FESAC Fusion Development Path

Rob Goldston

Graduate Student Seminar

March 21, 2005

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

MFE and IFE Worked Together on the Fusion Development Path

Rob Goldston, PPPL   John Sethian, NRL

Fusion Materials and Technologies, from A to Z

Mohamed Abdou, UCLA Steve Zinkle, ORNL

Pre-Halloween Development Path Meeting

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**

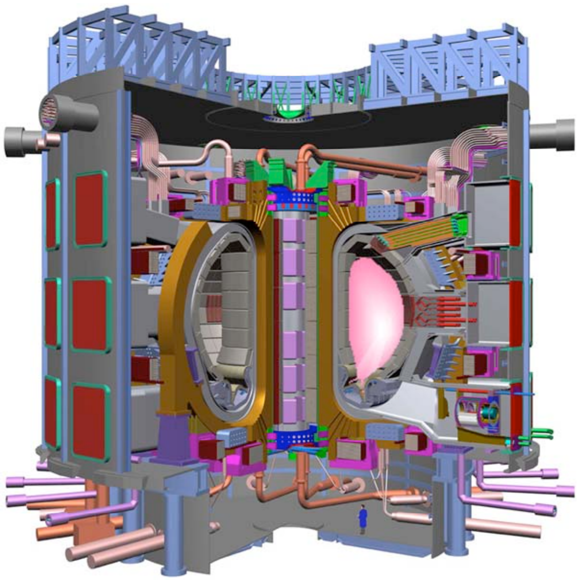
Outline of Report

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

NIF and ITER Drive the Urgency of the Plan

NIF

ITER

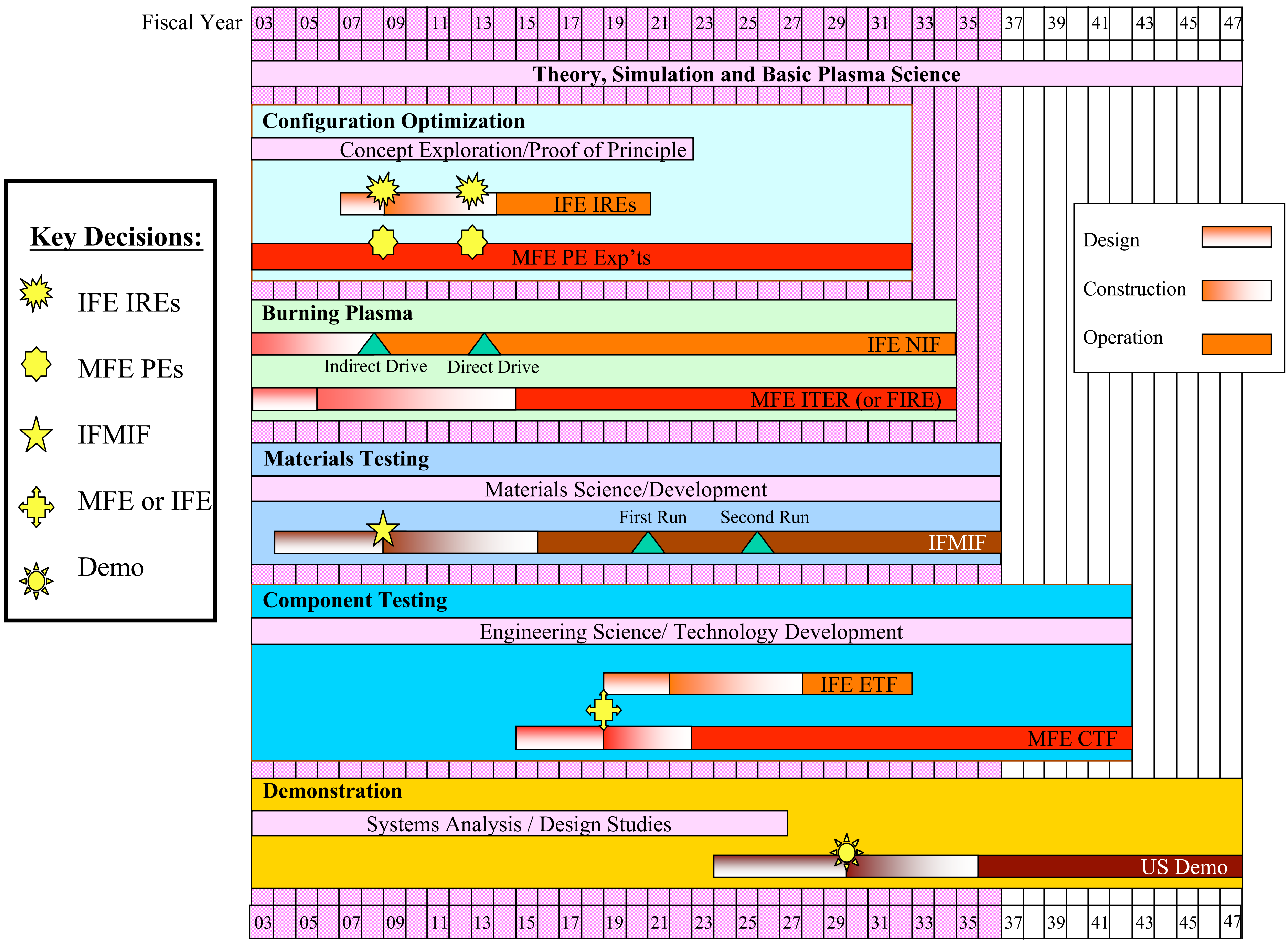


A strong parallel effort in the science and technology of fusion energy is required to guide research on these experimental facilities and to take advantage of their outcome.

