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A Plan for the Development of Fusion Energy

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This is the final report of a panel set up by the U.S. Department of Energy (DOE) Fusion Energy Sciences Advisory Committee (FESAC) in response to a charge letter dated September 10, 2002 from Dr. Ray Orbach, Director of the DOE's Office of Science. In that letter, Dr. Orbach asked FESAC to develop a plan with the end goal of the start of operation of a demonstration power plant in approximately 35 years. This report, submitted March 5, 2003, presents such a plan, leading to commercial application of fusion energy by mid-century. The plan is derived from the necessary features of a demonstration fusion power plant and from the time scale defined by President Bush. It identifies critical milestones, key decision points, needed major facilities and required budgets. The report also responds to a request from DOE to FESAC to describe what new or upgraded fusion facilities will "best serve our purposes" over a time frame of the next twenty years.

KEY WORDS: Fusion energy, fusion program plan.

"*This [progress in fusion science] is an enormous change that is enough to change the attitudes of nations toward the investments required to bring fusion devices into practical application and power generation.*"
Presidential Science Advisor John Marburger.

"*By the time our young children reach middle age, fusion may begin to deliver energy independence. . . and energy abundance. . . to all nations rich and poor. Fusion is a promise for the future we must not ignore. But let me be clear, our decision to join ITER in no way means a lesser role for the fusion programs we undertake here at home. It is imperative that we maintain and enhance our strong domestic research program. . . . Critical science needs to be done in the U.S., in parallel with ITER, to strengthen our competitive position in fusion technology.*"
Secretary of Energy, Spencer Abraham

"*The results of ITER will advance the effort to produce clean, safe, renewable, and commercially-available fusion energy by the middle of this century. Commercialization of fusion has the potential to dramatically improve America's energy security while significantly reducing air pollution and emissions of greenhouse gases.*"
President George W. Bush

EXECUTIVE SUMMARY

This report presents a plan for the deployment of a fusion demonstration power plant within 35 years,

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leading to commercial application of fusion energy by mid-century. The plan is derived from the necessary features of a demonstration fusion power plant and from the time scale defined by President Bush. It identifies critical milestones, key decision points, needed major facilities and required budgets.

Recent Advances and Anticipated Major Milestones

Recent advances in the science and technology of fusion energy have dramatically improved the prospect for practical fusion power. The goal of a self-sustaining, burning fusion plasma is planned to be achieved both in inertial fusion with the National Ignition Facility (Fig. 1) and in magnetic fusion with the international ITER experiment (Fig. 2). These experiments form a basis for this plan, and the need for their full exploitation underlies its near-term urgency.

Fusion powers the sun and the stars, and is now within reach for use on Earth. In the fusion process lighter elements are "fused" together making heavier elements and producing prodigious amounts of energy. Fusion offers very attractive features as a sustainable broadly available energy source, including no emissions of greenhouse gases or other polluting gases, no risk of a severe accident, no severe consequences of a terrorist attack and no long-lived radioactive waste. Furthermore fusion does not require large land use, very long-distance transmission or large-scale energy storage. Fusion energy can be used to produce electricity and hydrogen, and for desalination. The successful development of fusion energy over the next few decades will complement other new energy sources and support the President's hydrogen initiative, making a major, timely contribution to reduction of the build-up of greenhouse gases in the earth's atmosphere. Currently escalating international tensions underscore the importance of fusion's ultimate contribution to U.S. energy security.

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 (a superhot gas) that produces fusion energy continuously. In IFE, continuous power is produced by using repetitive pulses of energy to compress and heat small dense plasmas very rapidly, in order to produce fusion energy during the brief period that the plasmas are held in place by their own inertia.

The last decade has seen dramatic advances in the science and technology of both magnetic and inertial fusion energy, made possible by advances in detailed

Fig. 1. The National Ignition Facility, presently under construction, is designed to achieve ignition and moderate gain in inertial fusion.

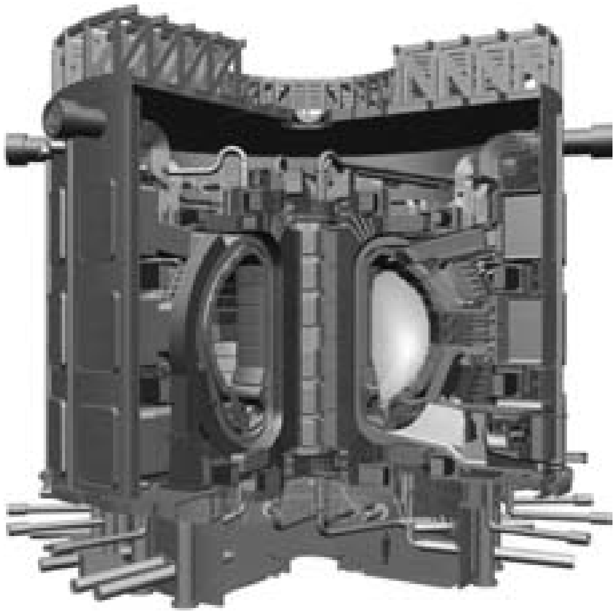

Fig. 2. The ITER facility, presently in international negotiation, is designed to integrate magnetic fusion burning plasma physics with fusion technologies, producing hundreds of megawatts of fusion power for long pulses.

plasma measurement technique and in advanced computing.

- Within MFE, the underlying turbulence that causes loss of heat from high-temperature magnetically confined ions has been identified, and in some cases quenched, in good agreement with computational models. Theoretical and computational models of the global stability of magnetically confined plasmas have been validated, and new techniques to stabilize high pressure plasmas, desirable for economic power production, have been demonstrated. Techniques have been developed to quench magnetic turbulence in self-organized systems with attractive power plant properties, and new configurations have been shown to sustain very high plasma pressure relative to magnetic pressure. New plasma configurations have been designed capable of operating at high plasma pressure with passive stability.
- Within IFE, multi-dimensional computational modeling of both direct and x-ray driven targets has successfully predicted experimental results with both laser and z-pinch drivers, and has been used to design high-gain IFE targets. Significant advances have been made in the repetitively pulsed "drivers" required for IFE. Large increases have been made in the production of x-rays with z-pinches, and megajoules of z-pinch x-rays have been used to drive high-quality capsule implosions. Cryogenic target implosions energy-scaled to simulate NIF experiments have begun. Experiments using a petawatt laser have demonstrated efficient heating of pre-compressed cores, a step towards higher gain inertial fusion energy.
- In the fusion technology program, materials originally developed for the fission breeder program have been reformulated for both enhanced performance and greatly reduced activation. Multi-scale modeling of neutron effects now captures the essential physics of neutron interactions in materials, allowing better understanding of the full range from nanophysics to large scale material properties. New designs for fusion blankets employing configurations featuring innovative combinations of materials open the way to higher temperature coolants and so higher efficiency power plant operation. Important advances have been made in both solid and liquid chamber wall technologies for IFE and MFE, as well as in IFE final focusing systems and target fabrication.

Building on these accomplishments, exciting results are anticipated from major new fusion facilities in the decade 2010–2020:

- Early in the decade powerful beams of light will flash through 192 laser channels in the NIF, converging on a diminutive pellet of fusion fuel. The core of the fuel will be compressed to pressures comparable to and heated to temperatures higher than the center of the sun. An intense brief fusion flame will be ignited and will propagate into the bulk of the fusion fuel, releasing a burst of fusion energy substantially greater than the applied laser energy.
- In the middle of the decade an international coalition will bring on line a fusion system, ITER, capable of producing power plant levels of fusion energy. Superconducting coils will produce magnetic fields 100,000 times stronger than the Earth's, capable of confining the superhot plasma in steady fusion conditions. A fusion power level of 500 million Watts will be produced in a steady flow up to an hour long. Should ITER not move forward,

the plan calls for construction of the domestic burning plasma experiment, FIRE.
- By the end of the decade an international team will obtain the first results on high-performance materials exposed to a fusion-relevant neutron environment in the International Fusion Materials Irradiation Facility (IFMIF). These accelerated exposure data will be used to validate experimentally emerging materials science models and to qualify specific materials for fusion application.

These accomplishments will form a strong basis for the development of practical, economically competitive fusion energy. A strong parallel effort in the science and technology of fusion energy is required to guide research on these experimental facilities and to take advantage of their outcome.

The Plan

In response to a charge from the Director of the DOE Office of Science, Dr. Raymond Orbach, a Fusion Energy Sciences Advisory Committee Panel was established to provide a plan for the development of fusion energy and specifically for the deployment of a fusion demonstration power plant (Demo) capable of producing net electricity within approximately 35 years. The demonstration power plant must open the way for a first generation of attractive commercial fusion power systems to be brought on line by mid-century. Consistent with the Charge to the Panel, this Final Report builds on recent work of FESAC and the 2002 Fusion Snowmass Summer Study and provides such a plan. Key features of the plan are:

- It works from a set of principles derived from the end goal of a Demo operating within 35 years that will lead directly to commercial fusion energy.
- It presents a development path for fusion energy that identifies development periods, key decision points, required facilities and estimated costs.

Key conclusions of the plan are:

- To develop fusion energy on this timescale, it is imperative to have a strong balanced program that develops fusion science and technology in parallel, for both IFE and MFE.
- Additional funding, starting now, is required to participate in the construction and utilization of ITER, or, if ITER does not advance to construction, to complete the design of and to construct the domestic FIRE experiment,
- to exploit NNSA's investment in inertial fusion,
- to participate in the design of IFMIF,
- to establish a research and development program that will lead to a demonstration power plant within 35 years.

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. As shown in Figure 3, these challenges are:

- *Configuration Optimization*, in which a range of potentially attractive configurations is tested and optimized for both MFE and IFE;
- *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;
- *Demonstration*, in which fusion is demonstrated to be an environmentally and economically attractive energy source.
- *Scientific and Technology Development Programs* in theory and simulation, basic plasma science, concept exploration and proof of principle experimentation, materials development and plasma, fusion chamber and power technologies form the foundation for this research.

This fusion development plan is guided by a series of specific, defined decisions. It also provides pathways for "breakthrough" developments that significantly improve the end product. Finally it assumes that difficult choices will be made on a timely basis, taking into account the key parameters of quality, performance and relevance to the plan. Such timely decisions are required for this plan to succeed.

The overlapping scientific and technological challenges will be met during four development periods,

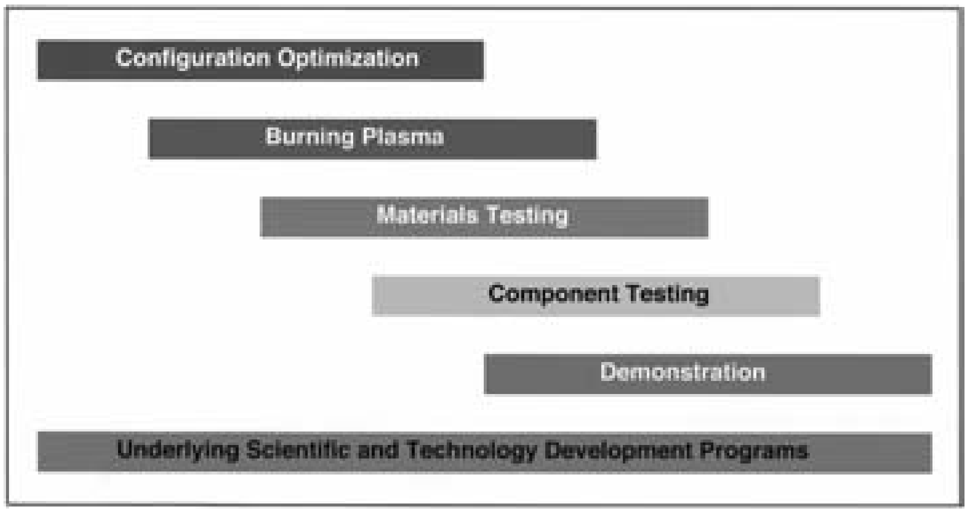

Fig. 3. Overlapping scientific and technological challenges define the sequence of major facilities needed in the fusion development path. Programs in theory and simulation, basic plasma science, concept exploration and proof of principle experimentation, materials development and plasma, fusion chamber, and power technologies form the foundation for research on the major facilities.

whose decision-driven goals and approximate time periods are:

- Present–2008: *Acquire Science and Technology Data to Support MFE and IFE Burning Plasma Experiments and to Decide on Key New MFE and IFE Domestic Facilities; Design the International Fusion Materials Irradiation Facility*
- 2009–2019: *Study Burning Plasmas, Optimize MFE and IFE Fusion Configurations, Test Materials and Develop Key Technologies in order to Select between MFE and IFE for Demo*
- 2020–2029: *Qualify Materials and Technology in Fusion Environment*
- 2030–2037: *Construct Demo*

Each of these development periods is characterized by specific scientific and technological objectives, as well as by key decisions required for the transition to the activities of the next period, as shown in Table 1 and Figure 4. The Table and Figure indicate the decisions assumed in the scenario used to define the cost of the development path (the cost-basis scenario), but it should be recognized that these decisions also provide opportunities for "off-ramps" for technologies, and thus the decision could be taken at these points not to proceed to the next stage of development of a given technology.

It is the judgment of the Panel that the overall decisions to make the major transitions (*i.e.*, in approximately 2008, 2019 and 2029) should be guided by an outside group, such as the National Research Council or the President's Council of Advisors on Science and Technology, while the specific decisions on particular facilities need to be made through peer review by technical experts. The panels of technical experts should increasingly include participants from the U.S. energy industry with a clear focus on key practical issues of economics and licensing.

The total cost to the U.S. of the plan to bring on line a first-generation Demonstration fusion power plant that will lead to commercial application of fusion energy by mid-century is approximately $24B in FY2002 dollars. The plan assumes an ongoing level of highly coordinated international programmatic activities, and international participation in ITER and IFMIF, but assumes U.S.-only support for the MFE Component Test Facility (CTF) or the IFE Engineering Test Facility (ETF), and for Demo. It assumes continuing strong NNSA support of Inertial Confinement Fusion.

