November 25, 2002

Dr. Ray Orbach
Director, Office of Science
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585

Dear Dr. Orbach:

The Fusion Energy Sciences Advisory Committee (FESAC) submits with this letter the preliminary report of its Fusion Development Path Panel. Chaired by Professor Rob Goldston, the Panel has responded to your charge of September 10, asking for a report on the "prospects and practicability of electricity into the U.S. grid from fusion in 35 years." The charge requests a report in two stages; here we submit the first stage, which outlines a plan and identifies (in the words of the charge) "significant issues that deserve immediate attention." The second stage, to be submitted in March, will provide a much more detailed plan, including cost estimates. The present Preliminary Report has the unanimous, unqualified endorsement of FESAC.

Upon receiving your charge in September, I wrote you on behalf of FESAC to emphasize that "recent advances in fusion science have wrought fundamental change. In particular, such advances allow a sober assessment of fusion power production as something that determined scientists and strong research support could achieve within three or four decades." The Panel's conclusions reinforce that statement. After identifying the key hurdles and outlining how they can be addressed, the Panel concludes that its preliminary plan "can lead to the operation of a demonstration fusion power plant in about 35 years and enable the commercialization of fusion power."

The Panel recognizes that "significant scientific and technological challenges remain for the development of fusion as a practical energy source…" These challenges will require continued strong emphasis on scientific research of the highest quality and breadth, including in particular both magnetic and inertial confinement. They will also call for significant funding increases, a matter to be explored in detail in the second phase of the panel's investigation.

FESAC wishes to underscore a key conclusion of the Development Path Panel by quoting from the Executive summary of the Preliminary Report:

> "Dramatic scientific and technological advances have been achieved over the last decade, from the understanding and control of turbulence in magnetically confined plasmas to the demonstration of the positive impact of improved symmetry control in inertial confinement. This strengthened scientific understanding of fusion systems, bolstered by the application of advanced computing, provides enhanced confidence that practical fusion systems can be realized. Increased concern about the impact of human activity on the global

> ecosystem points to the need for new broadly available, non-polluting energy sources such as fusion. In addition, escalating international tensions underscore the importance of long-term national energy security. A commitment now to expend the additional resources to develop fusion energy within 35 years is timely and appropriate."

This statement summarizes accurately the perspective of FESAC.

Yours truly,

Richard Hazeltine
Chair, Fusion Energy Sciences Advisory Committee

Enclosure

cc: N. A. Davies
FESAC

A Plan for the Development of Fusion Energy

Preliminary Report to FESAC, November 25, 2002

Executive Summary

Fusion powers the sun and the stars, and is now within reach for humankind. Lighter elements are "fused" together making heavier elements and prodigious amounts of energy. Fusion offers very attractive features as a sustainable, broadly available energy source, including no emissions of carbon dioxide, no risk of a severe accident, no long-lived radioactive waste, and no need for large land use, very long-distance transmission or large-scale energy storage. Fusion can be used to produce electricity and hydrogen, and can provide energy for desalination. The successful development of fusion over the next few decades will complement other energy sources under development, making a major, timely contribution to reduction of the build-up of greenhouse gases in the earth's atmosphere and ultimately to US energy security.

In response to a charge from the Director of the DOE Office of Science (Appendix B) a Fusion Energy Sciences Advisory Committee Panel (Appendix D) was established to provide a plan for the development of fusion energy and specifically for the deployment of a fusion demonstration power plant (Demo) producing net electricity within approximately 35 years. Consistent with the Charge to the Panel, this Preliminary Report provides a general plan for fusion energy development and identifies significant issues that deserve immediate attention. It builds on recent work of FESAC and the 2002 Fusion Snowmass Summer Study.

The plan presented here addresses the development path both for Magnetic Fusion Energy (MFE) and for Inertial Fusion Energy (IFE). In MFE, magnetic fields produced by coils carrying electric currents confine a plasma that produces fusion energy continuously. In IFE, continuous power is produced by repetitive pulses of energy that compress and heat a small dense plasma very rapidly, in order to produce fusion energy during the brief period that the plasma is held in place by its own inertia.

The Panel began by establishing three primary principles for the development plan:

First, the Demo is defined as the last step to enable commercialization of a generation of attractive fusion power systems. This very practical goal places challenging and specific requirements on the development path to Demo.

Second, it is recognized that significant scientific and technological questions remain for the development of fusion energy. As a consequence, a diverse research portfolio is required in both science and technology. In particular both magnetic and inertial approaches to plasma confinement need to be pursued. The research portfolio must be managed carefully according to criteria of quality, performance and relevance in order to optimize cost-effectiveness. Investments in, and direction of, later plan elements are guided by earlier advances.

Third, it is critical to enhance linkages to the world fusion program, to related fields of science and technology, and, in addition for Inertial Fusion Energy, to the Inertial Confinement Fusion program within the National Nuclear Security Agency. Throughout the development process, research in fusion energy science and technology will provide substantial collateral benefits to fundamental plasma physics, materials science and technological applications.

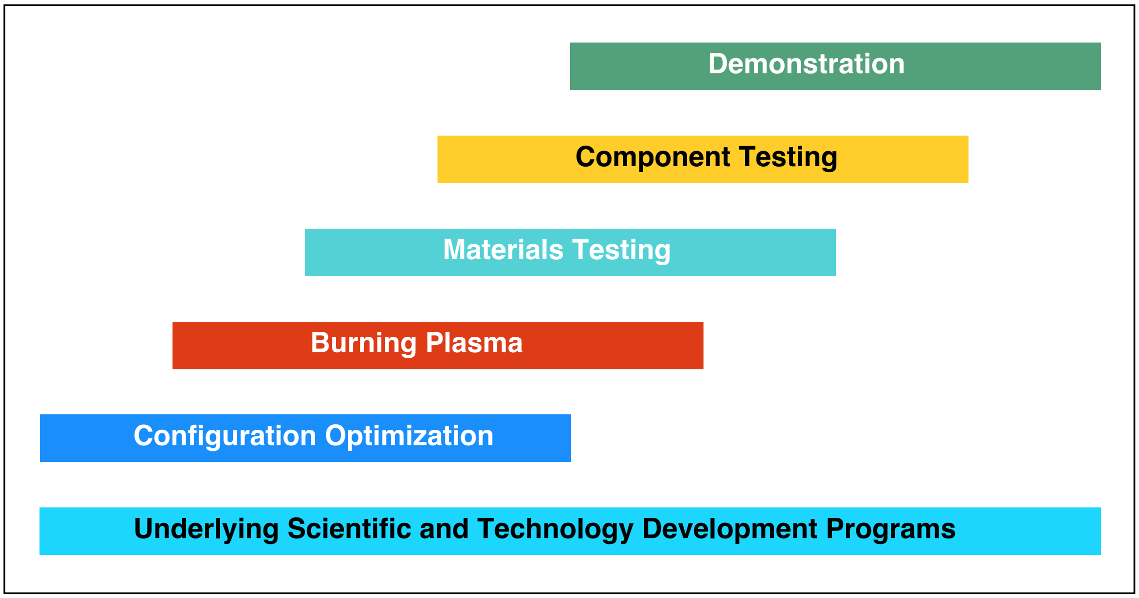

Figure 1. Overlapping scientific and technological challenges define the sequence of major facilities needed in the fusion development path. Programs in theory and simulation, basic plasma science, concept exploration and proof of principle experiments, materials development and plasma and fusion power technologies precede and then underlie research on the major facilities.

A set of overlapping scientific and technological challenges was found to determine the development path for both magnetic and inertial fusion energy. These challenges define a sequenced set of decisions for the construction of major facilities. A set of *Scientific and Technology Development Programs* in theory and simulation, basic plasma science, concept exploration and proof of principle experimentation, materials development and plasma and fusion power technologies must precede and then underlie research on the major facilities. The challenges are: *Configuration Optimization* in which a range of potentially attractive physics configurations is tested and optimized; *Burning Plasma,* in which a plasma is brought simultaneously to conditions of high temperature, density and confinement, so that the fusion process can be self-sustaining; *Materials Testing,* in which materials are qualified for use in the energetic neutron environment associated with fusion energy; *Component Testing,* in which near full-scale fusion power technologies such as chamber components are qualified in a realistic fusion environment; finally leading to *Demonstration*, in which fusion is demonstrated to be an environmentally and economically attractive energy source. This pathway is illustrated schematically in Figure 1. The required research programs and facilities are shown in Figure 2 of the main text.

The Panel has done a preliminary examination of the components of the plan, both their individual duration and the linkages between them, and has concluded that these are consistent with the operation of a Demo on the desired timescale. Achievement of this timescale requires that appropriate funding is provided so that the schedule for the design, construction and operation of facilities is technically driven. Furthermore in some cases design must begin before all information is in hand, and the decision to construct a facility must then be taken promptly when confirmatory information becomes available.

It is the judgment of the Panel that the plan illustrated here can lead to the operation of a demonstration fusion power plant in about 35 years and enable the commercialization of fusion power. It should be recognized, as noted above, that significant scientific and technological challenges remain for the development of fusion as a practical energy source, necessitating a portfolio approach. Furthermore, while costing of the plan is a task for the Panel's Final Report, it is clear that substantial additional resources will be needed to implement this plan. In particular, in order to initiate this plan, funding for fusion energy research including both MFE and IFE needs to begin to ramp up in FY2004.

The MFE portion of the plan depends fundamentally on US participation in a magnetically confined burning plasma experiment. It is time critical for the US to move forward with the burning plasma recommendations of FESAC. The IFE portion of the plan, including elements that are currently distributed between the Office of Science and the NNSA, needs to be adopted as a significant mission with appropriate emphasis within the DOE.

Dramatic scientific and technological advances have been achieved over the last decade, from the understanding and control of turbulence in magnetically confined plasmas to the demonstration of the positive impact of improved symmetry control in inertial confinement. This strengthened scientific understanding of fusion systems, bolstered by the application of advanced computing, provides enhanced confidence that practical fusion systems can be realized. Increased concern about the impact of human activity on the global ecosystem points to the need for new broadly available, non-polluting energy sources such as fusion. In addition, escalating international tensions underscore the importance of long-term national energy security. **A commitment now to expend the additional resources to develop fusion energy within 35 years is timely and appropriate.**

Table of Contents

1.0 Introduction

This Preliminary Report responds to the charge to "provide a general plan to achieve the aforementioned goal (operation of a demonstration power plant in approximately 35 years) and identify those significant issues that deserve immediate attention." Section 2 outlines the potential of Fusion as an attractive long-term energy source, establishing the goal to be achieved. Section 3 presents a set of principles of the plan established by the Panel for the fusion energy development path. Section 4 overviews the elements of the plan which are described in more detail in Appendix A. Section 5 examines the timeline of the plan. Section 6 identifies significant issues which deserve immediate attention. Section 7 presents the Panel's conclusion in response to the Charge.

