Fusion Development Path Panel

Final Report

Rob Goldston and
the Development Path Panel

Presentation to FESAC

March 5, 2003

Panel Members

- Mohamed Abdou, University of California, Los Angeles
- Charles Baker, University of California, San Diego
- Michael Campbell, General Atomics
- Vincent Chan, General Atomics
- Stephen Dean, Fusion Power Associates
- Robert Goldston (Chair), Princeton Plasma Physics Laboratory
- Amanda Hubbard, MIT Plasma Science and Fusion Center
- Robert Iotti, CH2M Hill
- Thomas Jarboe, University of Washington
- John Lindl, Lawrence Livermore National Laboratory
- Grant Logan, Lawrence Berkeley National Laboratory
- Kathryn McCarthy, Idaho National Engineering Laboratory
- Farrokh Najmabadi, University of California, San Diego
- Craig Olson, Sandia National Laboratory, New Mexico
- Stewart Prager, University of Wisconsin
- Ned Sauthoff, Princeton Plasma Physics Laboratory
- John Sethian, Naval Research Laboratory
- John Sheffield, ORNL, and UT Joint Institute for Energy and Environment
- Steve Zinkle, Oak Ridge National Laboratory

Process

- **October 3 – 4**
  - Preliminary definition of a Demo.
  - Key factors affecting logic and timeline.
  - Near-term issues for the plan.
- **October 28 – 30**
  - Experts on key factors.
  - EU and JA development path groups.
- **Nov 11 (UFA), 12 (FESAC), 15 (Dev. Path Committee)**
  - Report and input at APS
- **November 25 – 26, FESAC Review of Preliminary Report**
- **Dec 3, Presentation at FPA**
- **January 13 – 14, Community Workshop**
- **January 15 – 16, Panel Meeting**
  - Program Elements
  - Cost Basis Scenario
- **February 9 – 10, Panel Meeting**
  - Second Charge
  - Moving towards closure
- **February 27 – 28, Conference Calls**
  - Extensive conference calls to complete report
- **March 5, 2003, Report to FESAC**

Outline of Report

- ***Executive Summary***
- ***Introduction***
- **Fusion as an Attractive Energy Source**
- **Principles of the Plan**
- **Elements of the Plan**
- ***Cost-Basis Scenario***
- ***Conclusion***

(red italics: bulk of new material)

The Administration on Fusion

"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

The Last Decade has Seen Dramatic Advances - I

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***.

The Last Decade has Seen Dramatic Advances - II

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.

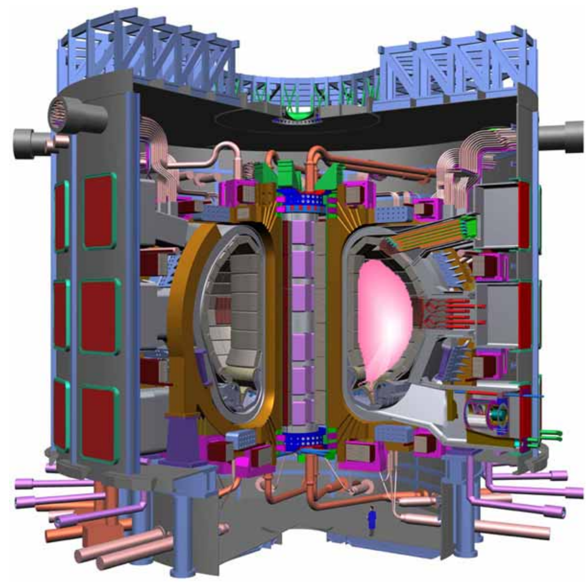
The Last Decade has Seen Dramatic Advances - III

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***.

