10/8/99

Report of the Panel

on

Criteria, Goals and Metrics

for the

Fusion Energy Sciences Advisory Committee

C. Baker, UCSD, Chair
J. Dahlburg, NRL
R. Davidson, PPPL

S. Dean, FPA
D. Grether, LBNL
J. Lindl, LLNL
M. Mauel, Columbia U.
N. Sauthoff, PPPL
J. Soures, U. Rochester
R. Stambaugh, GA
D. Steiner, RPI

REPORT OUTLINE

Page

Executive Summary

The Fusion Energy Sciences Advisory Committee (FESAC) has been asked to make recommendations "as to the proof-of-principle experiments now under review"…"balance of the program between tokamak and non-tokamak physics, and between magnetic and inertial fusion energy." This report provides background information and context on criteria, goals and metrics to support those recommendations. An overall approach to program balance is described, followed by a summary of the national program's mission and goals, as well as top-level goals and metrics for fusion as a commercial energy system. The report presents a program element structure, which provides a framework for deliberations on program balance. Also included here are proposed top-level objectives and metrics for these elements. Finally, the report discusses program evaluation criteria, which can be used to determine the readiness of concepts to proceed through the various development stages.

There are several approaches to the general question of determining the desirable balance within the program. The process must be consistent with the overall mission and goals of the Department of Energy's fusion energy sciences program. Furthermore, the process should reflect program balances that change with available funding levels and evolve over time.

The first key dimension of program balance is related to the stages of development and strives for a balanced portfolio consistent with available resources and the readiness of concepts for advancement. The 1996 FESAC Alternate Concept Review Panel describes five stages on the path toward commercial fusion energy: Concept Exploration (CE), Proof of Principle (PoP), Performance Extension (PE), Fusion Energy Development (FED), and DEMO. The different stages of development are meant to include not only Magnetic Fusion Energy (MFE) and Inertial Fusion Energy (IFE) concepts, but also experiments and related activities in technology, theory and computational support. Both science and technology research should be thought of as proceeding through the stages of development.

Progress through these stages should be governed by the program evaluation criteria, which include a combined expert- and peer-review process. The program evaluation criteria are intended to apply to program proposals ranging from Concept Exploration to Fusion Energy Demonstration. The importance of the different criteria varies, however, with the level of the concept. The program evaluation criteria for each activity/program element include the following:

- Quality of Research
- Confidence for Next Step
- General Plasma Science/Technology Benefit
- Issue Resolution for Particular Concepts
- Leading Edge Research
- Energy Vision
- Program Issues
- Portfolio Balance
- Broad-Based Science/Technology Goals
- Program Milestones

The second dimension uses a more detailed program element structure with a goal of ensuring that critical aspects of program development are not neglected. This approach ensures that all tasks necessary for success are being considered in a balanced manner.

In MFE, the international program is about 5-6 times the size of the domestic program. This provides opportunities for integration with a far-larger world effort, which allows the U.S. MFE effort to proceed more rapidly than would be feasible within the US budget alone. The U.S. MFE program should base its program balance decisions on a plan integrated with the worldwide effort in MFE, which identifies areas in which the U.S. desires to provide leadership, those areas in which it will participate in the directions identified by others or mutually, and areas in which it will not participate. Within this overall set of goals, the U.S.

MFE program will have a mix of Programs at various stages of development, which includes both the physics and technology of magnetically confined plasmas.

In IFE, the large DOE Inertial Confinement Fusion (ICF) program supported by Defense Programs (DP), provides most of the facilities and expertise required to develop the target physics for IFE. The U.S. ICF program is predominant in the world, and the international program in IFE is small. To develop IFE, it will be necessary to develop the elements beyond the target and high-energy density plasma physics that are required for energy production. The U.S. program in IFE will be heavily focused on the driver development and fusion technology required to complement the DP target physics program in ICF.

Objectives and metrics (measures for achieving the objectives) have been developed for each of the following top level program elements which are as follows:

1.0 Plasma Science and Technology
2.0 Physics of Magnetic Confinement
3.0 Physics of Inertial Confinement
4.0 Magnetic Confinement Configurations
5.0 Magnetic Confinement Plasma Technologies
6.0 Inertial Confinement Target Configurations
7.0 Inertial Confinement Driver Technologies
8.0 Fusion Energy Technologies
9.0 Systems Analysis for Fusion Energy

In a program with rich scientific content, we expect a continual generation of new ideas, which could complement, modify or eventually replace current approaches to achieve fusion conditions in the laboratory. At each stage of development, some fraction of the programs will not advance to the next stage. A balanced national program, which is regularly generating new ideas, will have a pyramid-shaped distribution of programs with larger numbers at earlier stages of development. Although there are expected to be more Programs at the lower levels than at the higher levels, the total budget is usually dominated by the cost of the most advanced stages. This is the principal reason that cost sharing through international collaboration or through national defense programs with shared missions is a key consideration. In a fusion energy sciences program, which is still developing the scientific and technology basis, and is still generating new ideas to optimize the path to fusion energy, a balanced program will certainly involve some Programs at each stage.

Achieving a balance between MFE and IFE also entails critical choices; both approaches must pass through the various stages of development. A balanced program, with rigorous peer review, should allow for funding of at least one deserving approach to MFE and IFE through the various stages. In both MFE and IFE, resources outside the Office of Fusion Energy

Sciences (OFES) are far more extensive than those available within OFES. The balance of programs within the OFES should be affected by these outside resource considerations.

The highly motivated and creative staff is the program's greatest asset. To the extent that CE programs can be carried out with a small staff and little infrastructure, they can be flexibly sited and initiated or terminated relatively easily, with the caution that a long view is generally required for basic research to show significant results. For the PoP and higher-level stages, significant local infrastructure and staffing levels are required for successful execution; however, it is highly desirable for these facilities to be operated as national research centers attracting off-site scientists and students to form national teams. Since there will be a major investment involved in establishing the capability of research at this scale, the possibility of cost-savings due to existing infrastructure should be given careful consideration prior to investing in new experimental research sites.

1.0 Introduction

On October 9, 1998, Dr. Martha A. Krebs issued a charge letter (see Appendix A) to the Department of Energy's (DOE) Fusion Energy Sciences Advisory Committee (FESAC) to: (1) "prepare a report on the opportunities and the requirements of a fusion energy science program"; and (2) "lead a community assessment of the restructured program." FESAC was asked to make recommendations "as to the proof-of-principle experiments now under review"…"balance of the program between tokamak and non-tokamak physics, and between magnetic and inertial fusion energy."

The first step of preparing a report on Opportunities in the Fusion Energy Sciences Program has been completed. To facilitate the second step, the FESAC Chairman, Dr. John Sheffield, appointed in February, 1999 a Panel on Criteria, Goals and Metrics. The basic purpose of this panel is to prepare for FESAC information on possible decision criteria, program goals and metrics to provide a methodology and framework in which to consider the key charge questions contained in Dr. Krebs' letter.

Dr. Sheffield appointed Dr. Charles C. Baker (UCSD) Chair of this panel, and together they developed the panel membership (see Appendix B) to provide the range and balance of expertise and experience necessary to carry out the panel's work. Except for one meeting in the Washington area on April 15-16, 1999, the panel has conducted its work via conference calls and electronic communication.

The output of the panel's deliberations has been made available, usually while the work was in progress, to seek feedback from a variety of sources in the national program including the full FESAC, the Secretary of Energy's Advisory Board Fusion Task Force, and participants in the 1999 Fusion Summer Study at Snowmass. The panel's work was completed when it reported to the FESAC at Snowmass on July 23-24, 1999.

Section 2.0 provides the background information and context to help understand the panel's approach to criteria, goals and metrics. An overall approach to program balance is described in Section 3.0, followed by a summary of the national program's mission and goals in Section 4.0. This section also provides top-level goals and metrics for fusion as a commercial energy system. The panel has developed a program element structure in Section 5.0, which will provide a framework for deliberations on program balance. Also included here are proposed top-level objectives and metrics for these elements. Section 6.0 discusses program evaluation criteria, which can be used to assist in determining the readiness of concepts to proceed through the various development stages.

2.0 Background Information

Developing the knowledge to create a controlled source of fusion energy is one of the grand challenges of basic and applied science. While the scientific and technical issues posed by fusion are great, so is its potential reward. The numerous near-term scientific and technical benefits of fusion research, and the long-term potential of fusion energy to reduce the national risk of conflicts arising from energy shortages, supply reductions and the environmental impacts from existing methods of energy production, are among the reasons to pursue fusion.