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
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/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.

What is CTF?

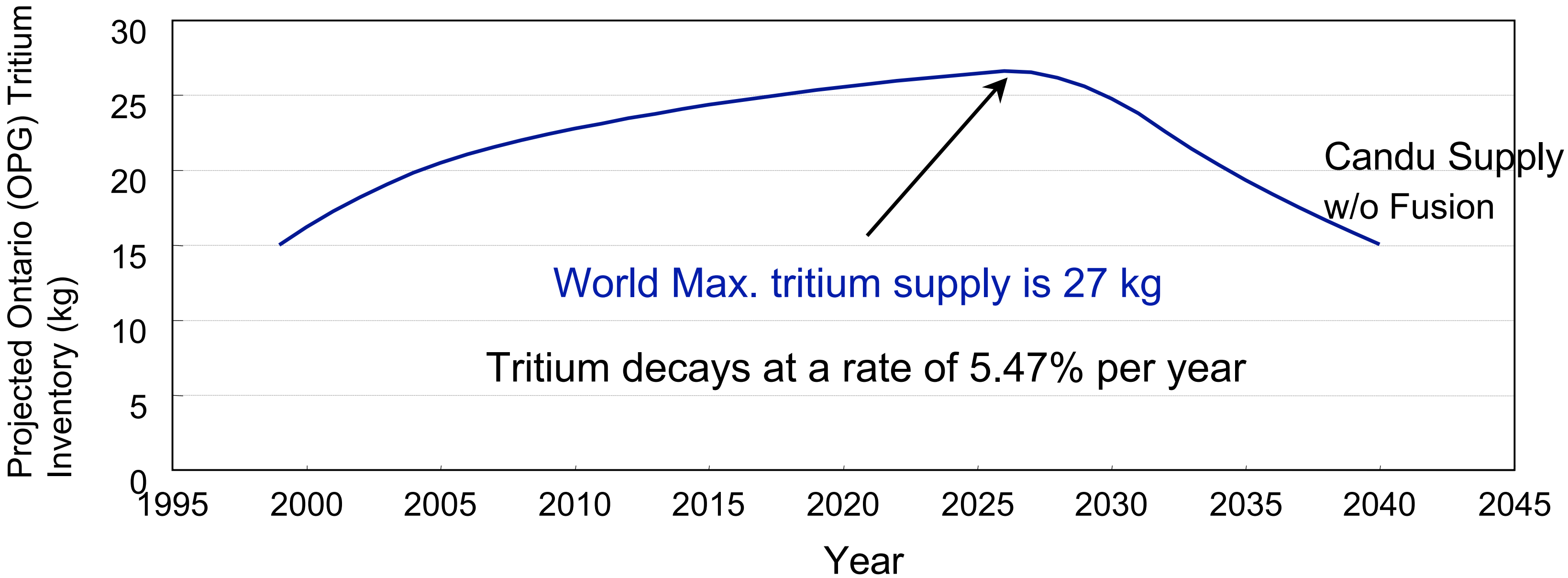
- The idea of CTF is to build a small size, low fusion power driven DT plasma-based device in which Fusion Nuclear Technology experiments can be performed in the relevant fusion environment at the smallest possible scale, cost, and risk.
  - In MFE: small-size, low fusion power can be obtained in a low-Q plasma device such as a tokamak, ST or possibly gas dynamic trap.
  - Equivalent in IFE: reduced target yield and smaller chamber radius