NIF and ITER Drive the Urgency of the Plan

NIF

ITER

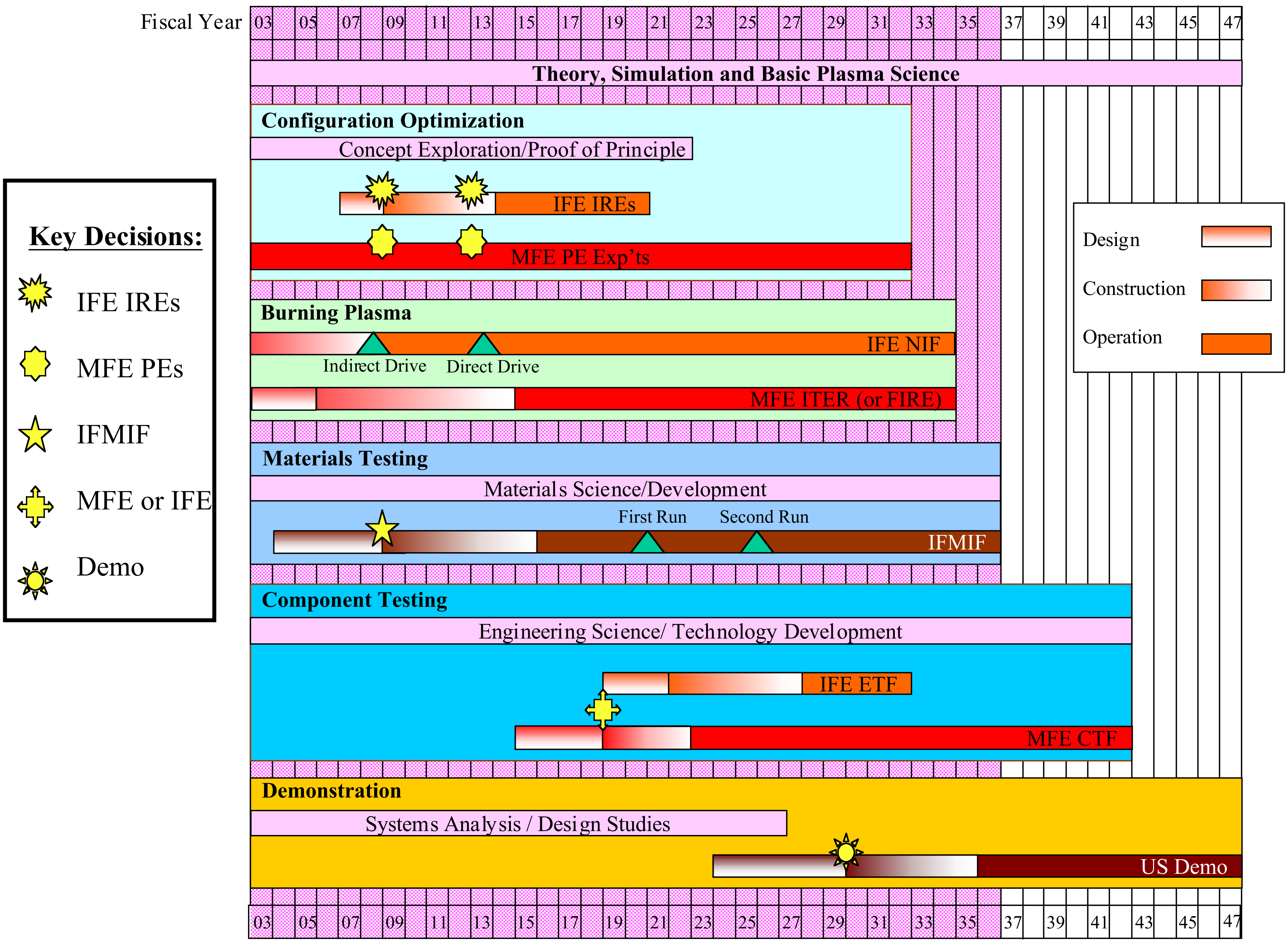


A strong parallel effort in the science and technology of fusion energy is required to guide research on these experimental facilities and to take advantage of their outcome.