As pointed out in the 1995 Report of the Fusion Review Panel, President's Committee of Advisors on Science and Technology (PCAST; Nov.1997), the involvement of the United States in fusion research and development is "a valuable investment in the energy future of this country and the world, as well as sustaining a field of scientific research -- that is important in its own right and has been highly productive of insights and techniques applicable in other fields of science and industry." Recent years have brought dramatic advances in the scientific understanding of fusion plasmas and in the generation of fusion power in the laboratory. Today, there is little doubt that controlled fusion energy production is technically feasible. Fusion energy research has reached a stage to produce copious thermonuclear power in the laboratory. The challenge is to use these advancements in scientific and technological understanding to make fusion practical.

There are two fundamental concepts for plasma confinement: magnetic and inertial. Magnetic fusion energy (MFE), which relies on strong magnetic fields to confine a plasma, has been widely studied in a combination of university, government and industrial laboratories, with a wide range of experiments, theoretical models, and an array of numerical simulation codes. Work on MFE in the U.S. has been funded primarily by the DOE Office of Fusion Energy Sciences (OFES). Inertial confinement fusion (ICF), which relies on the inertia of an imploding fusionable plasma to provide the required confinement, has also been the focus of active, intense research, with funding provided primarily by DOE Defense Programs (DP).

Recent advances in inertial confinement fusion research have made inertial fusion energy (IFE) an important candidate for increased emphasis as an energy system.

There is a substantial history of establishing and updating statements of the mission, goals, milestones and metrics of the national fusion programs. This history is summarized briefly in Appendix C. It has always been recognized that a robust national energy strategy, which ultimately develops an economically and environmentally attractive fusion energy source, requires both adequate funding and a stable research environment that nurtures aspects of fusion research that ranging from basic to applied research.

An historic challenge in executing the fusion program strategy has been in obtaining a level of funding commensurate with a schedule-driven development of a demonstration fusion power plant. Fusion program plans formulated prior to 1990 called for several, parallel large experimental facilities with annual program budgets reaching about $600M. In 1990, the goal of building a Demonstration Power Plant by the year 2025 was adopted. When funding resources to carry out such a program were not obtained, the program responded by focusing on the approach most likely to lead directly to a fusion demonstration power plant. This

led to a research focus on the tokamak approach, since the tokamak has strong international support and is the only approach to magnetic confinement scientifically prepared to produce fusion power in the near term. By 1996, however, it became clear that this objective could not be met with the available resources. Further, constraining the funding for potentially attractive alternate approaches to magnetic confinement had eroded the scientific diversity of fusion research that contributes to fusion's near-term scientific goals and the new ideas important to the long-term vitality of the research.

In January 1996, the Fusion Energy Advisory Committee (FESAC) recommended (J. Fusion Energy, December 1996, pp 183-206) a new program strategy with a new mission statement for the U.S. fusion program, which aims at a less schedule-driven, but more broadly-based, effort: "Advance plasma science, fusion science and fusion technology -- which constitute the knowledge base needed for an economically and environmentally attractive fusion energy source."

The January,1996 report provided the framework for the U.S. to achieve the goal of fusion energy as a partner in the international effort. A central element of the new fusion strategy was the importance of community-based governance. The report called for the formation of four review panels of fusion science experts to make recommendations for: (1) the development of alternative fusion concepts; (2) a review of the near-term priorities of the major fusion research facilities; (3) a U.S. review of the ITER EDA and its results; and (4) a review of the priority and management of inertial fusion energy in the DOE.

A March 1996 FESAC panel on Alternate Concepts (J. Fusion Energy, December 1996, pp. 249-280) suggested a strategic framework to achieve the goal of fusion energy consisting of "stages of development" for a variety of fusion concepts. This framework is summarized in Appendix D and is utilized in Section 3.

As noted in Section 1.0, the FESAC has prepared a report on Opportunities in the Fusion Energy Sciences Program, which outlines near-term and long-term research opportunities. The "Opportunities" report provides an overview of both the fusion energy and plasma science aspects of the fusion mission and describes in detail the many areas of topical research in which fusion scientists and engineers are engaged. The "Opportunities" report also adopts a "portfolio-based roadmap" approach, currently under development by the U.S. fusion community, which outlines a development strategy for MFE and IFE approaches to fusion energy in a unified manner.

3.0 Approach to Program Balance

There are several ways to approach the general question of determining the desirable balance within the program. The process must be consistent with the overall mission and goals of the program (Section 4). Furthermore, the process should reflect program balances that change with available funding levels, and evolve over time.

The panel suggests an approach which considers two key dimensions of program balance. One key dimension of program balance is based on stages of development as described below. It strives for a balanced portfolio consistent with available resources and the readiness of concepts for development. The different stages of development described in Section 3.1 are meant to include not only MFE and IFE concepts, but also experiments, related activities in technology, theory and computational support. Both science and technology research should be thought of as proceeding through the various stages of development. Progress through these stages will be influenced by the considerations outlined in Section 3.2, as well as the more formal program decision criteria described in Section 6. The second dimension is to consider a designation by the more detailed program element structure described in Section 5.0, with a goal of ensuring that critical aspects of program development are not neglected.

The net result should be a judgment on program balance from both a development stage and a program element point of view.

3.1 Stages of Development

The 1996 FESAC Alternate Concept Review Panel describes five stages of development on the path toward commercial fusion energy: Concept Exploration, Proof of Principle, Performance Extension, Fusion Energy Development, and DEMO. Scientifically and technically, the stages of development of a concept represent ranges on a continuous scale, and the stages tend to overlap each other. A particular experimental facility will usually be thought of as contributing primarily to a given stage but may well make contributions to other stages as well. However, pragmatically, the boundaries between various stages usually represent significant changes in the cost of the program, in the level of commitment to that concept, and in the focus of the program. At each stage, the research program contains elements of experiments, theory and computation, technology development, and power plant studies. The mix of these elements varies in each stage, but at least one main experiment is needed.

Program balance among the steps, between different approaches to fusion, and between the approaches and generic enabling developments is an important criterion. The decision to proceed from one stage to the next should be based on the maturity of the concept in order to be reasonably confident that: (1) the next stage of the program will be successful; and (2) the anticipated benefits of the next stage of the research justifies the increased level of effort. However, in a program with rich scientific content, we expect a continual generation of new ideas which could, if successful, complement, modify or eventually replace current approaches to achieve fusion conditions in the laboratory. At each stage of development, some fraction of the programs will not advance to the next stage. A balanced national program, which is regularly generating new ideas, will have a pyramid shaped distribution of programs with larger numbers at earlier stages of development. The decision to proceed to the next stage of development, or to terminate, should be based on rigorous peer review.

A few examples serve to illustrate the funding implications that might be expected in a balanced national program. Individual activities within each of the development stages will be referred to as a “Program”, including the required theory, computations, experiments, technology, and engineering activities. Table 1 below gives typical cost ranges and durations for the most expensive experiments in a Program, but not necessarily the other activities in the

Program. A total of 10-15 Concept Exploration Programs at an average annual cost of $3M would total about $30-45M/yr. Three to six Proof-of-Principle (PoP) programs, at an average cost of $20M, would total $60-120M/yr. Two to four Performance Extension (PE) programs at an average cost of $75M/yr. would total $150-300M/yr. Because this latter total is comparable to the present OFES budget, elements of the PE stage may well be good candidates for international participation. Finally, a Fusion Energy Development (FED) step will involve billion dollar class facilities. Such a step would require justification, based on national needs, and almost certainly require an increment to the federal budget (e.g., as a separate line item) and will likely be done on an international basis. [See below for a further discussion of the relationship of the U.S. program to the international effort.]

Table 1. Typical Cost and Duration of Experimental Facilities for Various Concept Development Stages.

Stage of Development	Construction Cost	Annual Operating Cost	Duration of Program
Concept Exploration	<$10M	<$10M	3-5 years, renewable
Proof-of-Principle	$10-$100M	$10-$50M	8-12 years
Performance Extension	$100-500M	$50-100M	10-20 years
Fusion Energy Development	$0.5-3B	$100-300M	15-20 years

Although there are expected to be more Programs at the lower levels than at the higher levels, the total budget is usually dominated by the cost of the most advanced stages. This is the principal reason that cost sharing through international collaboration or through national defense programs with shared missions is a key consideration. There is no hard principle which dictates the proper balance between the development stages, but in a fusion energy sciences program which is still developing the scientific and technology basis, and is still generating new ideas to optimize the path to fusion energy, a balanced program will certainly involve Program elements at each of the lower three stages.

