Priorities and Balance within the Fusion Energy Sciences Program

Report Submitted to
U.S. Department of Energy

By

The Fusion Energy Sciences Advisory Committee

September 1999

U.S. Department of Energy
Office of Science

9/13/99

Report of the FESAC Panel on Priorities and Balance

Meeting in

Knoxville, Tennessee

18-21 August, 1999

REPORT OUTLINE

Appendices

Summary

This report presents the results and recommendations of the deliberations of the FESAC Panel on Priorities and Balance for the DOE's Fusion Energy Sciences Program. The panel consisted of 36 people drawn from 23 different institutions which represented the spectrum of scientific and engineering disciplines involved in fusion energy research, including all key elements of magnetic fusion energy (MFE) and inertial fusion energy (IFE). The panel conducted most of its deliberations by working in four subpanels focused on the principal features of DOE's charge to FESAC on program balance and priorities:

- Balance between MFE and IFE.
- Balance within MFE.
- Balance within IFE.
- Proof-of Principle (PoP) Priorities.

The fundamental underpinnings of the Panel's efforts follow from recent reviews of the U.S. fusion program by PCAST, SEAB and FEAC which had the common themes that the U.S. should pursue fusion energy aggressively, that the recent restructuring of the MFE program is recommended and/or endorsed, that current funding is subcritical and that it is premature to narrow among the energy options offered by MFE and IFE.

The Panel has identified the achievement of a more integrated national program in MFE and IFE as a major programmatic and policy goal in the years ahead. Two areas of research common to both MFE and IFE deserve special encouragement in this regard: theory, including terascale computing, and selected areas of chamber technology. Establishing an optimal balance between IFE and MFE in a more integrated national program in fusion energy sciences should be based on the following guiding principles:

(1) The MFE and IFE programs should be consistent with their respective time frames, set in part by
    - MFE opportunities to participate in major international experiments;
    - IFE opportunities to leverage the DP funded ICF program.

(2) Specific elements of science and technology critical for evaluating the ultimate energy potential of IFE and MFE, such as interaction of the plasma with chamber walls, should be brought to comparable levels of maturity.

(3) The dramatic advances in the predictive power of modern theory and simulation make these tools essential elements of a cost-effective program.

(4) A common peer-review process for MFE, IFE, and cross-cutting activities should be implemented wherever possible.

(5) Cross-cutting science and technology, with application to both MFE and IFE, deserves special encouragement.

(6) Attracting and maintaining a talent pool of creative young scientists in the combined program, for example through research with broad scientific or technological implications, is crucial to fusion progress.

To consider the question of the balance between IFE and MFE, the Panel considered three budget cases with a total annual funding of \$300M, \$260M and \$222M. In order to position the U.S. to execute the combined MFE/IFE research program within the timeframes set by the worldwide MFE program and DOE's Defense Program (DP)-funded inertial confinement program, the Panel strongly endorses a funding level of $300M for the fusion energy sciences program. The Panel further recommends that the funding allocation at this level be $250M for MFE and $50M for IFE.

At an annual funding level of $260M, it will not be possible to have a combined MFE/IFE program consistent with the timeframes noted above, but it will be possible to augment modestly the four principal MFE thrust areas described in this report and develop at least one IFE driver (heavy-ions) for an integrated research experiment (IRE) and associated chamber technology. The recommended allocation is $230M for MFE and $30M for IFE.

At a FY2000 funding level of $222M, both MFE and IFE are subcritical for meeting program objectives. In order to develop critical aspects of at least one IFE driver (e.g. heavy-ion beam propagation in a target chamber), the Panel recommends an FY2000 funding allocation of $207M for MFE and $15M for IFE. Level or decreased funding of the MFE program would seriously delay new proof-of-principle initiatives, significantly curtail technology activities, and prevent full utilization of existing national research facilities.

The MFE research plan is motivated by three considerations central to the restructured fusion energy sciences program: the continued development of fundamental scientific understanding and innovative technologies, the advancement of innovative magnetic concepts, and the time frame of the international fusion effort. In the five-year time frame, the international fusion community will be making construction decisions for major next-step experiments. The MFE plan assures that the U.S. remains actively engaged with the international community and is able to participate in a meaningful way with the worldwide development of magnetic fusion energy. Also on approximately a five-year time scale, our understanding of some of the new magnetic fusion concepts can be sufficiently advanced to warrant consideration for study at the larger scales which more closely resemble fusion conditions.

With regard to overall balance and priorities within the MFE program, the Panel believes that at present the program is reasonably well-balanced given the available resources and the ongoing restructuring of the program since 1996. The Panel recommends funding increases (see Section 5 for illustrative numbers) to accomplish the following:

(1) Strengthen theory and computation as very cost effective means to advance fusion and plasma science, taking advantage of advances in computation science and technology. Strengthen activities in general plasma science and encourage research on near-term applications of plasma science and technology.
(2) Pursue an aggressive portfolio of confinement concepts through increased effort in the Proof of Principle area, and through strengthening of the Concept Exploration program.
(3) Focus the moderate-pulse advanced tokamak program, including U.S. collaboration on leading international facilities, and to a lesser degree the spherical torus program, towards a 5-year assessment point; and prepare for participation in a burning plasma experiment.
(4) Revitalize the technology program to provide for continued innovation in this area because of its overall importance to the success of fusion science and fusion energy and applications. Utilize systems studies to identify attractive fusion energy concepts and affordable development paths.

Approximately two-thirds of additional resources (relative to the Administration's request for FY2000) should be divided about equally between recommendations (2) and (3) above. However, it is high priority to increase support for (1) and (4), with a somewhat greater emphasis on (4), especially under small budget increases.

In the IFE program, the two central objectives are (1) to advance the understanding of high-energy density plasmas and (2) to develop an attractive rep-rated IFE power system. Since the DP program addresses critical target issues in single-shot experiments, the OFES program focuses on high-pulse rate, efficient and affordable drivers and associated fusion chamber and target technology.

The IFE research plan is motivated to enable the initiation of an Integrated Research Experiment (IRE) program which could be optimized and iterated as results are obtained on NIF and which is consistent with the expected completion of the direct-drive target physics programs on Omega and Nike, and the initiation of ignition experiments on NIF. One essential feature of the IFE program is an emphasis on chamber technology, including beam propagation. The IFE plan aims at making an IRE decision on a five-year time frame, and permits an effective interaction and leverage between a balanced IFE research program and the NIF program in target physics.

The recommended IFE program of $50M per year ($300M case) would prepare three driver candidates for an IRE stage, develop the necessary chamber and target technology and pursue some limited efforts at the concept exploration level. At a funding of $30M ($260M case), the emphasis would be on the heavy-ion driver option and associated chamber/target technology, while maintaining reduced efforts on advanced laser options.