Appendix A provides details on the elements of the Plan. Appendix B reproduces the Charge to FESAC. Appendix C presents the processes used by the Panel. Appendix D lists the Panel membership. Appendix E is a glossary.

2.0 Fusion as an Attractive Long-term Energy Source

Fusion powers the sun and the stars. Lighter elements are "fused" together making heavier elements and prodigious amounts of energy. Fusion offers very attractive features as an energy source. The basic fuels are deuterium, a naturally occurring heavy form of hydrogen, and lithium, from which tritium, an artificial heavy form of hydrogen, is derived for the fusion reaction. These fuels are abundantly available to all nations for thousands of years. There are no chemical pollutants or carbon dioxide emissions from the fusion process or from its fuel production. Radioactive byproducts from fusion, determined by the material choices for the power plant, are relatively short-lived, with the promise of requiring only near-surface burial. There is no risk of a criticality or melt-down accident because only a small amount of fusion fuel is present in a fusion system at any time. No public evacuation plan is required in the vicinity of a fusion power plant. In addition, although neutrons are produced from fusion the risk of nuclear proliferation is greatly reduced relative to fission systems because no fissionable or fertile materials such as uranium, plutonium or thorium are present in a fusion system, and surreptitious inclusion of even small amounts of such elements can easily be detected.

Fusion offers the promise of a steady non-carbon-emitting power source that can be located close to population centers, and is not subject to daily or seasonal weather variations. Large land-use, massive energy storage or very long distance transmission are not required for fusion systems. As population centers grow, according to projections for the US and abroad, such steady, concentrated power sources will be important elements in the world's energy mix. Fusion systems will supply base load electricity, and could cost-effectively power a future energy supply chain for transportation based on hydrogen and fuel cells, by producing hydrogen during off-peak hours. Energy from the fusion process could also be used for desalination. Thus fusion has the potential to satisfy a substantial fraction of the world's energy needs in an environmentally attractive manner for a long time to come.

Analyses of the build-up of atmospheric carbon dioxide indicate that the time scale for atmospheric stabilization of carbon dioxide at realistically achievable levels (550 – 750 ppm) is in the range of 100 to 200 years. As a result, the greatest need for non-carbon-emitting energy sources will come in the latter half of the 21st century and beyond. The world's energy economy must be dramatically transformed beginning during this century, and it must reach a radically different state in the next. Given the time scale for the introduction of new energy technologies a strong program for the development of attractive new energy sources such as fusion is required now.

3.0 Principles of the Plan

Against the background described above, the Panel has established a set of principles for a plan to develop fusion energy.

1. **The goal of the plan is operation of a US demonstration power plant (Demo), which will enable the commercialization of fusion energy. The target date is about 35 years.** Early in its operation the Demo will show net electric power production, and ultimately it will demonstrate the commercial practicality of fusion power. It is anticipated that several such fusion demonstration devices will be built around the world. In order for a future US fusion industry to be competitive, the US Demo must:
    a. be safe and environmentally attractive,
    b. extrapolate to competitive cost for electricity in the US market, as well as for other applications of fusion power such as hydrogen production,
    c. use the same physics and technology as the first generation of competitive commercial power plants to follow, and
    d. ultimately achieve availability of ~ 50%, and extrapolate to commercially practical levels.

2. **The plan recognizes that difficult scientific and technological questions remain for fusion development.** A diversified research portfolio is required for both the science and technology of fusion, because this gives a robust path to the successful development of an economically competitive and environmentally attractive energy source. In particular both Magnetic Fusion Energy (MFE) and Inertial Fusion Energy (IFE) portfolios are pursued because they present major opportunities for moving forward with fusion energy and they face largely independent scientific and technological challenges. The criteria for investment, in order to optimize cost-effectiveness, are:
    a. Quality:
        i. Excellence and innovation in both science and technology are central.
        ii. Development of fundamental plasma science and technology is a critical underpinning.
        iii. The US must be among the world leaders in fusion research for the US fusion industry to be competitive.

b. Performance:
   i. The plan is structured to allow for cost-effective staged investments based upon proven results. Decision points are established for moving approaches forward, as well as for "off-ramps".
   ii. Technically credible alternative science and technology pathways that are judged to reduce risk substantially or to offer substantially higher payoff ("breakthroughs") are pursued.

      It is not a requirement, however, that every pathway be funded at the level needed for deployment in 35 years.
   iii. Inevitably later elements of the plan are less well defined at this time than earlier ones; a goal of earlier elements is to help define later ones.

c. Relevance:
   i. Technical credibility
   ii. Environmental attractiveness
   iii. Economic competitiveness

3. **The plan recognizes and takes full advantage of external leverages.**

   a. The plan depends upon the international effort to develop fusion energy, positioning the U.S. to contribute to this development and ultimately to take a leadership position in the commercialization and deployment of fusion energy systems.

   b. The plan takes full advantage of developments in related fields of science and technology, such as advanced computing and materials nanoscience.

   c. The high quality of the science and technology developed for fusion gives rise to opportunities for broader benefits to society. Thus connections to other areas of science and technology are actively pursued.

   d. For Inertial Fusion Energy, the plan takes full advantage of advances supported by the US National Nuclear Security Administration (NNSA) in the area of Inertial Confinement Fusion (ICF).

4.0 Elements of the Plan

The plan presented here addresses the development path both for Magnetic Fusion Energy (MFE) and for Inertial Fusion Energy (IFE). In MFE, magnetic fields produced by coils carrying electric currents confine a plasma that produces fusion energy continuously. In IFE, repetitive pulses of energy compress and heat a small dense plasma very rapidly, in order to produce fusion energy during the brief period that the plasma is held in place by its own inertia.

A set of overlapping scientific and technological challenges defines the sequence of major facilities in the fusion development path, as illustrated in Figure 1. This sequence is similar between MFE and IFE. Programs in theory and simulation, basic plasma science, concept exploration / proof of principle, materials development and fusion energy technology precede and underlie research on the major facilities.

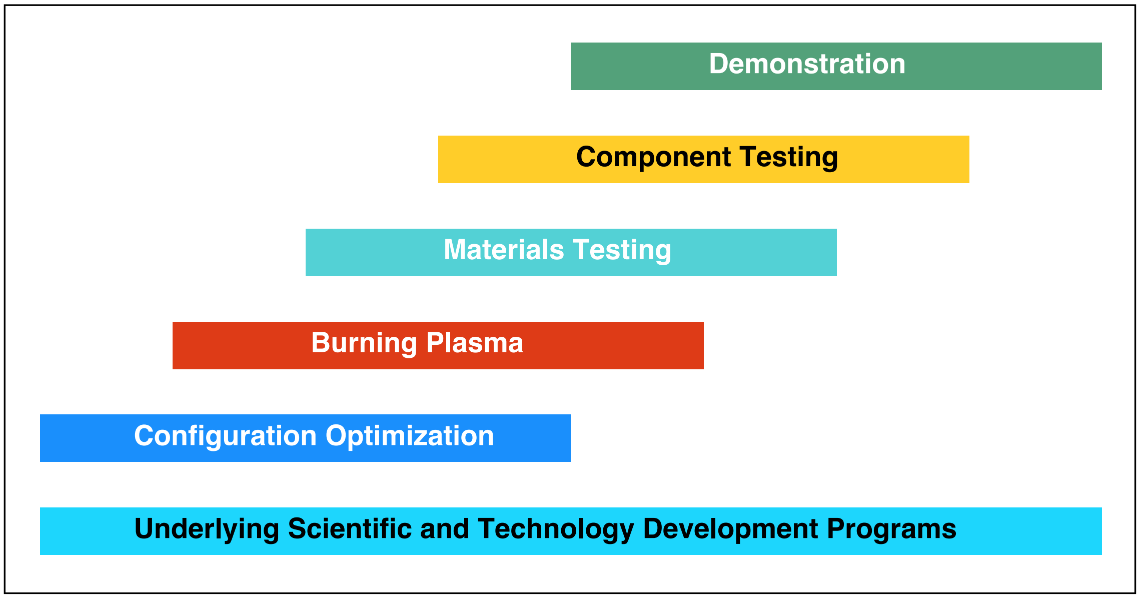

Figure 1: Overlapping scientific and technological challenges define the sequence of major facilities needed in the fusion development path. Programs in theory and simulation, basic plasma science, concept exploration and proof of principle experiments, materials development and plasma, fusion chamber and power technologies precede and then underlie research on the major facilities.

Figure 2 at the end of this section provides a more detailed timeline of the programs and facilities required to meet the series of challenges shown schematically in Figure 1, and a more detailed description of each of the elements is provided in Appendix A.

A concise description of the elements is given below.

Underlying Scientific and Technology Development Programs

Programs in theory and simulation, basic plasma science, concept exploration and proof of principle experiments, materials development and plasma, fusion chamber and power technologies precede and then underlie research on the major facilities.

Fundamental scientific understanding is a critical underpinning of all aspects of the fusion development path, from the definition and understanding of small innovative concept exploration experiments within both MFE and IFE to the design of the Demo based on the results from previous experiments. Fundamental engineering and materials science is critical as well to the development of both materials and chamber technologies.

These underlying programs are described individually in Appendix A.

Configuration Optimization

The development of a comprehensive understanding of magnetic confinement is required to evolve optimized magnetic configurations. The investigation of a range of configurations is needed both to provide a broad base for this comprehensive understanding, and also to advance particular configurations towards fusion power application. Desirable features for optimization include reliable plasma operation at high mass power density, with low recirculating power fraction. Reliability is a critical issue for any complex fusion system. Mass power density in effect measures the cost of a power plant core against its fusion power production. The recirculating power fraction is that fraction of the plant electrical output power needed to sustain the plasma configuration.

The tokamak is the most developed plasma configuration for magnetic fusion and is widely agreed to be well enough understood to allow the step to a burning plasma. Many experiments worldwide routinely obtain similar operating regimes with energy confinement scaling that meets the needs of a burning plasma experiment. Progress in fundamental understanding of plasma transport and stability has also improved confidence in extrapolating present results to future devices. In parallel, an aggressive effort is underway in US and international experiments to increase the attractiveness of the tokamak as a fusion power plant. Key features of such an "advanced tokamak" are steady-state operation with a high fraction of self-generated current to reduce recirculating power, and increased pressure limits to raise fusion power density. These features will be enabled largely through active control of current, transport and pressure profiles.