In the above example, the distribution among development stages allows for breadth of ideas and cost-effective innovation at the smaller scale, while concentrating resources at the more advanced stages. The base of the pyramid can be broader or narrower depending on the percentage of Programs that is expected or desired to advance to the next stage. Some scientific and technical issues, especially those associated with fusion energy gain, can only be addressed at the larger scales of the performance extension and fusion energy development stages. Therefore, the ability to investigate some of these critical issues requires sufficient overall funding to build and operate advanced-stage experiments without eliminating the opportunity for new ideas and innovations resulting from smaller, more focused experiments. Further, a necessary requirement for a successful research pyramid is that the funding should be stable, subject to rigorous peer review, so that the nascent basic research projects will attract the technically best risk-takers to perform the research, and allow the benefits of the investment to be realized.

In the case of level funding, new proposals at each stage must wait until a Program at the same or higher stage is terminated before they can be initiated. If the national program is going to develop new ideas, it must be able to terminate existing Programs, and even then only a fraction of the Programs can advance from one stage to the next. As an example, assume that the average CE Program with renewals takes 6 years, the average PoP Program takes 10 years, and the average PE Program takes 15 years. Since there are 2 PE Programs, on average one would be completed every 8 years. With 3 PoP Programs, one of these would be completed every 3 years. Based on this average, about 1/3 of the PoP Programs could advance to the next stage. At the CE level, there are about 3 Programs finishing every year, so that approximately 1/6 of these could advance to the PoP level. It is clear that only a fraction of Programs can advance to a higher level, and that a thorough and rigorous peer review process is essential to successful implementation.

A balance must be maintained between Programs which are completed at the present stage and those which progress to the next stage. It is evident that such a research pyramid is most successful when there is regular interaction among researchers from the various elements of the pyramid.

Achieving a balance between MFE and IFE also entails critical choices and both must also pass through the various stages of development. A balanced program, with rigorous peer review, should allow for funding of at least one deserving approach to MFE and IFE through the various stages. In both MFE and IFE, resources outside OFES are far more extensive than those available within OFES. The balance of programs within the OFES should be influenced by these outside resources. Indeed, without additional resources, facilities at the fusion energy development stage may not be affordable even when the scientific and technical basis exists to move forward confidently. A prudent program strategy is to build on these outside resources to achieve a balanced total effort, without sacrificing the principles of scientific and technical readiness.

In MFE, the international program is about 5-6 times the size of the domestic program. This provides opportunities to be integrated with a far larger world effort, which allows MFE to proceed more rapidly than would be feasible within the US budget constraints alone. The US MFE program should base its program balance decisions on a plan integrated with the worldwide effort in MFE, which identifies areas in which the US desires to provide leadership, those areas in which it will participate in the directions identified by others or mutually, and areas in which it will not participate. Within this overall set of goals, the US MFE program will have a mix of Programs which span both the physics and technology of magnetically confined plasmas.

In IFE, the large DOE Inertial Confinement Fusion (ICF) program supported by Defense Programs (DP), provides most of the facilities and expertise required to develop the target physics for IFE. The US ICF program is the predominant program in the world, and the international program on IFE is small. To develop IFE, it will be necessary to develop the elements beyond the target and high-energy-density plasma physics that are required for energy production. The U.S. program in IFE will be focused in the near term on the driver development and fusion technology required to complement the DP target physics program in ICF.

The highly trained and motivated staff of the fusion program is its greatest asset. At level funding, the impact of initiating and terminating programs on the professional staff will necessarily play an important role in determining program balance. Included in these considerations will be plans for attracting and training new staff. To the extent that CE programs can be carried out with a small staff and little infrastructure, they can be flexibly sited and initiated, or terminated relatively easily, with the caution that a long view is generally required for basic research to show significant results. Basic research grants must be perceived by a high-caliber research community as reliable in this respect; i.e., perhaps available on three-year, once- or perhaps twice-renewable cycles, depending on the technical progress and the results of peer review. This program stage is usually well-matched to university-scale research and is an excellent vehicle for training new staff. The level of university involvement should be stable and large enough to insure that there is a continual influx of new research talent. For the PoP and higher-level stages, significant local infrastructure and staffing levels are required for successful execution; however, it is highly desirable for these facilities to be operated as national research centers attracting off-site scientists and students to form national teams. There will be fewer Programs at this level.

Although the research will be concentrated in a few locations, the successful demonstration of remote experimental operation and data access in the medium-scale and large-scale MFE experiments illustrate the cost-effectiveness of national programs. Since there will be a major investment involved in establishing research activities at this scale, the possibility of cost-savings provided by existing infrastructure should be given careful consideration prior to investing in new experimental research sites.

3.2 Criteria for Progress Through the Various Stages of Development

The decision to proceed from one stage to the next should be based on the maturity of the concept in order to be reasonably confident that (1) the next-stage program will be successful, and (2) the anticipated benefits of the next stage of research justifies the increased level of effort.

Illustrative criteria for judging when a particular stage has been sufficiently successful to warrant proceeding to the next stage are given below. A more complete and formal set of program evaluation criteria are presented in Section 6.0. In all cases, a rigorous peer review is essential before proceeding to the next stage.

Concept Exploration

Examined the basic scientific feasibility of the concept.
Explored key scientific phenomena for advancing the concept.
Generated sufficient technical progress in advancing the concept to motivate a PoP effort.

Proof-of-Principle

Developed a broad understanding of all basic physical principles of the concept.
Measurement set was comprehensive enough to address key physics issues.
Critical technology issues bearing on either the scientific or technical feasibility of the concept have been addressed.
Verified that experimental results quantitatively agreed with theoretical models.
Enable evaluation of the potential of this concept for fusion energy applications.
Optimization, innovations and concept variation have been explored.
Organized as a National Program.

Produced the basis for a Performance Extension experiment or the basis for a decision not to proceed to the next step.

Performance Extension

Explored the physics of the concept at or near the fusion-relevant regime in absolute parameters.

Achieved dimensionless parameters approaching those of a fusion power system.

Deployed a variety of auxiliary systems at significant scale for control and optimization.

Extensive diagnostics provided thorough coverage in space and time.

Provided the endpoint of key scaling information developed first in the PoP stage.

Studied phenomena only observable at a significant scale of performance.

Integrated physics and technology elements into single demonstrations.

Theory and modeling provided a predictive capability of the concept.

Generated sufficient confidence that absolute parameters needed for a fusion development device can be achieved and a fusion development program with a reasonable cost can be implemented.

Conducted as a National Program.

Fusion Energy Development

Developed the technical basis for advancing the concept to the power plant level.

Resolved key alpha-particle physics issues internal to the plasma.

Fusion nuclear technology issues applicable to a power plant resolved.

Developed other key technologies.

Developed the database on operational reliability and maintainability, safety and licensing, and costing, to justify proceeding with a demonstration power plant.

Justified an increment to the federal budget for fusion based on national needs.

Conducted as a National or, more likely, International Program.

3.3 Implementing Characteristics for Balance Among Development Stages

The previous two subsections have described the stages of development and considerations for judging progress through the various stages. Here we present some additional programmatic features that will help to foster a sustained, healthy balance among the various stages of development:

Science Focus	The net effect of fusion research elements effectively combines interrelated disciplines that advance through large- and small-scale experimentation, theoretical and computational modeling, and materials and technological innovation. The suite of national and international experimental and theoretical facilities is integrated, mutually supportive, and coupled with numerous scientific subfields.
Consistency	Programs are managed to a logical completion of mission. Concept Exploration Programs can normally expect to obtain renewal, or advancement to the next stage, based on technical merit and rigorous peer review.
New Ideas	A continuous influx of new ideas is essential to the program at the Concept Exploration level and in innovative additions to concepts at the more advanced levels. Requires managed turnover and rigorous peer review.
Completion	Programs should be allowed to complete their missions when technically merited, as opposed to starting new programs that cannot be carried out in sufficient depth.
Depth & Breadth	All concepts of sufficient merit should be able to carry out a Proof-of-Principle level program to obtain broad resolution of all key technical issues. The required effort should take into account the international context.
Peer Review	Concepts should advance from one stage to the next based on peer review, and all elements of the fusion program should be peer reviewed and held to the highest standards of scientific excellence.
International Partnership & Selected Areas of Leadership	Fusion energy science research in the U.S. complements the international effort to develop a fusion energy source. U.S. fusion research is evaluated in the context of its potential contributions to international fusion research. Those areas of U.S. expertise having high leverage in the international effort to develop fusion energy are

identified and pursued vigorously.