The Reversed Field Pinch (RFP), Compact Stellarator (CS) and Magnetized Target Fusion (MTF) concepts were reviewed by an OFES technical review panel last year. Its conclusion was that each concept had a sufficient technical base to be considered for designation as a Proof of Principle (PoP) program. The task of the FESAC PoP subpanel was to determine the actual readiness of each concept for PoP designation and to make recommendations concerning implementation or additional work. The conclusions of the subpanel are as follows:

(1) The RFP is ready for PoP designation but a more focused sequential approach should be implemented. The modified budget levels generated in response to the original review are viewed as appropriate. Specifically, this calls for a budget increment of $2M in FY2000 and $3.5M in FY2001.

(2) The CS is not ready at this time for PoP designation because of one important technical concern about the NCSX. The subpanel believes that this concern will likely be addressed in the near future. The subpanel also believes that in the long run the NCSX promises a high probability of success and that a FESAC subpanel participate in the Conceptual Design Review (CDR) of the NCSX project to complete the evaluation of readiness to proceed as an approved PoP program. The subpanel further recommends that the design effort and supporting theory and modeling on NCSX be adequately funded to permit expeditious completion of an optimized design and a successful CDR. This is expected to entail an increment of $1M in FY2000 and $1.5M in FY2001.

(3) The MTF is not ready at this time for PoP designation. There are a number of important technical issues that must be resolved. The subpanel recommends a three-year continuation of the MTF concept exploration program at approximately the present level of effort to produce and translate the required target plasma for the experiment.

1.0 Introduction

This report has been prepared by a Panel of the U.S. Department of Energy's (DOE) Fusion Energy Sciences Advisory Committee (FESAC). The Panel was established by the FESAC Chair, Dr. John Sheffield, to respond in part to a charge issued on October 9, 1998, by Dr. Martha Krebs to lead a community assessment of the restructured U.S. program. The results of the deliberations of the Knoxville Panel was considered formally by FESAC at its meeting in Washington, D.C. on September 8-9, 1999.

FESAC and its panels have undertaken a year-long process to identify the opportunities and requirements of a fusion energy science program; to identify goals, metrics and decision criteria; to consider issues of program balance; and to make recommendations on program content, emphasis and balance. This response has been prepared by members of FESAC, a sequence of three FESAC panels, and it includes input from a summer meeting of representatives of the entire fusion community. A number of fusion sites were visited and presentations were heard on the entire fusion program. Over the 11 month period, various supporting documents were used including the Opportunities Document (prepared by FESAC) and input from SEAB and NRC panels. The process culminated with a four-day meeting in Knoxville.

Dr. Sheffield asked Dr. Charles Baker (UCSD and FESAC Member) to chair the Knoxville Panel, which is composed of 36 people from 23 different institutions (see Appendix A). The Panel is large enough to provide a broad representation of the fusion community, but small enough to carry out its work effectively. The Panel conducted most of its work by breaking into four groups to deal with the principal issues of its charge: balance between magnetic fusion energy (MFE) and inertial fusion energy (IFE), balance within MFE, balance within IFE, and recommendations on proposed proof-of-principle programs. The remainder of this report is organized by these four topics.

In addressing the relative balance and priorities, the Panel reaffirms the national custodial responsibility of OFES for the health and vitality of the discipline of plasma science. The well-established value of plasma science for near-term technological spin-offs is also noted by the Panel. With regard to fusion, the Panel endorses and takes as a starting point the following findings and recommendations by the 1999 SEAB Fusion Task Force:

- "OFES should be expected to use its program to leverage activities undertaken elsewhere (in the world and in DOE Defense Programs) to assure effective collaboration and coordination and to establish world leadership in selected niche areas."
- "It should not be anticipated that the restructured MFE program will be fully successful in all of its energy missions – simultaneously pursuing new concepts, supporting tokamak experimentation, and shepherding plasma science – unless some increment in funding is forthcoming."
- "Given the large DP (DOE Defense Programs) program in inertial fusion, only a modest increase in the OFES budget is needed to support the IFE activities that should be funded by the OFES program -- endeavors which address issues of significance to the energy objective and which are not supported by DP."
- "Since the present funding is barely adequate to sustain the restructured MFE program, and since OFES is the sole steward for MFE, any significant increase in IFE funding within OFES should come from an increment to the present budget."
- "Moreover, DP should dedicate funds to dual-purpose activities, consistent with DP's mission statement, that exploit the synergy between the defense work and IFE science. For example, DP might appropriately take the lead in the development of high-average-power lasers because of DP's very significant involvement and accomplishments in the laser field."

2.0 MFE Balance

2.1 Overview

The mission of the Office of Fusion Energy Sciences (OFES) program is "Advance plasma science, fusion science and fusion technology -- the knowledge base needed for an economically and environmentally attractive fusion energy source." In Magnetic Fusion Energy (MFE) research, magnetic fields are utilized to contain a plasma while it is heated to the temperatures and densities needed for a self-sustaining fusion "burn," similar to what occurs in the core of the Sun.

An MFE power plant would consist of five major components surrounding the magnetically-confined fusion plasma core, including (i) a magnetic coil set for generating and control of the confining magnetic field; (ii) plasma fueling, heating and current drive systems; (iii) a first wall and blanket system for energy recovery and tritium fuel breeding; (iv) power and particle exhaust/recovery system; and (v) a system for converting the fusion-generated energy into electricity. The long-term goal of the MFE program is an optimized magnetic configuration as the basis for a demonstration power plant (Demo). A coordinated effort advancing the necessary science and technology across a broad front is needed to accomplish this goal.

Because of the range of scientific ideas and plasma confinement configurations, the MFE approach to fusion energy is carried out through a "Portfolio Approach," as described in detail in the FESAC report on "Opportunities in the Fusion Energy Sciences Program". In that FESAC document, the portfolio elements are grouped into “Stages of Development” in a “Roadmap” for fusion energy development that is common for all fusion approaches.

To help guide program decisions on the key science and technology issues which must be addressed among the magnetic configurations, an extensive set of technical and scientific metrics was prepared by the fusion community at the 1999 Fusion Summer Study. These define targets which must be met for the various configurations, in order for their development to continue. In addition, an extensive set of power plant design studies has been carried out which identify the principal research and development needs for the different configurations.

The large international MFE program, over a billion dollars per year, provides important opportunities to US researchers. The portfolio of US investments is chosen to benefit maximally from the international effort, by complementing those efforts. By the same token, the major foreign facilities provide important opportunities for US MFE researchers to perform experiments, collaboratively, which are not possible on domestic facilities. The goals, balance considerations and recommendations provided in this report have been formulated to take the above aspects into account.