To achieve the goals of this plan, the program must be directed by strong management. Given constrained budgets, the wide variety of options and the linkages of one issue to another, increasingly sophisticated management of the program will be required.

Additional funding that would be needed in the second half of the development plan to maintain a strong core scientific capability, and to provide continued innovation aimed at improved configurations beyond Demo, is not included. The panel believes that these are necessary elements of an overall fusion R&D program. The panel has not attempted to analyze these

Table 1. Goals, Specific Objectives, and Key Decisions

- **Present–2009:** ***Acquire Science and Technology Data to Support MFE and IFE Burning Plasma Experiments and to Decide on Key New MFE and IFE Domestic Facilities; Design the International Fusion Materials Irradiation Facility***

Specific Objectives:
- Begin construction of ITER, and develop science and technology to support and utilize this facility. If ITER does not move forward to construction, then complete the design and begin construction of the domestic FIRE experiment.
- Complete NIF and ZR (Z Refurbishment) (funded by NNSA).
- Study attractive MFE configurations and advanced operation regimes in preparation for new MFE Performance Extension (PE) facilities required to advance configurations to Demo.
- Develop configuration options for MFE Component Test Facility (CTF).
- Participate in design of International Fusion Materials Irradiation Facility (IFMIF)
- Test fusion technologies in non-fusion facilities in preparation for early testing in ITER, including first blanket modules, and to support configuration optimization.
- Develop critical science and technologies that can meet IFE requirements for efficiency, rep-rate and durability, including drivers, final power feed to target, target fabrication, target injection and tracking, chambers and target design/target physics.
- Explore fast ignition for IFE (funded largely by NNSA).
- Conduct energy-scaled direct-drive cryogenic implosions and high intensity planar experiments (funded by NNSA).
- Conduct z-pinch indirect-drive target implosions (funded by NNSA).
- Provide up-to-date conceptual designs for MFE and IFE power plants.
- Validate key theoretical and computational models of plasma behavior.

  2008 Decisions: Assuming successful accomplishment of goals, the cost-basis scenario assumes that by this time decisions are taken to construct:
  - International Fusion Materials Irradiation Facility
  - First New MFE Performance Extension Facility
  - First IFE Integrated Research Experiment Facility

- **2009–2019:** ***Study Burning Plasmas, Optimize MFE and IFE Fusion Configurations, Test Materials and Develop Key Technologies in order to Select between MFE and IFE for Demo***

Specific Objectives:
- Demonstrate burning plasma performance in NIF and ITER (or FIRE).
- Obtain plasma and fusion technology data for MFE CTF design, including initial data from ITER test blanket modules.
- Obtain sufficient yield and physics data for IFE Engineering Test Facility (ETF) decision.
- Optimize MFE and IFE configurations for CRG/ETF and Demo.
- Demonstrate efficient long-life operation of IFE and MFE systems, including liquid walls.
- Demonstrate power plant technologies, some for qualification in CTF/ETF.
- Begin operation of IFMIF and produce initial materials data for CTF/ETF and Demo.
- Validate integrated predictive computational models of MFE and IFE systems.

  Intermediate Decisions: Assuming successful accomplishment of goals, the cost-basis scenario assumes a decision to construct two additional configuration optimization facilities, which may be either MFE or IFE.
  - MFE Performance Extension Facility
  - IFE Integrated Research Experiment

  2019 Decision: Assuming successful accomplishment of goals, the cost-basis scenario assumes a selection between MFE and IFE for the first generation of attractive fusion systems.
  - Construction of MFE Component Test Facility (CTF)

    or
  - Construction of IFE Engineering Test Facility (ETF)

- **2020–2029** ***Qualify Materials and Technologies in Fusion Environment***

Specific Objectives:
- Operate ITER with steady-state burning plasmas providing both physics and technology data.
- Qualify materials on IFMIF with interactive component testing in CTF or ETF, for implementation in Demo.
- Construct CTF or ETF; develop and qualify fusion technologies for Demo.
- On the basis of ITER and CTF/ETF develop licensing procedures for Demo.
- Use integrated computational models to optimize Demo design.

  2029 Decision:
  - Construction of U.S. Demonstration Fusion Power Plant

- **2030–2035:** ***Construct Demo***

  Specific Objective: Operation of an attractive demonstration fusion power plant.

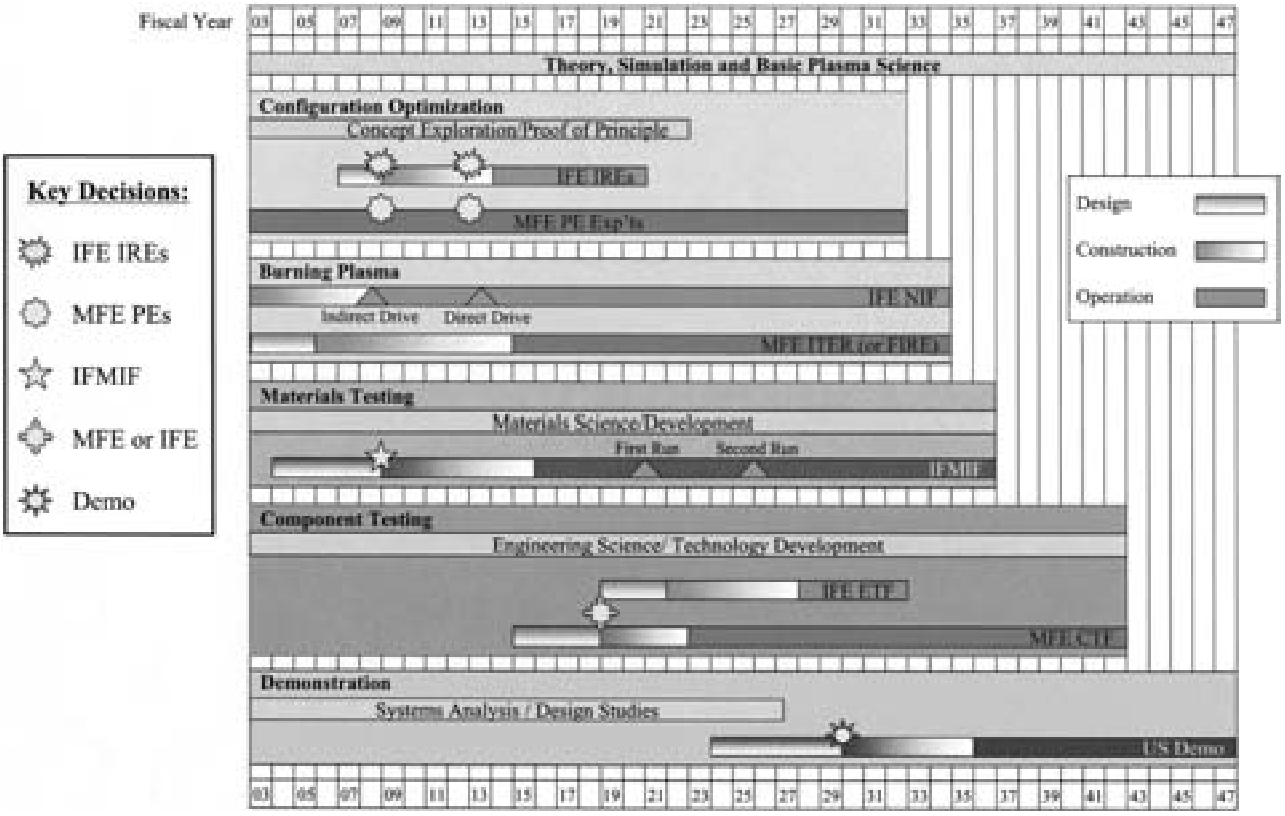

Fig. 4. Fusion Development Path including programs, major facilities, and key decision points.

costs in a systematic manner but estimates they would sum to a few billion dollars.

Why Now?

There have been dramatic scientific and technological advances in fusion in the last decade, and major accomplishments are expected in NIF and ITER in the next. A ramp-up in domestic fusion research and development is required now to impact the direction of these upcoming burning plasma research experiments, in order to guide them in addressing critical issues in the development of practical fusion energy. Rapid progress is also needed in configuration optimization experiments for both MFE and IFE, because critical decisions must be made on key future investments by 2008 in order to maintain the needed schedule. The design of IFMIF and the domestic fusion technology program must move forward as well, if materials and technologies are to be available for testing in ITER and in CTF/ETF and for application in Demo. A program funded at present levels cannot accomplish these essential schedule-driven steps, which are needed to provide fusion energy on the timescale envisioned by President Bush.

The U.S. fusion energy sciences program is still suffering from the severe budget cuts of the mid-1990s and the loss of a clear national commitment to develop fusion energy. The result is that despite the exciting scientific advances of the last decade it is becoming difficult to retain technical expertise in key areas. The President's fusion initiative has the potential to reverse this trend, and indeed to motivate a new cadre of young people not only to enter fusion energy research, but also to participate in the physical sciences broadly. With the addition of the funding recommended here, an exciting, focused and realistic program can be implemented to make fusion energy available on a practical time scale. On the contrary, delay in starting this plan will cause the loss of key needed expertise and result in disproportionate delay in reaching the goal.

The required funding over the next five years in constant \$FY2002, including the High Average Power Laser program and the z-pinch IFE studies currently funded within the NNSA, is:

2004	2005	2006	2007	2008
\$332M	\$393M	\$449M	\$522M	\$569M

In 2011–2018 the budget requirement reaches a peak value of $800–900M/year. This is approximately equal to the buying power of the fusion program in the late 1970's and early 1980's.

Establishing a program now to develop fusion energy on a practical time scale will maximize the capitalization on the burning plasma investments in NIF and ITER, and ultimately will position the U.S. to export rather than import fusion energy systems. Failure to do so will relegate the U.S. to a second or third tier role in the development of fusion energy. Europe and Japan, which have much stronger fusion energy development programs than the U.S., and which are vying to host ITER, will be much better positioned to market fusion energy systems than the U.S.–unless aggressive action is taken now.

A PLAN FOR THE DEVELOPMENT OF FUSION ENERGY

A. Introduction

This report presents a plan for the deployment of a fusion demonstration power plant within 35 years, leading to commercial application of fusion energy by mid-century. The plan is derived from the necessary features of a demonstration fusion power plant and from the time scale defined by President Bush. It identifies critical milestones, key decision points, needed major facilities and required budgets.

Recent Advances and Anticipated Major Milestones

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The last decade has seen dramatic advances in the science and technology of both magnetic and inertial fusion energy, made possible by advances in detailed plasma measurement technique and in advanced computing.

- Within MFE, the underlying turbulence that causes loss of heat from high-temperature magnetically confined ions has been identified, and in some cases quenched, in good agreement with computational models. Theoretical and computational models of the global stability of magnetically confined plasmas have been validated, and new techniques to stabilize high pressure plasmas, desirable for economic power production, have been demonstrated. Techniques have been developed to quench magnetic turbulence in self-organized systems with attractive power plant properties, and new configurations have been shown to sustain very high plasma pressure relative to magnetic pressure. New plasma configurations have been designed capable of operating at high plasma pressure with passive stability.
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Building on these accomplishments, exciting results are anticipated from major new fusion facilities in the decade 2010–2020:

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These accomplishments will form a strong basis for the development of practical, economically competitive fusion energy. A strong parallel effort in the science and technology of fusion energy is required to guide research on these experimental facilities and to take advantage of their outcome.

The plan presented here prepares the United States to take advantage of these scientific developments, with the goal of bringing practical fusion power on line within 35 years, leading to commercial exploitation of fusion power by the middle of the century.

Forty-two years ago, when President Kennedy committed the United States to put a man on the moon he inspired a generation of young people to pursue careers in science and technology. He drove the nation to develop important new technologies. And he opened up the path not only for human spaceflight, but also for practical, commercial applications that have benefited our nation and the world.

The plan presented here envisions a science-based solution for the nation's and the world's need for a plentiful and environmentally benign new energy source. It will inspire new interest in the physical sciences and result in the accelerated development of new technologies. Ultimately this plan will provide the nation and the world with a crucially needed new clean commercial energy source, available to all nations for millions of years.

President Kennedy promised a man on the moon in less than a decade, and the nation committed resources of $125B, as measured in today's dollars, to achieve that goal. This plan for the development of fusion energy lasts for approximately 35 years, takes advantage of strong international cooperation, and requires much less total U.S. resources, approximately $24B. The purpose is to provide the world with the capability to harness fusion energy for practical commercial application.

The world will change dramatically, and unpredictably, over the next few decades. The plan presented here provides a clearly defined development path for practical fusion energy. This plan takes advantage of the most developed approaches to fusion energy, while anticipating and encouraging new insights and developments that can result in improvements in the attractiveness of the ultimate product.

It is a major challenge for political systems to think in terms of decades, but human families easily comprise three or even four generations, and still look forward to the future beyond. Our children and our grandchildren will thank us if we invest in their lives, and succeed in providing them with a new technology that will make their world a much better, and a much safer place.

This Final Report responds to the Charge to FESAC to provide "a plan with the end goal of the start of operation of a demonstration power plant in approximately 35 years." Section 2 outlines the potential of Fusion as an attractive long-term energy source. 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 (described in more detail in Appendix B). Section 5 presents a Cost-Basis

Scenario for the development of fusion energy, including high-level goals, specific objectives and key decisions. Section 6 presents the Panel's overall conclusions in response to the Charge.

Appendix A presents an overview of the scientific and technological challenges for the development of fusion energy, as previously defined by FESAC. Appendix B provides details on the Programs and Major Facilities within the Plan. Appendix C reproduces the primary Charge to FESAC. Appendix D reproduces the FESAC response letter to DOE, transmitting this report. Appendix E presents the processes used by the Panel in developing the present report. Appendix F is a glossary. Appendix G reproduces a second Charge submitted to FESAC, asking for the definition of major new facilities to be operated within the next twenty years. Appendix H is the specific response to the second Charge.