Balance All program levels from Concept Exploration to Fusion Energy Development stage should contain programs in a pyramid-like structure with the majority of programs at the Concept Exploration level, and fewer programs at higher levels, to the degree of available funding. This pyramid distribution up through the Performance Extension stage should be maintained by a consistently-supported fusion energy sciences base program. Devices at the Fusion Energy Development stage require additional justification based on national needs, and should be funded as separate line items.

4.0 Fusion Program Mission and Goals

4.1 Overall Mission and Goals

Through the course of restructuring of the US fusion program over the past few years, there has evolved a fundamental shift in program strategy. Such a shift necessarily alters the metrics and objectives by which the fusion energy sciences program makes its priority decisions, and by which its progress is to be judged. As a result of the restructuring which was recommended by FEAC in 1996, the program Mission of the U.S. Fusion Energy Sciences Program is to:

- "*Advance plasma science, fusion science and fusion technology - the knowledge base needed for an economically and environmentally attractive fusion energy source.*"

The underlying theme of the restructuring is to focus on innovation and the critical science and technology foundations for fusion energy. This mission retains the long-term goal of facilitating the development of fusion energy, but it implicitly recognizes that a fusion energy demonstration can occur only when there is a perceived sense of national need. In the interim, program activities focus on advancing fusion science and technology, with both near-term and long-term applications, and assuring that the first DEMO will be as attractive as possible, as measured by both cost and environmental considerations. The means to accomplish this is to advance the underlying science and technology of fusion with the view to applying that understanding to optimize those characteristics which would enhance the attractiveness of potential fusion energy applications.

In support of accomplishing this Mission, FEAC recommended three Program Goals:

- *Advance Plasma Science in Pursuit of National Science and Technology Goals.*

  This Goal recognizes both the importance of plasmas as the medium of fusion and the role of fusion research in nurturing the development of the discipline of plasma physics, with applications in non-fusion areas as well.

- *Develop fusion science, technology and plasma confinement innovations as the central theme of the domestic program.*

  This Goal addresses the strategy of developing plasma science and technology to improve the reactor attractiveness of fusion by explicitly encouraging innovative solutions to both scientific and technological issues.

- *Pursue fusion energy science and technology as a partner in the international effort.*

  This Goal recognizes (1) the importance of fusion energy as viewed by the international community as a vital, environmentally attractive energy option for a growing world population, and (2) the high cost and complexity of the pursuit of fusion energy requires international collaboration.

The metrics and objectives to support this Mission must have scientific, technological and energy features; although, as described elsewhere in this report, these may weigh differently depending on the nature and maturity of a given activity. There are broad, high-level attributes of the quality of science, which should be used to assess performance, such as fundamental understanding, comprehensive predictive modeling, appropriate experimental diagnostic instrumentation, and validation through comparison between experiment and theory.

4.2 Fusion Energy Criteria and Metrics

In this section we consider the criteria and metrics associated with an economically and environmental attractive fusion energy source. We first discuss the fusion energy source in the context of electric power production and then examine alternate applications.

There is, at present, virtually no market in the U.S. for large, central fossil or nuclear power plants. The economies of scale and projected rapid growth in demand for electricity that favored such plants a few decades ago has yielded to low growth in demand and aeroderivative turbines burning natural gas. The virtual monopoly of electric utilities that could construct large plants and include the capital costs in the rate bases are giving way to "deregulation", and to competition at both the wholesale (power producers) and retail (individual customers) levels.

A trend back to larger and more centralized power plants could result from a variety of changes, including the following:

- Reducing CO_2 emissions to low levels becomes a global imperative because of concerns over climate change. Even for fossil fuel plants, large central plants would be favored because of the need to sequester the CO_2.

- Electrification of the transportation system (battery-powered vehicles, high-speed trains, electrified roadbeds), since there is no particular advantage to distributed generation.

- Rising price of natural gas because of resource limitations or political factors.

- Saturation of the market for cogeneration.

- A more rapid rise in the demand for electricity; e.g., the growth of information technologies.

- The almost inevitable consolidation of power producers results in larger firms willing to construct larger power plants and/or make longer-term investments.

In the context of current visions of future commercial fusion power plants, Table 2 presents a summary of anticipated economic and environmental metrics and goals.

Table 2. Anticipated Economic and Environmental Metrics for Commercial Fusion Power Plants.

Metric	Goal
Cost of electricity	50-60 mill/kWh ($1998)[a]
Dose limit to insure that no public evacuation plan is required	<1 rem at site boundary
Occupational dose to plant personnel	<5 rem/yr[b]
Rad. Waste disposal criterion	Class C or minimization of waste hazard and volume[c]
Fuel cycle closed on site	Yes
Atmospheric pollutants (CO_2, SO_2, NO_x)	Negligible[d]
Capacity factor	>80%
Unscheduled shutdowns	<0.1 per year
Must provide for operation at partial load conditions	50% of full power

[a]Includes environmental and safety credits.
[b]Application of ALARA principles expected to result in significantly lower doses.
[c]Thus permitting: (i) recycling of plant materials, (ii) on-site shallow burial of waste and plant components at end-of-life.
[d]Relative to competitive technologies.

Alternate applications of fusion plasmas have been considered since the early days of the fusion program, and have focused primarily on fusion energy systems as neutron sources. Initial considerations have included: (1) hybrids for fuel breeding, that is, in an energy-suppressed mode of operation, and also hybrids for energy production, that is, in a mode in which the fusion neutrons drive a subcritical blanket; (2) the use of fusion neutrons for the transmutation of radioactive waste from fission reactors; and (3) the application of a fusion-based neutron source for fusion materials and engineering testing.

More recent studies have added to the repertoire of applications such as tritium production, the burning of plutonium from dismantled weapons, radioisotope production, medical radiotherapy, hydrogen production, and the detection of explosives. A unique characteristic of the more recent studies is the consideration of applications allowing a range of neutron source strengths from $\sim 10^{11}$-10^{13} n/s, on the low end, up to $\sim 10^{19}$-10^{21} n/s on the high end. The high-end studies have considered plasmas based on ITER physics, advanced mode tokamak operation and the spherical torus. The low-end studies have focused on inertial electrostatic confinement concepts. Clearly, IFE systems could also be the basis for all these applications.

Most studies have considered the D-T fuel cycle, but a few have examined the D-D-T fuel cycle. Although less reactive than the D-T fuel cycle, the D-D-T fuel cycle has the advantages of eliminating the need for tritium breeding and providing a much greater neutron excess per unit power than the D-T fuel cycle.

For the most part, existing fusion neutron source studies have been at the conceptual level. As yet there has been no detailed, self-consistent study, which considers engineering, economics and environmental issues. Proposed metrics for neutron-source applications of fusion energy systems are summarized in Table 3. In addition to neutron source applications, other alternate applications have included high-temperature heat sources for hydrogen production and fusion plasmas for space propulsion.

Table 3. Proposed Metrics for Neutron-Source Applications of Fusion Energy Systems.

- Cost of Neutrons
- Total Number of Neutrons Produced Per Year
- Capital Cost
- Operating Cost
- Value of the Product
- Environmental, Safety and Health Implications
- Licensing Implications

5.0 Program Elements, Objectives and Metrics

In order to accomplish the overall mission and goals of the fusion energy sciences program and to address its balance, it is useful to categorize the necessary research and development tasks in terms of program elements and subelements. This approach is used to ensure that all activities necessary for success are being considered in a balanced manner.

The subelement structure can be divided into finer detail in order to identify the success criteria and milestones for individual tasks, along with the objectives and metrics appropriate for those tasks. In this chapter, we confine ourselves to only the "top-level" elements and subelements. These are identified in Table 4. Objectives and metrics (measures for achieving the objectives) have been developed for each of the top level program elements and are given in Table 5.