2.2 Goals

The Panel has developed the following four MFE goals or "thrusts" as a way of implementing the existing higher-level goals of the OFES program.

(1) Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.

(2) Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems, by investigating a broad range of innovative magnetic confinement configurations.

(3) Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma experiment.

(4) Develop enabling technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy; and apply systems analysis to optimize fusion development.

Detailed near-term, mid-term and long term objectives for each of these goals are provided in Table 1. The goals and objectives assume the resources associated with a funding level of $250M/yr for MFE.

2.3 Balance Considerations

The MFE program has undergone considerable restructuring and consolidation over the past few years brought about, in part, by severe budget reductions. The subpanel believes that the present MFE program is currently reasonably well balanced among its programmatic subelements. However, very attractive opportunities exist in four key thrust areas, discussed below, to make accelerated progress in a highly cost-effective manner.

The MFE program properly emphasizes steady-state, externally-controlled configurations, such as the advanced tokamak and the spherical torus. To maintain a proper balance, care must be taken to also maintain an emphasis on pulsed and/or self-organized concepts.

A significant assessment point will occur in roughly five years, when a combination of international opportunities are expected, and understanding of both the more developed configurations and those at lesser levels of development will have advanced to the point where decisions will be warranted. This 5-year program assessment should consider both the future evolution of domestic facilities and U.S. participation in international collaborations.

2.4 Recommendations

While the present MFE program is reasonably well balanced, the restructuring is not yet complete, and the restructured program can be significantly strengthened with moderate budget growth. Under the assumption of such budget growth in the near-term, the following specific enhancements to the MFE program are recommended:

(1) Strengthen theory and computation as very cost effective means to advance fusion and plasma science, taking advantage of advances in computation science and technology. Strengthen activities in general plasma science and encourage research on near-term applications of plasma science and technology.

Additional investments will be made in computational modeling and basic plasma science. These will allow critical evaluation of the full range of plasma configurations and performance, strengthening their integration. Increased resources in basic plasma science will support the education of the next generation of scientists and engineers.

(2) Pursue an aggressive portfolio of confinement concepts through increased effort in the Proof of Principle area, and through strengthening of the Concept Exploration program.

Additional resources in the Proof of Principal (PoP) programs will enable plasma diagnosis at a level approaching that of present tokamaks, and will initiate studies of alternate confinement configurations at this PoP level. Resources will be directed to strengthening a few critically underfunded Concept Exploration programs to allow their timely execution.

(3) Focus the moderate-pulse advanced tokamak program, including U.S. collaboration on leading international facilities, and to a lesser degree the spherical torus program, towards a 5-year assessment point; and prepare for participation in a burning plasma experiment.

Additional resources will be used to expedite evaluation of the viability and attractiveness of the advanced tokamak and spherical torus configurations at intermediate pulse lengths. These optimization experiments will position the US program to influence, and participate in, potential burning plasma experiments.

(4) Revitalize the technology program to provide for continued innovation in this area because of its overall importance to the success of fusion science and fusion energy and applications. Utilize systems studies to identify attractive fusion energy concepts and affordable development paths.

Additional resources would be used to enhance development of novel chamber wall concepts and extend safety analyses to increase the attractiveness of fusion systems. Systems analysis and design studies will provide guidance for future fusion development options. Plasma technology support will enhance performance of current experiments. Final tests of new, advanced magnet systems will reap the benefits of past capital investments.

Approximately two-thirds of additional resources relative to the Administration's proposed FY2000 budget should be divided about equally between support for goals (2) and (3). However it is also high priority to increase support for achieving goals (1) and (4), with somewhat greater emphasis on (4), especially under small budget increases.

Table 1: Goals and Near-Term/Long-Term Objectives for MFE.

Goal	*5 Years*	*10 Years*	*15 Years*
1. Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation	**Turbulence and transport**: Advance understanding of turbulent transport to the level where theoretical predictions are viewed as more reliable than empirical scaling in the best understood systems. **Macroscopic stability:** Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects. **Wave-particle interactions:** Develop predictive capability for plasma heating, flow and current drive, as well as energetic particle driven instabilities, in power-plant relevant regimes. **Multi-phase interfaces:** Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power- and particle-fluxes. **Advance the forefront of non-fusion plasma science**: (e.g., laboratory plasma physics, space and plasma astrophysics) and plasma technology (e.g., plasma aided environmental remediation, plasma thrusters, plasma etching) across a broad frontier, synergistically with the development of fusion science.	**Develop** fully integrated capability for predicting the performance of externally -controlled systems including turbulent transport, macroscopic stability, wave particle physics and multi-phase interfaces. **Develop** qualitative predictive capability for transport and stability in self-organized systems. **Advanc**e the forefront of non fusion plasma science and technology across a broad frontier, synergistically with the development of fusion science.	**Develop** a fully validated comprehensive simulation capability applicable to the broad range of magnetic confinement configurations. **Advance** the forefront of non-fusion plasma science and technology across a broad frontier, synergistically with the development of fusion science.

Goal	*5 Years*	*10 Years*	*15 Years*
2. Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.	**Make preliminary determination** of the attractiveness of the Spherical Torus, by assessing high-beta stability, confinement, self-consistent high-bootstrap operation, and acceptable divertor heat flux, for pulse lengths >> energy confinement times. **Begin determination** of the attractiveness of the Reversed-Field Pinch by assessing self-consistent confinement and plasma current sustainment. **Determine the performance** of a large Stellarator in the areas of confinement, stability, sustainment and divertor physics through international collaboration. **Resolve key issues** for a broad spectrum of configurations at the exploratory level.	**Assess the attractiveness** of extrapolable, long-pulse operation of the Spherical Torus for pulse lengths >> current penetration time scales. **Complete determination** of the attractiveness of the Reversed-Field Pinch by investigating high-beta stability, sustainment and plasma-wall interaction. **Determine attractiveness** of a Compact Stellarator by assessing resistance to disruption at high beta without instability feedback control or significant current drive, assessing confinement at high temperature, and investigating 3-D divertor operation. **Make preliminary determination** of the attractiveness of further configurations, as appropriate. **Resolve key issues** for an extended spectrum of configurations at the exploratory level.	**Assess the attractiveness** of one or more of the previously investigated configurations at the extended performance level. **Make preliminary determination** of the attractiveness of further configurations. **Resolve key issues** for an extended spectrum of configurations at the exploratory level.