B. 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 for the first generation of fusion systems are most likely to be 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 millions 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. As a result no public evacuation plan is required in the vicinity of a fusion power plant. The consequences of a terrorist attack are not anticipated to be severe. 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 U.S. 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 or in dedicated facilities. 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. In order to stabilize carbon dioxide concentrations, the world's energy economy must be dramatically transformed beginning in this century, and must reach a radically different state in the next. In addition, escalating international tensions underscore the importance of long-term national energy security. 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.

C. 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 U.S. 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 U.S. fusion industry to be competitive, the U.S. Demo must:
   a. be safe and environmentally attractive,
   b. extrapolate to competitive cost for electricity in the U.S. 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 while they share a common goal they face, in some areas, significantly different 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 U.S. must be among the world leaders in fusion research for the U.S. 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 requirment, however, that every pathway be funded at the level needed for development 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 (this topic is elaborated in section 5.9):
      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 U.S. National Security Administration (NNSA) in the area of Inertial Confinement Fusion (ICF).

D. 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 (a superhot gas) that produces fusion energy continuously. In IFE, continuous power is produced by using repetitive pulses of energy to compress and heat small dense plasmas very rapidly, in order to produce fusion energy during the brief period that the plasmas are held in place by their 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 3. 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 form the foundation for research on the major facilities.

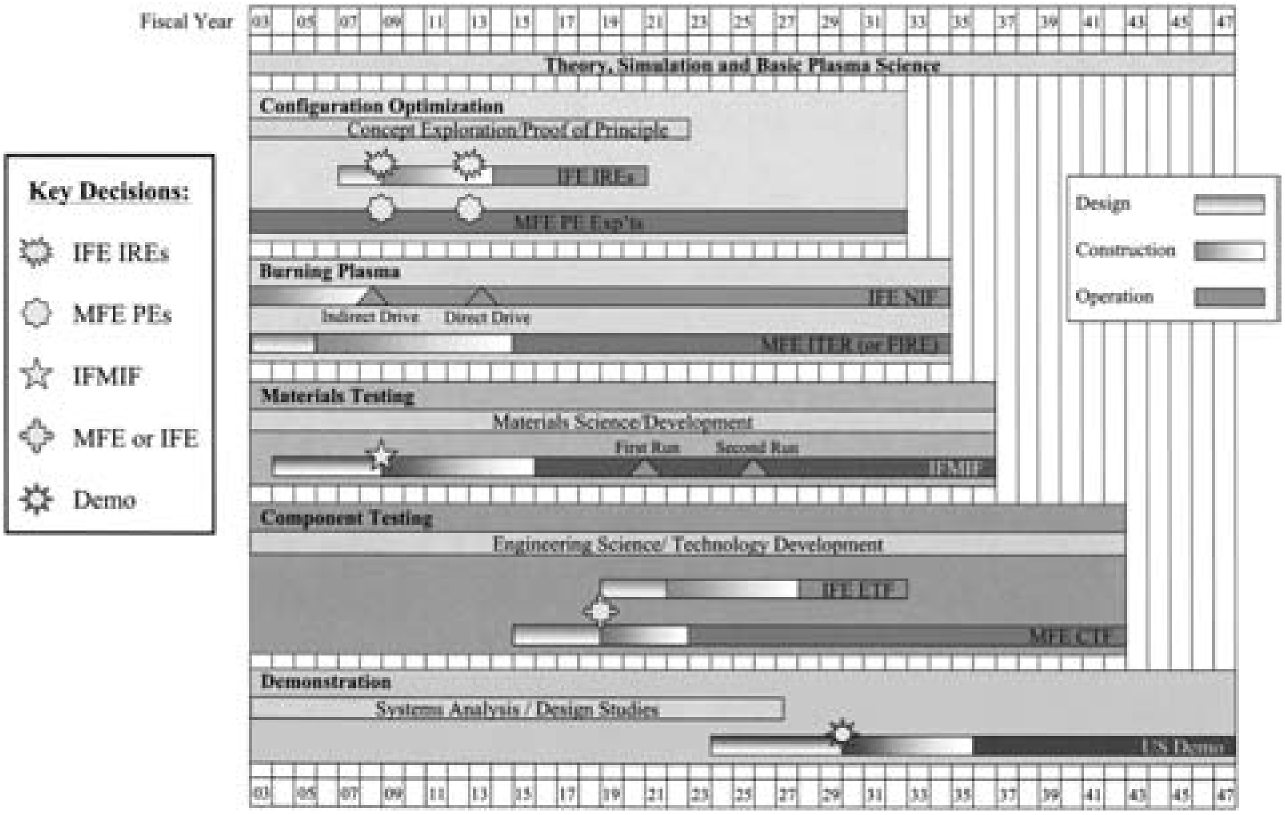

Fig. 5. Fusion Development Path including programs, major facilities, and key decision points.

Figures 5–7 provide more detailed timelines of the programs and facilities required to meet the series of challenges shown schematically in Figure 3. The underlying scientific and technological challenges, and associated milestones, are described in Appendix A. A more detailed description of each of the program and project elements is provided in Appendix B.

A concise description of the program and project elements is given below.

1. Configuration Optimization

For MFE, 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 projected to meet 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 U.S. 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.

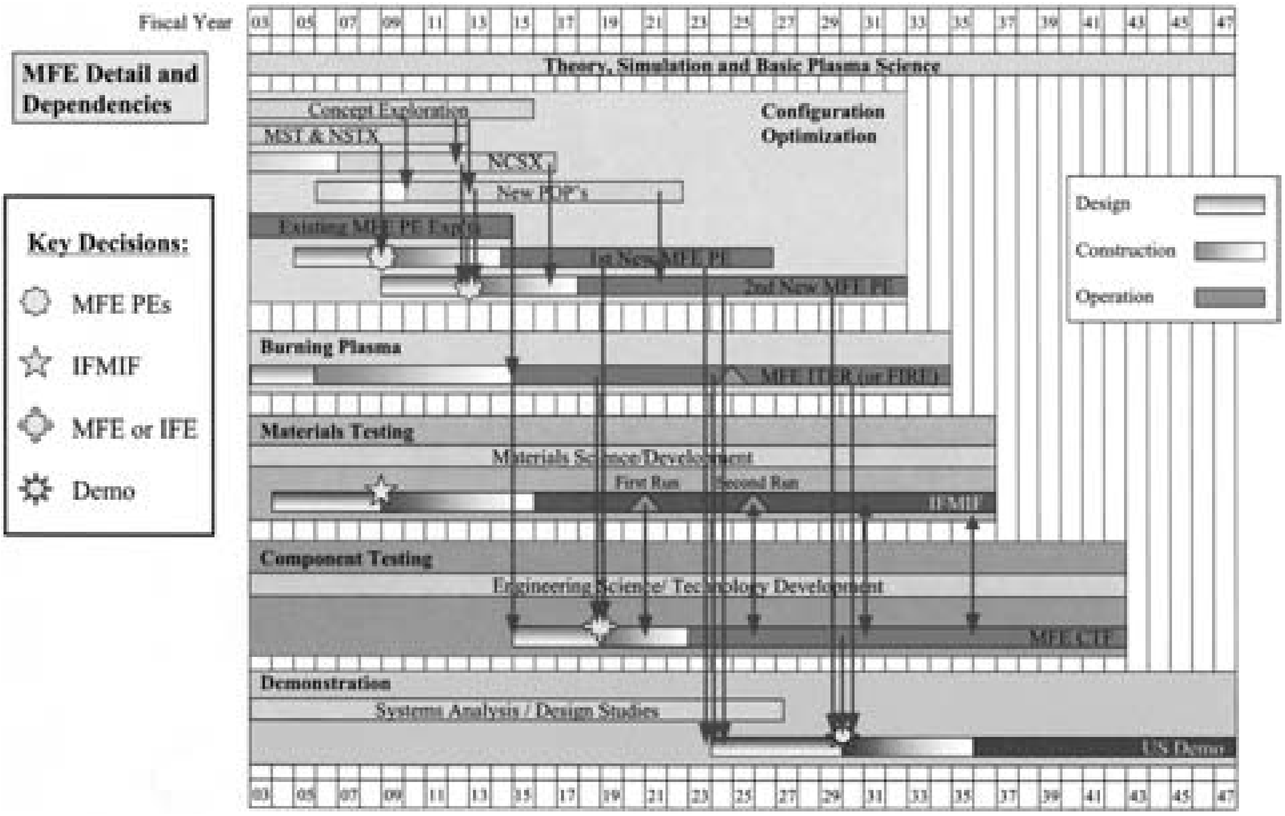

Fig. 6. MFE Fusion Development Path including programs, major facilities, and key decision points, with more detail in earlier years and key dependencies.

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, however, 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. Indeed a billion-dollar class superconducting stellarator is currently operating in Japan, and one is under construction in Germany. New configurations, building on the growing understanding of fusion plasmas, including quantitative numerical simulations, offer the potential for improved performance as fusion systems. Progress with these configurations has been very impressive as well. The understanding that arises from experimentation coupled closely with theory and advanced computing should make the step to Demo possible for non-tokamak configurations if merited.

It is important to recognize that there is an ongoing need for enabling technology development to support the configuration optimization experiments at all levels, through the burning plasma, component testing and Demo stages. 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.

For IFE, the challenge of configuration optimization is similar to that of MFE, with the exception that the criterion of mass power density is replaced predominantly by that of driver cost. Configuration optimization experiments focus on the development of reprated drivers and associated target physics, as well as target fabrication, target injection/placement, final optics/power focusing and chamber technologies. Target physics experiments of relevance to IFE are ongoing on the NNSA facilities Omega, Nike and Z, on facilities in Europe and Japan, and will be conducted on the NIF and Laser Megajoule (LMJ) in France in the future.

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

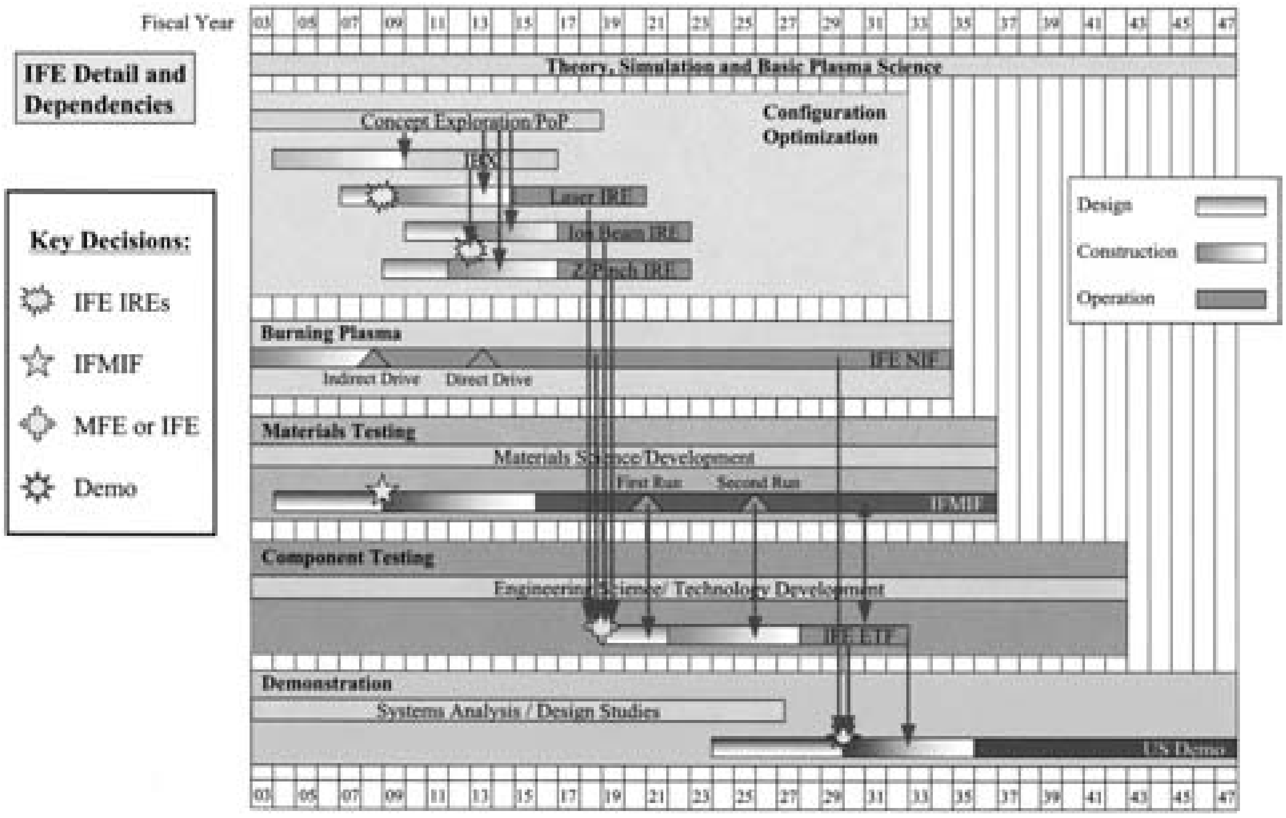

Fig. 7. IFE Fusion Development Path including programs, major facilities, and key decision points, with more detail in earlier years and key dependencies.

the target, final optics, and chamber development work. The last includes exposing candidate first wall chamber materials to relevant x-ray and ion fluxes, 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) needed for repetitively pulsed operation. 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 PoP phase.

The fast ignition approach is, in principle, compatible with all IFE drivers. Programs to study fast ignition are underway in Japan and at a lower level at present, in the U.S.

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 an IFE Engineering Test Facility (ETF) to Demo. Relatively low cost non-nuclear facilities are required to study thick liquid wall issues such as x-ray and ion flux 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.

2. Burning Plasmas

The burning plasma step is critical for both MFE and IFE. The defining feature of a burning plasma is that it is sustained primarily by the heat generated through its own internal fusion reactions.