Tokamak experiments are making good progress in studying key aspects of the advanced regimes for limited durations. Major new international facilities are being designed and constructed to demonstrate advanced performance in steady-state. It is a major challenge to achieve simultaneously all of the most desirable features with high reliability. Thus other less-developed configurations are pursued in parallel with the tokamak, potentially rising to the performance extension (PE) level of experimentation and ultimately to realization as Demo. Progress with these configurations has been very impressive as well. The understanding which arises from experimentation coupled closely with theory and advanced computation should make the step to Demo possible for a configuration which is not too distant from the tokamak.

It is important to recognize that there is an ongoing need for enabling technologies to support the configuration optimization experiments at all levels, as well as through the burning plasma and component testing stages. Continued innovation and long-term development for Demo are required as well. Work on techniques to drive current, to fuel plasmas, to heat them, and to efficiently remove power and particles are necessary components of this effort.

The challenge of configuration optimization within IFE is similar to that of MFE, with the exception that mass power density translates dominantly into driver cost.

Configuration optimization experiments focus on the development of rep-rated drivers and the associated target physics and chamber and target technologies. Target physics experiments of relevance to IFE are ongoing on Omega, Nike and Z and facilities in Europe and Japan.

Configuration optimization for IFE involves more than development of just the target physics, however. It includes the advanced research and development needed for the drivers, target fabrication, target injection/placement, final optics/power focusing system and chamber technologies.

For the laser IFE approach, the work is carried out through the High Average Power Laser program. This includes development of two types of lasers, krypton fluoride and diode pumped solid state, methods to fabricate direct drive targets on a mass production basis, a system to study target injection and tracking of the target, final optics, and chamber development work. The last includes exposing candidate first wall chamber materials to relevant x-ray and ion threats, as well as experiments to look at long term issues such as helium retention.

The heavy ion IFE work is carrying out driver development with three smaller scale machines that investigate the crucial issues of ion source development and beam injection (Source Test Stand), transport (High Current Experiment) and focusing (Neutralized Transport Experiment). These experiments need to be followed by an Integrated Beam Experiment (IBX), which will perform an integrated test of ion beam physics from formation to placement on target. The heavy ion program is also developing techniques to fabricate targets that meet both the physics requirements and requirements for low cost production. The heavy ion program will use the same target injector being developed in the HAPL program.

For the z-pinch IFE approach, experiments are underway to test the materials proposed for recyclable transmission lines (RTLs). Studies are in progress on RTL structural properties, RTL manufacturing and costing, thick liquid wall chambers, and power plant optimization. Z-pinch driven hohlraum capsule implosion experiments to optimize capsule compression ratios and compression symmetry are in progress on Z. A set of experiments (optimization of RTL's, rep-rated pulsed power, blast mitigation, and scaled RTL cycle demonstration) have been proposed. For the fast ignition approach, programs are underway in Japan, and at a lower level, in the US.

In both heavy-ion and z-pinch approaches to fusion a thick liquid first wall may alleviate materials and components issues associated with intense fluxes of high-energy neutrons, and so shorten the transition time from ETF to Demo. Non-nuclear facilities are required to study thick liquid wall issues such as x-ray and ion threat effects, scaled hydrodynamics for jets and streams, shock mitigation to the structural wall, vapor condensation and chamber clearing, molten salt fluid flow loops and materials/nozzles erosion/corrosion issues.

Burning Plasmas

The burning plasma step is critical for both MFE and IFE. Within MFE the fundamental issue is to determine the response of a magnetically confined fusion plasma to continuous heating by the products of its own internal fusion reactions. While measurable fusion self-heating has been produced in experiments both in the US and abroad, no experiment has yet penetrated into the regime where self-heating dominates the plasma dynamics. A facility to investigate this physics will provide critical information with application across a range of magnetic configurations.

A burning plasma is a crucial and missing element in the world magnetic fusion program. The defining feature of a burning plasma is that it is sustained primarily by the heat generated through its own internal fusion reactions. This is in contrast to previous experiments in which most of the heating was applied from outside the plasma. When these reactions occur in a fusion power system, energetic alpha particles (helium nuclei) and neutrons are generated. The alpha particles are confined by the magnetic field and slow down, transferring their energy to maintain the high temperature of the plasma. When fusion alpha heating dominates the plasma dynamics, important new scientific frontiers will be crossed. The creation of a burning plasma will enable major advances in all of the key areas of plasma science and technology, and contribute to the demonstration of magnetic fusion as a source of practical energy. While delivering the fusion-sustaining heat, the alpha particles also represent a new dynamic source of energy to change the plasma pressure profile. Such changes in the plasma structure and dynamics can increase the loss of heat and particles from the plasma, and consequently lead to a reduction in fusion power. Alternatively, these changes may lead to a further increase in temperature and fusion power production. Understanding and controlling these effects on heat and particle transport, the subject of “burn control,” are essential elements of power plant development.

The MFE burning plasma is planned to be either ITER or FIRE, as described by FESAC. The US is considering two different options for a burning plasma experiment because ITER and FIRE are each an attractive option for the study of burning plasma science. Each could serve as the primary burning plasma facility, although they lead to different fusion energy development paths. Both devices are designed to achieve their technical goals on the basis of conventional pulsed tokamak physics, but have capability to investigate advanced tokamak modes of operation. In the ITER case, the capability for long pulse and steady-state operation is provided. Moreover, a substantial amount of fusion technology development and testing is provided as well. In the FIRE case an additional high-performance (but non-burning) steady-state experiment would be required in parallel. For the purpose of this Preliminary Report, given the limited time available, the Panel has analyzed only the development path that incorporates ITER as the burning plasma element. The Final Report is planned to examine both options.

Within IFE the critical issue addressed in the burning plasma step is whether a sufficiently symmetrical, well-timed implosion, with adequate control of hydrodynamic instabilities can be produced, using a megajoule class driver, so that a small fraction of the fuel can be heated to the point where it initiates a propagating burn in the remainder of the colder fuel. (In the case of fast ignition the "hot spot" would be created by an external fast energy source.) This is a critical issue for all approaches to IFE, the results of which can be transferred to other configurations beyond those testable directly on the National Ignition Facility (NIF).

The configuration to be pursued initially on NIF is the best developed: a laser-driven x-ray hohlraum imploding a fusion capsule. Although initial targets in this configuration do not have adequate gain for IFE with lasers, such targets will provide most of the needed physics basis for IFE targets driven with ion beams and z-pinch drivers. NIF is also reconfigurable to study two other IFE-relevant configurations: laser direct drive and fast ignition. The results from NIF, coupled with results from configuration optimization experiments at Omega, Nike and Z as well as those abroad, and improved fundamental understanding, can lead to an Engineering Test Facility (ETF) configured differently from the NIF.

Materials Testing

Due to the diverse technological requirements of fusion power systems, a broad-based materials R+D program encompassing neutron-interactive and non-irradiation aspects is needed. For example high thermal-conductivity radiation-resistant materials are needed for both MFE plasma facing components and IFE dry wall chamber surfaces.

The development of radiation-resistant, low-activation materials for fusion applications is a critical element in both the MFE and IFE development paths. While heavy-ion and z-pinch IFE configurations using thick liquid walls may face less severe issues with respect to materials, it is clear that the issues for laser-driven IFE and for MFE are quite comparable. The present fusion materials science program has been quite successful, and attractive materials are under development. In particular ferritic steels evolved from those developed for the fission breeder program appear to be promising candidates to withstand the needed neutron fluence while retaining low activation properties. However, just as in the configuration optimization programs, a range of materials needs to be developed in order to have confidence that attractive materials will be available for Demo. Furthermore, these materials need to be tested in an intense, realistic energetic neutron environment, which can only be made available through a special-built facility, capable of providing an intense neutron flux onto an area of 100 cm^2. The international community (including the US) has been involved in the conceptual design of the International Fusion Materials Irradiation Facility, which would address this need.

Component Testing

Fusion power and fuel cycle components require testing, development and qualification in the fusion environment prior to Demo for both IFE and MFE. This activity includes testing and qualification of first wall/blanket modules that both breed tritium and convert the fusion energy flux to high grade heat, plasma interactive and high-heat flux components such as the divertor, tritium processing, pellet fabrication and delivery system, and remote maintenance systems.

Within the MFE path, significant experience is anticipated from testing plasma support technologies (e.g., superconducting magnets and plasma heating) in ITER. However testing of chamber technology in ITER is limited by the relatively low plasma duty cycle and the lower flux and neutron fluence than encountered in Demo. Thus a Component Test Facility (CTF) is judged to be necessary in addition to a burning plasma experiment in order for Demo to meet its goals of tritium self-sufficiency, and practical, safe, and reliable engineering operation with high thermodynamic efficiency, rapid remote maintenance and high availability.

The mission of the CTF in the MFE path is integrated testing and development of fusion power and fuel cycle technologies in prototypical fusion power conditions. This facility is to provide substantial neutron wall load (> 1 MW/m^2) and fluence (> 6 $MWyr/m^2$) at minimum overall fusion power (~150 MW) in order to enable integrated testing and optimization of a series of components at minimum tritium consumption and overall cost.

Within the IFE path, it is clear that an Engineering Test Facility (ETF) is needed, since the NIF does not provide significant information on high-average fluence technologies. The approach favored within IFE is to use reduced-yield targets relative to Demo, and a proportionally reduced size target chamber to develop components in order to minimize tritium consumption and simplify component development.

Since the Demo is to demonstrate the operation of an attractive fusion system, it must not itself be devoted to testing components for the first time in a fully realistic fusion environment. Furthermore the tritium consumption of a large facility such as Demo makes it impractical for developing tritium breeding components, as only very little operation without full breeding would be possible. Instead, reliable designs qualified in CTF for MFE or ETF for IFE should be implemented in Demo.

Demonstration

The US fusion demonstration power plant (Demo) is the last step before commercialization of fusion. It must open the way to commercialization of fusion power, if fusion is to have the desired impact on the world energy system. Demo is built and operated in order to assure the user community (*i.e.,* general public, power producers, and industry) that fusion is ready to enter the commercial arena. As such, Demo begins the transition from science and technology research facilities to a field-operated commercial system. Demo must provide energy producers with the confidence to invest in commercial fusion as their next generation power plant, *i.e.,* demonstrate that fusion is affordable, reliable, profitable, and meets public acceptance. Demo must also convince public and government agencies that fusion is secure, safe, has a low environmental impact, and does not deplete limited natural resources. In addition, Demo must operate reliably and safely on the power grid for long periods of times (*i.e.,* years) so that power producers and industry gain operational experience and public are convinced that fusion is a “good neighbor.” To instill this level of confidence in both the investor and the public, Demo must achieve high standards in safety, low environmental impact, reliability, and economics.

To provide consistent focus and integration of the program elements of this plan toward the end goal, the Demo, systems analysis and design studies of possible power plants must be carried out continuously. The designs, maintained current with the progress of the various program elements of this plan, provide guidance to the overall program.