Table 4. Fusion Energy Sciences Program Element Structure

1.0	**Plasma Science and Technology**		**6.0**	**Inertial Confinement Target Configurations**
	1.1 Basic Science			6.1 Direct-Drive Targets
	1.2 Generic Technology			6.2 Indirect-Drive Targets
	1.3 Applications Research			6.3 Other Configurations/Hybrids
	1.4 Computational Support			
	1.5 Education and Training			
2.0	**Physics of Magnetic Confinement**		**7.0**	**Inertial Confinement Driver Technologies**
	2.1 Transport and Turbulence			7.1 Ion Beams
	2.2 Magnetohydrodynamics			7.2 Lasers
	2.3 Wave-Plasma Interactions			7.3 Pulsed Power
	2.4 Plasma-Wall Interactions, Sheaths and Boundary Layers			
	2.5 Self-Heated Plasmas			
	2.6 Reactor-Scale Physics Integration			
3.0	**Physics of Inertial Confinement**		**8.0**	**Fusion Energy Technologies**
	3.1 Driver-Target Coupling			8.1 Plasma Chamber Technology
	3.2 Pulse Shaping			8.2 IFE Chamber Technology
	3.3 Irradiation Symmetry			8.3 Target Fabrication & Injection
	3.4 Hydrodynamic Stability			8.4 Tritium Systems
	3.5 Self-Heated Targets			8.5 Safety and Environment
	3.6 Physics Integration & Simulation			8.6 Maintenance Systems
				8.7 Advanced Materials
4.0	**Magnetic Confinement Configurations**		**9.0**	**Systems Analysis for Fusion Energy**
	4.1 Externally Controlled Configurations			9.1 Next-Step Options
	4.2 Self-Ordered Configurations			9.2 Power Plant & Application Studies
	4.3 Other Configurations/Hybrids			9.3 Socio-economic and Environmental Studies

				9.4 Development Pathways Analysis
5.0	**Magnetic Confinement Plasma Technologies**			
	5.1 Magnets			
	5.2 Plasma Facing Components			
	5.3 Heating and Current Drive			
	5.4 Particle Control			
	5.5 Instrumentation			

Table 5. Objectives and Metrics for the Top Level Program Elements

Fusion Program

Objective: Advance plasma science, fusion science, and fusion technology – the knowledge base required for an economically and environmentally attractive fusion energy source.

Metric: Demonstrated advancement of scientific frontiers and technological states-of-the-art, relative to the required knowledge base.

1.0 Plasma Science and Technology

Objective: Nurture the advancement of plasma science and other fusion-related sciences and technologies, and related educational opportunities, on a broad front in support of national science and technology goals.

Metric: Demonstrated contribution to fusion concept development and/or impact on other areas of science and technology.

2.0 Physics of Magnetic Confinement

Objective: Achieve a predictive understanding of the physics of magnetic confinement.

Metric: Quantitative correlations between theoretical predictions and experiments, with relevance to plasmas producing net power.

3.0 Physics of Inertial Confinement

Objective: Achieve a predictive understanding of the physics of inertial confinement

Metric: Quantitative correlations between theoretical predictions and experiments, with relevance to plasmas producing net power.

4.0 Magnetic Confinement Configurations

Objective: Test a range of magnetic configurations that show technical promise for fusion power applications, and advance the leading concepts to the extent needed to provide the necessary knowledge base.

Metric: Experimental demonstration of performance consistent with progressive stages of development of concept; termination of poorly performing concepts, and advancement of the most promising concepts, using a rigorous peer-review process.

5.0 Magnetic Confinement Plasma Technologies

Objective: Develop technologies required for magnetic fusion experiments.

Metric: Experimental demonstration of performance consistent with the particular stage of development; termination of poorly performing technologies and advancement of the most promising technologies, based on rigorous peer review, with due consideration of relevance to the concept configurations under investigation in 4.0.

6.0 Inertial Confinement Target Configurations

Objective: Test a range of inertial confinement target concepts that show promise for fusion power applications, and advance the leading concepts to the extent needed to provide the necessary knowledge base.

Metric: Experimental demonstration of predicted performance; termination of poorly performing concepts, and advancement of the most promising concepts, based on rigorous peer review.

7.0 Inertial Confinement Driver Technologies

Objective: Test inertial confinement driver concepts that show promise for fusion power applications, and advance the leading concepts to the extent needed to provide the necessary knowledge base.

Metric: Experimental demonstration of performance consistent with the particular stage of development; termination of poorly performing technologies and advancement of the most promising technologies, based on rigorous peer review, with due consideration of relevance to configurations under investigation under 6.0.

8.0 Fusion Energy Technologies

Objective: Develop technologies required for fusion energy throughout its stages of development.

Metric: Experimental demonstration of performance consistent with needs of the evolving stages of development.

9.0 Systems Analysis for Fusion Energy

Objective: Analyze systems aspects of fusion energy applications and pathways, identify key technical issues, and provide the perspective needed for fusion program decisions.

Metric: Identification of key issues and applications, and affordable development paths for fusion energy development.

6.0 Program Evaluation Criteria

Optimizing program balance among the set of activities funded by the Office of Fusion Energy Sciences requires not only evaluating the extent to which a given activity contributes to the achievement of the objectives outlined in Chapter 5 for a specific element, but also evaluating the interdependence of the program elements and cost-effectiveness and timeliness of the proposed activity.

As mentioned before, a peer-review process is the most objective way to review and judge the scientific merits of proposals and should always be applied. However, peer review of one proposal does not provide sufficient information on relative priority among many proposals, especially those of different concepts with different scientific issues and at different stages of development. It is, therefore, essential to set up a mechanism to periodically review and refine the status of concepts, update their development plan, judge if the concept is ready for further development or should be terminated, and provide scientific recommendations on the relative priority and balance in research among various concepts. We recommend that a continuing effort of community-based experts, and "white papers", be used to provide the needed scientific input to OFES and to FESAC. Proponents of fusion research programs should produce an assessment paper which includes information on the status of the concept, the critical issues, a research plan, metrics to evaluate progress, and the technical merits of the research. This process is consistent with the 1996 FESAC-SciComm Alternates Concept Report (Appendix D) and the 1996 FEAC recommendation which states that the governance system for the restructured Fusion Energy Sciences Program needs to "establish an open process for obtaining scientific input for major decisions, such as planning, funding, and terminating facilities, projects, and research efforts." In addition to providing up-to-date scientific assessments, research plans for various concepts, and lists of critical issues, active community involvement in such a process will help avoid miscommunications and will be correctly perceived as open and receptive to innovation and new ideas.

In order to guide the community in preparing assessments of fusion concepts, the panel proposes the program evaluation criteria summarized in Table 6. The criteria for proposal evaluation presented in Table 6 are intended to apply to program proposals ranging from Concept Exploration to Fusion Energy Demonstration. The importance of the different criteria vary, however, with the development level of the proposal. Weightings are important, whether they are assigned implicitly or can be made explicit, which is much more desirable. While the final determination on weights should be debated and decided by those formally responsible for making decisions on funding proposals, the Panel believed it would be very useful for it to provide its sense of appropriate weights, based on designation of high (H), medium (M), and low (L), as presented in Table 7. The "double arrow" notation for issue resolution at the CE and PoP levels derives from the expectation that a given proposal will likely emphasize either mainly physics or technology issued. Certain patterns are clear. Technical risk is more acceptable at the lower levels, and the emphasis shifts from science to energy potential in progressing from the lower to the higher levels. At all levels, the quality of science, leading-edge science and clearly defined milestones have high weights.

Table 6. Program Evaluation Criteria

0. Quality of Research

Is the proposed research program of high quality; does it have scientific and technical credibility; is it based on an understanding appropriate for its stage of the program; are personnel identified to achieve program objectives; and are the qualifications of the personnel appropriate to achieve the program objectives?

1. Confidence for Next Step

Does the proposed program provide reasonable expectation to develop the knowledge base required to proceed to the next stage?

2. Plasma Science/Technology Benefit

What is the benefit to the advancement of plasma science? Examples of scientific issues include:

- transport and turbulence
- hydrodynamics and magnetohydrodynamics
- wave-plasma interactions
- plasma-material interactions
- radiation transport and opacity
- dense matter physics

3. Issue Resolution

Is the proposed research likely to resolve key issues and provide the basis for a decision to advance to the next stage: to re-direct within a stage; to terminate the concept?

3a. Does the proposed program address the physics requirements, and does it contribute to the physics (theory and experiment) basis in the following areas?