Goal	*5 Years*	*10 Years*	*15 Years*
3. Advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma experiment.	**Assess profile control** methods for efficient current sustainment and confinement enhancement in the Advanced Tokamak, consistent with efficient divertor operation, pulse lengths >> energy confinement times. **Develop and assess** high-beta instability feedback control methods and disruption control/amelioration in the Advanced Tokamak, for pulse lengths >> energy confinement times. **Investigate** alpha particle and advanced tokamak physics in a low-gain burning plasma experiment, through international collaboration.	**Assess the attractiveness** of extrapolable, long-pulse operation of the Advanced Tokamak for pulse lengths >> current penetration time scales. **Assess potential** of Spherical Torus as a basis for burning plasma studies and/or fusion-nuclear component testing. **Participate in an international collaboration** to construct a high-gain burning plasma experiment.	**Demonstrate** high-gain burning plasma operation in a plasma regime relevant to the practical production of fusion power.

Goal	*5 Years*	*10 Years*	*15 Years*
4. Develop enabling technologies to advance fusion science; pursue innovative technologies and materials to improve the vision for fusion energy; and apply systems analysis to optimize fusion development.	**Develop enabling technologies** to support the goals of the scientific program outlined above, including advanced methods for plasma measurements, heating, current drive, flow control, and fueling. **Perform a range of system and design studies** to support the goals of the scientific program. **Demonstrate the feasibility** of innovative plasma chamber technologies for MFE (e.g., ability to handle increased power density, reduce waste volume, improve reliability and breed adequate tritium.) **Develop innovative materials** and fabrication methods to improve performance, enhance safety, and reduce overall fusion system costs to permit fusion to reach its full potential. **Assess the role of fusion energy** in the context of all energy systems. **Assess facility needs** for fusion nuclear materials/components testing, including opportunities for international collaborations. **Study potential improvements** in magnet technology (e.g., fabrication techniques and/or higher temperature superconductors) which could lead to significant reductions in the cost of fusion systems.	**Continue to develop** required enabling technologies. **Resolve key feasibility issues** for new and improved materials and technologies by testing and computation.	**Test attractive materials** and technologies in a realistic fusion environment. **Participate in the operations** of an international fusion test facility.

3.0 PoP Balance

3.1 Overview

The Reversed Field Pinch (RFP), Compact Stellarator (CS) and Magnetized Target Fusion (MTF) concepts were reviewed by an OFES technical review panel last year. Its conclusion was that each concept had a sufficient technical base to be considered for designation as a PoP program. The task of the FESAC PoP subpanel is to determine the actual readiness of each concept for PoP designation and to make recommendations concerning implementation or additional work.

The decision concerning PoP designation was based in part on the criteria as described in the “Draft FESAC Metrics Report". The specific criteria used are given in the next section. The subpanel set very high standards for designation as a PoP, requiring a maximal use of existing data, theory and computational modeling, and reactor studies to establish the case. In practice, this translated into considerably more theoretical modeling and reactor studies than required five to ten years ago. The balance between plasma science and reactor vision remains weighted towards the science.

Another issue faced by the subpanel was the rather disparate nature of the three PoP proposals with regard to cost and schedule. The CS program requests a new primary facility in the $45M range and a long 7 –10 year commitment. Approval implies a significant impact on the overall OFES budget for a substantial period of time with quantum leaps of funding at various stages of the program. The MTF and RFP proposals are heavily leveraged, one on defense spending and the other on the upgrade of an operating facility. Thus the funding requests are much smaller. Furthermore, the nature of the RFP and MTF proposals is such that the completion of the PoP program can be achieved in a gradual, serial fashion; that is, investment in the central PoP facility occurs more as a continuum than as a quantum step. These issues were an important consideration in the evaluation of the cost benefit metric.

The conclusions of the subpanel are as follows:

(1) The RFP is ready for PoP designation but a more focused sequential approach should be implemented.

(2) The CS is not ready at this time for PoP designation because of one important technical concern about the NCSX. The subpanel believes that this concern will likely be addressed in the near future. The subpanel also believes that in the long run the NCSX promises a high probability of achieving success.

(3) The MTF is not ready at this time for PoP designation. There are a number of important technical issues that must be resolved. The subpanel recommends a three year program at a reduced budget level (from that requested) to resolve these issues.

3.2 Evaluation Criteria

The following criteria were applied in the subpanel’s evaluation of the PoP Proposals:

(1) Science Benefit—Will the proposed program advance plasma/fusion science?

(2) Concept Readiness—Is the level of information supporting the proposal sufficient to justify moving forward to the PoP designation?

(3) Issue Resolution—Will the proposed program resolve the key issues required for a next stage decision?

(4) Leading Edge—Is the proposed program at the leading edge in the context of fusion research?

(5) International Perspective—Does the proposed program benefit from and contribute to the international effort for the concept?

(6) Energy Vision—What is the attractiveness of the energy vision for the proposed concept?

(7) Cost/Benefit—Are the likely scientific and programmatic gains commensurate with the costs?

3.3 RFP Assessment

The subpanel unanimously recommends that the RFP program be raised to PoP designation.

The proposal identified five main RFP issues. These issues are confinement, current drive, beta limits, stabilization of resistive wall modes and power/particle handling. The subpanel agrees with the proposal and the previous technical review that these are indeed the main issues and that the full RFP program as envisioned can address them. As proposed, MST will address the first three issues and other program components will address the other two. The RFP proposal was ranked high in the categories of scientific interest, readiness, issue resolution and international leadership. The subpanel also agrees with the previous technical review that the initial goals of the program were somewhat ambitious and the program should therefore focus on the scientific issues sequentially.

The modified budget levels generated in response to the original review are viewed as appropriate. Specifically this calls for a budget increment of $2M in FY2000, and $3.5M in FY2001.

3.4 Compact Stellarator Assessment

At present the subpanel does not recommend approval of CS as a PoP program, because of an important technical issue that needs to be resolved; specifically, the conceptual design embodiment (NCSX) must exhibit robustness of the equilibrium configuration throughout the plasma evolution. However, the subpanel is confident that the Compact Stellarator can become an important PoP program. The CS program ranked high in scientific benefit, energy vision and international integration.

It is recommended that a FESAC subpanel participate in the Conceptual Design Review (CDR) of the NCSX project to complete the evaluation of readiness to proceed as an approved PoP program. It is further recommended that the design effort and supporting theory and modeling on NCSX be adequately funded to permit expeditious completion of an optimized design and a successful CDR. This is expected to entail an increment of $1M in FY00 and $1.5M in FY01.