Principles

The goal of the plan is operation of a US demonstration power plant (Demo), which will enable the commercialization of fusion energy. The target date is about 35 years. Early in its operation the Demo will show net electric power production, and ultimately it will demonstrate the commercial practicality of fusion power.

The plan recognizes that difficult scientific and technological questions remain for fusion development. A diversified research portfolio is required for both the science and technology of fusion, because this gives a robust path to the successful development of an economically competitive and environmentally attractive energy source. In particular both Magnetic Fusion Energy (MFE) and Inertial Fusion Energy (IFE) portfolios are pursued because they present major opportunities for moving forward with fusion energy and they face largely independent scientific and technological challenges.



Fiscal Year
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Theory, Simulation and Basic Plasma Science
Configuration Optimization
Concept Exploration/Proof of Principle
IFE IREs
MFE PE Exp'ts
Burning Plasma
IFE NIF
Indirect Drive
Direct Drive
MFE ITER (or FIRE)
Materials Testing
Materials Science/Development
First Run
Second Run
IFMIF
Component Testing
Engineering Science/ Technology Development
IFE ETF
MFE CTF
Demonstration
Systems Analysis / Design Studies
US Demo
Key Decisions:
IFE IREs
MFE PEs
IFMIF
MFE or IFE
Demo
Design
Construction
Operation

Goals, Specific Objectives and Key Decisions – I

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

Goals, Specific Objectives and Key Decisions – II

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)

Goals, Specific Objectives and Key Decisions – III

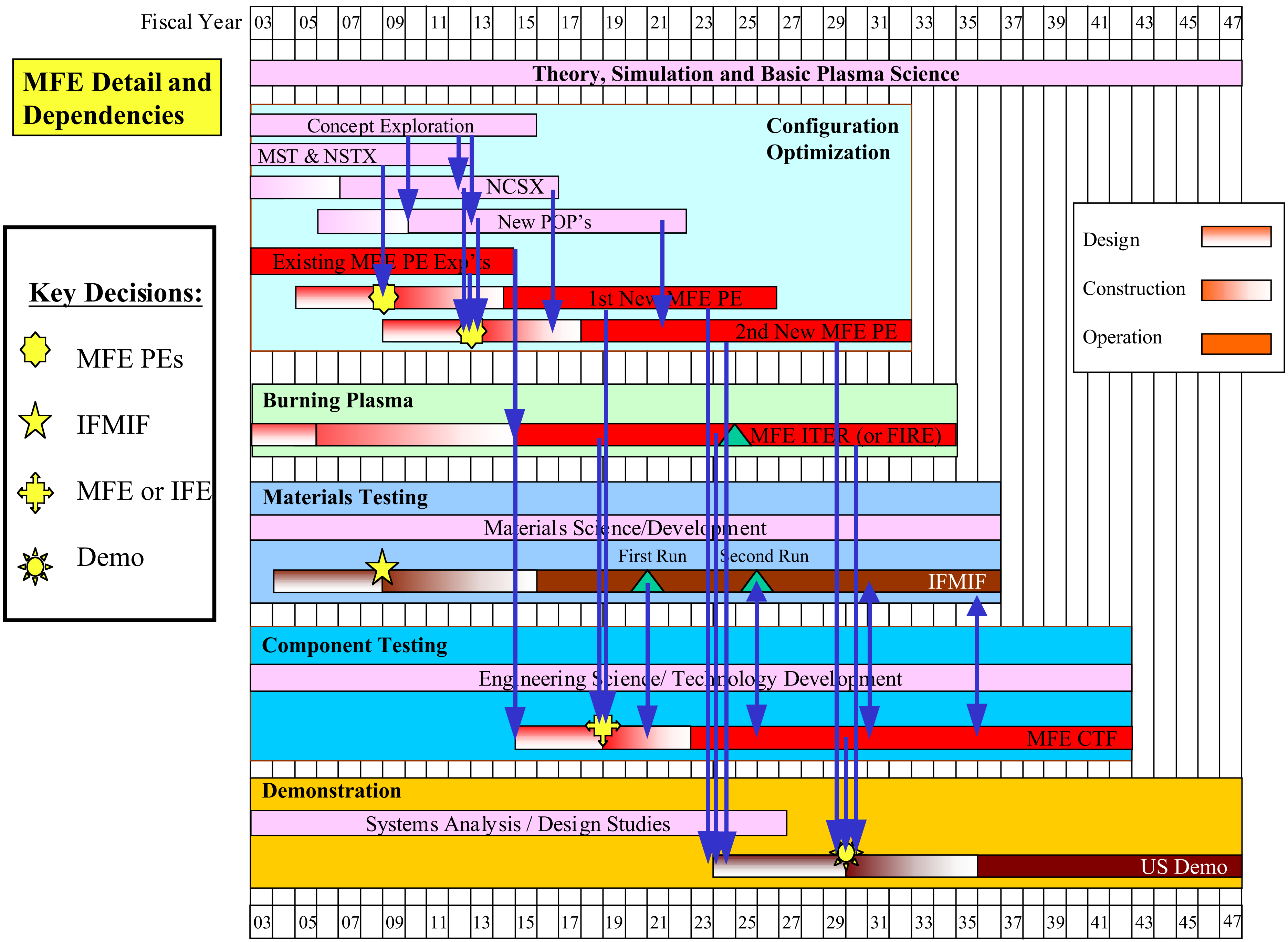
2020 – 2029 *Qualify Materials and Technologies in Fusion Environment*
Specific Objectives:

- 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.

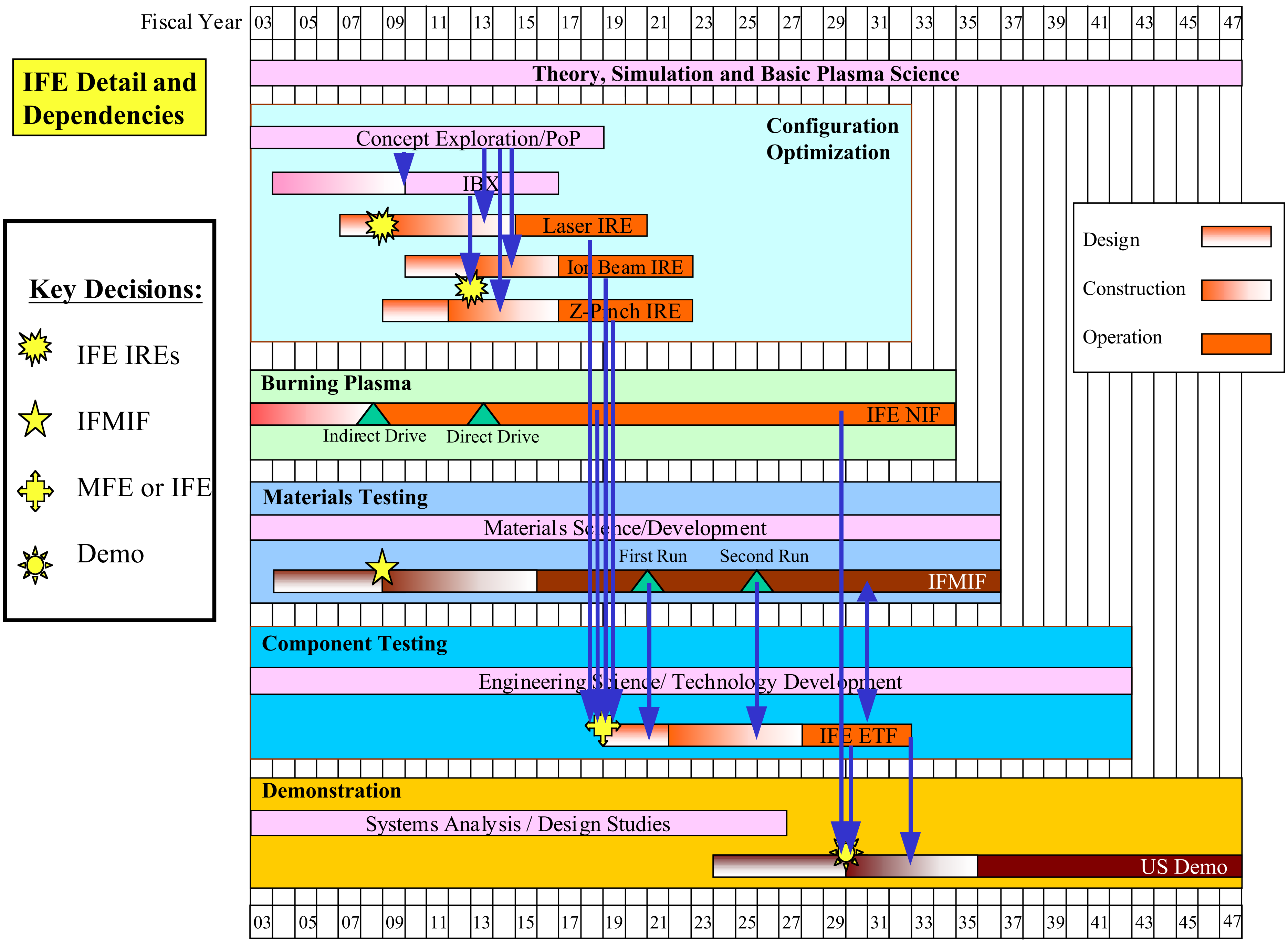
2029 Decision:

- Construction of U.S. Demonstration Fusion Power Plant

2030 – 2035: *Construct Demo*
Specific Objective: Operation of an attractive demonstration fusion power plant.



MFE Detail and Dependencies
Fiscal Year
03 05 07 09 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47
Theory, Simulation and Basic Plasma Science
Configuration Optimization
Concept Exploration
MST & NSTX
NCSX
New POP's
Existing MFE PE Exp's
1st New MFE PE
2nd New MFE PE
Burning Plasma
MFE ITER (or FIRE)
Materials Testing
Materials Science/Development
First Run
Second Run
IFMIF
Component Testing
Engineering Science/ Technology Development
MFE CTF
Demonstration
Systems Analysis / Design Studies
US Demo
Key Decisions:
MFE PEs
IFMIF
MFE or IFE
Demo
Design
Construction
Operation


IFE Detail and Dependencies
Fiscal Year
03 05 07 09 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47
Theory, Simulation and Basic Plasma Science
Configuration Optimization
Concept Exploration/PoP
IBX
Laser IRE
Ion Beam IRE
Z-Pinch IRE
Burning Plasma
IFE NIF
Indirect Drive
Direct Drive
Materials Testing
Materials Science/Development
First Run
Second Run
IFMIF
Component Testing
Engineering Science/ Technology Development
IFE ETF
Demonstration
Systems Analysis / Design Studies
US Demo
Key Decisions:
IFE IREs
IFMIF
MFE or IFE
Demo
Design
Construction
Operation