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 U.S. 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. In present experiments most of the plasma heating is applied externally. In a burning plasma, intense fusion reactions occur and energetic alpha particles (helium nuclei) are generated and are then confined by the magnetic field and slow down, transferring their energy to maintain the high temperature of the plasma. When such 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 many 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 potentially 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 U.S. has decided to join the negotiations for the construction of ITER, as recommended by FESAC. If ITER goes forward it will fulfill all of the requirements for an MFE burning plasma experiment. On the other hand, if the international negotiations do not succeed, and ITER does not go forward, the domestically designed experiment, FIRE, would be an attractive option for the study of burning plasma science, as discussed by FESAC. Either ITER or FIRE 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. A scenario including FIRE, rather than ITER, is considered in Section 5.8.

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, such as a petawatt laser.) The burning plasma step for IFE will be addressed in the National Ignition Facility (NIF), currently under construction. This step is a critical issue for all approaches to IFE, and its results can be transferred to other configurations beyond those testable directly on the NIF, through the use of advanced numerical simulations.

The configuration to be pursued initially on NIF is the best developed at present: a laser-driven x-ray hohlraum imploding a fusion capsule. Although targets in this configuration are not presently projected to have adequate gain for IFE with lasers, such targets will provide much of the needed physics basis for IFE targets driven with the three types of drivers under consideration: ion beams, z-pinches and direct-drive lasers. NIF is also reconfigurable to study in more detail 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.

3. 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 face significantly less severe issues with respect to neutron-interactive materials than other approaches, it is clear that materials issues for solid-wall laser-driven IFE and for MFE are comparable.

Guided by coordination from the International Energy Agency fusion materials working groups, the fusion materials science program has developed a suite of high-performance reduced-activation metallic and ceramic composite materials systems. In particular ferritic steels evolved from those developed for the fission breeder program appear to be promising candidates to withstand the intense 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 one or more attractive materials will be available for Demo. Furthermore these materials need to be tested in an intense, realistic energetic neutron environment, which will be made available through a special-built facility, capable of providing an intense neutron flux with an appropriate energy spectrum onto an area of 100 cm^2. The international community (including the U.S.) has been involved in the conceptual design of the International Fusion Materials Irradiation Facility, which would address this need.

4. *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, as well as plasma interactive and high-heat flux components such as the divertor, tritium processing, IFE target fabrication and delivery system, and remote maintenance systems. Since the world supply of tritium is very limited, this activity must be carried out in very much reduced-scale facilities until tritium breeding technology is reliably developed.

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, while important, will be limited to initial functional tests and screening due to 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 will require iteration and coordination with materials qualification in IFMIF. The CTF facility is to provide substantial neutron wall load (>1 MW/m^2) and fluence (>6 MWyr/m^2) at minimum overall fusion power ($\sim$150 MW) in order to enable integrated testing and optimization of a series of components at minimum tritium consumption and overall cost. An important goal of MFE configuration optimization experiments through 2019 is to provide an optimized configuration for the CTF.

Within the IFE path, an Engineering Test Facility (ETF) is needed to (1) produce repetitive pulses for component testing and (2) demonstrate (for the first time for some drivers) high yield targets. For component testing the approach favored is to use reduced-yield targets relative to Demo, and a proportionally reduced distance to the chamber 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 must be implemented in Demo.

5. *Demonstration*

The U.S. 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 power producers and the general public 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 sum, Demo must operate reliably and safely on the power grid for a period of years so that industry gains confidence from operational experience and the public is convinced that fusion is a "good neighbor."

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

6. *Underlying Scientific and Technology Development Programs*

Programs in theory and simulation, basic plasma science, concept exploration and proof of principle experimentation, materials development and plasma, fusion chamber and power technologies form the foundation for 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.

E. Cost-Basis Scenario

The purpose of this section of the Report is to present a scenario for the development of fusion energy on the time scale envisioned by President George W. Bush and by Energy Secretary Spencer Abraham. For fusion energy to begin to be commercially available by mid-century, a demonstration power plant, as it has been defined in this Report, will be required about 35 years from today.

The scenario presented in this section builds on the descriptions of the projects and programs defined in Section 4, and elaborated in Appendix B. This scenario also builds on the principles presented in Section 3. In particular, in order to have acceptable assurance of success, it provides for the development of portfolios within both magnetic and inertial fusion energy. The development of these portfolios is guided by a series of specific, defined decisions on whether or not to construct significant new facilities. It also provides pathways for "breakthrough" developments that significantly improve the end product. Finally it assumes that difficult choices will be made on a timely basis, taking into account the key parameters of quality, performance and relevance to the plan. This scenario is used to estimate a U.S. cost for the development of a fusion demonstration power plant.

Four time periods are envisioned along the pathway to Demo, as shown in Table 2. Each of these time periods is characterized by scientific and technological goals, specific objectives, and key decisions required for the transition to the activities of the next period. Necessarily the level of detail that can be provided at this time is much greater for the earlier periods and decisions than for the later ones, but the Panel believes that this overall structure provides a valuable guide to the needed activities.

At the transition between periods major decisions and commitments must be made. It is the judgment of the Panel that the overall decisions to make the major transitions (*i.e.*, in approximately 2008, 2019 and 2029) should be guided by an outside group, such as the National Research Council or the President's Council of Advisors on Science and Technology, while the specific decisions on particular facilities need to be made through peer review by technical experts. The panels of technical experts should increasingly include participants from the U.S. energy industry with a clear focus on key practical issues of economics and licensing.

An overview of the plan is provided in Table 2, and detailed in the subsections 5.1–5.4. Figures 5–7 illustrate the structure of the plan graphically.

1. *Acquire Science and Technology Data to Support MFE and IFE Burning Plasma Experiments and to Decide on Key New MFE and IFE Domestic Facilities; Design the International Fusion Materials Irradiation Facility (Present – 2008)*

Over this time period existing projects and programs are strengthened in order to produce timely results. The specific goal is to be prepared for the major decisions

Table 2. Goals, Specific Objectives, and Key Decisions

- **Present – 2008:** ***Acquire Science and Technology Data to Support MFE and IFE Burning Plasma Experiments and to Decide on Key New MFE and IFE Domestic Facilities; Design the International Fusion Materials Irradiation Facility***

Specific Objectives:

- Begin construction of ITER, and develop science and technology to support and utilize this facility. If ITER does not move forward to construction, then complete the design and begin construction of the domestic FIRE experiment.
- Complete NIF and ZR (Z Refurbishment) (funded by NNSA).
- Study attractive MFE configurations and advanced operation regimes in preparation for new MFE Performance Extension (PE) facilities required to advance configurations to Demo.
- Develop configuration options for MFE Component Test Facility (CTF).
- Participate in design of International Fusion Materials Irradiation Facility (IFMIF)
- Test fusion technologies in non-fusion facilities in preparation for early testing in ITER, including first blanket modules, and to support configuration optimization.
- Develop critical science and technologies that can meet IFE requirements for efficiency, rep-rate and durability, including drivers, final power feed to target, target fabrication, target injection and tracking, chambers and target design/target physics.
- Explore fast ignition for IFE (funded largely by NNSA).
- Conduct energy-scaled direct-drive cryogenic implosions and high intensity planar experiments (funded by NNSA).
- Conduct z-pinch indirect-drive target implosions (funded by NNSA).
- Provide up-to-date conceptual designs for MFE and IFE power plants.
- Validate key theoretical and computational models of plasma behavior.

2008 Decisions: Assuming successful accomplishment of goals, the cost-basis scenario assumes that by this time decisions are taken to construct:

- International Fusion Materials Irradiation Facility
- First New MFE Performance Extension Facility
- First IFE Integrated Research Experiment Facility

- **2009–2019:** ***Study Burning Plasmas, Optimize MFE and IFE Fusion Configurations, Test Materials and Develop Key Technologies in order to Select between MFE and IFE for Demo***

Specific Objectives:

- Demonstrate burning plasma performance in NIF and ITER (or FIRE).
- Obtain plasma and fusion technology data for MFE CTF design, including initial data from ITER test blanket modules.
- Obtain sufficient yield and physics data for IFE Engineering Test Facility (ETF) decision.
- Optimize MFE and IFE configurations for CTF/ETF and Demo.
- Demonstrate efficient long-life operation of IFE and MFE systems, including liquid walls.
- Demonstrate power plant technologies, some for qualification in CTF/ETF.
- Begin operation of IFMIF and produce initial materials data for CTF/ETF and Demo.
- Validate integrated predictive computational models of MFE and IFE systems

Intermediate Decisions: Assuming successful accomplishment of goals, the cost-basis scenario assumes a decision to construct two additional configuration optimization facilities, which may be either MFE or IFE.

- MFE Performance Extension Facility
- IFE Integrated Research Experiment

2019 Decision: Assuming successful accomplishment of goals, the cost-basis scenario assumes a selection between MFE and IFE for the first generation of attractive fusion systems.

- Construction of MFE Component Test Facility (CTF)

  or
- Construction of IFE Engineering Test Facility (ETF)

- **2020–2029:** ***Qualify Materials and Technologies in Fusion Environment***

Specific Objectives:

- Operate ITER with steady-state burning plasmas providing both physics and technology data.
- Qualify materials on IFMIF with interactive component testing in CTF or ETF, for implementation in Demo.
- Construct CTF or ETF; develop and qualify fusion technologies for Demo.
- On the basis of ITER and CTF/ETF develop licensing procedures for Demo.
- Use integrated computational models to optimize Demo design.

2029 Decision:

- Construction of U.S. Demonstration Fusion Power Plant

- **2030–2035:** ***Construct Demo***

  Specific Objective: Operation of an attractive demonstration fusion power plant.

that will be required in 2008. It is assumed that ITER negotiations lead expeditiously to a construction project. Other than ITER, during this time period there are no construction decisions made on major projects (PE-class MFE facilities or IRE-class IFE facilities) that carry major out-year commitments, but some commitments are made, as warranted, to new facilities at the PoP level.

The Cost-Basis Scenario assumes that the following activities are undertaken during this period:

Design Studies/Demo

- Design studies are strengthened, in order to help guide future programmatic decisions. Particular focus is required during this time period on laser inertial fusion energy and on configuration options for the Component Test Facility (CTF), since decisions relative to these two areas (IFE laser IRE, MFE PE with possible application to CTF) will be required at the end of this time period.

Engineering Science/Technology Development

- Engineering science and technology development are strengthened from their current levels in order to more fully support configuration optimization experiments, to support inertial fusion IRE and ITER issues as they develop, to prepare for ITER blanket testing even during its initial operation, and ultimately to prepare for CTF.

IFMIF

- The U.S. engages in the Engineering Validation and Engineering Design Activity for the International Fusion Materials Irradiation Facility (IFMIF), in order to be prepared for a construction decision at the end of this time period.

Materials Science/Development

- Materials science activities are strengthened to prepare for the use of IFMIF, ITER and CTF.

MFE Burning Plasma

- Construction of ITER commences.

IFE Burning Plasma

- Initial megajoule-class compression results on non-cryogenic targets are obtained from the NIF, giving new information on laser-plasma interactions, relevant for both direct and indirect drive, and on the degree of symmetry achievable with high energy laser driven hohlraums.
- High compression “energy scaled” cryogenic direct drive implosions are conducted at Omega and high intensity planar experiments are carried out at Nike, playing a major role for evaluating the prospects of high gain direct drive at the NIF.
- Z-pinch driven indirect drive target experiments on Z/ZR demonstrate high capsule compression ratios and symmetry that scales to that required for high yield and substantial DD neutron production, using megajoules of z-pinch x-rays.

MFE Performance Extension Facilities

- Performance Extension-class tokamak experiments are strengthened in the U.S. to support decisions on ITER advanced features, CTF design, and to contribute to basic understanding of toroidal magnetic confinement.
- Assuming continuing success in ongoing MFE PoP and PE experiments, design work is commenced on a new Performance Extension (PE) MFE experiment, with interest potentially both for application for Demo and for CTF, in preparation for a 2008 decision. PoP activities on the Spherical Torus (ST) and Reversed Field Pinch (RFP) configurations are strengthened both in preparation for this decision and to contribute to basic understanding of toroidal magnetic confinement.

Concept Exploration/Proof of Principle

- The Proof-of-Principle (PoP) HAPL laser fusion work currently underway continues and is brought to a favorable conclusion. Assuming that this work is successful, design work is commenced on a laser Integrated Research Experiment.
- The construction of the PoP-class National Compact Stellarator Experiment proceeds, along with the associated national stellarator program, in order to prepare for the possibility of a CS configuration for the 2nd new MFE PE experiment.
- A PoP-class heavy ion fusion experiment, the Integrated Beam Experiment, is brought to a Physics Validation Review, confirmed by FESAC for Proof-of-Principle status, passes a DOE Conceptual Design Review, and moves into construction during this time period.
- Concept exploration activity is strengthened for the Z-pinch and Fast Ignition IFE concepts and for MFE configurations at Concept Exploration (CE) level of development in order to prepare for expeditious transition to PoP scale. This will allow selected approaches to be moved forward more rapidly. It is assumed in the Cost-Basis Scenario that success at the CE

level of development leads to construction of two further configurations at the PoP scale (either MFE or IFE) during this time period.

Theory, Simulation and Basic Fusion Experiments

- Theory and advanced computing are strengthened, and the Fusion Simulation Project is initiated, in collaboration with the DOE-SC Office of Advanced Scientific Computing Research, taking advantage of advances in computing technology to both support ITER directly and also to provide the basis for extrapolating results from ITER to other MFE configurations.
- Credible IFE targets are designed with sufficient gain and stability using 2 and 3D modeling. Underlying codes are benchmarked against experiments.
- Fusion Frontier Centers, as recommended by the NRC FuSAC Panel, are opened in collaboration with the NSF.

In the Cost-Basis Scenario it is assumed that the decisions at the end of this time period lead to the following outcomes:

- Results from the Engineering Design Activity lead to construction of the IFMIF beginning in 2009.
- Results from the ongoing HAPL laser PoP program, cryogenic target implosion results from Omega, high-intensity planar target results from Nike, initial 120 beam implosion results from the NIF, and initial design studies lead to the start of construction of a laser Integrated Research Experiment.
- Results from the current MFE PoP and PE programs lead to the start of construction of a first new MFE PE experiment. Likely configurations for this facility could be the RFP, the ST, or a specialized tokamak. A potential goal for this facility would be scientific development for a cost-effective CTF.