3.5 MTF Assessment

The subpanel does not recommend the MTF program be raised to the PoP level because of two primary concerns: (a) the target plasmas produced to date have not met the simultaneous requirements of temperature, density, and size; and (b) the reactor vision needs to be more compelling. With regard to the reactor vision, in addition to the well known engineering issues there is a critical physics issue: reactor relevant FRC's need to be stable during the implosion and burn particularly at the large expected values of s (plasma radius/gyro-radius). The MTF program ranked high in uniqueness and leading edge.

The subpanel recommends a three-year continuation of their concept exploration program at approximately the present level of effort (with an OFES increase to offset the loss of internal funds) to produce and translate the required target plasma for the experiment. During this time OFES should also consider supporting the development of the reactor vision.

4.0 IFE Balance

4.1 Overview

Inertial fusion research involves the production, study and use of high energy density plasmas similar to those found in the center of stars. The two central objectives of inertial fusion energy (IFE) research are:

- Advance the fundamental understanding and predictability of high energy density plasmas
- Develop the science and technology of attractive rep-rated IFE power systems leveraging from the single shot work in the DP ICF Program.

In IFE, a power plant would consist of four major components including a target factory to produce low cost targets, a driver capable of rep-rated operation to heat and compress the targets to ignition, a fusion chamber to recover the fusion energy pulses from the targets, and the equipment to convert fusion heat into electricity.

There is a high level of synergy between the Department of Energy Office of Fusion Energy (OFES) IFE program addressing IFE-specific needs, and the DOE Defense Program (DP) Inertial Confinement Fusion (ICF) target physics program.

- The DP program addresses the critical target physics issues in single shot experiments.
- This allows a modest cost OFES program to focus on the development of high pulse-rate, efficient, reliable, and affordable drivers and associated fusion chambers, target fabrication, and target injection.

The proposed OFES IFE program follows the stages of development in the combined MFE/IFE fusion energy development roadmap, with a set of metrics and goals for transitions from one stage to another. These metrics and goals were refined at the Snowmass meeting. The program elements are discussed in the FESAC Opportunities Document. There is a significant degree of separability of each of the major elements of an IFE Power plant and various combinations of drivers, targets, and chambers are promising. At the present time, two approaches are the most advanced and have the greatest potential of meeting near term IFE requirements.

- One approach utilizes indirect drive targets, heavy ion drivers, and chambers with first walls protected from neutrons by a thick liquid layer.
- The other approach utilizes direct drive targets, either a krypton fluoride (KrF) or diode pumped solid-state laser (DPSSL), and a dry wall chamber.
- It is important to emphasize that there are other possible combinations of drivers and chambers, as well as other approaches including z-pinches, fast-ignition targets, and light ions.

These approaches leverage the Defense Program’s large investments in laser and pulsed power facilities, target design capabilities, and experimental infrastructure including target fabrication and diagnostics. The heavy ion driver approach leverages the large worldwide program in accelerator development.

4.2 Goals

Near Term - 5 years

For the most advanced approaches, a detailed set of program metrics and goals has been identified for ion beam and laser drivers, dry wall and protected wall chambers, direct and indirect drive target fabrication, and target injection. These metrics and goals assume a funding level for IFE of $50M/yr. The purpose of the PoP level IFE program is to provide the database for a decision on an Integrated Research Experiment (IRE) and the associated program.

The IRE objective for the heavy ion approach is a completely integrated ion accelerator from injector to beam focus in target chamber center. The size and characteristics of the accelerator will be chosen so that the performance and cost of a driver for the fusion-engineering-development stage Engineering Test Facility (ETF) can be accurately projected. For lasers, the IRE plan is to develop and optimize one complete laser beam line that would be prototypical of an Engineering Test Facility (ETF) driver.

The objectives of the IFE program are coordinated with the timescale of results expected from the defense program (DP) on NIF. Recent discussions within DP indicate that only 96 of 192 beams might be completed within the near term IFE time frame. It is expected that this first phase of NIF will be adequate for the near term IFE objectives needed for an IRE decision. A reassessment of the schedule and performance to be obtained from NIF, and coordination with the IFE program will be carried out when the revised NIF program plan is finalized.

In order to have the knowledge base required to make a proposal for an IRE scale ion driver experiment, the near term program must meet several objectives:

- Perform single-beam, high-current experiments to validate ion production, acceleration, and transport in a driver-relevant regime (line charge ten times higher than in present experiments).
- Perform focusing and chamber transport experiments at intermediate scale (midway between present experiments and IRE experiments).
- Complete detailed end-to-end (ion source-to-target) numerical simulations of the IRE and full-scale drivers.
- Develop technologies to minimize the cost of the IRE. Ignoring economy of scale, the cost goals for the IRE are very close to the cost goals for fusion power production.
- Before a construction decision on an indirect drive IRE is made we anticipate that experiments on implosion symmetry consistent with the requirements of IFE high-gain targets will have been successfully demonstrated using non-cryogenic targets on NIF.

In the PoP stage, the key objectives to be demonstrated by both of the candidate laser drivers on a component or sub-scale system include:

- Energy of several hundred joules in a laser architecture scalable to 2 MJ at a cost of ≤ $500/J.
- Wall plug efficiency of 6-10% at a repetition rate of 5 Hz.
- Reliability of 10^5 to 10^8 shots between maintenance cycles.
- Irradiation uniformity of ≤ 0.3%.

Fusion chamber characteristics and lifetime, target fabrication methods, and target injection techniques play a critical role in determining the optimal driver and target combinations for IFE. In order to make an IRE decision, the PoP program must achieve the following goals:

- Demonstrate that an IFE chamber can be cleared of droplets and/or vapor in less than ~200 ms to a level that lasers or ion beams can be focused on a target.
- Driver/Chamber Interface issues:
  1. Heavy ions: Produce a self-consistent design for final-focus magnets consistent with heavy ion target requirements and the standoff of protected wall chamber designs;
  2. Lasers: Tests to determine the plausibility of achieving laser final optics lifetimes of >1 full-power-year after being subjected to neutron, x-ray, and target debris.

- Identify methods for low cost manufacture and rapid injection of both direct and indirect drive targets.

In addition, concept exploration work will continue to be undertaken in these areas.

Further concept exploration (CE) level research should be performed in a number of areas e.g.: rep-rated z-pinch driver concept based on a recyclable transmission line could be investigated; initial studies could include demonstration of a frozen FLiBe transmission line on Z, along with studies of z-pinch power plant concepts using solid Li packing (with variable density) in the chamber; other possible target concepts such as the fast ignitor could be examined; and science level studies of light ion sources could also be appropriate.