For MFE:

- demonstrating robust macroscopic equilibrium and stability limits
- generating reliable confinement data at relevant temperatures
- demonstrating methods of particle and power exhaust
- demonstrating methods of plasma sustainment
- including adequate diagnostics to accomplish the above

For IFE:

- demonstrating sufficient coupling of driver energy into target
- compressing the fuel with low entropy
- demonstrating sufficient irradiation symmetry
- demonstrating sufficient target stability

- obtaining a sufficiently large hot spot to achieve ignition and burn
- including adequate diagnostics to accomplish the above

3b. Does the proposed program address the technology requirements and does it contribute to the technology basis in the following areas?

For MFE:
- magnets
- plasma facing components
- heating and current drive
- particle control
- instrumentation

For IFE:
- ion beam technologies
- laser technologies
- pulsed power technologies
- target fabrication and injection

For Both MFE and IFE:
- advanced materials
- chamber technologies
- tritium systems
- safety & environment
- maintenance systems

4. Leading Edge

Is the research at the leading edge in the context of the national and international fusion programs?

- In which areas would the proposed research contribute at the leading edge?
- In which areas would the proposed research be behind the leading edge?
- What are the opportunities for leveraging broad knowledge bases?

5. Energy Vision

What is the overall attractiveness of the energy vision for this concept?

- Have the important issues been identified?
- Can the issues be addressed in the context of the broader national and world programs?
- What is the proposed activity to contribute to this effort?
- What is the potential for energy applications?
- What is the definition and impact on development pathway: costs, schedule and risks?

6. Program Issues

The following program issues should be considered:

- What are the construction and operating costs and their basis?
- Are there adequate resources to accomplish proposed program goals?
- Are there opportunities to be a national research facility?
- Are there opportunities to leverage existing facilities?

7. Portfolio Balance

Does the proposed program maintain a balanced portfolio of research opportunities?

8. Science/Technology Goals

How does the proposed program contribute to broad-based national science and technology goals and to educational opportunities?

9. Milestones

What are the key milestones to accomplish the proposed program?

Table 7. Recommended Weightings for Concept Proposals

	Concept Exploration	Proof of Principle	Performance Extension	Fusion Energy Developmen
0. Quality of Research	H	H	H	H
1. Confidence for Next Step	L	M	H	H
2. Plasma Science/Technology Benefit	H	H	M/H	L/M
3. Issue Resolution				
a. Physics	H L	H M	H	M
b. Technology	H L	H M	H	H

4. Leading Edge	H	H	H	H
5. Energy Vision	L	M	H	H
6. Program Issues	M	M	H	H
7. Portfolio Balance	H	M	M	L
8. Science / Technology Goals	H	H	M	L
9. Milestones	H	H	H	H

H = high priority **M = medium priority** **L= low priority**

Appendix A
Charge Letter from Dr. Krebs

October 9, 1998

Dr. John Sheffield, Chair
Fusion Energy Sciences Advisory Committee
Energy Technology Programs
Oak Ridge National Laboratory
Bethel Valley Road
Oak Ridge, TN 37831

Dear Dr. Sheffield:

When I arrived at DOE in 1993, I found a technically excellent fusion program focused on a long-term energy goal, but with a great deal of science yet to be done and funding requirements that exceeded the expectations of both the Congress and the Administration.

Three years ago, a new Congress, taking note of fusion's time scale and estimated developmen t costs, reduced the funding for fusion research by one-third and called for a restructured science program with an emphasis on near-term progress. Since that time, the Department and the community have restructured the program, based on the Fusion Energy Advisory Committee's (FEAC) planning report.

We replaced FEAC with the Fusion Energy Sciences Advisory Committee, to reflect the scientific orientation of the program. We terminated work on the Tokamak Physics Experiment and shut down the Tokamak Fusion Test Reactor. We have redirected resources from the tokamak and technology elements of the program, including ITER, to alternate concepts and a small, clearly identified plasma science initiative. We are building the National Spherical Torus Experiment; we have conducted a grant competition for innovative confinement concepts and funded the highest ranked proposals; and we have increased funding for existing alternate concept experiments. We are now considering a set of proposals for proof-of-principle experiments.

The remaining tokamak experiments are becoming national user facilities with increasing operating efficiencies, and Program Advisory Committees have been established for DIII-D, Alcator C-Mod, and NSTX.

The Department has also assumed a leadership role for the field of plasma science. We are working with NSF on a Basic Plasma Science and Engineering Program initiative, and we have initiated a Plasma Science Junior Faculty Development program. The community is reaching out to other disciplines through the APS/DPP Speakers program, and PPPL recently hosted a workshop on magnetic reconnection, of interest to space plasma science as well as to fusion science.

We are restructuring our technology program, which had been almost entirely devoted to the needs of ITER over the last three years, to emphasize the needs of the U.S. domestic program. In FY 1999 we will suspend our ITER design efforts but still complete important and related technology research. At the same time we will work with our ITER partners to identify complementary international collaborations.

I am proud of Fusion Energy Sciences Program staff, the fusion research community, and the FESAC. All of these changes have been hard won in the face of organizational and personal difficulty, if not trauma . They have maintained research progress, written and reviewed new proposals, sustained core team capability for the future while saying goodbye to deeply held goals and cherished colleagues and I believe we are through the darkest hours but not finished.

While the pace of the restructuring has been limited by funding constraints, the Department and the community are focused on continuing the program shifts begun three years ago. However, fusion will never be simply a science program; it must have an energy vision, as well. This dual nature of the program will always cause tension within the community. The continued call for clearly defined progress toward energy application, from Congress and others, will highlight that tension.

Constrained budgets also naturally result in increasing competition for resources within the community without necessarily increasing program participants' appreciation for each others' work. This makes it difficult to develop consensus within the community and, ultimately, to sustain support within the Administration and the Congress. I am pleased that the community is planning a workshop for next summer to address the technical issues of fusion energy science and contribute to the development of a community-wide consensus on scientific status.

In addition, we need to make final a program plan for the fusion energy science program by the end of 1999. Such a program plan needs to include paths for both energy and science goals taking into account the expected overlap between them. The plan must also address the needs for both magnetic and inertial confinement options. It will have to be specific as to how the U.S. program will address the various overlaps, as well as international collaboration and funding constraints. Finally, this program plan must be based on a "working" consensus (not unanimity) of the community, otherwise we can't move forward. Thus I am turning, once again, to FESAC.

I would like to ask FESAC's help in two steps. First, please prepare a report on the opportunities and the requirements of a fusion energy science program, including the technical requirements of fusion energy. In preparing the report, please consider three timescales: near-term, e.g. 5 years; mid-term, e.g. 20 years; and the longer term. It would also be useful to have an assessment of the technical status of the various elements of the existing program. This document should not exceed 70 pages and should be completed by the end of December 1998, if at all possible. I would expect to use this work, as it progresses, as input for the upcoming SEAB review of the Magnetic and Inertial Fusion Energy programs.

Using this effort as a starting point, I would like FESAC to lead a community assessment of the restructured program thus far, including recommendations for further redirection given projected flat budgets for fusion. With this assessment as background, I would like your recommendations as to the proof-of-principle experiments now under review, as well as your recommendations regarding the balance of the program between tokamak and non-tokamak physics, and between magnetic and inertial fusion energy. Working with the Office of Fusion Energy Sciences, please develop goals and metrics to use in making your recommendations. I would also welcome any other recommendations on program content, emphasis, or balance.

This effort, I realize, is a large undertaking. I believe it will be helped by the community workshop planned for next summer, by the SEAB review, and by the National Research Council review of the scientific quality of the program. I would like to receive this second report by September 1999, so that we can use it to prepare a program plan/roadmap for submission to Congress with our FY 2001 budget.