2. Study Burning Plasmas, Optimize MFE and IFE Fusion Configurations, Test Materials and Develop Key Technologies in order to Select between MFE and IFE for Demo (2009–2019)

During this period, in the MFE area there will be results from ITER, in which it is anticipated that power plant levels of fusion power will be produced for long durations. Coupled with this will be results from existing tokamaks, and up to two additional Performance Extension experiments. In the IFE area there will be ignition and moderate gain results from the NIF, coupled with results from up to three Integrated Research Experiments demonstrating technology for IFE. There may be high-yield results from a new z-pinch facility. In both the MFE and IFE cases, the first Performance Extension or IRE facility is anticipated to be based on a configuration currently being developed at the PoP or PE scale, but in both cases the second such facility could also be based on new ideas, or ideas currently at the Concept Exploration stage.

The experience with ITER will have blazed the trail for licensing of fusion systems, and initial results from IFMIF will provide critical information on the performance of materials in a fusion neutron environment.

Key project decisions that will be required during this time period include:

- The construction of further PoP experiments within either MFE or IFE. In the Cost-Basis Scenario it is assumed that two new PoP's (either MFE or IFE) are constructed early in this time period, and the currently existing PoP's are shut down during this period.
- The construction of other IFE Integrated Research Experiment(s). In the Cost-Basis Scenario it is assumed that one or two further IREs are constructed during this time period. Thus two or three IFE configurations are assumed to be well enough developed to contribute to the design of an Engineering Test Facility and thence to Demo. It is assumed that if a third IRE is constructed, a second new MFE PE is not constructed.
- Research on Fast Ignition may lead to a decision to incorporate this feature into IFE facilities.
- The construction of other MFE Performance Extension experiment(s). In the Cost-Basis Scenario it is assumed that one further such experiment is constructed during this time period. Possible candidates include an RFP, ST, Compact Stellarator, a specialized tokamak or a configuration currently at the CE level, which, most likely, has been tested by this time at the PoP scale. It is assumed that if a second new MFE PE is constructed, a third IFE IRE is not constructed.
- It is anticipated that current U.S. PE-class tokamak facilities will have completed their research programs midway through this period,

demonstating the extent to which key advanced operation features can be achieved in an integrated manner. Their results contribute to ITER operational scenarios and to optimized designs which may compete for the new PE experiment. U.S. participation on long-pulse superconducting tokamaks abroad increases.

In order to prepare for the transition to the *Qualification of Materials and Technology in Fusion Environment* period it will be necessary to:

- Strengthen considerably efforts in engineering science and technology development.
- Begin design of both the MFE Component Test Facility and the IFE Engineering Test Facility.

On the basis of the information available at the end of this time period, it is assumed in this plan that a decision will be made on whether the Demo that will lead to the first generation of attractive fusion power plants will be based on Magnetic or on Inertial Fusion Energy. This will form the basis for the decision between an MFE Component Test Facility and an IFE Engineering Test Facility.

3. *Qualify Materials and Technologies in Fusion Environment (2020–2029)*

During this time period either the MFE Component Test Facility or the IFE Engineering Test Facility will be constructed and begin operation, providing critical technological information for the final design and construction of the Demo. An aggressive materials and technology qualification program will be required. The configuration of the Demo is decided during this time period and design commences.

4. *Construct Demo (2030–2035)*

During this time period a Demonstration Power Plant is constructed and then begins operation, leading to the commercial deployment of fusion energy by mid-century.

5. *Cost Profile*

Input was collected from technical experts in each relevant area, in order to develop cost profiles for the programs and major facilities included within the plan. In the case of MFE theory, configuration optimization and technology development, as well as materials development for both MFE and IFE, it is assumed that coordinated programmatic activities of similar scale are undertaken in Europe and Japan. For IFE, it is assumed that strong support by the NNSA for Inertial Confinment Fusion continues. For the major facilities in the plan, the following assumptions are made with respect to Total Project Costs (all costs are in $FY2002). Operating costs are also included in the cost profile.

- The overall cost for the construction of ITER is estimated at $5B. The total U.S. contribution to ITER construction, including also U.S. contingency, R&D and design of diagnostics, heating and current drive systems, and U.S. oversight of industrial activities, is taken to be $1B, consistent with FESAC estimates.
- The Total Project Cost for construction of the International Fusion Materials Irradiation Facility, IFMIF, is estimated at $600M, based on current international estimates, including 20% contingency. It is assumed that the U.S. contributes 25% of the cost of IFMIF.
- The Total Project Cost for construction of the first new Performance Extension MFE facility is taken to be $400M taking into account a range of estimates provided to the Panel.
- The Total Project Cost for construction of a Laser Integrated Research Experiment is assumed to be $320M, based on estimates provided to the Panel for either a KrF or a DPSSL based system. Associated laser IFE technology development is included within the Engineering Science/Technology Development program line.
- The Total Project Cost for a second IFE Integrated Research Experiment is estimated to be $300M, taking into account a range of estimates provided to the Panel.
- The Total Project Cost for construction of the second new Performance Extension MFE facility is taken to be $400M taking into account a range of estimates provided to the Panel.
- Note that the overall plan logic allows for up to three new MFE PE's and up to three IFE IRE's, but only a total of four such facilities is in the cost basis.
- During the 2009–2019 time period, the currently existing MFE PE's and PoP's complete operation.

In 2019 a decision will be made to proceed with either MFE (Component Test Facility leading to MFE

Demo) or IFE (Engineering Test Facility leading to IFE Demo). For the purpose of estimating a cost profile for the development path, therefore, the costs are averaged between these two options. The cost profile for the IFE path peaks earlier than that for MFE. It should be recognized that accurate estimations are difficult for facilities to be constructed in this time frame.

- The Total Project Cost for an MFE Component Test Facility is taken to be $1.5B, taking into account a range of estimates provided to the Panel. All costs are assumed to be borne by the U.S.
- The Total Project Cost for a U.S. MFE Demo is set at $5B. All costs are assumed to be borne by the U.S.
- The Total Project Cost for an IFE Engineering Test Facility is estimated at $4.5B, taking into account a range of estimates provided to the Panel. All costs are assumed to be borne by the U.S.
- The Total Project Cost for a U.S. IFE Demo is set at $1B, taking into account a range of estimates provided to the panel, assuming that the ETF facility can be upgraded to function as the Demo. All costs are assumed to be borne by the U.S.

Additional funding that would be needed in the second half of the development path plan for the optimization of a second generation of fusion power systems and to sustain a strong program in high-temperature plasma science and associated science and technology expertise is not included. MFE and IFE configurations not selected for Demo and first generation commercial application should be funded, if merited, at an appropriate level to contribute to a second generation of attractive fusion systems. The Panel has not attempted to analyze these costs in a systematic manner, but estimates they would sum to a few billion dollars.

Decommisioning costs for ITER, IFMIF and CTF, which would fall outside of the time-window of this plan are not included in its cost.

The cost profile for the development of Demo, based on this scenario, is presented in Figure 8 and Table 3.

Several specific issues of importance relative to the structure and execution of the plan are discussed in the following sections:

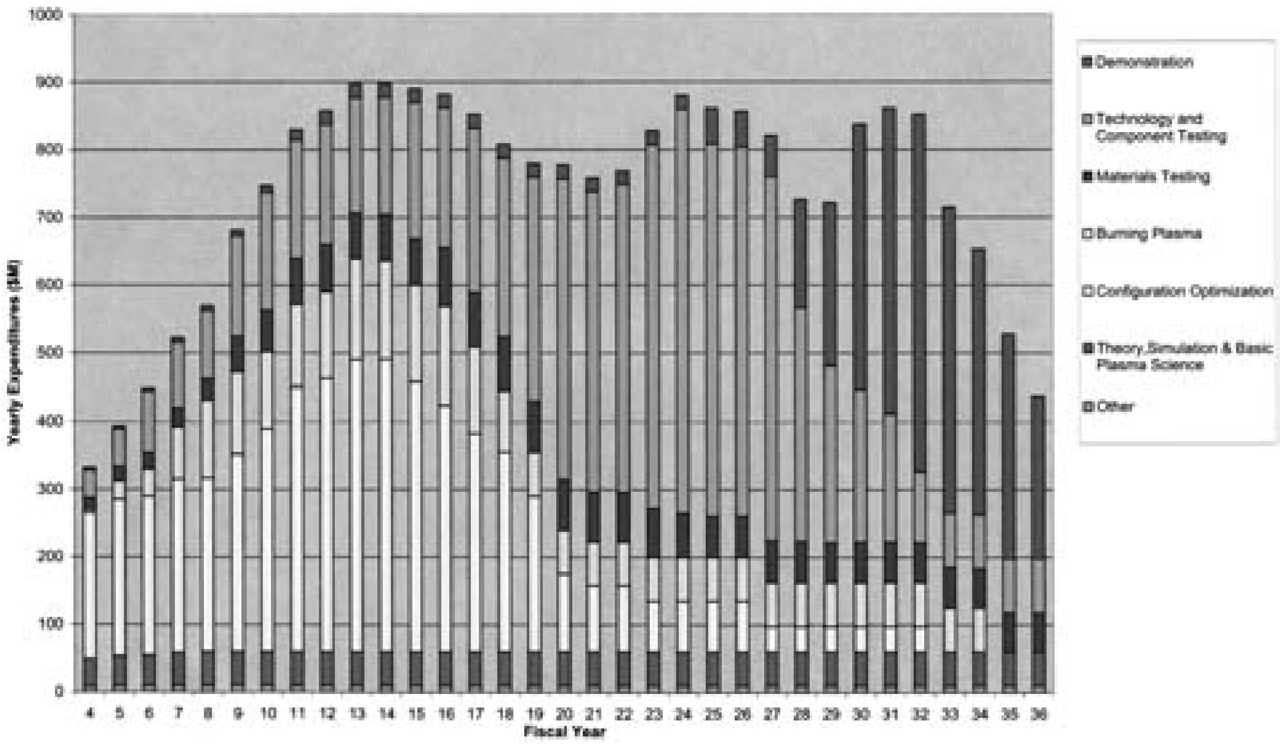

Fig. 8. Cost profile for fusion development plan to provide a Demonstration Power Plant.

Table 3. Cost Profile for Fusion Development Plan (FY2002 $M)

	2004	2005	2006	2007	2008	2013	2018	2023	2028	2033
Demonstration	4	4	5	7	7	20	20	20	159	450
Tech., Components	41	55	90	95	100	170	264	535	344	80
Materials, Testing	17	21	25	28	31	67	79	72	61	60
Burning Plasmas	5	28	42	77	114	150	90	65	65	65
Config. Optimiz.	216	233	235	257	257	430	295	75	38	0
Theory, etc.	41	44	46	48	50	50	50	50	50	50
Other	8	9	9	10	10	10	10	10	10	10
Total	332	393	449	522	569	897	808	827	726	715
Total: $24.2 B										

6. *Criteria for Advancement of Fusion Configurations*

For both MFE and IFE, the decision to proceed from one stage of development to the next is based on the maturity of the configuration, in order to be assured that (1) the next-stage program will be successful, and (2) the anticipated benefits of the next stage of research justifies the increased level of effort.

Common criteria for each level of any approach to proceed to the next stage are given in Table 4. In addition to these common criteria for all approaches, there are additional criteria for judging resolution of scientific and technical issues that are unique to each approach at each level that are described in Appendix A and Appendix B. In all cases, rigorous peer review is essential before proceeding to a higher stage.

7. *The Plasma Configuration of the MFE Demo*

The tokamak is the only plasma configuration that is currently well enough developed to allow confident extrapolation into the burning plasma domain. As a result ITER is designed as a tokamak. An attractive operating mode for the tokamak, called the "advanced tokamak," offers the promise of steady state operation with moderate recirculating power and acceptable mass power density. However there are still significant physics and technology issues that remain to be resolved for a Demo based on the advanced tokamak. On-going tokamak research and ITER plan to resolve these issues in time for the design of the Demo. It is uncertain, however, how much of the promise of the advanced tokamak can be realized in a practical system. It is also uncertain what the demands of the market will be 30+ years into the future. Thus the advanced tokamak may prove to be the correct configuration for the first generation of U.S. commercial fusion power plants, but it is also possible that a more attractive alternative may become available, or may be required for commercial practicality.

This plan supports research on a range of magnetic configurations, which will also support the development of the tokamak by contributing to innovation and scientific understanding of magnetic confinement. These configurations include the Spherical Torus, Reversed Field Pinch and Compact Stellarator, which are closely related to the tokamak and are being investigated at the Proof of Principle (PoP) scale. A number of other configurations, which are significantly more distant from the tokamak, are currently under investigation at the smaller Concept Exploration (CE) scale.

The plan includes the option for two MFE configurations to be tested at the larger Performance Extension (PE) scale, in parallel with ITER. The first of these experiments must be based on a configuration currently at the PoP or PE scale, and could also help to provide the basis for a cost-effective Component Test Facility. With success in the Concept Exploration program, and test at the PoP scale, the second such Performance Extension experiment could be based either on a configuration currently under investigation at the PoP level, or on a configuration currently at the CE scale–or possible even a very successful new idea. This explicit allowance for "breakthroughs" is consistent with the overall Principles articulated in Section 3. This approach requires, however, a vigorous U.S. Concept Exploration and Proof-of-Principle program as well as advanced numerical simulation and plasma diagnostics.

A flexible and well-diagnosed Performance Extension experiment, coupled through theory and advanced computing with burning plasma results from ITER, should provide the physics basis for the step to Demo. Whether the experiment will require deuterium-tritium operation (as in TFTR and JET) is a matter that will depend on the configuration being considered and on the degree of confidence that can be placed at that time in theoretical calculations and experimental simulations using, for example, high-energy beams. A firm

Table 4. Common Decision Criteria for Up-selection of Fusion Approaches to Next Development Levels

- New configuration defined with potential for fusion energy or experiment proposed for improving existing configuration.
- Basic analysis shows potential for scientific feasibility.