Medium Term to 20 years:

- Develop optimized target designs based on information from the IRE and NIF Programs.
- Demonstrate that ion beams and lasers can be focussed on a target in a reactor relevant chamber several times a second with sufficient intensities to obtain moderate gain in an ETF.
- Demonstrate that a rep-rated final-focus magnet/optics system can successfully operate in the radiation environment characteristic of an ETF.
- Demonstrate the injection of both direct and indirect drive targets into a reactor relevant chamber and the low cost manufacture of about 10,000 representative targets.
- Demonstrate that reactor relevant materials can successfully operate after exposure to 10% of the goal of neutron, x-ray, and target debris exposure expected in an ETF.
- Qualify materials for candidate ETF chambers that can meet current safety and environmental standards.
- Carry out ETF design studies.
- Complete the IRE program to provide the economic, scientific, and technological foundations for full-scale driver construction, allowing down-selection of options.

Long Term

- Design and begin construction of the ETF.
- Through the ETF program and associated programs on materials and nuclear technologies,
- develop the database for a DEMO.

Continuing Science Goals

- Improve understanding of high density plasma behavior, laser-materials interactions, driver science and technology, etc;
- Continue laboratory astrophysics studies; and
- Continue to spin-off developments of the program.

4.3 Balance Considerations

To complete the IFE program on ion and laser drivers, protected wall and dry wall chambers, and indirect drive and direct drive target fabrication over about 4 to 5 years, while allowing for some concept exploration experiments, the required budget level would be about $50M/yr. A detailed assessment of appropriate levels of activity for program elements has been made for this case. An IFE budget at this level is unlikely to be supported except with the increased total budget of $300M discussed in section 5 of this report budget. An illustrative distribution of funds is in that section.

At a total budget level of $260M a budget of around $30 M for IFE would be more appropriate and it would allow a vigorous development of the ion beam program in preparation for its IRE as described above. But it would lead to delays in the development of the laser path and reduce opportunities for concept exploration. The ion beam component of the program would account for about half of the budget. More work is needed to refine the budget breakdown.

At budget levels lower than $30M/yr, it is not possible to maintain the IRE decision date for even a single approach to IFE without abandoning the other driver approaches completely. Such a decision would reduce the vitality of the IFE program. At a budget of $20M/yr, the laser driver development program would be further reduced and progress would be very slow. The ion driver and technology program would also be reduced and the IRE decision delayed. More work is needed to refine the budget breakdown.

At a total budget level of $10M, an IFE program could not address critical issues such as rep-rated drivers and chamber issues that prepare for a timely decision (about 5 years) for any IRE. IFE activities at this level could address only a few critical issues such as heavy ion driver transport/focusing and fundamental chamber issues such as neutronically thick walls. In this case, the ability to capitalize on the DOE-DP investment in laser technology, that has positioned the U.S. as the world leader in IFE, would be weakened.

In regard to concept exploration work, it is assumed that its sum, over the various areas of IFE, will be a few percent of the IFE budget.

4.4 Recommendations

- At a budget of $260 M in FY 2000, the sub-panel recommends that the IFE program should be funded at about $30 M, with about a half of the budget supporting development of the ion beam path.
- If funding of greater than $30 M is provided for the IFE program in FY 2000, the sub-panel recommends that the bulk of the increase should support development of the laser path and for exploratory concepts.
- If the budget were reduced to $20 M, the sub-panel recommends mounting an adequate, albeit delayed program to develop the ion beam option, while reducing the funding for the laser option.

5.0 MFE and IFE Balance

5.1 Overview

In this section, the subpanel identifies key programmatic and policy goals to achieve a more integrated national effort in MFE and IFE (Sec. 5.2), address the balance between major MFE and IFE program elements over the next five years (Sec. 5.3), make specific recommendations to achieve this balance (Sec. 5.4), and address cross-cutting opportunities (Sec. 5.4).

By way of relative context, the U.S. MFE effort funded by OFES ($212M in FY1999) constitutes about 17% of the worldwide research effort (about $1.3B in FY1999) on magnetic fusion energy, with particularly large programs in Europe and Japan. On the other hand, the U.S. IFE effort funded by OFES ($10M in FY1999) constitutes about 4.5% of the total OFES program, and leverages heavily on the significant inertial fusion program funded by DOE Defense Programs ($504M in operating and construction funds in FY1999), including $10M for the development of high-average-power diode-pumped and KrF lasers. Unlike MFE, foreign programs in inertial fusion (excluding defense programs), while high quality and complementary to the U.S. effort, are relatively small and the U.S. is the clear world leader.

As a general remark, the subpanel agrees with the recommendations of the 1999 SEAB Fusion Task Force. In particular, in deciding the priorities and balance of program elements within OFES, it is essential to build effectively on the large fusion efforts abroad and in Defense Programs.

5.2 Goals

The technical goals for the MFE and IFE programs have been delineated in Secs. 2.0 – 4.0 of this report and are not repeated here. The subpanel identifies achievement of a more integrated national program in MFE and IFE as a major programmatic and policy goal in the years ahead. While employing different technologies and plasma regimes, both approaches have a clear fusion energy goal with a strong science focus, and would greatly benefit from increased cross-fertilization of ideas, exchange of personnel, and joint use of facilities. There are also many specific cross-cutting technical areas as discussed in Sec. 5.4. At the planning level, the MFE and IFE program leaders have already taken the important step of developing a joint “Discussion Draft Roadmap” (November, 1998) and a joint FESAC Opportunities document has been prepared.

Program integration is an important goal which will require a deliberate effort by the fusion community and OFES. Implementation of a common peer-review process for MFE, IFE, and cross-cutting research activities will be a key ingredient in developing a more integrated national fusion energy sciences program. The subpanel further endorses the recommendation made by the SEAB Fusion Task Force that DOE establish “some strengthened means for overall coordination” between the fusion efforts of Defense Programs and OFES.

5.3 Balance Considerations

The priorities and balance within the MFE program and the IFE program are addressed in Secs. 2.0 – 4.0 and are not repeated here. Rather, the subpanel has focused on issues related to the relative balance between the MFE and IFE activities supported by the DOE. Both of these programs have made remarkable technical progress under difficult funding circumstances. By any measure, the funding for fusion energy is now subcritical. OFES support for MFE has declined from $350M in FY1995 to about $212M in FY1997-99. This significant decrease in funding has prevented adequate support for the new innovative magnetic concepts central to the restructured fusion energy sciences program and may result in the inability of the U.S. to participate in and influence major international decisions for next-step experiments, expected in a five-year time frame. Similarly, the present level of direct support for IFE from OFES ($10M) and of dual-use support from Defense Programs ($10M) is inadequate to establish the scientific and technological database for even one driver (heavy ions or lasers) in preparation for an IRE decision in a five-year time frame.

