluation of environmental and safety issues, to evaluate the cost/benefit of fusion power and to increase the involvement of the eventual market community, i.e., both users and vendor groups. These areas are discussed below in two separate activities.

1. Environment and Safety

a. Strategy and Description

The ultimate acceptability of fusion power reactors as a major national energy source will depend, in part, on the safety and the environmental impact of their operation. The objective of the Environment and Safety subactivity is to assure that the development and ultimate operation of fusion power reactors are accomplished with minimum adverse effect on the environment and with maximum safety for both the public and for DOE and DOE-contractor personnel and property. Within this overall objective, there are three specific objectives:

1. Identification and evaluation of potential hazards related to operation of fusion research facilities and power reactors.
2. Development of appropriate safety technology and design criteria to control potential hazards.
3. Formal environmental assessment and safety analysis to assure that environmental impacts and plant safety implications are fully evaluated for each major facility and for the Magnetic Fusion Program as a whole.

Reactor Safety Research

Activities in this category are aimed at identification and characterization of fusion reactor accident risks and development of appropriate safety and control features. The primary goal is to provide timely input into the design of each major fusion facility, to assure that construction and operation are accomplished safely and with minimal environmental impact.

The R&D activities are planned to anticipate the needs of the development of magnetic fusion technology. These activities should provide a base of experience and technical data which can be translated directly into licensing criteria when the program approaches the commercialization phase. Milestones are established for key developments which are required for planned major fusion facilities.

c. Milestones

Environment and Safety milestones are shown in Table 23.

2. Commercialization Studies

a. Strategy and Description

The evaluation of a technology that will not be introduced commercially for perhaps 20 years is extremely difficult at

TABLE 23

best. The market attitudes which may prevail are impossible to forecast. It is essential, however, that a continuing evaluation of these factors be undertaken. Such studies provide the basis for evaluating on a consistent basis the attractiveness of various technical and programmatic decisions which must be made as the development program evolves. By evaluating a wide range of market conditions and social perspectives, it may be possible to define the relative merits of technical decisions and thereby minimize the risk associated with any given decision.

The strategy for this element of the program is to perform preliminary market analysis, cost/benefit studies and social perception studies to establish the critical elements of the program and then to expand these activities commensurate with the level of progress in the technical program. The involvement of the vendor and user communities will be developed such that user groups can be called upon to review the anticipated commercial product and to provide recommendations on program directions. Industrial groups will be brought into the program via two mechanisms -- one operating through the individual program elements where industry is brought into the program as components, systems fabrication, and projects are identified that can be fabricated by industry.

The other mechanism is to go directly to industry and to award selected commercialization tasks to industrial contractors on a competitive basis. Industrial expertise gained in other programs, e.g., space and fission development, can thus be brought to bear on the solution of fusion problems.

Status and Plans

This activity is at a relatively low level of funding and in a very embryonic stage. Initial non-classical cost/benefit studies

are underway and look promising. Semi-formal and some formal arrangements have been established with user/vendor groups and very preliminary discussions on public/political perceptions of fusion have been initiated.

The plans for this area over the next five years call for the assessment of these initial activities in late FY 79. Based on this assessment new programs will be identified to address the cost/benefit for fusion power on a broad scale considering all potential applications. Similarly, evaluation of the public perceptions of fusion will allow critical issues to be addressed by this program element in FY 80 through 84.

VII. ENHANCEMENT PROGRAMS

The program described in the preceding sections describes a magnetic fusion energy program in which the physics and technology base for fusion would be systematically developed. The program would be conducted at a constant level of effort (allowing 7.5% per year for inflation) and consequently would be committed to specific target dates only through the major scaling experiments stage. No energy-producing reactors would be initiated and there would be no specific target dates for commercial applications, although the program would continue to pursue these as major goals.

The enhancement programs described in this section would, if adopted in whole or in part, permit (a) acceleration of physics proof-of-principle programs, (b) R&D required prior to construction of energy-producing experimental reactors, and (c) initiation of construction of energy-producing experimental reactors. Adoption of (a) would maintain the program on a Logic II pace; adoption of (b) and (c) would return the program to a Logic III pace and would permit the program to commit to operation of an energy-producing experimental reactor around 1990 and to reinstate the previous goal of operating a commercial demonstration reactor by the year 2000. No funds are required to implement (c) until FY 1982.

A summary of the enhancement programs follows. More detail is given in Appendix A.

A. ACCELERATION OF PROOF-OF-PRINCIPLE PROGRAMS

The goal of this enhancement is to accelerate the development of a solid scientific base so that various fusion energy applications can be assessed at an early date. Near-term objectives are to bring one or more concepts to proof-of-principle, in addition to the tokamak and mirror concepts. It should be noted that much of the research on tokamak and mirror concepts is directly relevant to other toroidal and linear concepts so that the

effort which would otherwise be required to bring new concepts to proof-of-principle is reduced.

EBT, TORMAC, Reversed-Field Pinch, Stellarators and Long Solenoids are examples of the type of systems considered promising; however, there are other concepts which might also be candidates for proof-of-principle programs.