5.0 Timeline of the Plan

Figure 2 provides the timeline of an illustrative plan, including both facilities and the programs that precede and then underlie them. Appendix A provides descriptions of each of the programs and facilities.

The Panel has done a preliminary examination of the components of the plan, both their individual duration and the linkages between them, and has concluded that these are consistent with the operation of a Demo on the desired timescale. Achievement of this timescale requires that appropriate funding is provided so that the schedule for the design, construction and operation of facilities is technically driven. Furthermore in some cases design must begin before all information is in hand, and the decision to construct a facility must then be taken promptly when confirmatory information becomes available.

Within both MFE and IFE a key linkage passes through materials science and materials development to component testing and then deployment on the Demo. It is clear from our discussions that increased emphasis is needed in this program area, and that the next step in the design process for the International Fusion Materials Irradiation Facility (IFMIF), called Engineering Validation, should proceed expeditiously.

Within MFE a fundamental linkage is from the burning plasma experiment to Demo. The design of the Demo must begin within approximately ten years of first operation of the burning plasma, so obtaining data from the burning plasma is time critical. Another key linkage is from the burning plasma and configuration optimization programs to the Component Test Facility (CTF). Since the CTF will be a substantial investment, it is reasonable that favorable results be obtained from a burning plasma before the commitment is made to the construction of CTF. This will require that design of the CTF begin before burning plasma results are available, and that the decision for construction be made promptly when these results are obtained. In addition, since the fundamental design of the CTF is not decided, it is time critical to evaluate configuration options for this facility. More broadly within the configuration optimization program, it is time-critical that successful elements be brought forward, ultimately to the performance extension stage, in order to be able to be ready for the Demo step if judged more attractive.

Within IFE a key linkage appears between NIF results and the initiation of the anticipated single ETF. On the present schedule, NIF will be able to demonstrate ignition for indirect drive before design of an ETF is planned, but the timing is close for the construction decision for other target types. Other NNSA facilities (Omega, Nike, and Z) and international facilities are expected to supplement these data to support the decision to move ahead with the ETF. Information from the IRE's is also time critical for ETF. The proof-of-principle Integrated Beam Experiment for heavy-ion IFE is also time critical for an ETF decision. There are similar schedule-based needs for development of Recyclable Transmission Lines for z-pinch IFE and for the investigation of fast ignition.

The timing of the linkages described here is in many cases tight, but in the judgment of the Panel technically credible. The information needed for key decisions is provided on the required timescale. The plan provides sufficient parallelism that the deployment of an attractive Demo in approximately 35 years is a credible and indeed exciting goal – with the devotion of sufficient resources.

It is the judgment of the Panel that the plan illustrated here can lead to the operation of a demonstration fusion power plant in about 35 years and enable the commercialization of fusion power.

6.0 Significant Issues that Deserve Immediate Attention

MFE Burning Plasma

The MFE portion of the plan depends fundamentally on US participation in a magnetically confined burning plasma experiment. It is time critical for the US to move forward with the burning plasma recommendations of FESAC. This is a dual-path strategy including both the ITER and FIRE options, that begins with US participation in the ITER negotiations with the aim of becoming a partner in the undertaking undertaking and continuing preparation for a FIRE conceptual design activity. The sooner the US joins ITER negotiations the larger will be US leverage on critical decisions. There are matters of urgent concern to the US, such as cost-control, project management, research decision-making and – of course – its own benefits and obligations.

Domestic Research – MFE and IFE

Materials science and fusion chamber and power technology development work needs to be accelerated for both MFE and IFE. The Engineering Validation phase of the International Fusion Materials Irradiation Facility must begin expeditiously.

MFE facilities devoted to configuration optimization (from concept exploration to performance extension) need to be adequately utilized and innovative new such facilities need to be constructed at a cost-effective pace. The enabling technology program needs to provide necessary plasma control tools to support these experiments, and new opportunities in theory and advanced computing need to be pursued. Preparations for a burning plasma experiment need to be started.

The IFE portion of the plan, including elements that are currently distributed between the Office of Science and the NNSA, needs to be adopted as a significant mission with appropriate emphasis within the DOE. Within IFE, the heavy ion beam program needs to begin design of a next-step proof-of-principle experiment. The z-pinch approach to IFE and fast ignition research need to be pursued more aggressively. The development of laser fusion energy has been supported through the high-average-power laser program. This activity is of critical importance to the laser IFE development path, and needs to be supported on a continuing basis.

The recommendation by the NAS/NRC to strengthen connections to other areas of science and technology needs to be implemented.

Dramatic scientific and technological advances have been achieved over the last decade, from the understanding and control of turbulence in magnetically confined plasmas to the demonstration of the positive impact of improved symmetry control in inertial confinement. This strengthened scientific understanding of fusion systems, bolstered by the application of advanced computing, provides enhanced confidence that practical fusion systems can be realized. Increased concern about the impact of human activity on the global ecosystem points to the need for new broadly available, non-polluting energy sources such as fusion. In addition, escalating international tensions underscore the importance of long-term national energy security. **A commitment now to expend the additional resources to develop fusion energy within 35 years is timely and appropriate.**

While costing of the plan is a task for the Panel's Final Report, it is clear that substantial additional resources will be needed to implement it. In particular, in order to initiate this plan, funding for fusion energy research including both MFE and IFE needs to begin to ramp up in FY2004.

7.0 Conclusion

It is the judgment of the Panel that the plan illustrated here can lead to the operation of a demonstration fusion power plant in about 35 years and enable the commercialization of fusion power. It should be recognized, however, that significant scientific and technological challenges remain for the development of fusion as a practical energy source, necessitating the use of a portfolio approach. Furthermore, while costing of the plan is a task for the Panel's Final Report, it is clear that substantial additional resources will be needed. In particular, in order to initiate this plan, funding for fusion energy research including both MFE and IFE needs to begin to ramp up starting in FY2004.

The MFE portion of the plan depends fundamentally on US participation in a magnetically confined burning plasma experiment. It is time critical for the US to move forward with the burning plasma recommendations of FESAC. The IFE portion of the plan, including elements that are currently distributed between the Office of Science and the NNSA, needs to be adopted as a significant mission with appropriate emphasis within the DOE.

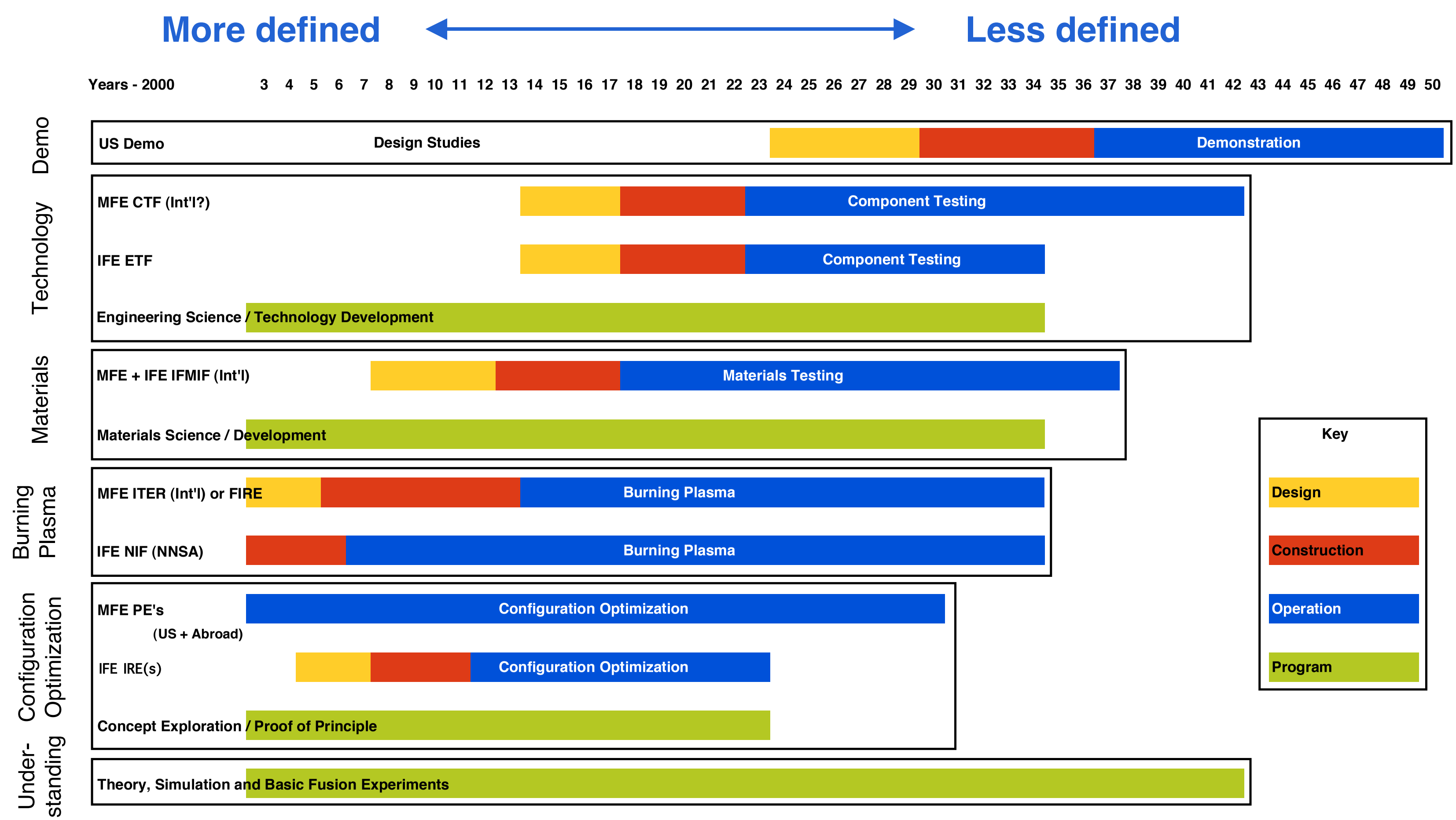

Figure 2: Programs and major facilities that comprise the general fusion development plan (illustrative).

Appendix A: Programs and Facilities in the Illustrative Fusion Development Plan

This appendix provides descriptions of each of the programs and major facilities in the illustrative plan shown in Figure 3.

1) *Theory, simulation and basic plasma science*

The goal of theory and simulation in the fusion energy development path is to provide the theoretical underpinning for understanding and predicting the behavior of fusion plasmas, and to develop a comprehensive simulation capability for carrying out "virtual experiments" of fusion core systems. This capability is essential for rapid scientific and technological progress in all plasma experiments from concept exploration through Demo, as well as in other critical areas, such as materials development, in order to reach the plan's goal.