- This is a faster, much less expensive, less risky approach than testing in a large device which will be strongly limited by tritium consumption as full breeding and tritium purging is achieved, and which will have a very large blanket to be replaced in multiple tests.

Stages of Nuclear Technology Testing in Fusion Facilities

	Fusion "Break-in"	Design Concept & Performance Verification	Component Engineering Development & Reliability Growth	Demo
Stage:	**I**	**II**	**III**	
Required Fluence ($MW\text{-}y/m^2$)	**~ 0.3**	**1 - 3**	**> 4 - 6**	
Size of Test Article	**Sub-Modules**	**Modules**	**Modules / Sectors**	
	• Initial exploration of performance in a fusion environment • Calibrate non-fusion tests • Effects of rapid changes in properties in early life • Initial check of codes and data • Develop experimental techniques and test instrumentation • Narrow material combination and design concepts • 10-20 test campaigns, each is 1-2 weeks	• Tests for basic functions and phenomena (tritium release / recovery, etc.), interactions of materials, configurations • Verify performance beyond beginning of life and until changes in properties become small (changes are substantial up to ~ 1-2 $MW \cdot y/m^2$) • Data on initial failure modes and effects • Establish **engineering feasibility** of blankets (satisfy basic functions & performance, 10 to 20% of lifetime) • Select 2 or 3 concepts for further development	• Identify failure modes and effects • Iterative design / test / fail / analyze / improve programs aimed at improving reliability and safety • Failure rate data: Develop a data base sufficient to predict mean-time-between-failure with sufficient confidence • Obtain data to predict mean-time-to-replace (MTTR) for both planned outage and random failure • Develop a data base to predict overall availability of FNT components in DEMO	