B. ENHANCEMENT OF ENERGY PRODUCING EXPERIMENTAL REACTORS: R&D REQUIRED PRIOR TO CONSTRUCTION

Proof-of-principle programs for both tokamaks and mirrors will be completed by 1980-82. The understanding developed in these programs, combined with the data to be generated in TFTR and MFTF in the 1982-84 period will provide the basis for initiating an energy producing experimental reactor. The reactor could be either a tokamak or mirror; either a pure fusion electric prototype or a hybrid fission-fusion reactor for the production of synthetic fuels or fissile material.

The enhancement programs could include upgrading the Doublet III facility to higher magnetic field and temperature, initiation of a new facility to test high magnetic field or long-pulse tokamak concepts, conceptual design studies of experimental power reactors (tokamaks, mirrors, pure fusion and hybrids), supporting physics and supporting technology programs.

C. ENHANCEMENT OF ENERGY PRODUCING EXPERIMENTAL REACTORS: INITIATION OF CONSTRUCTION

If the enhancement programs suggested in Section B are authorized, Title I engineering design of an experimental reactor could begin in FY 1982 with actual construction beginning in late FY 1983. Total estimated cost of the program is \$800M, with operation beginning in 1988-89.

If the enhancements suggested in Section A are also authorized, the reactor could be based on one of the alternate concepts; otherwise it would be either a tokamak or a mirror.

APPENDIX A ENHANCEMENT PROGRAMS

The program described in the main text is based on a constant level of effort (allowing 7.5% per year for inflation) and describes a program in which the physics and technology base for fusion would be systematically developed. The program would be committed to specific target dates for physics proof-of-principle programs and major scaling experiments, but no energy producing reactors would be initiated and there would be no specific target dates for commercial applications, although the program would continue to pursue these latter as major goals.

The enhancement programs described in Section VII and this Appendix would, if adopted in whole or in part, permit (a) acceleration of physics proof-of-principle programs, (b) R&D required prior to construction of energy-producing experimental reactors, and (c) initiation of construction of energy-producing experimental reactors. Adoption of (a) would maintain the program on a Logic II pace; adoption of (b) and (c) would return the program to a Logic III pace and would permit the program to commit to operation of an energy-producing experimental reactor around 1990 and to reinstate the previous goal of operating a commercial demonstration reactor by the year 2000.

A. ACCELERATION OF PROOF-OF-PRINCIPLE PROGRAMS

The goal of this enhancement is to accelerate the development of a solid scientific base for various alternate confinement options so that their viability as fusion reactors can be assessed at an early date. Near-term objectives are to bring one or more concepts to proof-of-principle, in addition to the tokamak and mirror. It should be noted that much of the research on tokamaks and mirrors is directly relevant to other toroidal and linear systems so that the effort which would otherwise be required to bring new concepts to proof-of-principle is reduced.

EBT, Tormac, Reversed-Field Pinch, Stellarators, and Long Solenoids are examples of the type of systems considered promising; however, there are other concepts which might also be candidates for proof-of-principle programs.

A-1. PROGRAM: Toroidal Advanced Fusion Concept

OBJECTIVE:

- . To provide a program for advanced fusion concepts with experimental, theoretical, systems study, and technology development which will be able to exploit aggressively several variations on toroidal confinement configurations which presently hold promise of development into successful fusion power systems.
- . To support proof-of-principle experiments needed to produce the physics data base for identifying the most promising alternate concepts.
- . To select the most promising toroidal concepts based on strong technical grounds that have been established by coordinated input from several technical areas.

BENEFIT:

The identification, evaluation, development, and optimization of alternate concepts for fusion power reactors may lead (1) to fusion power in a shorter time; (2) to a more compact, economical, or environmentally desirable reactor; (3) to the advancement of existing reactor approaches by exploiting technological breakthroughs; and (4) to the development of concepts which are particularly well suited for alternate applications of fusion power in addition to electric power generation.

DESCRIPTION:

This program leads to the development of toroidal fusion concepts at the proof-of-principle stage. The progress of several of the alternate toroidal configurations to this stage benefits substantially from the experience gained in the tokamak development programs. Thus, it is anticipated that these ideas will be ready for development somewhat earlier and at a reduced cost per concept than previous experiments of this scale.

The primary candidates for the proof-of-principle experiments are EBT, RFP (Reversed Field Pinch), TORMAC, and possibly a Torsatron type of stellarator.

The proof-of-principle activity requires an integrated theoretical and experimental effort.

(1) Experimental

Experimental devices to produce the necessary physics data base to permit an effective identification of the most promising concepts will be fabricated. Included among the proof-of-principle devices are a device to be initiated in FY 1980 such as EBT-II, and a second toroidal configuration in FY 1982. They would begin experimental operations in FY 1983 and FY 1985. Each would extend the present parameter regimes which have been established by the past experiments and would provide high confidence level tests of key physics issues.