Improvements in physics understanding and theoretical descriptions for all physical processes in key areas that govern the performance of fusion systems will be needed. This should translate into a capability to perform detailed numerical simulations of individual components utilizing high performance computers, which will be used to quantitatively validate against experimental measurements. For MFE, this effort has been accelerated under the DOE Scientific Discovery through Advanced Computing initiative (SciDAC), and further development of integrative capabilities is being proposed by the Integrated Simulation of Fusion Systems (ISOFS) FESAC Panel. Within the National Nuclear Security Administration advanced computing for Inertial Confinement Fusion is incorporated within the Advanced Scientific Computing Initiative (ASCI), but increased efforts are required in parallel with ASCI to understand ion beam dynamics and to optimize target designs for IFE.

The progress of the theory and simulation program will be measured by the quality of its scientific publications including impact on related fields of science; effectiveness in supporting the understanding, interpretation, and planning of ongoing fusion experiments; means to enable the exploration of new concepts and configurations to improve the prospects for economical fusion power and enhanced ability to predict the performance of future fusion devices.

The primary goal of basic plasma experiments is to study fundamental plasma phenomena in the simplest and most flexible situation possible and over a wide range of relevant plasma parameters. Although basic plasma experiments are not intended to focus directly on a particular application, they can be expected to provide a quantitative understanding of the underlying physical principles and to have significant impacts on an entire spectrum of applications including, but not limited to, fusion energy development. The interconnections to other areas of science and technology broaden the impact of fusion research and bring new ideas and techniques into the fusion arena. Another important consequence of this effort is the training of future plasma experimentalists needed for implementing the fusion energy development plan.

The success of the basic plasma experimental program can be measured by its contributions to the understanding of basic plasma processes such as chaos, turbulence and magnetic reconnection; and to spin-off technologies such as plasma processing of computer chips, space thrusters and waste remediation. It is expected that new knowledge and technology will also directly benefit fusion energy development. The quality of the plasma scientists entering the field will be another indicator of success.

To maintain a strong basic plasma experimental program in the most efficient and cost-effective way, emphasis should be placed on university-scale research programs. The on-going Partnership in Basic Plasma Science and Engineering, funded jointly by DOE and NSF, is an effective way to ensure the continued availability of the basic knowledge that is needed for the development of applications. The creation of the joint DOE/NSF Centers of Excellence in Fusion Plasma Science recommended by the NAS/NRC in its 2001 fusion Report would be extremely beneficial. In addition, creation of joint programs between the Office of Fusion Energy Science and the Office of Basic Energy Science would further leverage DOE's investment in plasma science and strengthen investigations in other energy-related areas of plasma science and technology.

2) *Configuration optimization*

Configuration optimization is required in order to have confidence that an attractive fusion configuration will be available for Demo. In the MFE case this includes the advanced tokamak, the most developed configuration, as well as the spherical torus, the compact stellarator, the reversed-field pinch and a range of more self-organized systems, typically at lower levels of investment. There is strong scientific cross-fertilization between these configurations. In the IFE case driver systems include diode-pumped solid-state lasers and krypton fluoride lasers, heavy ion beams and Z pinches. A range of compression and heating schemes is under study (indirect drive, direct drive and fast ignition), as well as a range of chamber technologies (dry wall, thin wetted wall and thick liquid wall). Specific combinations are considered most compatible based on physics, engineering and economic viewpoints and are being pursued as integrated approaches.

MFE Concept Exploration / Proof of Principle Experiments

A peer review process ensures that the most innovative and potentially attractive systems are constantly being evaluated at the introductory Concept Exploration stage. Two illustrative examples are the Spheromak and the Levitated Dipole. The Spheromak is highly self-organized plasma, in which plasma ejected from an electromagnetic "gun" forms itself into a toroidal configuration within a conducting shell. The interesting aspect of this configuration from a power plant perspective is that no material structure links the torus, simplifying the fusion chamber considerably. The plasma science challenges are great, however, as control of the strong magnetic turbulence within the plasma, which spoils confinement, is needed to make this an attractive candidate for fusion energy application. The goal of present experiments is to understand this turbulence and determine if higher temperature plasmas will be more quiescent. The Levitated Dipole in many ways examines an extreme opposite configuration. In this case most of the magnetic field is formed by a levitated superconducting ring, which is surrounded by a plasma with such weak pressure gradients that it is calculated to be very stable, in analogy to the high pressure plasma atmosphere found around Jupiter. For fusion application the greatest challenges will be to maintain such a floating ring in a fusion environment, even using advanced low-neutronic fuels such as D-^{3}He, and to collect fusion power efficiently at low overall power density.

Two systems are currently being investigated within MFE at the next level of development, Proof of Principle. These are the Spherical Torus and the Reversed Field Pinch. The Spherical Torus is the low-aspect ratio limit of the tokamak, in which the central doughnut hole is minimized. This configuration offers very high β_t, the ratio of the plasma pressure to the applied toroidal magnetic field pressure. As a result it can employ rather low magnetic fields, with the result that the potential impacts of plasma "disruptions" are reduced, and the magnets can be made simpler. The slender center column of such a system can be removed easily for maintenance, providing simpler access to the core of the system. This system is a possible candidate for use as a Component Test Facility (see below). Its application to Demo would require minimization of the recirculating power needed to maintain the electric current in the copper center column. The other system under investigation, the Reversed Field Pinch, is similar to a tokamak, but with a very low toroidal magnetic field. Recent experiments have shown transient techniques to stabilize the magnetic turbulence in such systems, giving tokamak-like confinement. If long-pulse approaches to turbulence stabilization can be devised, this approach could lead to significantly less expensive fusion systems. A third system has been approved by FESAC for Proof of Principle, the Compact Stellarator, and is currently under construction. It is similar in many ways to the advanced tokamak, but uses complex asymmetric magnetic coils to provide stability and confinement. This system does not require external drive to maintain its magnetic configuration, as does the tokamak, and is experimentally found to disrupt only under very unusual circumstances. Through the exploitation of a new form of underlying symmetry this system is calculated to combine the high power density of a tokamak with the stability and steady-state features of stellarators, thus potentially providing improvements in all three key areas: reliability, mass power density and recirculating power.

MFE Performance Extension (PE) Experiments

The next level of development beyond Proof of Principle is Performance Extension (PE). At this level configurations are tested at more fusion-like plasma conditions. While there are PE-class stellarators in construction and operation abroad, the only PE devices in the US are tokamaks. These devices are productive experiments providing critical results for the final design and then operation of a burning plasma experiment. Examples include control and amelioration of instabilities that limit the achievable fusion power density or potentially damage the plasma facing components; and disruption avoidance and mitigation. Many experiments worldwide routinely obtain similar operating regimes with energy confinement scaling meeting the needs of a burning plasma experiment. Progress in fundamental understanding of plasma transport and stability has improved our confidence in extrapolating present results to future devices. In addition PE-class tokamaks have a strong focus on developing the improved performance operating mode called "Advanced Tokamak" operation. Desirable features are steady-state operation with a high fraction of self-generated current, to reduce recirculating power, and increased pressure limits to increase fusion power density. These will be accomplished largely through active control of current, transport and pressure profiles. This mode offers the potential to resolve key issues facing the tokamak, allowing it to progress confidently to the CTF and/or Demo stage.

Existing PE tokamaks are making good progress in studying key aspects of the advanced regimes for limited durations, in parallel with efforts to mitigate the impact and frequency of plasma disruptions. Major new international facilities in China, Japan and Korea are being designed and constructed to demonstrate advanced performance in steady-state for plasmas with minimal self-heating. It is a major challenge to achieve simultaneously all desirable features with high reliability, which is a necessary step for the tokamak to proceed to a Demo.

In the period before Demo it is anticipated that one or more of the configurations currently at the Proof-of-Principle stage could graduate to Performance Extension. It should not be excluded even that an attractive configuration currently at the Concept Exploration stage could advance rapidly. Together with results from a burning plasma, and advanced computation, a successful Performance Extension experiment could allow Demo to take on a configuration different from the advanced tokamak.

IFE Concept Exploration / Proof of Principle Experiments

Smaller scale experiments evaluate selected scientific and technical feasibility issues for promising IFE approaches. Current experiments in this category include the Electra krypton fluoride (KrF) laser, the Mercury diode pumped solid-state laser (DPSSL), a set of high-current heavy-ion beam experiments that address three key aspects of a heavy-ion accelerator-injection (Source Test Stand), transport (High Current Experiment) and focusing (Neutralized Transport Experiment). For heavy ions, an Integrated Beam Experiment (IBX) that in effect combines the current set of three beam experiments is required before a heavy-ion Integrated Research Experiment (IRE, see discussion below). For z-Pinch IFE, following present experiments to test the recyclable transmission line (RTL) concept on the Saturn z-pinch facility, a set of experiments (RTL optimization, rep-rated pulsed power, blast mitigation, scaled RTL cycle) is required before a z-pinch IRE. There are concept-exploration level experiments on the physics of fast ignition being carried out by US researchers on the Gekko-XII laser facility in Japan, the LULI laser facility in France, and on the Vulcan laser facility in the Rutherford-Appleton Laboratory in the UK. Also hemispherical capsule compression experiments for the fast ignition approach are being carried out on Z.

To qualify for the IRE level, each IFE approach must (a) resolve key proof-of-principle driver issues (efficiency, reliability, focusability, cost) that are specific to each approach, (b) have adequate gain IFE target designs with 2-D hydrostability for plausible beam non-uniformities, (c) show plausible pathways for target fabrication and injection or placement, (d) have a chamber design concept that is self-consistent with target illumination geometry, final focus and beam propagation or RTL placement, chamber clearing, and adequate lifetime. Target physics experiments relevant to (b) are currently being carried out on Omega, Nike and Z. Target fabrication/injection R&D is carried out leveraging existing NNSA target R&D facilities, plus a new target injection experiment, for both direct and indirect drive targets. Universities carry out a number of small scale chamber experiments to benchmark models for both liquid and dry wall chamber concepts, and IFE materials testing is being performed on Z (for x-rays) and on RHEPP (for ions).