Establishing an optimal balance between IFE and MFE in a more integrated national program in fusion energy sciences should be based on the following guiding principles:

(1) The MFE and IFE programs should be consistent with their respective time frames, set in part by
    - MFE opportunities to participate in major international experiments;
    - IFE opportunities to leverage the DP funded ICF program.

(2) Specific elements of science and technology critical for evaluating the ultimate energy potential of IFE and MFE, such as interaction of the plasma with chamber walls, should be brought to comparable levels of maturity.

(3) The dramatic advances in the predictive power of modern theory and simulation make these tools essential elements of a cost-effective program.

(4) A common peer-review process for MFE, IFE, and cross-cutting activities should be implemented wherever possible.

(5) Cross-cutting science and technology, with application to both MFE and IFE, deserves special encouragement.

(6) Attracting and maintaining a talent pool of creative young scientists in the combined program, for example through research with broad scientific or technological implications, is crucial to fusion progress.

5.4 Recommendations

In order to position the U.S. to execute the combined MFE/IFE research programs within the time frames set by the worldwide magnetic fusion program and the DP-funded inertial fusion program, the panel strongly endorses a funding level of $300M for the fusion energy sciences program. This target budget represents a total funding increase of about 30% ($68M) over the FY1999 level but is still substantially smaller than the $360M level in FY1995. It represents a balanced program for both MFE and IFE, and the two approaches are able to capitalize on respective advances in the worldwide magnetic fusion program and the DP-funded inertial fusion program in a timely manner.

In order to illustrate further the impact of the funding on the balance of MFE and IFE research, three budget cases are considered:

1. **$260M Case:** This case corresponds to the $250M OFES plus $10M DP funding level recommended by the House Energy and Water Appropriations Subcommittee for FY2000.

2. **$222M Case:** This case corresponds to the OFES funding level for FY1999 and assumes no DP support for advanced laser development.

3. **$300M Case:** This case corresponds to an annual funding level of $300M, possibly including $290M OFES plus $10M DP in the FY2001 – FY 2004 time frame.

Case 3 ($300M) is highly recommended by the Panel, and would result in a strong, national program in MFE and IFE, with a focus on innovation, and it includes the resources needed to address the energy goal in a timely manner. The recommendations for the first two budget cases are specifically targeted at FY2000, although the relative priorities and balance would also pertain to averages over a five-year period if Budget Case 3 were not realized in FY2001 and beyond.

The overall annual funding allocations recommended by the Panel in the three budget cases are shown in Table 2.

Budget Case ($)	MFE ($)	IFE ($)
300M	250M	50M
260M	230M	30M
222M	207M	15M

Table 2. Funding breakdown between MFE and IFE in the three budget cases.

Recommendations in the $260M Case

In the $260M case, the Panel recommends allocation of $230M for MFE and $30M for IFE. In the text that follows, the numbers in parentheses represent illustrative *increments* (relative to the FY2000 Presidential request) used by the Panel for analysis purposes for the case of the four MFE thrust areas, and illustrative *totals* for the case of the three IFE major program elements.

Magnetic Fusion Energy: At the $260M total funding level, the subpanel recommends incremental funding of $18M for MFE research. This increment (1) initiates and enhances the investigations of several promising innovative magnetic confinement configurations at a limited scale, (2) provides new tools and resources to more fully utilize existing large research facilities and U.S. participation in international facilities, and (3) strengthens the theory/computation and technology areas. The larger facilities are now being used to understand and optimize the performance of the more developed configurations under consideration by the international community as candidates for major next-step experiments capable of studying burning plasma physics. At the $260M level, the funding for all four MFE thrust areas (described more fully in Section 2) should increase. However, the subpanel believes this funding level will delay the planned assessment of confinement configurations and may over time disengage the U.S. program from the international community.

The four interrelated research thrust areas in MFE are: (1) advance fundamental understanding and predictability, (2) resolve outstanding issues by investigating innovative confinement configurations, (3) optimize and understand the performance of plasmas at or near the scale for fusion energy production, and (4) develop the technologies required for fusion science and fusion energy development. Support for fusion theory and computation and fundamental sciences should increase (+ $2.5M) with emphasis in those areas which allow critical evaluation of a wide range of magnetic confinement configurations which advance the predictability of fusion energy performance projections, and enhance basic plasma science studies. Support for the investigations of innovative confinement configurations should increase (+ $5.1M) in order to adequately diagnose proof-of-principle programs, initiate programs to study new configurations at this level, and strengthen exploratory programs. Support for operating and upgrading the larger fusion research facilities should increase (+ $6.2M) in order to install new plasma control tools, to increase the operation of domestic advanced tokamak and spherical torus experiments, and to augment U.S. research collaborations with the larger tokamak facilities abroad. Finally, support for innovative plasma and fusion technologies and system analysis should increase (+ $4.2M) with emphasis on those technologies which enable fusion science research, and appear as high-leverage areas for establishing reduced-cost paths to more attractive end products.

Inertial Fusion Energy: At the $260M total funding level, an IFE program which maintains some breadth of options while addressing critical technical issues can be formulated at $30M. Progress in key areas for laser development would take place ($10M), e.g., key component lifetime tests for Krypton Fluoride (KrF), and gain media and diode performance and cost evaluations for solid state lasers (SSD). Because the stewardship of heavy ion drives is solely the responsibility of OFES, at the $30M budget level for IFE, this element of the IFE program is maintained at $13M at the $30M budget level for IFE. This enables key beam experiments, theory and simulation (focusing, beam transport), component development, target design, and enabling technologies, to move forward. Finally, at this level, chamber technologies (lasers and ions, target fabrication and injection) would be increased to $7M. This funding recognizes the high leverage that this area has on the feasibility of IFE. Of this budget, a few-percent IFE contribution to IFE initiatives in concept exploration, high energy density physics, and plasma theory would be set aside. It should be emphasized that, if this budget level were maintained, it would not enable a five-year time scale for an IRE decision that maintains the necessary breadth of driver options, and re-evaluation would be required.

Recommendations in the $222M Case

This case corresponds to $222M of OFES funding, and zero DP funding for advanced lasers. The severe reduction of advanced laser capability as a driver option, and the associated personnel, would effectively narrow the number of driver options for the IRE to one (heavy ions), supported by OFES. Level or decreased funding of the MFE program would seriously delay new proof-of-principle initiatives, significantly curtail technology activities, and prevent full utilization of existing national research facilities. As already noted in Sec. 5.3, the $222M case is already subcritical for meeting MFE and IFE program objectives. Nonetheless, the Panel recommends in this case that about $15M (up from $10M in the FY2000 Presidential request) of the $222M be applied to IFE activities in FY2000. In the $5M incremental funding for IFE, particular emphasis should be placed on chamber technologies, beam propagation issues in the target chamber, and maintenance funding for high-average-power laser development.