(2) Theory

The major portion of the enhanced theoretical activity on toroidal concepts will be directed at configurations such as TORMAC, EBT, and field-reversed pinches. This will include anomalous losses and scaling in TORMAC, ambipolar diffusion and turbulence in EBT, and line reconnection in reversed-field geometries. The effects of impurities in pulsed systems on radiative and end losses will be investigated. Enhanced studies of Rayleigh-Taylor instability and driver material-plasma mixing in liners. This work will permit much better prediction of radiative losses in imploding liners. An increased effort will be made in transferring and applying theories developed for the mainline confinement devices to alternate geometries.

In addition, increased emphasis will be placed on the development of new concepts, models, and methods needed to understand the collateral growth of the data base produced by these experimental devices. It is expected that the theoreticians will draw heavily from existing theories and models developed for more advanced toroidal systems (with and with-

out axisymmetry) and for mirrors. However, transport theory and many MHD issues such as equilibrium and stability will have to be significantly revised to confirm to the geometry appropriate to each alternate concept.

(3) System Studies

Reference studies will be undertaken which will outline approximate operating regimes, plasma physics conditions, and hardware components. Results of such studies will be used as part of the selection procedure in identifying which alternate concept to advance to the proof-of-principle stage.

Most likely, the activity will be accomplished at locations where the corresponding proof-of-concept program is being conducted.

A-2. PROGRAM: Linear Advanced Fusion Concept

OBJECTIVE:

The objectives of this program are similar to the toroidal enhancement package, with the addition of a proof-of-principle experiment for development of linear magnetic fusion systems.

BENEFIT:

The identification, evaluation, development, and optimization of alternate concepts for fusion power reactors may lead (1) to fusion power in a shorter time; (2) to a more compact, economical, or environmentally desirable reactor; (3) to advancement of existing reactor approaches by exploiting technological breakthroughs; and (4) to the development of concepts which are particularly well suited for alternate applications to fusion power in addition to electric power generation.

DESCRIPTION:

This program leads to the development of an alternate linear fusion concept at the proof-of-principle stage, with fabrication to begin in FY 1983.

This proof-of-principle device would follow operation of the proof-of-concept experiments for the linear option. This would allow selection of a linear option for a proof-of-principle experiment from among several heating and confinement variations with conventional solenoids or options of the imploding, flux conserving solenoids.

(1) Experimental

Fabrication of the proof-of-principle experimental device includes in this enhancement would begin in FY 1983 with an anticipated fabrication duration of 3-4 years depending on the approach. The linear device would establish end loss control, radial transport, and column stability in the necessary reactor parameter regimes for extended durations. Staged heating and energy recovery would be fully developed with this device.

(2) Theory

Depending on the precise geometry and heating option selected for the linear system concept, a computational capability will be established with sufficient lead time to aid the design and planning of the experiments. It is expected that this activity will draw heavily on the current knowledge and understanding of the pertinent plasma physics. In addition, effort will be mounted to address specialized models and theories peculiar to the chosen configurations.

(3) System Studies

Reference studies will be undertaken which will outline approximate operating regimes, plasma physics conditions, and hardware components. Results of such studies will be used as part of the selection procedure in identifying which alternate concept to advance to the proof-of-principle stage.

Most likely, the activity will be accomplished at locations where the corresponding proof-of-concept program is being conducted.

A-3. PROGRAM: Proof-of-Principle: Supporting Physics

OBJECTIVE:

The objective of the projects described in this enhancement program is primarily to extend experiments of the base program to larger plasmas with parameters closer to those of fusion devices. There are three elements in this enhancement with specific objectives in each case.

- . Advanced Diagnostics - Develop methods for space and time resolved measurements of current density, neutral particle density, impurity density, and magnetic field.
- . Plasma Properties - Critical studies of fundamental issues of stability, equilibrium, and transport in larger devices at higher temperatures.
- . TEXT Facility - Provide support for additional experiments to be undertaken on TEXT, particularly for rf heating, verification of new diagnostic techniques, and detailed studies of impurity generation and distribution.

BENEFIT:

This package will develop needed diagnostic techniques, will improve instrumentation for data handling, and will permit quantitative measurements to be made on a variety of plasma and field parameters. It will eliminate, to the maximum extent possible, ambiguity in measurements on different devices and is necessary for substantive understanding and control of plasma processes.

The pace of the fusion program and sometimes insufficient funds have left several observed or theoretically predicted plasma phenomena insufficiently explained and investigated. This package will provide definitive tests of theory and computer codes in several areas. The benefits will be evident in significant optimization of the design of confinement experiments.

Benefits in the enhanced TEXT program will be in the development of a viable rf heating method, in verification of current density diagnostic techniques and in providing comprehensive impurity studies in a tokamak.

DESCRIPTION:

Advanced Diagnostics - This package will provide for three levels of approach. First, new projects will be initiated in areas not presently supported such as diagnostics for current density and magnetic fields. Second, existing programs funded at low levels due to priorities for the period FY 1978-1979 will be significantly accelerated so that the resulting products and techniques would be available for new machines coming online in the period FY 1980-1982. This would include diagnostics for neutral and impurity density, x-ray imaging, and neutron measurement, data acquisition and signal processing instrumentation. Finally, full benefit will be derived from the utilization of existing high priority developments for other purposes, e.g., the use of far infrared diagnostics for transport and conductivity measurements. This package would also permit routine procedures to be established for various measurements such as density fluctuations.