Projected Tritium Supply Impacts Blanket Testing

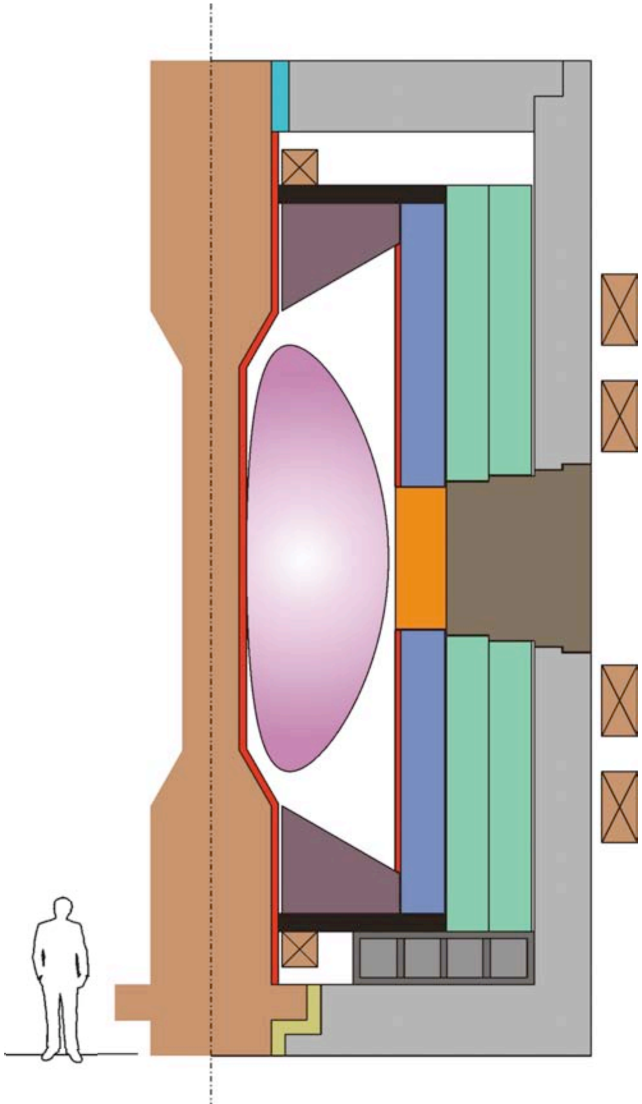


- ITER will burn ~7.5 kg T and provide ~2 weeks of Demo neutron fluence.
- A fission reactor can produce a few kg of tritium per year, at $200M/kg.
- A DT facility burns tritium at a rate of:

3 kg/week per 2800 MW of fusion power