IFE Integrated Research Experiments (IREs)

Integrated Research Experiments (IREs) are non-nuclear facilities for qualifying approaches to IFE whose objective is to validate driver and chamber technologies required for an Engineering Test Facility (ETF). Both full scale and subscale components are tested in the IRE programs, which are designed to ensure that key driver, chamber and target components can work together with the required efficiency, pulse-rate, durability and precision, and at costs that scale to economical fusion energy. The IRE programs, together with target physics results from the National Ignition Facility (NIF), Omega, and Z, are to provide the scientific and technical basis for the Engineering Test Facility (ETF, see below). Initial megajoule-class implosion results from the NIF are expected at about the earliest time that a construction decision would be required for an IRE. Current research focuses on three approaches: (1) krypton-fluoride (KrF) or diode-pumped solid state (DPSSL) laser drivers with direct-drive targets and dry-wall chambers, (2) heavy ion accelerator driver with X-ray indirect-drive targets and thick-liquid protected chambers, and (3) z-pinch driver with X-ray indirect-drive targets and thick-liquid protected chambers. Fast ignition, if successful, may enhance the gain of either direct-drive or indirect-drive targets, and may relax driver requirements in each approach.

To qualify an ETF, each IRE program must resolve the key issues that enable an ETF: for the laser approaches – laser efficiency, durability, cost and beam quality, target fabrication and injection, first chamber wall materials and protection, and final optics durability; for the heavy ion approach – focal spot size under fusion chamber relevant conditions, accelerator cost, target fabrication, thick liquid protected chambers with target material recovery and focus magnet lifetime; for the z-pinch approach – economical

RTLs, blast mitigation effects for the first wall, rep-rated pulsed power, target fabrication, and thick liquid protected chambers with target material recovery. In addition to these IRE outputs, the ETF would require adequate target physics data from NIF and other ICF facilities on implosion symmetry and capsule/fuel layer smoothness, and high confidence 3D calculations for IFE targets, validated with data from NIF, Omega, and Z.

3) *Burning plasma*

Burning plasma experiments are required in order to provide understanding of the physics of self-heated plasmas. In both MFE and IFE a burning plasma experiment will contribute basic physics information of relevance to a range of fusion configurations.

The world effort to develop fusion energy is at the threshold of a new stage in its research: the investigation of burning plasmas. This investigation, at the frontier of the physics of complex systems, would be a dramatic step in establishing the potential of fusion energy to contribute to the world's energy security.

The defining feature of a burning plasma is that it is self-heated: the 100 million degree temperature of the plasma is maintained mainly by the heat generated by the fusion reactions themselves, as occurs in burning stars. The fusion-generated alpha particles produce new physical phenomena that are strongly coupled together as a nonlinear complex system. Understanding all elements of this system poses a major challenge to fundamental plasma physics. The technology needed to produce and control a burning plasma presents challenges in engineering science largely along the path to the development of fusion energy.

MFE Burning Plasma

A burning plasma is a crucial and missing element in the world magnetic fusion program. The defining feature of a burning plasma is that it is sustained primarily by the heat generated through its own internal fusion reactions. This is in contrast to previous experiments in which most of the heating was applied from outside the plasma. When these reactions occur in a fusion power system, energetic alpha particles (helium nuclei) and neutrons are generated. The alpha particles are confined by the magnetic field and slow down, transferring their energy to maintain the high temperature of the plasma. When fusion alpha heating dominates the plasma dynamics, important new scientific frontiers will be crossed. To create a burning plasma on Earth and systematically determine its properties will be an enormous step forward for fusion energy research. It will enable major advances in all of the key areas of plasma science and technology, and contribute to the demonstration of magnetic fusion as a source of practical energy. While delivering the fusion-sustaining heat, the alpha particles also represent a new dynamic source of energy to change the plasma pressure profile. Such changes in the plasma structure and dynamics can increase the loss of heat and particles from the plasma, and consequently lead to a reduction in fusion power. Alternatively, these changes may lead to a further increase in temperature and fusion power production. Understanding and controlling these effects on heat and particle transport, the subject of "burn control," are essential elements of power plant development.

For MFE the burning plasma is planned to be either ITER or FIRE, as described by FESAC. The US is considering two different options for a burning plasma experiment because ITER and FIRE are each an attractive option for the study of burning plasma science. Each could serve as the primary burning plasma facility, although they lead to different fusion energy development paths. Both devices are designed to achieve their technical goals on the basis of conventional pulsed tokamak physics, but have capability to investigate advanced tokamak modes of operation. In the ITER case, the capability for long pulse and steady-state operation is provided. Moreover, a substantial amount of fusion technology development and testing is provided as well. In the FIRE case an additional high-performance (but non-burning) steady-state experiment would be required in parallel.

For the purpose of this Preliminary Report, given the limited time available, the Panel has analyzed only the development path that incorporates ITER as the burning plasma element. This development path is chosen as an illustration of a plan for fusion energy, motivated in part by the statement of the Snowmass fusion summer study that "Assuming a successful outcome (demonstration of high-performance advanced tokamak burning plasma) an ITER-based development path would lead the to the shortest development time to a demonstration power plant." The Final Report will evaluate both ITER-based and FIRE-based development paths, consistent with the FESAC recommendation that both options are attractive.

IFE Burning Plasma

The National Ignition Facility (NIF), a National Nuclear Security Administration (NNSA) facility scheduled for completion in 2008, is tasked with achieving thermonuclear ignition. The NIF experimental program will begin soon after first light with the first 4 beams, which is currently expected toward the end of FY03. As more beams are added, increasingly complex target experiments will be possible. By the end of FY07 it should be possible to begin high quality symmetry experiments in support of ignition. The full capability of NIF for ignition experiments is planned to be available at the end of FY08.

NIF will be capable of testing a variety of ignition target approaches. In all IFE targets the fusion fuel is compressed before it is ignited. There are two broad methods of compression and two methods of ignition. The fuel is compressed either through an implosion driven directly by the driver beams (direct drive) or by converting the driver energy to x rays that then drive the implosion (indirect drive). The two classes of ignition are central hot-spot ignition and fast ignition. In hot-spot ignition, the implosion both compresses and heats a hot spot in the center of the fuel. This spot ignites and subsequently burns the rest of the fuel. These target designs are the most mature. In fast ignition, the target is compressed by one driver, and a spark is ignited by a separate, very high intensity source such as a short pulse laser. Fast ignition could be used with any of the main driver concepts.

NIF will initially be configured for indirect drive with hot spot ignition, and can later be configured for direct drive. With the development of new technology, it could also be configured for fast ignition. Although NIF will be carrying out laser driven ignition experiments, much of the physics is applicable to targets imploded with other drivers. This is particularly true for indirect drive where almost all the physics, except the process of x-ray generation, applies to targets imploded with ion beams or Z-pinch pulsed power drivers. In addition to NIF, over the next decade, critical physics data for ignition physics including fast ignition will be provided by other NNSA facilities (Omega, Nike and Z) as well as international facilities.

NIF employs a flash-lamp pumped glass laser which is quite flexible as a research facility, but is designed only to explore single-shot target physics. Hence the NIF will provide relatively little information on the repetitive high average power driver or chamber technology required for IFE, although some specific data, *e.g.,* on debris creation, will be relevant.

4) *Materials*

Materials Science / Development

The neutrons produced by fusion reactions, which are more energetic than those produced by nuclear fission, lead to unique damage problems for the materials surrounding the fusing plasma. The development of advanced materials is required for MFE and for the IFE development pathways that do not make use of a thick liquid wall, and even in the latter case some materials development and testing will be required. Accelerated lifetime testing of materials to be used in a fusion power plant must be available in order to have confidence in the materials employed for Demo.

One of the main technical challenges for the successful development of fusion energy is the development and qualification of materials for the first wall, high heat flux components, breeding blanket components, and various special purpose materials (optical materials, insulators, mirrors, etc.). The overarching goals of the fusion materials R&D program are 1) to establish the technical and economic feasibility of environmentally attractive fusion energy systems, and 2) to improve the attractiveness of fusion energy by utilization of improved, innovative materials systems.

Due to the wide range of performance requirements for the various individual materials needed in diverse assemblies in a fusion power plant, a broad-based R&D program is required to guide power plant design and provide key input for integrated component tests. The final product is the validated database (and associated knowledge base) required for Demo approval decisions. At the present time there are over ten different fusion power conversion (blanket) concepts that have been identified as viable candidates for MFE and IFE. The underlying knowledge base from the fusion materials R&D effort will be key in the initial down-selection to a handful of the most promising concepts. The R&D program must include both non-irradiation and irradiation tests, along with underlying theory and modeling that guide the interpretation and extrapolation of experimental results. Both structural and non-structural materials systems must be examined, as well as chemical compatibility issues. The performance capabilities of irradiated materials will largely determine the allowable temperature (and therefore thermodynamic efficiency, which directly affects cost of electricity), power density, and lifetime. Utilization of high-performance radiation-resistant reduced activation materials can significantly improve the safety aspects and waste disposal burden of fusion power plants.

The time scale to develop fully a new material for commercial use is typically well over 10 years. An enhanced, sustained and focused materials research program is essential to meet the specialized materials needs of the demanding environment in Demo 35 years from now. The most promising materials systems would be subjected to integrated component testing.

International Fusion Materials Irradiation Facility (IFMIF)

Since the development and qualification of radiation-resistant structural materials that can survive exposures to >10 MW yr/m^2 (essential for the technological viability of fusion) is considered to be the most challenging and schedule-controlling materials issue, a dedicated intense fusion neutron source is needed early in the 35 year fusion development path.

Fundamental experimental and modeling studies performed over the past 20 years have established that most of the key atomic displacement features for DT fusion neutrons interacting with materials are similar to those found with fission neutrons. This validates much of the fission test reactor database as a valuable initial screening tool for evaluating the radiation stability of fusion materials. However the higher production of transmutation products such as H and He by energetic fusion neutrons is predicted to have significant influence on the microstructural stability of materials for fluences above ~0.5 – 1 MW yr/m^2 (~5 – 10 displacements per atom). Therefore an intense high-energy neutron source is an essential facility for development and qualification of the materials of the first wall, plasma facing components, and breeding blanket components of Demo concepts that do not utilize a thick liquid wall. International assessments have concluded that the minimum requirements for this facility include: $\geq$0.5 liter volume with $\geq$2 MW/m^2 equivalent neutron flux to enable accelerated testing up to at least 10 MW yr/m^2 (and larger volumes at lower neutron fluences), availability $\geq$70%, and flux gradients $\leq$20%/cm. International assessments have concluded an accelerator-driven D-Li stripping neutron source, with two 125 mA deuteron beams of 40 MeV energy focused onto a flowing Li target (5 x 20 cm beam footprint) would meet the requirements. The international conceptual design of such a facility, called the International Fusion Materials Irradiation Facility is now complete, with a stage of engineering validation required before engineering design can commence. In order to obtain the required information for the design of a Demo reactor that would operate in 2037, this engineering validation phase should be entered expeditiously and engineering design should begin with five years.

5) Engineering Science / Technology Development

Plasma Technologies

It is important to recognize that there is an ongoing need for enabling plasma technologies to support the configuration optimization experiments at all levels as well as the burning plasma and component testing stages. Continued innovation and long-term development for Demo are required as well.