Plasma Properties - The program would provide for operation of a refurbished device that was originally built for confinement experiments (such as Alcator A, DIIA, ATC, etc.) or for fabrication of a new device for research purposes. The machine must be of sufficient diversity in operating parameters to permit the study of specific physics issues in particular regimes. The work would primarily focus upon stability, equilibrium, and energy and particle transport, but could also address other vital issues such as ripple injection and end plugging in mirrors. From these studies, a firmer understanding of the basis of scaling laws will be obtained, a better understanding of impurity transport and energy transport via electrons will be obtained, and the reasons for anomalous electron heat conduction and gradient effects will be determined.

TEXT - This program would test and compare several types of rf heating and determine the details of energy deposition into ions in a fusion grade plasma. An accelerated program would be initiated to test current density measurement techniques in energetic plasmas. Heavy impurity density profiles would be measured and surface generation of impurities would be determined in the device.

A-4. PROGRAM: Proof-of-Principle: Supporting Technology

OBJECTIVE:

The general objective of this enhancement program is to provide engineering and technology support that is required to bring one or more concepts to proof-of-principle, in addition to the tokamak and mirror concepts. It should be noted that much of this supporting technology effort on the tokamak and mirror concepts is directly applicable to other toroidal and linear concepts, so that the effort that would otherwise be required to bring new concepts to proof-of-principle is reduced.

BENEFIT:

This enhancement package provides the necessary technology support to bring alternate concepts to the proof-of-principle stage. This package would provide for the expeditious development of supporting technology discussed in the enhancement package 1, 2, and 3 above. The benefits of this package would be reduced cost for power supply systems, enhanced heating capability and increased ability to operate with clean, controllable plasma conditions. The overall benefit would be a significant acceleration in the evaluation and understanding of alternative confinement system experiments.

DESCRIPTION:

This package includes three major areas which are discussed individually below. The three areas are (1) energy transfer which includes such items as high voltage high power switches, power storage and pulsed power system; (2) plasma engineering which includes density control, vacuum pumps, vacuum valves, and materials for plasma/wall interfaces; and (3) auxiliary heating which includes both radio frequency (rf) and neutral beam (nb) heating. These items are basically in support of the experimental programs described in the previous enhancement packages on Toroidal and Linear systems.

A. Energy Transfer

High Voltage, High Power Switch Development

This effort would develop improved switches and capacitors of various types and qualify them under simulated and actual test conditions.

Switch test facilities already existent would be upgraded to meet the testing requirements and environments. While there would be substantial emphasis on generic switch problem areas such as electrode erosion, arc quench times, and triggering mechanisms, specific switch types will be selected and developed for alternate concept needs. Specific switch development will include light-activated solid state switches, spark gaps, liquid metal types, vacuum types, and gas discharge types.

Energy Storage

Prior joint studies by the Office of Fusion Energy, EPRI, LASL, Texas, and Westinghouse have laid the groundwork for the development and demonstration of unique homopolar motor generators and specially configured alternators for fusion needs. Anticipated milestones are:

1. Demonstration of high voltage, <1 ms pulsed alternator concept for alternate concept use Mid 1981
2. Demonstration of multi-drum, air-bearing homopolar machine Early 1982
3. Fabrication of nominal 1 sec, reversible, 20 MJ homopolar for TOH system test Late 1982
4. Fabrication of superconducting 10-20 MJ homopolar with replaceable fast and slow discharge rotors Mid 1984

B. Plasma Engineering

Plasma Density Control/Startup

Deflagration guns of appropriate energy levels would be constructed and tested on present tokamaks for startup and fueling experiments. These guns may provide efficient and clean operation with low power requirements. It is anticipated that these guns, if successful, would significantly reduce the power supply costs associated with toroidal (closed) plasma systems.

Materials Development

The general description of the work required is contained in the Materials and Radiation Effects Branch Program Plans entitled "Plasma-Materials Interactions" and "Special Purpose Materials",

however, coordination and collaboration in the engineering support for specific devices or projects will require establishment of technical staff and management interfaces among the various parts of the Office of Fusion Energy and the laboratories.

A development plan for low Z coatings has been prepared and is ready for implementation. Specific plans to use available confinement devices must be developed.

The more general aspects of materials development and engineering support for near-term fusion experiments will be developed by a special ad hoc group composed of both Office of Fusion Energy staff and laboratory staff. It would be charged with creating a detailed plan (including comprehensive review of current activities) within the balance of FY 78 with program implementation to start in FY 79.

C. Auxiliary Heating

Microwave Component Development

This task provides for the development and application of high power millimeter microwave sources and circuits to alternate confinement concepts. A base program provides for the development of a rf tube for heating EBT and for starting up a tokamak. This tube is a 120 GHz, 200 kw, cw tube and may have application to other confinement schemes. This program would provide the resources to develop these applications for other schemes, e.g., tandem mirrors, stellarators, tormac, etc.