Recommendations in the $300M Case

In the $300M case, the Panel recommends allocation of $250M for MFE and $50M for IFE. In the text that follows, the numbers in parenthesis represent illustrative *increments* (relative to the FY2000 Presidential request) used by the Panel for analysis purposes for the case of the four MFE thrust areas, and illustrative *totals* for the case of the three IFE major program elements.

Magnetic Fusion Energy: For this budget case, the subpanel recommends an incremental funding of $38M for MFE. As detailed in Section 2, funding at this level enables (1) a more thorough investigation of several innovative confinement configurations, (2) the timely evaluation of advanced operating modes in large-scale, high-temperature plasma devices, (3) more aggressive development of comprehensive modeling/simulation tools, and (4) development of innovative solutions to important fusion technology issues. Progress in these areas is needed to be ready for a U.S. assessment of the leading approaches to magnetic confinement in the five-year time frame. This time frame coincides with expected international decisions to construct major next-step experiments capable of investigating the physics of burning plasmas. By completing sufficient investigation of possible optimizations and extensions of advanced tokamak and spherical torus operating modes, the U.S. fusion program may have greater influence on major next-step decisions, become better prepared to participate in future international experiments, and create new domestic opportunities for the study of one or more of the most promising innovative configurations at larger scale. In order to be scientifically and technically ready for a U.S. assessment, the MFE plan requires proportionally larger incremental funding in all four thrust areas than in the $260M case, while maintaining a balance among them. The funding increases for the four thrust areas should be +$5.7M for theory and computation and fundamental science, +$12M for investigation of a range of promising confinement configurations, +$13M for the optimization and expeditious evaluation of advanced tokamak and spherical torus configurations, utilizing both domestic and international facilities, and +$7.3M for technology development and system analysis required for magnetic fusion science and fusion energy development.

Inertial Fusion Energy: At an overall fusion energy budget of $300M, an IFE program can be constructed that leverages the DOE DP inertial fusion activities, maintains the breadth of options now appropriate, and addresses the critical issues in drivers and target chamber science and technology. This IFE program, funded at a level of $50M, adequately prepares OFES for a decision on an integrated research experiment (IRE) in a five-year time period. This program would fund high-average-power rep-rated laser development ($26M) for both Krypton Fluoride (KrF) and solid state lasers (SSL), heavy ion drivers ($16M), and the critical associated technologies ($8M) such as chamber technologies, target fabrication and injection, and driver interfaces. (Funding levels are four-year averages.) Of this budget, a few-percent of the IFE budget would contribute to IFE initiatives in concept exploration, high-energy-density physics, and plasma theory would be made. A small level of concept exploration in rep-rated Z pinches, fast igniter, and low-mass ions would be encouraged.

Cross-Cutting Areas

The subpanel has noted in the fifth Guiding Principle in Sec. 5.3 that areas of research that apply to both MFE and IFE deserve special encouragement. Two areas are cross-cutting in this sense and it is recommended that strong OFES support be given: theory and technology.

Theory. The restructured fusion program must deal with a broader range of physics issues than the present program. Such issues as ion beam propagation in the target chamber, and nonlinear, non-ideal MHD must be studied. The subpanel believes that a strong theory and computational program is an essential component in making informed choices and evaluating experimental progress. The subpanel recognizes that advances in computational capabilities may enable a dramatic advance in the ability to predict the performance of magnetically and inertially confined plasmas. The overlap between MFE and IFE physics allows stronger coordination in an integrated national program to provide improved algorithms and more efficient use of advanced computers. To be effective, this new theory initiative must have both increased resources as well as a stronger focus. Coordination of theoretical activities, with the goal of assisting particular CE and POP groups, as well as advancing simulation of the highest-performance plasmas, is recommended. The U.S. should maintain its position as the clear worldwide leader in fusion terascale computing. OFES should have a plan coordinated with the Strategic Simulation Initiative , providing resources to insure that this capability is effectively utilized.

Technology. Technology, like theory, addresses issues common to IFE and MFE in several areas. Concepts such as liquid walls also have application to both IFE and MFE programs, and could increase the potential first wall power density and reduce radioactive wastes. Fusion power system studies carried out in a collaborative mode could help provide a common basis for assessments of the technical approaches. Technology research also provides important contributions to the underlying materials and engineering sciences. The integration of MFE and IFE technology research has already begun under the Virtual Laboratory for Technology; such efforts should be further encouraged.

Because of the cost effectiveness and leverage of both these cross-cutting areas to fusion energy development, the increases for these areas represented by the recommendations earlier in Sec. 5.4 for the $260M and $300M cases are strongly endorsed. In the event of level funding at $222M, every effort should be made to enhance these areas above their FY1999 levels.

Appendix A
FESAC Priorities and Balance Panel Membership

Charles Baker (Chair)
University of California, San Diego

MFE Balance	PoP Balance	IFE Balance	Overall MFE/IFE Balance
Stephen Dean* *(Fusion Power Assoc)*	Jeffrey Freidberg* *(MIT)*	John Sheffield* *(ORNL)*	Ronald Davidson* *(PPPL)*
Raymond Fonck *(Univ. of Wisc.)*	Thomas Jarboe *(Univ. of Wash.)*	Roger Bangerter *(LBNL)*	Charles Baker *(UCSD)*
David Hill *(LLNL)*	Joseph Johnson, III *(Florida A&M Univ.)*	Gerald Kulcinski *(Univ. of Wisc.)*	David Baldwin *(General Atomics)*
Wayne Houlberg *(ORNL)*	Gerald Navratil *(Columbia Univ.)*	John Lindl *(LLNL)*	Richard Briggs *(SAIC)*
Kathryn McCarthy *(INEEL)*	David Newman *(Univ. of Alaska)*	Craig Olson *(Sandia Nat'l Lab)*	E. Michael Campbell *(LLNL)*
Cynthia Phillips *(PPPL)*	Tony Peebles *(UCLA)*	John Soures *(Univ. of Rochester))*	Jill Dahlburg *(NRL)*
Miklos Porkolab *(PSFC/MIT)*	Don Steiner *(Rensselaer)*		Rob Goldston *(PPPL)*
Ned Sauthoff *(PPPL)*	Tony Taylor *(General Atomics)*		Richard Hazeltine *(Univ. of Texas)*
Kurt Schoenberg *(LANL)*	Harold Weitzner *(New York Univ.)*		Michael Mauel *(Columbia Univ.)*
Clement Wong *(General Atomics)*			Marshall Rosenbluth *(UCSD)*
Michael Zarnstorff *(PPPL)*			

***Subpanel Chair**