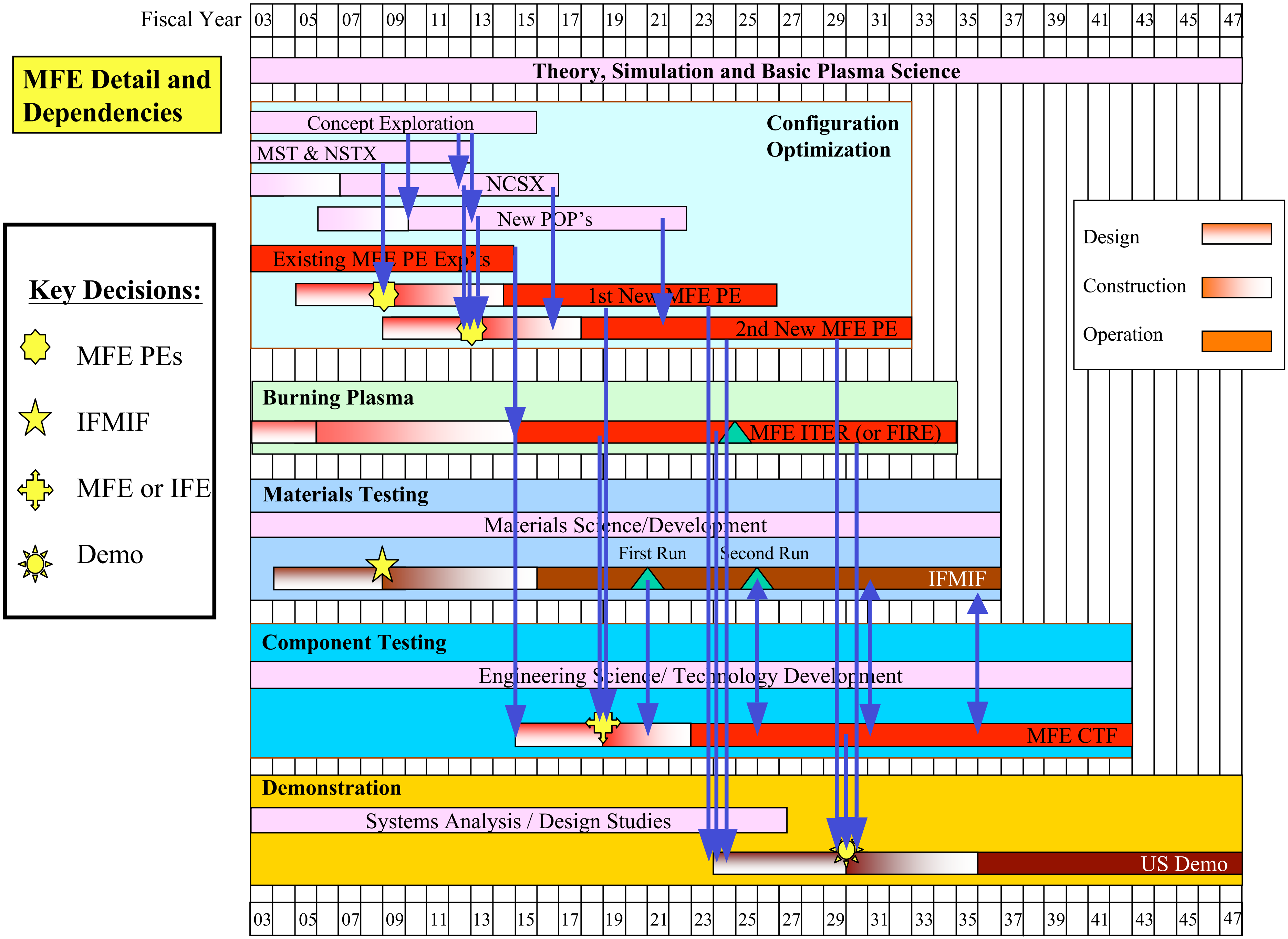
You must stop any test and replace the full blanket if 500g of tritium is not regenerated or is held up in the blanket. At 3% loss this is ***6 weeks*** *for Demo – an unacceptable period to change out* ***~1000 m^2*** *of blanket. For a 100 MW CTF the period is* ***3 years*** *and the area is* ***~50m^2****.*