If the above criteria are satisfied, the configuration is a candidate for:

Concept Exploration (for fusion approaches, not for basic plasma science experiments)
- Clear potential to improve some important aspect of fusion power systems.
- Experiments and modeling show basic scientific feasibility of the concept.

If the above criteria are satisfied, the configuration is a candidate for:

Proof-of-Principle
- Conceptual study shows attractive (economic/environmental) power plant example.
- Experiments and modeling show broad understanding of physical principles of concept, and key physics issues favorably resolved for the next (PE/IRE) stage.
- Small-scale experiments show power plant technologies feasible to develop.
- Organized national team with development plan to DEMO decision.

If the above criteria are satisfied, the configuration is a candidate for:

MFE Performance Extension/IFE Integrated Research Experiment
- Detailed power plant design updated with PE/IRE data confirms attractive power plant.
- Well-diagnosed physics and technology demonstrated at sufficient scale, integration, and duration show that cost, performance, and reliability goals can be met.
- Data available from a burning plasma experiment from which reasonable extrapolation can be made to CTF/ETF and/or Demo.
- Theory and modeling proves adequate predictive capability for CTF/ETF and Demo.
- Development plan through DEMO to commercialization with the participation of U.S. industry.

If the above criteria are satisfied, the configuration is a candidate for advancement to the Component Testing and/or Demo stage:

Component Testing (MFE CTF/IFE ETF)
- Individual component reliability and integrated operation of fusion chamber and power technologies demonstrated.
- Safety and environmental requirements for U.S. licensing demonstrated.
- Sufficient fuel cycle closure demonstrated.
- For IFE, integrated near full scale driver demonstrated.
- For IFE, high yield targets optimized.

If the above criteria are satisfied, demonstrated technologies are candidates for application in:

Demonstration Power Plant
- Acceptable safety and environmental impacts demonstrated.
- Attractive economics projected for U.S. market.
- Technology is prepared for commercialization.
- 50% availability is demonstrated, extrapolable to commercial practicality.

If the above criteria are satisfied, fusion will be prepared for commercialization.

technology basis for the step to Demo will be supplied by ITER, IFMIF and CTF.

The cost-basis scenario as articulated provides for the option that Demo can be configured differently from the advanced tokamak as it is presently understood. It should be anticipated, however, that the initial operation of Demo will require more learning in this case and the initial production of electricity would be somewhat delayed as a result.

8. *The FIRE Scenario*

The U.S. is considering two options for a burning plasma experiment: ITER and FIRE, as discussed in Section 4. For simplicity, only the ITER option is used for the cost basis scenario presented above. Both ITER and FIRE would make significant scientific and technological contributions in burning plasma science. However there are differences in the opportunities offered by the two approaches. As discussed by FESAC in *A Burning Plasma Program to Advance Fusion Energy (2002)*,

- FIRE offers an opportunity for the study of burning plasma physics in conventional configurations for a few plasma current redistribution time periods and in advanced tokamak configurations under quasi-stationary conditions (several plasma current redistribution time periods), and would contribute to plasma technology.

- ITER offers an opportunity for the study of burning plasma physics in conventional configurations for a few plasma current redistribution time periods and in advanced tokamak configurations for long durations (many current redistribution time periods) with steady state as the ultimate goal, and would contribute to the development and integration of plasma and fusion technology.

The FESAC report also discussed differences in the roles of the two approaches within the development paths for fusion energy, as follows:

- A FIRE-based development plan reduces initial facility investment costs and allows optimization of experiments for separable missions. This option aims at smaller extrapolations in physics and technology. Assuming a successful outcome, a FIRE-based development path provides for additional optimization before further integration steps are needed, allowing a more advanced and/or less costly integration step that will follow.
- An international tokamak research program centered around ITER, which includes other performance-extension devices throughout the world, has the highest chance of success in exploring burning plasma physics in steady-state. ITER will provide valuable data on integration at power-plant relevant plasma support technologies. Assuming a successful outcome (demonstration of high-performance AT burning plasma), an ITER-based development path would lead to the shortest development time to a demonstration power plant.

From the perspective of the total cost to the U.S. for the development of commercial fusion energy, the difference between the FIRE and ITER paths is relatively minor. However there are some differences in the program schedule. Since ITER can operate essentially in steady-state, it would be the first test of an integrated Demo-scale fusion device operating in a nuclear environment, with initial tests of some fusion chamber technologies. Since the FIRE pulse length is about 20–40 seconds, in the FIRE path a steady-state DD experiment operating in parallel with FIRE is relied on to address steady-state issues. The KSTAR tokamak being constructed in South Korea and the JT60-SC tokamak under discussion in Japan are examples of such steady-state devices, which are assumed to be fully accessible to U.S. researchers. In the FIRE path the integration of burning plasmas with steady state operation is deferred to a later time. One impact of the deferral is that the integration would then first occur in the Component Test Facility. Thus an initial period of CTF operation, likely of several year duration, would be required to acquire operating experience with steady-state deuterium-tritium plasmas and fusion chamber technology. Similarly the start-up time of the DEMO might be extended for integration at large scale.

9. *Management Considerations*

In its August 1999 report "Realizing the Promise of Fusion Energy," the DOE Secretary of Energy Advisory Board (SEAB) stated "To achieve its goal, the program must be directed by strong management–a management that leads the effort toward the fusion energy goal at a reasonable pace, with sufficient budget, with solid accountability, and high-quality science and technology." This is especially true if the program seeks to operate a demonstration power plant on a set timetable within constrained financial resources. As stated by SEAB, "Given constrained budgets, the wide variety of options and the linkages of one issue to another, increasingly sophisticated management of the program will be required."

A successful fusion program requires the solution and integration of many disparate scientific, technological, economic and systems issues. As stated by SEAB, "Although each task could be initiated independently, conducting the tasks in parallel (through an integrated planning process) allows better cross-linking and integration of tools, understanding, and expertise." This approach is sometimes referred to as systems management and its adoption is essential to properly implement the development plan described in this report. The recent Integrated Program Planning Activity (IPPA) is a positive step in this direction.

The approach to fusion program planning today is, however, primarily "roll-forward" in nature, *i.e*, scientific and technological results from the ongoing program are weighed and, largely based on such considerations, the nature and timing of future decisions and steps is determined. This gives especial weight to the criteria of Quality and Performance discussed in Section 3. A successful fusion power development program requires, in addition, increased emphasis on Relevance of each step to the Plan described here and its ultimate goal, an attractive demonstration fusion power plant. This is sometimes referred to as a "roll-back" approach, *i.e.*, one in which the nature of the desired end-product (a fusion power demonstration plant that extrapolates readily to commercial power plants) is defined sufficiently that the physics, technology and engineering required for the Demo are identified and programs established and judged with respect to the goal of providing the required data. Clearly "roll-forward" and "roll-back" planning must be used in a complementary fashion for fusion ultimately to be successful. Quality, Performance and Relevance to the plan and its ultimate goal must all be key decision criteria.

Top level power plant objectives include, among others, minimization of projected cost of electricity, maximization of investment protection, minimization of capital costs, minimization of operating costs, maximization of availability, minimization of development costs, and maximization of public safety. Such targets, as well as relevance to the Plan presented here, should be incorporated into the fusion decision making process as a way to formally incorporate "roll-back" planning into fusion program management. Many aspects of this approach have been incorporated in the ARIES power plant design studies program. Such considerations should be formally used in guiding the evolution of the fusion program as a whole.

F. Conclusion

There have been dramatic scientific and technological advances in fusion in the last decade, and major accomplishments are expected with NIF and ITER (or FIRE) in the next. A ramp-up in domestic fusion research and development is required now to impact the direction of these upcoming burning plasma research experiments, in order to guide them in addressing critical issues in the development of practical fusion energy. Rapid progress is also needed in configuration optimization experiments for both MFE and IFE, because critical decisions must be made on key future investments by 2008 in order to maintain the needed schedule. The design of IFMIF and the domestic fusion technology program must move forward as well, if technologies are to be available for testing in ITER and materials are to be made available for testing in CTF/ETF and Demo. A program funded at present levels cannot accomplish these essential schedule-driven steps.

The total cost to the U.S. of the plan to bring on line a first-generation Demonstration fusion power plant that will lead to commercial application of fusion energy by mid-century is approximately $24B in FY2002 dollars. The plan assumes an ongoing level of highly coordinated international programmatic activities, and international participation in ITER and IFMIF, but assumes U.S.-only support for CTF or ETF, and Demo. It assumes continuing strong NNSA support of Inertial Confinement Fusion.

To achieve the goals of this plan, the program must be directed by strong management. Given constrained budgets, the wide variety of options and the linkages of one issue to another, increasingly sophisticated management of the program will be required.

Additional funding that would be needed in the second half of the development plan to maintain a strong core scientific capability, and to provide continued innovation aimed at improved configurations beyond Demo, is not included. The panel believes that these are necessary elements of an overall fusion R&D program. The panel has not attempted to analyze these costs in a systematic manner but estimates they would sum to a few billion dollars.

The U.S. fusion energy sciences program is still suffering from the severe budget cuts of the mid-1990s and the loss of a clear national commitment to develop fusion energy. The result is that despite the exciting scientific advances of the last decade it is becoming difficult to retain technical expertise in key areas. The President's fusion initiative has the potential to reverse this trend, and indeed to motivate a new cadre of young people not only to enter fusion energy research, but also to participate in the physical sciences broadly. With the addition of the funding recommended here, an exciting, focused and realistic program can be implemented to make fusion energy available on a practical time scale. On the contrary, delay in starting this plan will cause the loss of key needed expertise and result in disproportionate delay in reaching the goal.

Establishing a program now to develop fusion energy on a practical time scale will maximize the capitalization on the burning plasma investments in NIF and ITER, and ultimately will position the U.S. to export rather than import fusion energy systems. Failure to do so will relegate the U.S. to a second or third tier role in the development of fusion energy. Europe and Japan, which have much stronger fusion energy development programs than the U.S., and which are vying to host ITER, will be much better positioned to market fusion energy systems than the U.S.–unless aggressive action is taken now.

It is the judgment of the Panel that the plan presented here can lead to the operation of a demonstration fusion power plant in about 35 years, enabling the commercialization of attractive fusion power by mid-century as envisioned by President Bush.

APPENDIX A: SCIENTIFIC AND TECHNOLOGICAL CHALLENGES

The plan laid out in this report leads to a demonstration fusion power plant. A key feature is that there are many major accomplishments and discoveries that will occur along the way. These accomplishments are part of a coordinated plan to provide key information needed for design of a DEMO. However, they will themselves constitute major advances in plasma science, technology, and fusion energy science. These advances will provide, to both fusion scientists and the public, crucial information on the feasibility and characteristics of fusion power. Below are summarized some of these major goals for MFE and IFE, building on previous work by FESAC.

A.1 Magnetic Fusion Energy

In December, 2000, the Integrated Program Planning Activity (IPPA) carried out by the fusion community identified challenges for magnetic fusion energy in four areas: fundamental plasma science, configuration optimization, burning plasma science, and materials and technology. We discuss each of these major areas in turn, focusing only on selected grand challenges. Fundamental plasma science underlies all of the endeavors. However, to connect advances in fundamental plasma science to specific milestones, we merge its discussion with that of configuration optimization. Other areas of science, in particular materials and engineering science, underlie the materials and technology endeavor.

A.1.1 Fundamental Plasma Science and Configuration Optimization

The overarching goals, stated in the IPPA report is

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

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

Advances in fusion energy rely upon discoveries in fundamental plasma physics. These advances are, in part, used to evolve magnetic configurations to confine fusion plasmas. Research on a variety of magnetic configurations are planned for two reasons. First, the optimal fusion system will be evolved, and critical fusion science issues will be resolved, through research on a spectrum of configurations, linked through theoretical understanding and advanced computing. Second, specific configurations have potential to extrapolate into fusion systems with favorable attributes, either for the first DEMO or for the second generation DEMO.

Three dominant scientific challenges are:

i. *What is the fundamental upper limit to the plasma pressure, and how can it be optimized?* The fusion power increases with plasma pressure. The plasma pressure is gauged relative to the magnetic pressure that contains the plasma. All plasmas are subject to a pressure limit, beyond which the plasma will disassemble or lose its energy. The scientific challenge is to understand the mechanisms that limit the pressure and how the plasma behaves at the limit. Confinement configurations are being developed that optimize the pressure limit.

ii. *What is the mechanism for energy transport from electric and magnetic turbulence, and how can the transport be minimized?* Plasmas tend spontaneously to develop turbulence in which the electric and/or magnetic fields fluctuate, releasing energy from the plasma. This energy loss cools the plasma, inhibiting fusion. Treatment of plasma turbulence in fusion plasmas has been revolutionized in recent years through new understanding of its cause and new techniques for its control.

iii. *How can plasmas be sustained in steady-state against resistive decay?* It is desirable that a plasma in a fusion system persist in a steady-state. In recent years it has been discovered that a tokamak plasma current is spontaneously generated in the plasma–a form of a thermo-electric effect unique to a plasma in a complex magnetic field. This "bootstrap current" has the potential to sustain a tokamak or spherical torus in steady-state. Other configurations are under study that do not require plasma current for confinement (the magnetic field is produced entirely by external magnets), and are thereby inherently steady-state devices. Self-organized configurations such as the RFP and spheromak may take advantage of reconnection and magnetic helicity conservation for non-inductive startup and steady-state sustainment.

A.1.2 Burning Plasma Science

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

A crucial step in fusion energy research is the study of a high-performance (*i.e.*, well-confined, high pressure, parameters in the reactor range), burning plasma. The defining feature of a burning plasma is that it is self-heated: the 200 million degree temperature in the core 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 similarly essential to the development of fusion energy.

A.1.3 Technology

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

The technological challenges of containing and controlling a fusion plasma, and producing the tritium fuel, are large and require both fundamental technological development and innovation. These challenges include the development of new low-activation materials that can withstand the fusion neutron environment and new technologies including plasma facing components, chamber technologies, current drive and heating systems, tritium technology and superconducting magnets. Systems studies guide both the technology and physics research, providing information on the impact of specific design elements on fusion reactor attractiveness.