Sincerely,

/s/

Martha A. Krebs

Director
Office of Energy Research

Appendix B
Panel Membership

Charles Baker* (Chair)
University of California, San Diego

Jill Dahlburg
Naval Research Laboratory

Ron Davidson
Princeton Plasma Physics Laboratory

Steve Dean
Fusion Power Associates

Don Grether
Lawrence Berkeley National Laboratory

John Lindl*
Lawrence Livermore National Laboratory

Mike Mauel
Columbia University

Ned Sauthoff*
Princeton Plasma Physics Laboratory

John Soures
University of Rochester

Ron Stambaugh (Dave Baldwin)
General Atomics

Don Steiner
Rensselaer Polytechnic Institute

*FESAC Member

Appendix C
History of Program Planning

The fusion program has a long history of establishing and updating statements of mission, goals, milestones and metrics. The first detailed program plan resulted from six months intensive community-wide effort from January - July 1976. The 5-volume plan, Fusion Power by Magnetic Confinement (ERDA-76/110, July 1976), described five possible "Program Logics," aimed at the goal "Develop and Demonstrate Pure Fusion Central Station Power Stations for Commercial Applications." The Logics varied in their budget profiles and corresponding end-dates for operation of a Demonstration Power Plant. It was claimed that a Demonstration Power Plant could be operational in 15 - 30 years, depending on funding. The total program costs ranged from $15 - $20 billion. Several concepts were to be carried forth, with a final concept down selection not made until the initiation of construction of the Demo. The fusion program began to implement this plan with the congressional authorization of the Tokamak Fusion Test Reactor in FY 1976. Although the plan was codified into law in the Magnetic Fusion Energy Engineering Act of 1980, it soon became clear that the government was not willing to provide the necessary funding or facility construction decisions, and the plan was abandoned.

The next detailed plan, with broad community participation, was prepared under the leadership of Argonne National Laboratory during April - December 1986. This plan, called the Technical Planning Activity (TPA), developed a detailed multi-level set of program elements and subelements, grouped in classical Work Breakdown Structure (WBS) format (Technical Planning Activity Final Report, ANL/FPP-87-1), and sought to implement the then current fusion program goal: "Establish the scientific and technological base required to assess the economic and environmental aspects of fusion energy." The assessment was "projected to occur by about 2005, although clearly the timing will depend on the pace of the program." Although the technical requirements were analyzed in detail in this plan, no budget requirements were specified in the final report. The plan specified detailed objectives, attributes (metrics), and quantitative planning targets for all elements and subelements of the plan. Attempts to implement the more forward-looking elements of this plan, e.g., construction of a burning plasma experiment, failed, again for budgetary reasons.

During March - August 1990, a program review was carried out by the Fusion Policy Advisory Committee (FPAC), a group commissioned by DOE Energy Secretary James Watkins. In their report (Fusion Policy Advisory Committee Final Report, DOE/S-0081, September 1990), the Committee stated, "This report presents a conceptual program plan that can achieve the goals of at least one operating Demonstration Power Plant by 2025 and at least one operating Commercial Power Plant by 2040." A unique feature of this plan was its recommendation that "The fusion energy program should have two distinct and separate approaches, magnetic fusion energy (MFE) and inertial fusion energy (IFE), both aimed at the same goal of fusion energy production." The FPAC recommended an MFE plan that "includes four major new facilities to be initiated in this decade." These were a Burning Plasma Facility, an Engineering Test Facility, e.g., ITER, a steady-state hydrogen/deuterium plasma tokamak, and a 14 MeV neutron source. The FPAC endorsed the facilities plans of the inertial confinement fusion program in DOE's Defense Programs Office and recommended a complementary program on driver development, materials, reactors and targets for IFE. Budget increases were recommended by FPAC to implement their recommendations and DOE officially adopted the FPAC goals. It soon became clear that the budgets required to implement the FPAC goals for MFE and IFE were not going to be forthcoming.

In the Fall of 1990, faced with a $50 million Congressional cut in the FY 1991 budget, DOE narrowed the fusion energy program to the tokamak for MFE and a very small effort on heavy ion drivers for IFE, in an attempt to maintain the 2025 target date for operation of a Demo, recently recommended by FPAC. Negative fusion community reaction to the narrowing of the program essentially to the tokamak concept, led DOE Director of Energy Research, Dr. William Happer, to request the Fusion Energy Advisory Committee (FEAC) in September 1991 to provide recommendations for a "Concept Improvement Program." Happer requested of FEAC, "The overall policy question is whether, given the demands of the mainline tokamak program and current budget constraints, we should encourage and fund proposals on concepts other than tokamaks." In its report ("Report of Panel 3: Concept Improvement," J. Fusion Energy, December, 1992), the FEAC responded to Happer, "Although research priority should reward the more successful fusion confinement and technology options, it is essential not to concentrate so heavily on a single line of development (no matter what the budget) that better concepts cannot continue to be developed for improved second-generation configurations." The FEAC said that DOE should "retain the flexibility to test some non-tokamak concepts at intermediate scale, when their technical readiness and promise so warrants." The FEAC further noted, "A program as large and long-range as fusion must find mechanisms for encouraging innovation. A small, but formal and highly-visible annual competition to foster new ideas, modeled after the IR&D programs of large institutions, is a mechanism that could serve this purpose." The FEAC also said, "In addition to the science and technology in direct support of a confinement concept, the fusion program should maintain some level of support for basic plasma science and forefront technology that provide the underpinnings of fusion plasma science and fusion technology." The FEAC Concept Improvement panel was restricted to consider MFE. However, the FEAC was subsequently given a charge in 1993 to review IFE and recommended a doubling of that effort (from $7 million to $15 million).

Continued deterioration of the fusion budget, and policy pressure from Congress, led DOE to conclude that the goal of operating a Demo by 2025 should be abandoned. In January 1996, in response to a charge from DOE, the FEAC recommended a "Restructured Fusion Energy Sciences Program (J. Fusion Energy, December, 1996)." FEAC recommended that "the mission of the U.S. Fusion Energy Sciences Program be modified to be consistent with both the most recent programmatic guidance and the level of resources provided by Congress." FEAC recommended that the new mission be to "Advance plasma science, fusion science and fusion technology -- which constitute the knowledge base needed for an economically and environmentally attractive fusion energy source." This currently is the official mission statement of the U.S. fusion program.

Appendix D

A Strategy for Concept Development from the FESAC-SciCom Alternative Concepts Review Panel (July, 1996)

The FESAC Alternative Concepts Review Panel report of July, 1996 laid out an investment strategy for the fusion program and defined a concept development program with emphasis on science and innovation. The review panel characterized the stages of development of fusion concepts based on their level of maturity and program size, and identified the mix of experiments, theory and modeling, and power plant and design studies for each stage. In order to develop an overall strategy, the Panel developed four criteria to measure the benefit of the research; they are: (1) advancement of general plasma physics; (2) advancement of fusion plasma physics; (3) contribution to fusion energy development; and (4) development of candidates for fusion power plants. The panel also recommenced that the decision to expand the research effort in any concept should be solely based on its contributions to the goals of the restructured fusion program and on the peer-review evaluation of specific proposals.

This characterization of fusion concept development has proven useful in describing the structure of a portfolio based Fusion Energy Sciences Program. In the material that follows, we briefly summarize the recommendations from the 1996 FESAC panel, but we also update it to include a view of IFE research in the portfolio. We also further highlight the stages of development and the metrics to be applied to programs at their various stages of development.

It is an implicit assumption of a portfolio-based strategy that different approaches to fusion energy will share an underlying science and technology and it will be found practical to obtain fusion energy from a number of concepts. An important task of the Fusion Energy Sciences Program is to provide a path to establish the knowledge base for the optimization of technically meritorious concepts and to be able to evaluate the possibility of an economically and environmentally attractive fusion energy source. The present situation is that various concepts differ in their maturity or stage of development. Different criteria and metrics and considerations about portfolio balance apply at different stages of development.

All concepts can be considered to pass through five stages of development:
1) Concept Exploration (CE)
2) Proof of Principle (PoP)
3) Performance Extension (PE)
4) Fusion Energy Development (FED)
5) Fusion Demonstration Power Plant

These various stages of development are defined by the set of scientific and technical issues to be addressed in a logical sequence. Although the specific research content of the MFE and IFE programs differ in their early development stages, MFE and IFE share many technical issues in the Fusion Energy Development and Fusion Demonstration stages. Pragmatically, the boundaries between various stages represent changes in the cost of program, in the level of commitment to that concept, and in the focus of the program. At each stage, the research program should be comprised of an interwoven mix of experiment, theory, technology elements, and forward-looking power-plant studies, with the percentage-of-effort on these elements varying at each stage. These stages of concept development are briefly described below. The decision to proceed from one stage to the next should be based on rigorous peer review of the maturity of the concept in order to be confident that the next-stage program will be successful and that the anticipated benefits of the next stage of research justifies the increased level of effort.