The development of the technological tools to heat, fuel and control high-temperature plasmas has been crucial to progress in plasma science. Next generation confinement devices will need improved tools such as more efficient plasma heating systems, more robust in-vessel components (*e.g.,* RF antennas), high-throughput fueling systems, plasma facing components able to withstand higher heat and particle fluxes and improved and less expensive magnets. The development of the plasma technologies proceeds hand-in-hand with plasma confinement improvements. Burning plasma devices in particular carry plasma technologies into the scale required for fusion energy systems and require the development of plasma technologies that will function in a fusion environment.

Fusion Chamber and Power Technologies

The fusion chamber is the core of the fusion power plant that surrounds the plasma in MFE (or the target in IFE) and includes the blanket and plasma facing components that must breed the tritium fuel and convert the high fluxes of neutrons and alpha power from the fusion reaction into high grade heat. The goal of the Chamber Technology Program is to develop the technologies required to attain tritium self sufficiency, operate at high temperatures to achieve high thermodynamic efficiency, and provide the particle pumping, impurity control and vacuum conditions necessary for stable plasma operation. High performance, safety, reliability, and maintainability are key objectives of the program as they are fundamental to the development of attractive fusion energy systems.

Several concepts for the chamber are being pursued in the US, Japan and Europe. The lithium-containing tritium breeder can be a liquid metal, ceramic, or molten salt. Liquid metals, molten salts and helium are options for cooling. Ferritic steels, vanadium alloys and SiC/SiC composites are options for structural materials. Beryllium is required as a neutron multiplier in most concepts. Tungsten, tantalum, molybdenum and copper are options for the plasma facing components. The chamber may also include a variety of electric and thermal insulators and tritium permeation barriers. All these concepts have some common and many widely different feasibility and attractiveness issues that must be addressed in an extensive R&D program.

Key issues include sufficient tritium breeding in a highly heterogonous system, in-situ tritium release and recovery, tritium containment, thermomechanical loadings and responses, MHD effects, integrity of insulators and structure, materials interactions, synergistic effects, resistance to off-normal events, failure modes, effects and rates, and rapid remote maintenance. Interestingly, promising new concepts for MFE chambers, based on flowing liquid metals along the chamber walls, have emerged based on interactions with the IFE community.

The R&D program includes developing phenomenological and computational models; exploring design options with emphasis on innovation, fundamental understanding, and comprehensive engineering analysis. Experiments in laboratory scale non-neutron test stands, fission reactors, and accelerator-based neutron sources are able to simulate single effect phenomena and a limited number of multiple effect phenomena. Hence they are useful in narrowing material and design concept options but they cannot establish the engineering feasibility of the fusion chamber for Demo. Testing in the fusion environment is required.

A fusion chamber must operate under intense fluxes of neutrons, surface heat loads, and particles, mechanical and electrical forces, and, for MFE, magnetic fields.. There are large gradients in the loading conditions and responses (e.g. radiation field, magnetic field, nuclear heating, temperature, stress, atomic displacement, tritium concentration) that make numerical and experimental simulations challenging. Synergistic effects due to combined environmental conditions (neutron / magnetic / electrical / thermomechanical / chemical interactions) and interactions among the physical elements of the chamber components (*e.g*. tritium producer / multiplier / structure / coolant / insulators) result in new phenomena unique to the fusion environment. Such new interactive phenomena and synergistic effects require testing in the fusion environment. Multiple interaction and integrated tests in the fusion environment are necessary to resolve the key issues, establish the engineering feasibility, select the most promising concept, and to improve the performance, safety, reliability, and maintainability toward an attractive and competitive fusion energy system.

For heavy-ion and z-pinch IFE (and possibly some MFE configurations), the primary approach is thick liquid wall concept, in which about 1m of lithium containing molten salt (FLiBe) is formed around the target cavity. Liquid walls allow high heat and neutron fluxes and do not experience permanent deformation in the intense radiation field. Most materials are located behind the thick liquid in a lower radiation field environment where they may last the lifetime of the plant and long-term radioactivity is low even for currently available austenic stainless steels. Fission tests may suffice to determine the neutron-damage lifetime of such structures.

The key issues for the thick liquid wall concept are fluid hydrodynamics (including shock mitigation), reliable operation of the oscillating nozzles used to form the liquid wall and vapor condensation and chamber clearing. These issues can be largely resolved by computational modeling and testing in low-cost laboratory experiments. Final validation of the concept will be performed in the integrated fusion environment of the ETF.

The dry wall chamber concept for laser IFE has similarities to those considered for MFE. Many of the key issues are similar, except for the absence of magnetic field interactions and the presence of pulsed x-ray, heat, neutron and debris-ion effects.

MFE Component Test Facility (CTF)

For MFE, the Component Test Facility, CTF, is an experimental DT-fusion facility which is to provide a fusion environment for affordable testing, optimization, and qualification of prototypes of fusion chamber subsystems for Demo, including first wall / blanket modules that both breed tritium and convert fusion power to high-grade heat, plasma-interactive and high-heat-flux components such as the divertor, and tritium processing and remote maintenance systems. The facility's concept is optimized to provide high neutron wall load and fluence at minimum overall fusion power in order to enable integrated testing and optimization of a series of components at minimum tritium consumption and overall cost.

The CTF will enable a Demo with performance sufficiently attractive to motivate rapid deployment of fusion as a commercial energy source. A development path with a CTF provides a significant competitive advantage over development paths that perform component testing on Demo, because the flexibility of the smaller, lower power facility enables more rapid and broader-ranging prototyping. The facility must enable testing at a neutron wall load of $1MW/m^2$ and cumulative neutron fluence greater than 6MW years/m^2 over a testing area greater than 10 m^2 and volume greater than 5 m^3, with duty cycle greater than 80%, and overall availability above 30%. To enable cost-effective operation with affordable tritium consumption, the facility is optimized for minimum size and fusion power (~150MW) and would likely be operated in a driven mode. In later stages, the facility may achieve a tritium-breeding ratio sufficient for the facility to be a supplier of tritium for the start-up of Demo, and could also achieve higher output power, potentially even leading to net electric production. Candidate concepts for the facility include the steady-state tokamak, the spherical torus and the gas-dynamic trap. High power density and high availability are challenging metrics for the success of the CTF.

CTF will be a full nuclear facility, and the decision to take this step will depend upon success in the initial phases of the burning plasma experiment and the development of an attractive cost-effective configuration for this device.

IFE Engineering Test Facility (ETF)

The ETF, or Engineering Test Facility, is the final step in the development of inertial fusion energy before building the DEMO. It may be capable of generating net electrical power at low levels (between 100 and 300 MW) and low availability. The ETF will have operational flexibility and will carry out three major functions:

1. Demonstrate and integrate a near full scale driver.
2. Optimize targets for high yield. It is anticipated that NIF will map out parts of the gain curve, but will not provide the required data to optimize targets for IFE.

3. Test, develop, and optimize the chamber configuration in a full nuclear environment. This includes the first wall and blanket, tritium breeding, tritium recovery, and thermal management.

For Tasks 1 and 2 the ETF will need a driver, and final optics/power focusing system for lasers or heavy ions, or recyclable transmission line (RTL) for z-pinches, that is roughly on the same scale as that needed for the DEMO. The ETF will have a target factory and target injection/placement system that is capable of producing and injecting full targets on a repetitive (5-10 Hz) long-term basis for lasers or heavy ions, or on a repetitive (0.1 Hz/chamber) long term basis for z-pinches. These are expensive components, and it is anticipated they will be carried over to the Demo with little modification, although technological development may provide improved options. For Task 3 (chamber optimization) the ETF will use reduced yield targets (about 1/4 to 1/9 full yield), and a chamber that is about 1/2 to 1/3 the linear dimension expected for DEMO. This keeps the wall loading at power plant levels, but reduces the total fusion power in the system, which in turn lowers development costs as well as minimizes heat transfer and tritium handling issues. At this point IFE would be ready to proceed to the DEMO phase. Under some approaches the DEMO might only require the addition of an advanced chamber to the ETF. It is recognized that the ETF is a major step. It is a full nuclear facility of a scale comparable to Demo and at most one IFE concept will be carried to this phase.

6) Demo

The US fusion demonstration power plant (Demo) is the last step before commercialization of a fusion concept. It must open the way to rapid commercialization of fusion power, if fusion is to have the desired impact on the world energy system. Demo is built and operated in order to assure the user community (*i.e.,* general public, power producers, and industry) that fusion is ready to enter the commercial arena. As such, Demo represents the transition from a laboratory experiment to a field-operated commercial system. Demo must provide energy producers with the confidence to invest in commercial fusion as their next generation power plant, *i.e.,* demonstrate that fusion is affordable, reliable, profitable, and meets public acceptance. Demo must also convince public and government agencies that fusion is secure, safe, has a low environmental impact, and does not deplete limited natural resources. In addition, Demo must operate reliably and safely on the power grid for long periods of times (*i.e.,* years) so that power producers and industry gain operational experience and public are convinced that fusion is a “good neighbor.” To instill this level of confidence in both the investor and the public, Demo must achieve high standards in safety, low environmental impact, reliability, and economics. Table 1 presents the top-level goals for the US Demo.

Table 1: Top-level goals for the US fusion Demo

Safety and environmental impact:

1. Not require an evacuation plan
2. Generate only low-level waste
3. Not disturb the public's day-to-day activities
4. Not expose workers to a higher risk that other power plants.
5. Demonstrate a closed tritium fuel cycle

Economics:

6. Demonstrate that the cost of electricity from a commercial fusion power plant will be competitive, and that other applications such as hydrogen production are also attractive.

Scalability:

7. Use the physics and technology anticipated for the first generation of commercial power plants
8. Be of sufficient size for confident scalability (>50%-75% of commercial)

Reliability

9. Demonstrate robotic or remote maintenance of fusion core
10. Demonstrate routine operation with minimum number of unscheduled shutdowns per year
11. Ultimately achieve an availability > 50% and extrapolate to commercially practical levels.

To provide consistent focus and integration of the program elements of this plan toward the end goal, the Demo, systems analysis and design studies of possible power plants must be carried out continuously. The designs, maintained current with the progress of the various program elements of this plan, provide guidance to the overall program.

Appendix B: Charge Letter

September 10, 2002

Professor Richard D. Hazeltine, Chair
Fusion Energy Sciences Advisory Committee
Institute for Fusion Studies
University of Texas at Austin
Austin, TX 78712

Dear Professor Hazeltine:

I would like the Fusion Energy Sciences Advisory Committee (FESAC) to comment, from our present state of understanding of fusion, on the prospects and practicability of electricity into the U.S. grid from fusion in 35 years.