Long Pulse/cw Neutral Beam Source

The present positive ion neutral beam source work will be extended for long pulse/cw operation. This requires cathode and grid technology for long pulse capability. Most of the technology developed will also apply to negative ion neutral beams. This development would

support the enhanced efforts on alternate concepts such as stellarators, EBT, Tormac, Mirrors and any other steady state devices.

Auxiliary heating is extremely important for increasing the plasma characteristics and cw beams are necessary for the devices with steady state or near steady state operation.

Neutral Beam Direct Conversion

The direct conversion techniques will be extrapolated to long pulse/cw operation for neutral beam lines, and mirror plasma experiments to beam line converter will be developed for integration with long pulse/cw operation. These developments will reduce the power supply costs and also reduce the technical requirements for the power supplies.

B. ENHANCEMENT OF R&D REQUIRED PRIOR TO CONSTRUCTION OF ENERGY PRODUCING EXPERIMENTAL REACTORS

Proof-of-principle programs for both tokamaks and mirrors will be completed in 1980-82. The understanding developed in these programs, combined with the data to be generated in TFTR and MFTF in the 1982-84 period will provide the basis for initiating an energy-producing experimental reactor. The reactor could be either a tokamak or mirror; either a pure fusion electric prototype or a hybrid fission-fusion reactor for the production of synthetic fuels of fissile material.

The enhancement programs include upgrading the Doublet III facility to higher magnetic field and temperature, initiation of a new facility to test high magnetic field tokamak concepts, conceptual design studies of experimental power reactors (tokamaks, mirrors, pure fusion and hybrids), supporting physics and supporting technology programs.

B-1. PROGRAM: Doublet III (DIII) Upgrade

OBJECTIVE:

This Upgrade of Doublet III would provide additional power supplies and neutral beam systems to allow DIII to operate at maximum field, current and

beam power with plasma parameters ($n\tau$, temperature, and beta) simultaneously in the reactor level regime.

BENEFIT:

The hardware of this package would allow full utilization of the DIII facility; successful achievement of the physics objectives would provide an early demonstration, in hydrogen, of near-Lawson plasma conditions.

DESCRIPTION:

This package calls for an addition of 14 MW of neutral beams to the Doublet III base program, for the total of 21 MW. Furthermore to increase the attainable plasma density and, therefore, the potential fusion yields, it would provide additional power supplies to increase the magnetic field from 26 to 40 kG and the current from 2.5 to 5 MAmps. The physics objectives would be to attain simultaneously an $n\tau$ of $10^{14}\text{cm}^{-3}\text{sec}$ and an ion peak temperature in excess of 7 keV, i.e., the plasma conditions corresponding to a DT peak thermonuclear bulk fusion gain close to unity, and a beta close to 10%. Such an achievement would demonstrate doublet-type pure fusion reactors and on a time scale comparable to the TFTR beam driven demonstration in a circular DT plasma.

B-2. PROGRAM: High Field Tokamak Facility

OBJECTIVE:

To determine the potential for producing fusion power with high field (high power density) tokamak devices.

BENEFIT:

High field tokamak concepts hold the promise of achieving economical fusion power on a small scale, perhaps with conventional copper magnets and without minimal auxiliary heating, thus eliminating two major development uncertainties. This package would test a concept which if successful could result in the achievement of the practical application of fusion power by 1996.

DESCRIPTION:

The degree of maturity for a fusion power confinement concept can be described roughly by the combination of $n\tau$ and T . The U.S. high field tokamak program (centered at MIT) holds the world's record for $n\tau$. In 1979, a new machine,

Alcator C, will operate at predicted $n\tau$ values which represent the quality of confinement necessary for energy breakeven. Assuming a successful program, by 1982 a breakeven condition in hydrogen will be achieved on a machine which is approximately 2 meters in diameter and 1 meter high. In addition to the U.S. program, there are two foreign programs. One is in Italy centered about the Frascati tokamak. The other is in Germany and is just beginning to plan a major experimental program.

This high field concept can also be readily adapted for use as a small intense neutron source. It has merit as a test bed for alternate applications such as hydrogen production and as a materials components testing device.

This enhancement package would provide for the design and construction of a facility to test the high field tokamak as a fusion energy producer. The facility would have the capacity to accept small, high field tokamaks and test their operation with hydrogen, deuterium and tritium. Auxiliary support systems -- power supplies, auxiliary heating, pumping, etc., would be provided as required.

This package would provide for an aggressive program to pursue the experimental results which are being developed in the near-term base program. This package permits the aggressive exploitation of non-mainline tokamak concept (high magnetic field with minimum auxiliary heating) which is currently a leading tokamak concept in terms of the critical parameters, n, τ, T .

B-3. PROGRAM: Reactor Designs

OBJECTIVE:

To complete conceptual designs for experimental energy producing facilities based on the mirror and on the tokamak confinement concepts so that a decision to construct an experimental power facility could lead to Title I funding in FY 1982 if deemed appropriate.