A.2 Inertial Fusion Energy

In December, 2000, the Integrated Program Planning Activity (IPPA) carried out by the fusion community identified challenges for inertial fusion energy in two areas: inertial fusion energy targets, and repetitive driver power plants. We discuss these major areas in turn.

A.2.1 Inertial Fusion Energy Targets

Advance the fundamental understanding and predictability of high energy density plasmas for IFE, leveraging from the ICF target physics work sponsored by the National Nuclear Security Agency's Office of Defense Programs.

A crucial step in inertial fusion energy research is the development and demonstration of target physics leading to ignition and high-yield/high-gain targets. The target categories include direct-drive (where the driver energy couples directly to the target), indirect-drive (where the driver energy is converted to x-rays, which then couple to the target), and fast ignition (where an intense petawatt driver ignites a spot in a target compressed by a main driver–laser, heavy ion, or z-pinch). Target physics challenges include driver/target interaction and coupling, energy transport and symmetry to the target, implosion dynamics and equation of state (EOS) of materials, hydrodynamic instability and mix, and ignition and burn propagation. The development of target physics research in NNSA leads naturally into the development of high-yield/high-gain targets needed for IFE.

A.2.2 Repetitive Driver Power Plants

Develop the science and technology of attractive rep-rated IFE power systems, leveraging from the work sponsored by the National Nuclear Security Agency's Office of Defense Programs.

An IFE system consists of a main driver (laser, heavy ion, z-pinch), a target (indirect-drive, direct-drive, fast ignition), and a chamber concept (dry-wall, wetted-wall, thick liquid wall). The mainline approach for lasers is to use a rep-rated KrF laser or rep-rated diode-pumped solid-state laser, a direct-drive target, and a solid-wall power chamber. The mainline approach for heavy ions is to use a rep-rated induction linac heavy ion driver, an indirect-drive target, and a thick liquid wall chamber. The mainline approach for z-pinches is to use a rep-rated z-pinch driver, an indirect-drive target, and a number of thick liquid wall chambers. A fast ignition target is an option for any of the three main drivers.

Each driver concept must pass through the proof-of-principle (PoP) phase of development and the Integrated Research Experiment (IRE) phase of development. Each phase of development includes R&D on rep-rated drivers, energy transport to the target (final focus magnets for heavy ions, final optics for lasers, and recyclable transmission line placement for z-pinches), IFE target physics, target fabrication, target injection or placement, chamber walls, and power plant system optimization.

Following the PoP and IRE phases of development, the three approaches will then compete for development of a single Engineering Test Facility (ETF) that will lead to a DEMO. This ETF will be in competition with an MFE Component Test Facility (CTF), and in this plan, only one of these will go forward to support Demo.

APPENDIX B: PROGRAMS AND MAJOR FACILITIES

This appendix provides descriptions of each of the programs and major facilities in the plan shown in Figures 5–7.

B.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. A key long-term deliverable is the Fusion Plasma Simulator that is capable of comprehensive simulation of all relevant processes in fusion systems. It will also serve the important purpose of transferring knowledge gained from more mature systems to exploratory configurations. 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 including the fast ignition approach.

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.

B.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. Some Concept Exploration facilities, particularly in the tokamak, stellarator and ST areas, examine specialized issues in support of larger facilities. There is strong scientific cross-fertilization between configurations, ideas are exchanged and hybrid configurations emerge. A broad portfolio strengthens the quality of fusion science, and widens its application beyond the fusion arena. An important aspect of this research is the development and application of innovative plasma measurement tools so that theory and simulation can be validated against experiment in specific detail.

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.

B.2.1 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 experimentally stellarators are 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.

B.2.2 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 U.S. 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 provided confidence in extrapolating present results to future devices. In addition PE-class facilities have a strong focus on developing improved performance operating modes. In tokamaks this is 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. In the advanced tokamak 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.

B.2.3 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 U.S. 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 capsule compression experiments for the fast ignition approach are being carried out on Z and Omega.

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, as well as 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).

B.2.4 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 and target requirements in each approach.

To qualify for the 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.

B.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.

B.3.1 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.

The U.S. has decided to join the negotiations for the construction of ITER, as recommended by FESAC. If ITER goes forward it will fulfill all of the requirements for an MFE burning plasma experiment. On the other hand, if the international negotiations do not succeed, and ITER does not go forward, FIRE is an attractive option for the study of burning plasma science as discussed by FESAC. Either ITER or FIRE 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. A scenario including FIRE, rather than ITER, is considered in Section 5.7.

B.3.2 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. Direct drive capability is anticipated to be available in 2013.

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.

B.4 Materials

B.4.1 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.

B.4.2 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 $\sim 0.5-1$ MW yr/m^2 ($\sim 5-10$ 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: ≥ 0.5 liter volume with ≥ 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 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 (5×20 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.

B.5 Engineering Science/Technology Development

B.5.1 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. Most of the improvements in plasma performance were made possible by improved plasma technologies such as plasma facing components, plasma fueling methods, and better heating technologies.

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.

The successful development of high performance plasma facing components (PFCs) is central to the overall development of fusion, and has posed progressively more difficult challenges as the power of fusion devices has increased. Helium ash removal requires particle flow to the first wall region (e.g., divertor) and with the particles comes intense heat. PFCs are bombarded by energetic neutrals, ions, electrons and photons and must survive intense plasma-materials interactions, without contaminating the plasma. In long pulse devices, PFCs must continuously remove high heat fluxes while withstanding off-normal heating transients. In DT devices, remotely maintained PFCs must survive neutron radiation and cyclic thermal heat loads while avoiding unacceptable tritium inventories.

In order to complete the R&D for ITER, it will be necessary to demonstrate reliable operation of a prototype, multimegawatt, 170 GHz gyrotron, window, power supply, transmission line and launcher. A development path would consist of final development of each component, construction of a test stand and lifetime testing of the system. Cost reduction in manufacturing would also be an objective.

Present day ion-cyclotron heating (ICH) systems have demonstrated the viability of this technology, but substantial R&D will be required to make robustly reliable systems that could be used on ITER and potentially DEMO. Prototypes of antenna launchers should be built to validate the mechanical and electrical designs. It is necessary for these antenna systems to operate reliably at the required voltage levels. R&D is needed to understand the fundamental reasons for breakdown, to develop techniques to avoid it, and to acquire the desired confidence level in the projected performance. Advanced antenna designs encompasses several innovative ideas that should improve the operation and reliability of the ICH system. Testing of these new concepts will be needed in dedicated test stands as well as in a real plasma environment.

Future fueling (and, for tokamaks, related disruption mitigation) systems will require significant extrapolations beyond present-day performance in both throughput (ie. approaching steady state), velocity (ie. to the burning plasma regime) and reliability and flexibility. A progression in development objectives for ITER, CTF, and DEMO is envisaged along with increasing-scale dedicated test stands for prototype testing with full DT capability.

Superconducting magnet systems represent a major cost element for long-pulse or burning-plasma devices. While dramatic progress has been made in development of large-scale DC and pulsed Nb_3Sn magnets for ITER at up to 13 T, further increases in performance (16T) and reductions in cost should be realized by development of higher performance superconductor (both low and high temperature), higher strength structural materials, more radiation-resistant insulators, improved quench detection techniques, and related R&D on joints, leads, feedthroughs, refrigeration etc. Dedicated test stands such as a Pulsed Superconducting Magnet Facility and full-scale prototypes will complement this component development program.

B.5.2 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 U.S., 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/thermomchanical/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.

B.5.3 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 will be 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 1 MW/m^2 and cumulative neutron fluence greater than 6 MW $years/m^2$ 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 ($\sim$150 MW) and would likely be operated in a driven mode. In later stages, the facility may achieve a tritium-breeding ration 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.

B.5.4 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.

B.6 Systems Analysis, Design, and Demo

B.6.1 Systems Analysis and Design

Systems analysis and design supports major program evaluation and decision points and guides fusion research and development toward practical products.

Table 5. Top-Level Goals for the U.S. 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 than 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.

System designs for all configurations, magnetic and inertial, need to be updated in a timely manner as new advances are made in fusion science and technology. Objectives of such activities include (1) establish, standardize and maintain codes for evaluating costs and systems issues for fusion designs, (2) evaluate various potential commercial applications, (3) prepare and evaluate designs of Demo, power plant and other applications for all credible fusion concepts and approaches, (4) identify high leverage issues, (5) evaluate and optimize various possible development paths, (6) identify and evaluate issues associated with safety, environment and licensing, (7) establish and maintain an engineering database, (8) evaluate the potential of non-DT fuel cycles, and (9) maintain and critically evaluate market factors and status of competitive technologies.

B.6.2 Demo

The U.S. 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 power producers and the general public 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 gain operational experience and the public is 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 5 presents the top-level goals for the U.S. Demo.

APPENDIX C: PRIMARY 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 D: FESAC RESPONSE TO CHARGE

March 5, 2003

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) here submits the final report of the Fusion Development Path Panel, with FESAC's strongest, unanimous endorsement. In response to your charge of September 10, 2002, the Panel has constructed a plan to provide what the President has described as "commercially available fusion energy by the middle of this century." The first stage of the report, which outlined the key scientific and technical issues, was submitted to you on December 12, also with unanimous FESAC endorsement. The present, final stage of the report brings additional structure and detail to the information of Stage 1; in particular, it includes cost estimates.

On December 18, after the Development Path Panel had begun its work, you submitted a second charge to FESAC, to study new and upgraded facilities within the fusion program, as part of the Twenty Year Facilities Plan being constructed by the Office of Science. Because this charge overlapped in several respects the Development Path work already underway, I asked the Development Path Panel to respond to both charges in a single report. Hence the present Report includes, beginning on page 77, a detailed response to the facilities charge. Of course FESAC's unqualified endorsement applies equally to this segment of the Report.

In endorsing this report, FESAC congratulates and thanks the members of the Development Path Panel and its Chair, Professor Goldston, for their extraordinary effort. Despite the complexity of the task and the rigorous schedule that was imposed, the Panel completed a thorough, systematic study, identifying "critical milestones, key decision points, needed major facilities and required budgets." FESAC finds the Report to be rational, impressively detailed and altogether convincing.

Beginning with the observation that "recent advances in the science and technology of fusion energy have dramatically improved the prospect for practical fusion power," the Report identifies key tasks whose accomplishment "will form a strong basis for the development of practical, economically competitive fusion energy." It concludes that "establishing a program now to develop fusion energy on a practical time scale will maximize the capitalization on the burning plasma investments in NIF and ITER, and ultimately will position the US to export rather than import fusion energy systems."

Yours truly,

Richard Hazeltine
Chair. Fusion Energy Sciences Advisory Committee

APPENDIX E: PROCESSES USED BY THE PANEL

October 3–4
A panel, Appendix E, 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
The Fusion Energy Sciences Advisory Committee met in Gaithersburg, MD, reviewed the Preliminary Report, concluding that "The present Preliminary Report has the unanimous, unqualified endorsement of FESAC."

January 13–16
An open community meeting was held at General Atomics in San Diego on January 13–14, in which invited speakers presented cost and schedule requirements for the major project elements of the Plan and contributed speakers also made oral presentations to the Panel. A substantial fraction of the time on the agenda was devoted to public discussion with the fusion community present. Written submissions were received as well. The Panel then met on January 15–16 and discussed Program elements and worked to develop the Cost-Basis Scenario.

February 9–10
A Panel meeting was held at the Princeton Plasma Physics Laboratory focused on completing the response to the second Charge Letter and moving towards closure on the Final Report.

February 27–28
The Panel completed its work through two extensive conference calls.

APPENDIX F: 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 U.S. 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 (REP): 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.

APPENDIX G: ADDITIONAL CHARGE LETTER

December 18, 2002

Professor Richard D. Hazeltine
University of Texas at Austin
Institute for Fusion Studies
One University Station-C-15 00
Austin, TX 78712-0262

Dear Professor Hazeltine:

For more than a half-century the Department of Energy's Office of Science has envisioned, designed, constructed and operated many of the premiere scientific research facilities in the world. More than 17,000 researchers and their students from universities, other government agencies, private industry and from abroad use Office of Science facilities each year-and this number is growing. For example, the light sources built and operated by DOE now serve more than three times the total number of users, and twenty times as many users from the life sciences, as they did in 1990.

Creating these facilities for the benefit of science is at the core of our mission and is part of our unique contribution to our Nation's scientific strength. It is important that we continue to do what we do best: build facilities that create institutional capacity for strengthening multidisciplinary science, provide world class research tools that attract the best minds, create new capabilities for exploring the frontiers of the natural and physical sciences, and stimulate scientific discovery through computer simulation of complex systems.

To this end, I am asking all the Office of Science's advisory committees to join me in taking a new look at our scientific horizon, and to discuss with me what new or upgraded facilities will best serve our purposes over a timeframe of the next twenty years. More specifically, I charge the committees to establish a subcommittee to:

A. Consider what new or upgraded facilities in your discipline will be necessary to position the Office of Fusion Energy Sciences at the forefront of scientific discovery. Please start by reviewing the attached list of facilities, assembled by Dr. Anne Davies and her team, subtracting or adding as you feel appropriate, with prudence as to cost and timeframe. For this exercise please consider only facilities/ upgrades requiring a minimum investment of $50 million.
B. Provide me with a report that discusses each of these facilities in terms of two criteria:
   1. The importance of the science that the facility would support. Please consider, for example: the extent to which the proposed facility would answer the most important scientific questions; whether there are other ways or other facilities that would be able to answer these questions; whether the facility would contribute to many or few areas of research; whether construction of the facility will create new synergies within a field or among fields of research; and what level of demand exists within the scientific community for the facility. In your report to me please categorize the facilities in three tiers, such as "absolutely central," "Important," and "don't know enough yet," according to the potential importance of their contribution. Please do not rank order the facilities.
   2. The readiness of the facility for construction. Please think about questions such as: whether the concept of the facility has been formally studied in any way; the level of confidence that the technical challenges involved in building the facility can be met; the sufficiency of R&D performed to-date to assure technical feasibility of the facility; and the extent to which the cost to build and operate the facility is understood. Group the facilities into three tiers according to their readiness, using categories such as "ready to initiate construction," "significant scientific/engineering challenges to resolve before initiating construction," and "mission and technical requirements not yet fully defined."