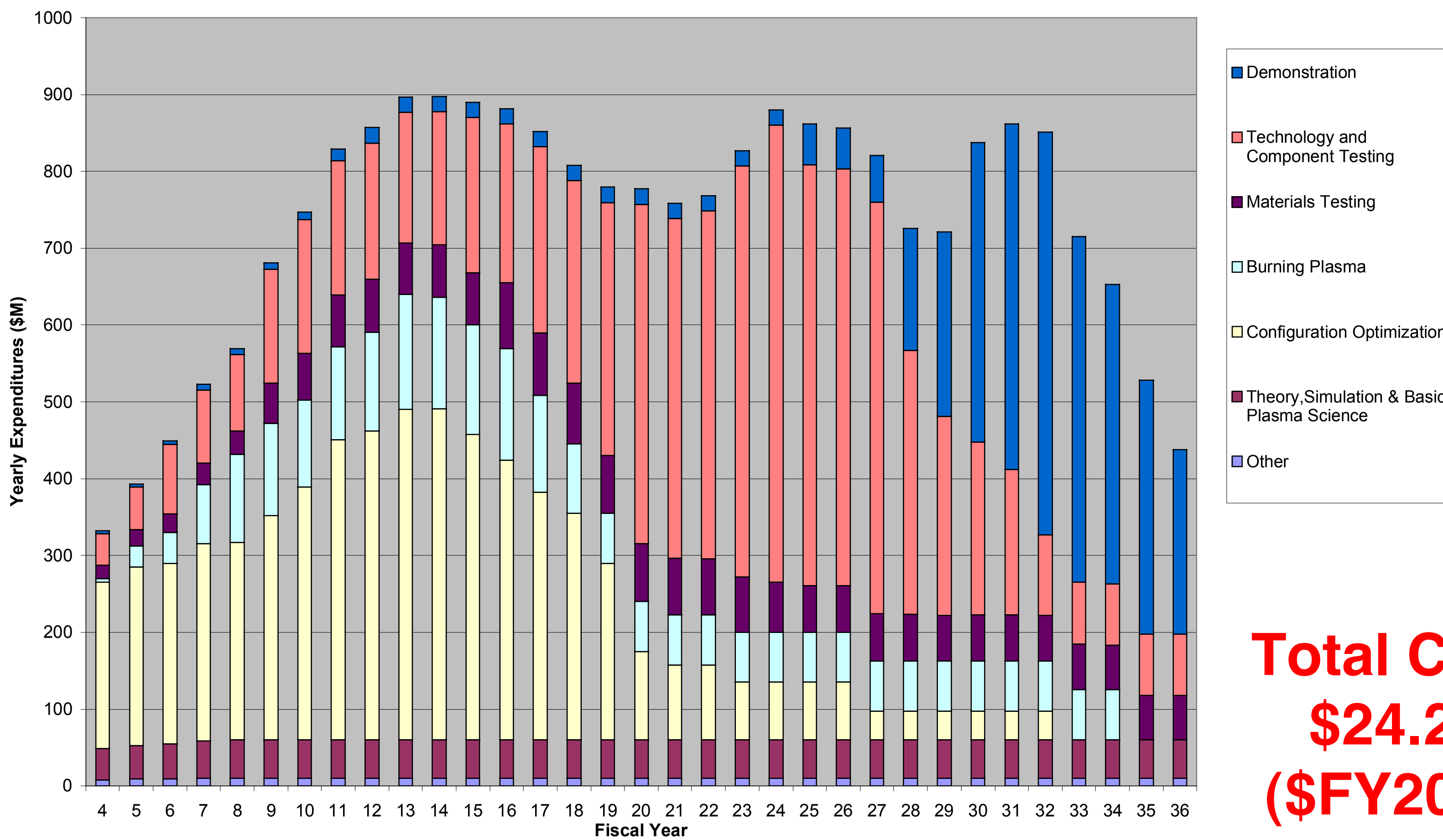
Cost Assumptions

Cost profiles for major facilities and programs were provided by experts and reviewed by the Panel. The U.S. contribution to ITER construction was estimated at $1B, per FESAC.

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***.

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 Fusion Budget Needs to ~ Double over the Next Five Years, and if Positive Decisions are then made, will Need to Rise by a Further ~ 50%, to ~ 1980 Level



Total Cost: $24.2B ($FY2002)

Key Observations

The FIRE Scenario

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.

The Plasma Configuration of the MFE Demo

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.

Management Considerations

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.

Conclusions - I

The U.S. fusion energy sciences program is ***still suffering from the severe budget cuts of the mid-1990's 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.***

Conclusions - II

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.