BENEFIT:

The base program for the tokamak and mirror confinement concepts will establish the basis for physics scaling by 1982. This package would provide the benefit of allowing the fusion program to proceed expeditiously to the next generation of devices if such a step was deemed appropriate.

DESCRIPTION:

This package would allow the benefits of the extensive tokamak and mirror program to be reaped at the earliest reasonable time. The base programs will provide by 1982 the understanding that is necessary to make the programmatic decision as to the most appropriate evolutionary step. The prognosis is that this understanding will support proceeding to a power-producing experimental facility using either a mirror or tokamak confinement concept.

This enhancement package provides for the completion in 1982 of the conceptual design of two basic facilities -- one for a toroidal (tokamak) geometry and one for a linear (mirror) geometry. Title I funding could be initiated in FY 1982 to 83 period. For each facility, the specific application will be retained as an option; i.e., whether the power is in the form of electricity fissile fuel or synthetic fuel.

This package further provides for the subsequent adaption of the basic toroidal and linear power facility design for alternate confinement concepts. This package would then provide for the completion in FY 1984 of a conceptual design for an experimental power facility using an alternate confinement concept.^{1/} This would permit construction of such a facility to proceed in FY 1985.

B-4. PROGRAM: R&D Prior to Experimental Reactor: Supporting Physics

OBJECTIVE:

To conduct a coordinated experimental and theoretical program on physics problems of tokamaks and mirror reactors including the effects of impurities, tests of confinement in field-reversed mirrors, plasma wall interaction, computer code validation, and theoretical models of high-beta operation and burning plasmas. Atomic physics studies will provide data on radiative and transport properties of heavy tokamak impurities.

BENEFIT:

Mirrors are the principal backup to tokamaks and yet the physics understanding for mirror options with improved Q significantly lags that of tokamaks. This program focuses theory and experiments on basic physics issues and at attaining improved plasma parameters that will provide the data base and understanding required to evaluate reactor options in the mirror program.

^{1/}Should this design be made, then additional resources would be required in FY 1983 and FY 1984 to complete this design.

The increased tokamak theory effort will provide detailed models of the behavior of burning plasmas including alpha-particle heating and alpha-particle driven instabilities. Atomic physics studies will provide experimental and theoretical data on heavy impurity ions to enable the determination of the source and transport of impurities in tokamaks and their effect on plasma parameters in a reactor.

DESCRIPTION:

Mirror Experiments and Theory - A mirror machine located off-site from LLL will be fabricated starting in 1980. Experiments on this machine will address critical issues in coordination with experiments at LLL including fundamental problems of equilibrium, stability, transport, heating, and impurities. Extensive diagnostics will be provided. Methods of obtaining and maintaining field reversal, e.g., by e-beam injection, and the use of techniques such as rf heating and e-beam injection to stabilize the drift loss-cone instability will be studied. Resources of this package will be used to develop a transport theory in the small aspect ratio, finite-Larmor-radius limit which is suitable for field-reversed layers. The effort will address both revised neo-classical effects and microinstabilities. Corresponding growth of the effort in high beta MHD studies (equilibrium and stability) will be undertaken. Off-site theoretical effort will be expanded to validate independently various LLL code simulation models. Ion sources of base program experiments will be increased in power to guarantee that field reversal by ions will be obtained.

Tokamak Theory - The intensity and emphasis of the base tokamak theory program will be enhanced. A major portion of the theory funds will be used to bring the theory efforts at GA and MIT to a level necessary to adequately support the Doublet and Alcator programs. New research areas include the physics of burning plasmas and high-beta operation. The increased data base will stimulate plasma theory activities in several areas, including increased emphasis on resistive nonlinear MHD stability and transport calculations. In the transport area, there will be major emphasis on multi-species impurity transport, including different stages of ionization and plasma-wall and plasma-limiter interactions.

Atomic Physics - Quantitative evaluation of the effect of impurities on the overall power balance, on ignition conditions, on plasma temperatures, and on density levels and profiles requires detailed information on atomic cross sections, spectroscopic parameters and recombination rates for large numbers of charge states and at a large number of interaction energies. More information is needed that can be readily obtained by direct atomic physics experiments, especially as it is very difficult to obtain many of the highly ionized heavy ions in the laboratory. Theory and detailed calculations must be the primary source of this data with the theory carefully calibrated by a relatively few definitive experiments. Theory and calculations of basic atomic quantities for heavy ions will be increased including work on cross sections, recombination rates, and x-ray line strengths. Procedures will be developed to include these effects in a simple and rapid manner. The activity requires increased manpower in the present research groups and considerably increased computer capability. In addition, detailed modeling efforts of power balance in fusion plasmas using the atomic rates will be increased by adding resources to the present modeling group and by adding a second modeling group with particular expertise in rapid calculations.

B-5. PROGRAM: Supporting Technology for Enhancement of R&D Required Prior to Construction of an Energy-Producing Experimental Reactor

OBJECTIVE:

The general purpose of this enhancement program is to provide the engineering and technology support that is required prior to construction of an energy-producing experimental reactor. Whatever the form of the reactor, tokamak or mirror, pure fusion-electrical prototype or a fusion-fission hybrid reactor for production of synthetic fuels or fissile materials, the result of the supporting technology efforts described below will provide the necessary component development and design data base generation needed in conceptual and preliminary design.