In addition, I would like FESAC to develop a plan with the end goal of the start of operation of a demonstration power plant in approximately 35 years. The plan should recognize the capabilities of all fusion facilities around the world, and include both magnetic fusion energy (MFE) and inertial fusion energy (IFE), as both MFE and IFE provide major opportunities for moving forward with fusion energy.

The report would be most helpful if it could be done in two phases. Building as much as possible on previous work of FESAC, the first phase would be a preliminary report, completed by December 1, 2002, which would both provide a general plan to achieve the aforementioned goal and identify those significant issues that deserve immediate attention. As a second phase, I would like by March 2003, or earlier, a more detailed plan upon which budgeting exercises can be based. This detailed plan would be most useful if it:

- Identifies all important technical and scientific issues, the tasks that would lead to their resolution, and the sequence in which these tasks should be accomplished in order to reach the program goal most effectively;

- Identifies specifically all of the major facilities needed to support the tasks, and provides the mission and approximate cost of each facility;

- Provides a set of general performance measures by which the progress toward the accomplishment of the tasks and/or the mission of related facilities can be measure;

- Identifies key decision points where choices can be made among the various concepts and technologies being pursued; and

- To the extent possible, an estimate of the overall cost of such a plan, and optimum funding scenario(s).

These are historic times for the fusion program, and the work of FESAC will help ensure that the policy issues before us are fully informed.

Sincerely,

Raymond L. Orbach
Director
Office of Science

Appendix C: Processes used by the Panel

October 3-4.
A panel, Appendix B, was set up by FESAC. It held its first meeting at PPPL on October 3-4 and discussed the approach to preparing the reports including the key factors determining the timeline for electricity generation and how best to obtain fusion community input. A first attempt was made at identifying the key factors which could affect the logic and timeline for electricity production in a Demo power plant for both IFE and MFE. A preliminary definition of a Demo was made.

It was noted that there was a very short time available to prepare the Preliminary Report. Therefore the Panel determined to concentrate its efforts in preparing the Preliminary Report on the key factors which affect the logic and timeline, and determined that it was not practical to hold a large community meeting before the completion of the Preliminary Report. A more complete analysis, including all of the items requested in the Charge letter, along with broader community input, will be undertaken in preparation for the Final Report. It was agreed to hold a meeting to obtain input on the key factors, then to complete the Preliminary Report and to start preparation of the Final Report.

October 28-30.
A Panel meeting was held at LLNL on October 28-30 first to hear from experts on some of the key factors determining the logic and timeline and then to prepare drafts of Preliminary Report sections. European and Japanese views on the fusion development path were provided as well.

November 11-12.
Public meetings were held at the American Physical Society, Division of Plasma Physics meeting during November 11 – 12 to inform the fusion community about the Panel's progress in preparing the Preliminary Report and to obtain input. These meetings were held in association with the University Fusion Association annual meeting and at a general discussion of the Snowmass and FESAC processes. Input was also received through a publicly announced email reflector: devpath@pppl.gov. Very valuable input was obtained and taken into account in this report.

November 15-16.
The Panel met at the end of the APS Division of Plasma Physics meeting (November 15-16) to complete the Preliminary Report, and made final refinements in the following few days. Public comment was received on the morning of November 15. The report was submitted to FESAC on November 21.

November 25-26.
FESAC meeting in Gaithersburg which will review Preliminary Report.

January 13-16.
An open meeting will be held at General Atomics on January 13-14, followed by a Panel meeting on January 15-16. This meeting will allow detailed discussion of all aspects of the

MFE and IFE development path with members of the fusion community. The Panel will welcome written input as well.

Further steps and processes remain to be defined.

Appendix D: Panel Membership

Professor Mohamed Abdou, University of California, Los Angeles

Dr. Charles Baker, University of California, San Diego

Mr. Michael Campbell, General Atomics

Dr. Vincent Chan, General Atomics

Dr. Stephen Dean, Fusion Power Associates

Professor Robert Goldston (Chair), Princeton Plasma Physics Laboratory

Dr. Amanda Hubbard, MIT Plasma Science and Fusion Center

Dr. Robert Iotti, CH2M Hill

Professor Thomas Jarboe, University of Washington

Dr. John Lindl, Lawrence Livermore National Laboratory

Dr. Grant Logan, Lawrence Berkeley National Laboratory

Dr. Kathryn McCarthy, Idaho National Engineering and Environmental Laboratory

Professor Farrokh Najmabadi, University of California, San Diego

Dr. Craig Olson, Sandia National Laboratory, New Mexico

Professor Stewart Prager, University of Wisconsin

Dr. Ned Sauthoff, Princeton Plasma Physics Laboratory

Dr. John Sethian, Naval Research Laboratory

Dr. John Sheffield, ORNL – UT Joint Institute for Energy and Environment

Dr. Steven Zinkle, Oak Ridge National Laboratory

Appendix E: Glossary

Advanced Tokamak (AT): A tokamak operating mode currently under investigation which depends predominantly on the self-sustained "bootstrap" current to provide steady-state operation and on feedback stabilization to allow high plasma pressure.

Compact Stellarator (CS): A new MFE configuration that is designed to achieve the favorable features of the stellarator in a more compact configuration.

Component Test Facility (CTF): A small steady state MFE fusion facility to test components at neutron fluxes representative of first-wall values in fusion power systems. Could be funded internationally.

Configuration Exploration (CE): Experiments in both MFE and IFE that provide initial investigation of a new fusion configuration.

Demo: A demonstration fusion power plant. Likely several Demo's will be built around the world.

Diode Pumped Solid State Laser (DPPSL): One of the candidate laser IFE drivers. DPPSLs are solid state lasers that use high intensity diodes to pump the laser crystal medium.

Direct Drive: The pellet is compressed directly by the driver beams. This is the current choice for laser IFE.

Driver: The source of intense, pulsed energy used to compress and heat an IFE target. Current driver choices are lasers, heavy ions, or z-pinches.

Dry Wall IFE: Use of a solid wall to protect the chamber in IFE. These chambers may contain gas to protect the wall from x-rays, charged particles, and target debris. This is the favored approach for laser IFE.

Engineering Test Facility (ETF): The last component in the IFE development path before Demo. The ETF will demonstrate and integrate a near full scale driver, will be used to optimize targets for high yield, and will develop and evaluate chamber configurations.

Fast Ignition: An IFE target is compressed by one driver, and a spark is ignited by a separate very high intensity source such as a short pulse laser, eliminating the need for hot-spot formation.

Fusion Ignition Research Experiment (FIRE): A copper-coil burning MFE plasma physics facility, to be funded primarily nationally if the US does not participate in ITER.

Heavy Ion Beams: One of the three driver choices for IFE. High current beams of low charge state ions are accelerated to high energies and focused onto an IFE target.

High Average Power Laser Program (HAPL): The enabling technology Proof-of-Principle program for laser IFE. Includes development of lasers, target fabrication and injection, final optics, and chamber concepts and materials.

Hohlraum: The hohlraum, which is heated by a driver, is an "oven" that bathes a target symmetrically in x-rays. Used in indirect drive IFE targets.

Hot Spot Ignition: The IFE target implosion both compresses and heats a hot spot in the center of the fuel. This hot spot ignites and initiates a propagating burn.

Indirect Drive: The IFE capsule containing DT is imploded by x-rays in a hohlraum. This is the current choice for heavy ion IFE and for z-pinch IFE

Integrated Beam Experiment (IBX): A proof-of-principle class facility designed to perform an integrated test of heavy ion beam physics for IFE from formation to placement on target.

Integrated Research Experiments (IREs): One or more facilities which demonstrate that key driver, chamber and target components can work together with the efficiency, durability and precision required for inertial fusion energy.

International Fusion Materials Irradiation Facility (IFMIF): Accelerator-based energetic neutron source for testing material samples at fluxes close to first-wall values in fusion power systems, to be funded internationally.

International Thermonuclear Experimental Reactor (ITER): A long-pulse MFE burning plasma physics and engineering test facility, to be funded internationally.

Krypton fluoride (KrF) laser: One of the candidate laser IFE drivers. KrF is a gas laser medium that is pumped by electron beams.

National Ignition Facility (NIF): A large glass laser facility currently under construction. This NNSA facility is tasked with achieving thermonuclear ignition using laser-compressed targets.

Nike: A krypton fluoride laser that accelerates planar targets to study the physics of direct-drive IFE.

NNSA: National Nuclear Security Agency. The Department of Energy Agency that is responsible for maintaining and securing the nuclear stockpile. The Agency's mission includes the goal of achieving fusion ignition by inertial confinement in the laboratory.

Omega: Omega is a glass laser capable of spherical implosions to study direct-drive inertial confinement.

Performance Extension (PE): Experiments in MFE that study a fusion configuration at near-fusion parameters.

Proof of Principle (PoP): Experiments in MFE and IFE that study a fusion configuration in an integrated manner.

Recyclable Transmission Line (RTL): For z-pinch IFE, a low-mass transmission line structure conducts current from the pulsed power driver to the z-pinch load. In operation, an RTL is vaporized and the materials are recycled to make subsequent RTLs.

Repetitive High Energy Pulsed Power (RHEPP): A repetitive pulsed power source. For IFE, RHEPP is configured to produce high energy ions that mimic the emissions from a fusion target, to evaluate the effect of such ions on candidate wall materials.

Reversed Field Pinch (RFP): A toroidal MFE configuration with a very low magnetic field the long away around the torus, leading to the potential for low-cost magnets in a fusion power plant.

Spherical Torus (ST): A toroidal MFE configuration in which the hole in the center of the doughnut is shrunken nearly to zero, resulting in capability to sustain relatively high plasma pressures and so fusion power density at a given magnetic field.

Stellarator: A toroidal MFE configuration whose cross-sectional shape varies around the torus, allowing disruption-free operation and no need for external sustainment of plasma current.

Target: For laser direct-drive IFE, the DT capsule; for heavy ion and z-pinch IFE, a hohlraum containing a DT capsule.

Tokamak: An axisymmetric toroidal MFE system with a much stronger magnetic field directed around the torus the long way than the short way. Conventional tokamaks have a ratio of the major to the minor radius of ~ 3, The tokamak is the most developed MFE configuration, and is prepared for testing in a burning plasma.

Z: A large z-pinch machine that produces intense, energetic pulses of x-rays. The primary role for "Z" in IFE is to investigate indirect drive. The Z-machine is also used to evaluate the response of candidate wall materials to x-rays.

Z-pinch: One of the three driver choices for IFE. It delivers a large electrical current to an annular wire array, gas puff, or foil that becomes a plasma and collapses radially under its self-magnetic forces. When the plasma stagnates on axis, the kinetic energy is converted into an intense x-ray burst.