Concept Exploration (CE)

The Concept Exploration research programs are aimed at innovation and basic understanding of relevant scientific phenomena. They consist of experiments (costing typically up to $10M/year per device) and/or theory and strive at establishing the basic feasibility of a concept and/or exploring certain phenomena of interest and benefit to other specific, more advanced concepts. For toroidal magnetic confinement systems, these issues include basic existence of equilibrium and gross stability, limited characterization of confinement, initial demonstration of heating, existence of particular magnetic topologies for power and particle control, feasibility of new heating technologies, innovation of new materials, high-temperature superconductors, *etc.* For inertial confinement fusion, examples of activities found at this stage are the basics of coupling energy to targets, ability to compress a target, new driver concepts, new X-ray generation concepts, and new chamber wall concepts.

Many independent experiments and theoretical activities are preferred at this level and can be attempted in parallel, each focusing on a small set of issues. High risk, large payoff research is desirable and should be encouraged. Activities should be of moderate duration (e.g., three-year, once- or twice-renewable) in order to allow for a stable research environment with due regard to an appropriate project turnover rate. Renewal decisions should be based on a rigorous peer review, assessing prospects for proceeding to the next stage.

The major benefits of these programs are in encouraging innovation and advancing basic and fusion plasma physics, and in the training of students and research staff.

Proof-of-Principle (PoP)

The basic purpose of programs at the Proof-of-Principle stage is developing a sufficiently broad understanding of basic scientific aspects of the concept to enable evaluation of the potential of this concept for fusion energy applications. All key issues for the concept in question should be resolved in a PoP program, albeit perhaps singly or even in different devices (as opposed to integrated experiments in a single device as appropriate at the PE stage). Experimental activity at this stage requires at least one device of sufficient size and performance that can examine a range of physics issues. For a toroidal magnetic confinement system, the plasma should be hot enough and large enough to generate reliable confinement data, explore MHD stability, examine ways for plasma sustainment, and explore means of particle and power exhaust. Examples of presently operating devices in the US program that can perform research at this level are the NSTX spherical torus in its early basic understanding phase, as well as the Alcator C-Mod and DIII-D experiments performing specialized research tasks in optimization, control and concept variation characteristic of the later stages of PoP work, although the plasmas produced in the Alcator C-Mod and DIII-D facilities extend well into what are normally considered Performance Extension (PE) regimes. In inertial confinement fusion, issues to be addressed at the PoP level include target ablation physics, radiation coupling to targets, instabilities in the target, direct and indirect drive physics, and testing of new driver approaches at the module level. For example, NOVA, Omega, and Nike have provided proof-of-principle information in both target and laser module development. For both MFE and IFE experiments, the diagnostic set must be comprehensive enough to measure the relevant profiles and quantities needed to address key physics issues. Plasma conditions created in PoP experiments are some distance from the fusion-relevant regime in many of the absolute parameters but provide initial data for scaling relationships and preferably experimental validation of theory useful in establishing predictive capability for the concept.

It is often beneficial for the Proof-of-Principle program to include Concept Exploration class research activities, which focus on certain key issues of the concept and help develop further innovations and concept variation. Theory, modeling, and bench-marking with experiments should be vigorously pursued in order to provide a theoretical basis for scaling the physics of the concept and evaluating its potential; the technical output of a PoP Program should also include quantitative computational tools to evaluate fusion power systems based on the concept. Power-plant studies, including in-depth physics and engineering analysis, should be carried out to identify key physics and technological issues and help define the research program. Any technological issue specific to the concept should also be addressed during the Proof-of-Principle stage.

The construction and operation of a Proof-of-Principle-class experiment takes roughly eight to twelve years which sets the lower bound on the duration of a Proof-of-Principle program. Devices in this class may cost $10 to $100 M to construct and $10 to $50 M per year to operate. Furthermore, substantial resources are necessary to operate a Proof-of-Principle-class experiment. These programs, therefore, should be a national endeavor, drawing expertise from many institutions. Sufficient resources should be committed both to the Proof-of-Principle-class device as well as the supporting smaller experiments, theory and modeling, related technologies and power-plant studies in order to assure a healthy return on the investment.

The major benefits of this stage are the advancement of fusion plasma physics, with some important contributions to fusion energy development and power sources.

Performance Extension

The Performance Extension programs explore the physics of the particular concept at or near the fusion-relevant regime in absolute parameters albeit without a burning plasma. This stage aims at generating sufficient confidence that absolute parameters needed for a fusion development device can be achieved and that a fusion development program with a reasonable cost can be attempted. To the greatest degree possible, the plasmas in these devices should also approach the dimensionless parameters of a fusion power system. Because of the demand on absolute performance, usually a large single device ($100-500M to construct, $50-100M per year to operate, 10-20 year total program duration) is needed, which is equipped with a variety of auxiliary systems for control and operational flexibility as well as extensive diagnostics providing complete coverage in space and time.

In the MFE area, devices in this class have provided the endpoint of scaling information developed first at the PoP stage. High-power auxiliary systems may have been developed and deployed to enable study of driven phenomena like transport barriers and high bootstrap fraction equilibria. Reactor level fusion triple products and equivalent $Q_{DT} \sim 1$ have been achieved in tokamaks at this stage. Large steady-state devices also belong in this stage. While it was adequate to study key phenomena separately in the PoP stage, integration of physics elements into single-discharge demonstrations should be found in the PE stage. Devices that are examples of this stage of development are the JET, JT-60U, and TFTR tokamaks and the LHD stellarator. The currently operating U.S. tokamaks DIII-D and Alcator C-mod are also able to produce plasma parameters appropriate to the PE stage of development.

In IFE, the PE stage brings the first deployments of drivers sufficient to evaluate the prospects for fusion gain. Issues addressed are driver intensity, energy, symmetry, efficiency, and convergence on target. Integrated systems from driver to target at a fusion level are tested. The NIF facility will seek to demonstrate driver and target implosion physics at the level suitable for high gain. The use of cryogenic DT targets in NIF is an activity that extends somewhat into the Fusion Energy Development Stage.

The Performance Extension program should contain elements from the lower-level development stages to help in the area of concept optimization. Extensive coordinated theory and modeling activities should be carried out to analyze the experimental results on all issues and start providing a predictive capability of the concept. Both power-plant and design studies, including in-depth physics and engineering analysis, should be carried out to focus on critical issues, help in optimizing physics regime, and evaluate the potential of the concept for fusion energy development and power plants. Even more important than at the Proof-of-Principle level, the PE programs must be a national endeavor, should include expertise from many institutions, and sufficient resources should be allocated to the supporting activities.

The major benefits of this stage are scientific and engineering contributions to fusion energy development and power sources and the advancement of fusion plasma physics.

Fusion Energy Development

This program is aimed at developing the technical basis for advancing the concept to the power plant level in a full fusion environment. It includes all experiments with substantial fusion energy gain, as well as devices such as volume neutron sources and pilot plants. The Fusion Energy Development stage can be usefully divided into an early phase concentrating on the alpha particle physics internal to the plasma (e.g. alpha confinement, heating and instabilities) and a later nuclear technology development phase concentrating on systems external to the plasma (e.g. remote maintenance, fueling and removal of fusion products). The TFTR and JET tokamaks have carried out research extending some distance into this regime, as far as detecting alpha heating. To obtain substantial alpha heating and progress to such issues as burn control, MFE systems with their intrinsically high average power must also engage some fusion nuclear technology issues early in this stage such as remote maintenance and activation issues. In IFE, the division between DT physics and nuclear technology issues can be more easily separated. The NIF experiment will be able to study alpha physics issues and target chamber clearing and final optics issues without engaging remote maintenance, activation, or a large tritium inventory. Devices in this class are in the cost range of $0.5-3B to construct and require annual operating budgets in the $50-300M range and program durations of 15-20 years.

Facilities at this stage should resolve the fusion nuclear technology issues in a way that is directly applicable to a power plant. These devices must also develop the database for operational reliability and maintainability, safety and licensing, and costing, to justify a demonstration power source. These issues are similar for MFE and IFE.

The major benefits of this stage include resolving critical technical issues for fusion energy development and energy applications, as well as advancement of fusion plasma physics, particularly in the long-pulse, burning plasma area .

Fusion Demonstration

The device(s) at this stage are constructed to demonstrate to potential users that a particular concept is ready for fusion energy application. These are fully integrated and effectively scaleable power sources with the same physics and technology as envisioned for a particular application. At the end of this stage, there should be no remaining physics issues to be addressed in these devices which prevent their future use as a source of energy. Furthermore, their operation should demonstrate that the technological development at previous stages has been successful.