BENEFIT:

This enhancement package would provide the necessary technology base to support the development of experimental energy producing facilities based on the tokamak and mirror confinement concepts. In particular, the resource base would be

established which would support the application of fusion power as "a producer" of either synthetic fuel, fissile fuel or electricity. The benefits would include reduced cost of superconductors, reduced risk of failure of key components, reduced risk of failure of key components, reduced risk in environmental impact and increased confidence in basic technology used for plasma control.

DESCRIPTION:

Accomplishment of the supporting technology developments described above will provide the necessary technology base to support the development of experimental energy-producing facilities by:

- . Provide a sound basis for development and selection of structural materials for both pure fusion and fusion-fission hybrid systems.
- . Provide the facilities and supporting developments for purification and handling of tritium.
- . Provide the facilities and supporting developments for environmental and safety related issues for both pure fusion and fusion-fission hybrid systems.
- . Provide the facilities and supporting developments for simulation of plasma systems and instrumentation and control.
- . Provide the facilities and supporting developments for design and verification of blanket and shield concepts, plasma fueling concepts, and vacuum pump and valve concepts for both pure fusion and fusion-fission hybrid systems.

This package can be catalogued in five major areas: magnetics, materials, plasma engineering, reactor engineering and environment and safety. Each of these is discussed in detail below.

A. Magnetics

High Field Mirror Magnet Development

Nb_3Sn superconductors operating at 12T and above provide a large physics safety factor and increase the energy gain of the experiment. To accomplish the objective, experimental lengths of niobium-tin conductors would be tested in short sample lengths, in a solenoid insert for the High Field Test Facility, and in a miniature prototype coil. Also some conductor manufacturing technology would be supported to ensure economical production.

This program is divided into three main phases:

1. Selection of promising alloy compositions and evaluation of their strength, toughness, and fabricability in increasing heat size, starting from 50 lb. heats to semi-commercial heats in the 8-ton size. Materials to be produced by a steel company and evaluated by a national laboratory/structural steel fabricator (i.e., CBI, Pittsburgh-Des Moines team).
2. Selection and evaluation of 1-2 promising compositions for each base (Fe-Ni, Fe-Mn) in production-sized (~50-ton) heats. Organization of the production/evaluation team to be as for Phase One. Some material will be used in 1-2 smaller physics experiments, which would be retrofitted with magnet cases of the chosen alloy(s) for "proof-of-principle" testing under actual Office of Fusion Energy operation conditions.
3. Development of a multi-heat design and fabrication data base on one composition per base (Fe-Ni, Fe-Mn). Obtain approval of necessary consensus organizations (ASME, ASTM) and any regulatory bodies, if necessary (i.e., NRC, etc.).

Superconductor Fabrication

This effort will cover preliminary tests to determine billet size effect on extrusion pressure requirement; design of insert that will convert normal press into hydrostatic extrusion type; fabrication of insert that will enable extrusion of about a 10-inch diameter and 40-inch long billet; and testing and qualification of insert and personnel in industry.

High Field Toroidal Magnet Development

Based on current work with force-cooled Nb₃Sn conductors, a large coil will be demonstrated up to fields of 8 T in 1981. With modest extensions of the technology, fields up to 12 T may be achieved in the Large Coil Test Facility two years later.

This development effort would consist of three major phases: design, fabrication, and testing, according to the following schedule:

1. Complete preliminary design Sep 1980
2. Complete detailed design, component verification testing, and advanced material procurement Dec 1981
3. Complete superconductor procurement and coil fabrication Nov 1982
4. Complete coil testing in LCTF Sep 1983

B. Materials

This work would include the following activities which could be in support of any power producing facility regardless of application.

1. The vigorous development of testing methods and specimen design specific to Office of Fusion Energy materials data needs.
2. Vigorous utilization of the RTNS-II and other available high energy neutron test environments to the limits of their testing capability and initiation of testing in the FMIT.
3. The design, construction, and operation of an irradiation test assembly (MOTA) for Office of Fusion Energy studies in the FFTF fast reactor.
4. The solicitation, evaluation, implementation, and completion of scoping studies of innovative concepts for first wall materials applications.
5. Acceleration in the pace of work on Path B ("Superalloys") and Path C ("Reactive and Refractory Metal Alloys") in order to meet the major milestones of selecting prime candidate alloys for these developmental paths.