Many additional criteria, such as expected funding levels, are important when considering a possible portfolio of future facilities, however for the moment I ask that you focus your thoughts on the two criteria discussed above.

I look forward to hearing your findings and discussing these with you in the future. I would appreciate at least a preliminary report by March, 2003.

Sincerely,

Dr. Raymond L. Orbach
Director
Office of Science

APPENDIX H: RESPONSE TO ADDITIONAL CHARGE

The facilities described here are those considered to be essential elements of a fusion energy development path that provides acceptable confidence of achieving a Demonstration power plant within 35 years, leading to commercialization of a generation of attractive fusion power systems.

For this goal to be achieved, each of these facilities must operate during the time window of the Charge. Other facilities which must begin construction during the next twenty years, but will not operate during this time window, have not been detailed here. The overall cost profile for the fusion energy development program is included in the main body of the report in response to the Charge to FESAC of September 10, 2002.

PROJECT: MFE BURNING PLASMA (ITER OR FIRE)—COST CATEGORY: ABOUT $1B US COST

Mission:

Demonstrate the scientific and technological feasibility of magnetic fusion power.

Importance of the Science:

Burning plasmas at near power plant scale will present new scientific challenges that must be explored and understood to enable the development of fusion energy. Research on a burning plasma, where the plasma is mainly self-heated by fusion reaction products, explores the complexity of the nonlinear behavior of magnetically confined plasma at high temperature and pressure, a behavior that in turn may be modified by the fusion-generated alpha-particle heating. Scientific topics include turbulent confinement of the plasma, the spectrum of energetic particle modes and Alfvénic modes, alpha particle-effects on MHD modes, and plasma-material interactions. Operation of the power plant at high plasma pressure in steady state, which would lead to an efficient, robust energy-production system, will be more challenging at the larger scale of a burning plasma and in the presence of nonlinear alpha-particle heating, where new phenomena and changes in previously studied behavior are expected.

A burning plasma experiment will offer an early opportunity to apply technologies needed for a fusion power plant, at a level depending on its scope and scale: heating, current drive, and fueling systems; hardened diagnostics; remote handling, superconducting coils of unprecedented size and energy; tritium-processing of the effluent and re-injection as fuel; high-heat-flux components at reactor-relevant loads; and tritium-producing blanket designs, which both handle the fusion power and create tritium via interaction of the fusion-produced 14 MeV neutrons with lithium. A burning plasma experiment will provide an integrated demonstration of the reliability and effectiveness of the subsystems. In addition a burning plasma experiment can demonstrate the favorable safety characteristics of a fusion power plant.

Readiness:

Scientific Readiness

1. There is high confidence in confinement projections.
2. Operational boundaries (*e.g.*, plasma pressure and current limits) are well-understood, and feedback control techniques are being developed.
3. There is confidence that abnormal events can be avoided or mitigated, although further R&D is needed to present less stringent heat loads to plasma-facing components.
4. There is confidence that the required plasma purity can be obtained, including helium removal and the inhibition of impurity influx from the first wall and divertor.
5. Diagnostic techniques are available to characterize and evaluate most of the important parameters in a burning plasma.
6. Plasma control techniques are available to produce and evaluate burning plasma physics and to explore steady-state advanced operational regimes.

Technical Readiness

1. The ITER design is prepared to enter construction, based on comprehensive international Engineering Design Activities and extensive associated R&D. The FIRE design will complete a Physics Validation Review in FY2003.
2. It is clear that the necessary components, including magnetic field coils, the vacuum vessel, the divertor, and the first-wall components, can be manufactured.
3. Major components can operate within the design requirements in the expected nuclear environments.
4. There has been adequate progress in the construction of plasma-facing components that can accept high heat flux, particle flux, and mechanical stresses, including during disruptions.
5. There is confidence in the ability to minimize tritium retention. However, further research is needed to increase the operational duty cycle of the device.
6. The required remote maintenance for a burning plasma experiment has been demonstrated.
7. There must be adequate fueling, heating, and current drive techniques to control and explore burning plasmas. There is high confidence that these can be provided.

PROJECT: INTEGRATED BEAM EXPERIMENT (IBX)—COST CATEGORY: $50-99M

Mission:

The mission of the IBX is to validate the key physics of high current heavy-ion beams with injection, acceleration, longitudinal pulse compression and focusing to spot sizes necessary for energy-producing targets.

- The IBX would be the first of three integrated facilities, the next being the Integrated Research Experiment, a prototype accelerator to validate an intense ion-beam driver, and the last being the inertial fusion Engineering Test Facility (ETF) that would demonstrate the viability of inertial fusion energy.
- The IBX would provide well-diagnosed beam data essential to benchmark and improve the physics used in the development of an integrated beam model, which in turn would optimize the designs for IRE, ETF, and power plant drivers.

Importance of the science:

- For heavy-ion fusion accelerators as well as for many high ion current accelerators in the world such as the PSR at LANL, the SNS at Oak Ridge, and the GSI-SIS-18 storage ring at Darmstadt, Germany, the scientific research in IBX will provide new insight into the behavior of high current beams which are non-neutral plasmas with sufficient space charge to exhibit many collective effects, such as longitudinal space charge waves, production and loss of halo ions, and electron-ion two-stream instabilities. Understanding these issues will benefit the success of high current ion accelerators world-wide.
- In heavy-ion fusion in particular, the IBX would provide the *first* proof-of-principle test of source-to-target heavy-ion fusion-relevant beam physics needed to predict the focal spot size in the following IRE and ETF.
- The IBX is the essential proof-of-principle facility for the next step in heavy-ion fusion research, and would be unique in the world due to the high-current capability of its induction accelerator. It would provide capability for a variety of beam transport, compression and focusing experiments by researchers from several U.S. fusion laboratories and universities, and collaborations with scientists from heavy-ion physics laboratories in Germany and Japan.

Readiness of the facility for construction:

- The technical basis for the IBX is presently being developed by three separate, modest-scale experiments that address, by FY04, the source, transport, and final focus issues that will each contribute to understanding parts of the beam quality evolution (for beam focusing) in IBX.
- Existing induction accelerator technology largely satisfies the hardware needs to build IBX, in the induction modules of the Experimental Test Accelerator at LLNL, in the injector of the Relativistic-Two-beam Accelerator at LBNL, and in prototype beam transport magnets that have been built and tested at MIT and LBNL.
- The mission, scope and general pre-conceptual design principles of IBX are well understood. The project cost estimate of $50–70M is benchmarked against earlier accelerator designs of similar scale. The project will be ready to proceed to a Physics Validation review and FESAC approval for PoP status leading to CD-0 in FY04, assuming adequate funding for preconceptual design.

PROJECT: INTERNATIONAL FUSION MATERIALS IRRADIATION FACILITY (IFMIF)—U.S. COST: $150M

Mission:

The mission of the IFMIF, developed by the international fusion community, is to qualify materials for fusion application. IFMIF will experimentally validate emerging models of the effects of exposure of materials to fusion-relevant environments and identify potentially new physical phenomena associated with intense high energy fusion neutron irradiation not achievable with existing or other planned fission, fusion or spallation neutron facilities. IFMIF will qualify materials for use in an MFE Component Test Facility or an IFE Engineering Test Facility, as well as a fusion Demo power plant.

Importance of the science:

- A major long-standing critical issue for fusion energy is the development of materials that can adequately function in the intense DT fusion neutron environment. 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 in fusion is predicted to have significant influence on the microstructural stability of materials for fluences above ~0.5–1 MW yr m^{-2} (~5 to 10 displacements per atom). Therefore, an intense high-energy neutron source is essential for development and qualification of the materials for the first wall, plasma facing components, and breeding blanket components of Demo configurations that do not utilize a thick liquid wall.
- In addition to providing key scientific insight into the microstructural stability of materials in a fusion environment, this facility will enable important experimental validation of current materials science radiation effects models. This information will be valuable for establishing comprehensive radiation effects models that can be usefully applied to a wide range of future nuclear facilities including Gen IV fission reactors, spallation neutron sources, etc.
- IFMIF is the key materials science facility for fusion, and timely deployment of the facility is required in order to develop fusion energy within the next 35 years. This facility will leverage and enhance current international materials science collaborations.

Readiness of the facility for construction:

The international design team has completed a conceptual design for IFMIF. The team has proposed a five-year engineering validation phase in parallel with a detailed engineering design activity, to commence in 2004. This activity is intended to resolve the remaining key technology issues for the facility and to provide a robust cost estimate for construction. The technology for IFMIF is based on state-of-the-art accelerator design. IFMIF is 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 × 20 cm beam footprint). Work at recent facilities such as LEDA at Los Alamos and the Spallation Neutron Source project has been instrumental in validating much of the physics and resolving cost issues. Preliminary cost estimates for construction of this international facility are ~0.6 B$ over a period of 6 years. Construction of the facility should commence in FY2009 to meet the goal of deploying a fusion demonstration power plant in 35 years.

**PROJECT: MAGNETIC FUSION ENERGY PERFORMANCE EXTENSION FACILITIES—
COST RANGE: 2 ± 1 FACILITIES @ $200M-$600M EACH**

Mission:

A Performance Extension class experiment in magnetic fusion energy is a facility designed to test a magnetic confinement configuration in plasma parameter regimes close to those which would be encountered in a burning plasma. This will provide good understanding of the science and performance potential of the configuration as a fusion power source. The fusion development path towards Demo envisions two new such facilities, one to begin construction in approximately FY2009, and a second in approximately FY2013. The configuration tested in either could be employed in Demo, through use of burning plasma data from ITER and advanced computation. Whether the experiment will require deuterium-tritium operation (as in TFTR and JET) is a matter which will depend on the configuration being considered and on the degree of confidence that can be placed at that time in theoretical calculations and experimental simulations using, for example, high-energy beams. The first facility could have the mission of preparing the physics basis for a compact Component Test Facility (CTF).

Importance of the Science

A range of magnetic confinement configurations is being explored in the laboratory. Small-scale Concept Exploration and mid-scale Proof of Principle experiments are able to test many aspects of the basic physics of a new configuration. However dimensionless parameters such as ρ^* (ion gyroradius/system size) are sufficiently different from fusion energy systems that confident extrapolation is not possible. A Performance Extension experiment addresses such critical fusion science issues as turbulence and resulting energy and particle transport, MHD stability limits, discharge initiation and sustainment and plasma-material interactions at fusion-relevant plasma parameters. Key configuration-specific technologies are also developed and tested.

Examples of attractive configurations which could compete for the first future MFE PE experiment include those now being tested at the Proof-of-Principle level, such as the reversed field pinch and the spherical torus, and those which already are being tested at the PE level, such as the advanced tokamak, but would propose to explore new operation regimes, for example in support of the CTF. The second future MFE PE experiment, in addition to the above, could be based on a configuration currently at the concept exploration level, such as the spheromak or FRC after a successful Proof-of-Principle scale test, or could follow on from the proof-of-principle compact stellarator experiment currently under construction.

Readiness for construction

At present there is no proposed facility in this category designed to a level of detail sufficient for a near-term construction decision. Several pre-conceptual designs exist, but await confirmatory physics results from current experiments and more detailed engineering design studies. Further consideration of application to the CTF mission is required. Clear criteria have been defined by FESAC to assess readiness for PE class experiments. These include plasma science and technology benefit, likelihood of resolving key physics and technology issues, and the attractiveness of the energy vision for the configuration. The decision making process would include a peer-based Physics Validation Review, approval by FESAC for PE status, and then peer-based Conceptual, Preliminary and Final Design reviews.

**PROJECT: INERTIAL FUSION ENERGY INTEGRATED RESEARCH EXPERIMENTS—
COST RANGE: 2 ± 1 FACILITIES @ $150M-$350M**

Mission:

The Integrated Research Experiments (IRE) will establish the science and technology required to justify and build the Engineering Test Facility (ETF) for inertial fusion energy (IFE). The development of each IFE concept (Z-Pinch, Heavy Ions, and Lasers) requires an IRE.

Importance of the Science:

The IREs integrate both full scale and subscale components to ensure the key driver, chamber, target and final optics components can work together with the required efficiency, precision, and durability. The IREs, coupled with target physics results from the National Ignition Facility (NIF), Omega, and Z, will answer all the important scientific and technical questions needed to proceed to the ETF.

The ETF is a multi-billion dollar class nuclear facility that will be the last step before a commercially viable Demo. It will be used to demonstrate and optimize high gain and it will demonstrate power plant scale final optics/power focusing, target production, and target injection. It will operate at pulse repetition rates suitable for a fusion power plant. It will optimize blanket/chamber technologies, and potentially produce net electricity.

To start such a major program, the underlying science and technology must be mature enough that we can confidently predict they will lead to an economically viable fusion power plant. The goal of the IRE is to establish that science and technology.

The IRE and its associated research program are essential for developing a given IFE configuration into a fusion power source. The IRE will require research and development in a wide range of scientific disciplines, including the physics of plasmas, particle beams, lasers and z-pinches; the science of materials and related nanotechnologies; the behavior of complex fluid flows; and low temperature physics, optics and chemistry. Thus the underlying science will contribute to a wide range of research and technology development both inside and outside fusion research.

Readiness:

None of the IFE configurations is now ready to proceed to the IRE, as significant scientific and technical challenges must be resolved. However the mission and technical requirements for the IRE are well defined and the present R&D programs will validate the technical feasibility of the IREs and fully establish their cost.

The technical goals for justifying the IREs are similar for all three IFE approaches. Each approach must meet specific criteria for each of the principal components: Driver, final optics/power focusing system, target fabrication, target injection, chamber, and target physics. Each must produce a viable point design as well. The decision making process would include a peer-based Physics Validation Review, approval by FESAC for PE status, and then peer-based Conceptual, Preliminary and Final Design reviews.