C. Plasma Engineering

Energy Transfer/Plasma Control

This effort is to develop pulsed superconducting coils, switches and efficient reversible energy storage devices. These components would be integrated into appropriate systems for demonstration testing. Anticipated milestones are:

1. Demonstration of a 20 MJ scaled superconducting TOH system Late 1981
2. Demonstration of energy control system for superconducting Tokamak equilibrium field (EF) coils Early 1982
3. Demonstration of modular 1 MJ pulsed superconducting energy storage system for alternate concepts Mid 1982
4. Fabrication of 50-100 MJ superconducting energy storage system for alternate concepts or a 50-100 MJ OH or EF system for a Tokamak depending on program needs Mid 1984

Plasma Divertor Development

The design, construction and testing of divertor modules will be carried out for longer pulse operation of tokamak systems. The testing will incorporate simulation of the plasma exhaust conditions and interfaces. This activity will be coordinated with the experimental programs on ISX, PLT, PDX, DIII and TFTR.

Plasma Analysis

This activity requires mathematical modeling of the interaction of the plasma with fueling, heating, shaping and purging related technologies in a reactor system, and the modeling of the plasma's response to these interactions. The interaction of the responses is sufficiently complex to justify the use of major transport codes to investigate technology and control scenarios for operating reactor plasmas.

Vacuum Control

Vacuum pump/valve systems should be able to work under the ignition environment requirements.

Vacuum pumps and valves for the main pumping system as well as the auxiliary systems such as the neutral beam lines will be selected and prepared for demonstration testing under simulated ignition conditions. The system testing will also include necessary reliability engineering.

D. Reactor Engineering

TSTA Engineering

This package can bring the TSTA project to completion in accordance with baseline schedule. Also the package will modify TSTA to include: manifold accommodating multiple vacuum pump installation; loop interfaces and connections for test blanket modules, including capability for model heat exchanger tests; connections for full scale testing and tritium qualification of neutral beam and fuel injection systems; and facilities for special tritium processing developments, such as advanced tritium systems instrumentation and waste stream cleanup. Instrumentation and control systems will be upgraded to provide full simulation and training capabilities.

Blanket and Shield

This package will accomplish the following:

1. Potential blanket and shield designs will be scoped in order to define the requirements on the facility.
2. The facility will be designed and built, including capabilities for the following:
 - a. Generation of prototypical energy fluxes with associated cooling systems.
 - b. Cycling stress within the blanket test module to simulate startup and shutdown cycles.

Instrumentation and Control

A computer model of a fusion power reactor would be developed and studied to define methods of accomplishing I&C functions.

I&C systems would be designed and built and interfaced with the computer simulation of the power plant to test their function.

Possible follow up is to hook the I&C equipment to a fusion experiment to test it.

E. Environment and Safety

Base Program

The base program will be enhanced to accomplish the following:

Delegation of major E&S program coordination responsibilities to lead laboratory. Lithium spill experimental program to define characteristics of lithium reactions with concrete, air, insulating materials, and other materials, to develop lithium aerosol cleanup capability, to develop lithium fire fighting techniques and materials, and to conduct large scale verification tests of protective measures developed. Identification, in close coordination with TNS design teams, of critical system and component development needs to meet E&S requirements. Comprehensive evaluation of fusion reactor E&S issues, leading to identification of appropriate developmental needs.

Initiate and maintain studies of issues pertinent to the commercialization of fusion energy, and provide regular feedback and results to program management.

Safety of Alternate Fusion Power Applications

This package will initiate major program activities in fusion-fission environment and safety area, including: preparation of Hybrid Environmental Development Plan; preparation of programmatic Hybrid Environmental Impact Statement; safety studies of conceptual hybrid designs; experimental studies of easily identifiable critical issues (e.g., need for emergency cooling capability for blanket).

C. INITIATION OF CONSTRUCTION OF AN ENERGY PRODUCING EXPERIMENTAL REACTOR

If the enhancement programs suggested in Section B are authorized, Title I engineering design of an experimental reactor could begin in FY 1982 with actual construction beginning in late FY 1983. Total estimated cost of the program is \$800M, with operation beginning in 1988-89.

If the enhancements suggested in Section A are also authorized, the reactor could be based on one of the alternate concepts; otherwise it would be either a tokamak or a mirror.

PROGRAM: Experimental Power Facility Construction

OBJECTIVE:

To initiate the final design and construction of an experimental power facility in FY 1982 and to support specific project technology requirements.

BENEFIT:

This package would provide an early demonstration of the application of fusion power. The operational date for a power facility could be 1990 with this package rather than 1993 without the package.

DESCRIPTION:

This package would initiate the Title I and II design of a power producing fusion experimental facility based on results available from the base mirror and tokamak program in FY 1982. The specific design would evolve from the base programs and a decision between the mirror and tokamak confinement scheme would be made in FY 1982. Additionally, the possible applications of fusion energy will be kept as an option so that the experimental facility could produce either electricity, synthetic fuels or fissile fuel.

If it is determined that one of the latter two applications appear the most beneficial then actual initiation of the project might have to be delayed until FY 1983. This package would permit the specific project research and development to proceed at a pace consistent with completing the final design by 1986 and operating the facility in FY 1990. Specific development on auxiliary heating, magnets, plasma control, materials design analysis tools etc., would be controlled by the project.

This device would be comparable to the EBR-I of the fission industry. Prototype power reactor systems would be incorporated within the device to provide information for the commercial demonstration stage of the program which could occur shortly after the turn of the century.