Single Turn TF Leads to an Attractive ST CTF



R = 1.2m, a = 0.8m

Wall Loading at Test Modules (MW/m²)	1.0	3.0
HH (ITER98pby2)	1.4	1.8
Applied toroidal field (T)	2.4	2.2
Plasma current (MA)	12.6	11.4
Normalized beta (β_N)	4.1	7.0
Toroidal beta (β_T, %)	26.8	45.1
n/n_{GW} (%)	17	52
Q (using NBI H&CD)	2.4	5.8
Fusion power (MW)	72	214
Number of radial access ports	7	7
Radial access test area (m²)	12.8	12.8
P_{Heat}/R (MW/m)	37	67
Tritium burn rate (kg/full-power-year)	4	12
Total facility electrical power (MW)	286	272
Fraction of neutron capture (%)	81.6	81.6
Local T.B.R. for self-sufficiency	1.23	1.23
Toroidal field coil current (MA)	14.6	13.2
Center post weight (ton)	89	89
Capital cost ($B) with 40% contingency	1.47	



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MFE Detail and Dependencies
Theory, Simulation and Basic Plasma Science
Concept Exploration
Configuration Optimization
MST & NSTX
NCSX
New POP's
Existing MFE PE Exp'ts
1st New MFE PE
2nd New MFE PE
Design
Construction
Operation
Key Decisions:
MFE PEs
IFMIF
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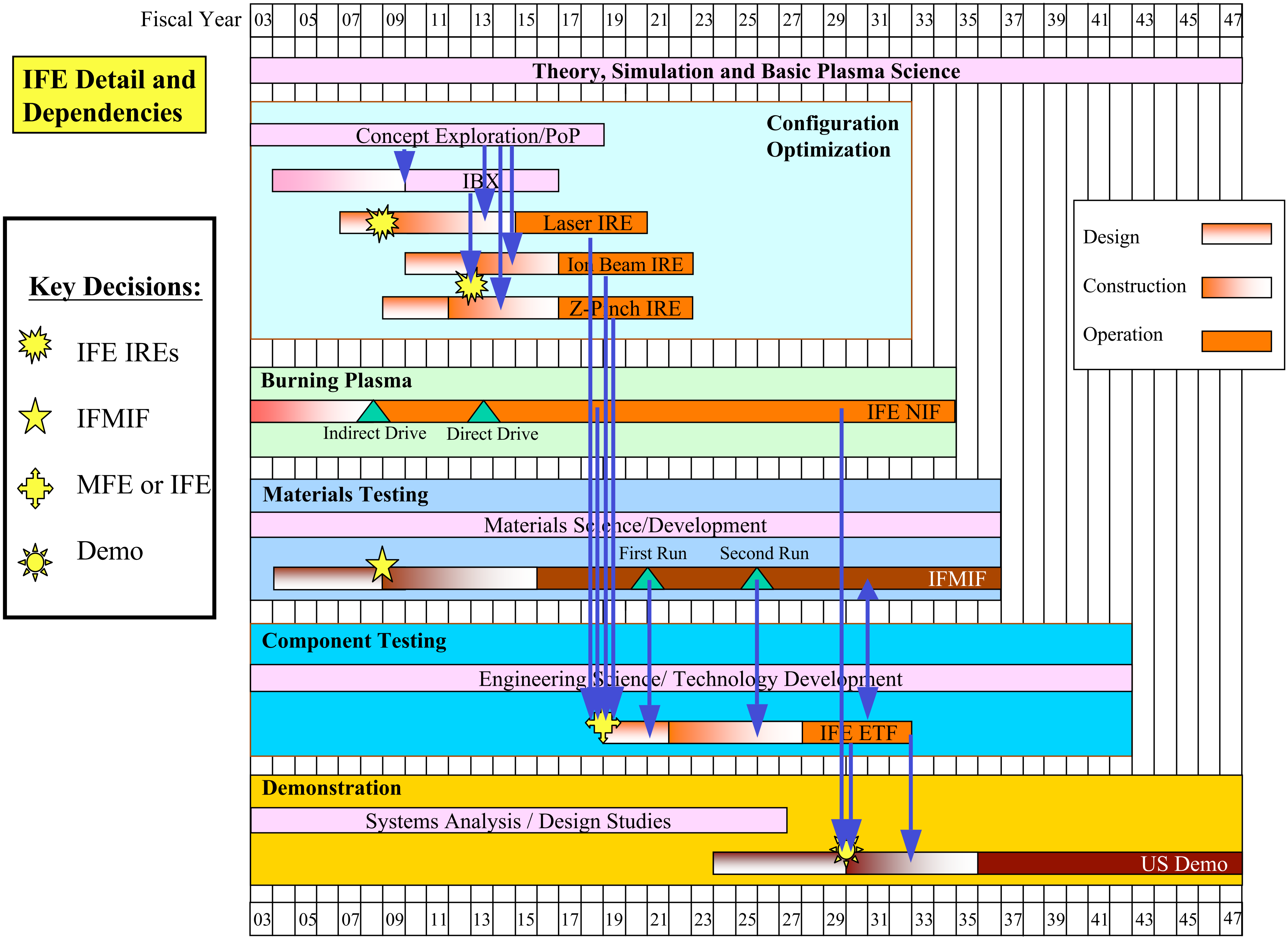

IFE Detail and Dependencies
Fiscal Year
03 05 07 09 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47
Theory, Simulation and Basic Plasma Science
Concept Exploration/PoP
Configuration Optimization
IBX
Laser IRE
Ion Beam IRE
Z-Pinch IRE
Burning Plasma
IFE NIF
Indirect Drive
Direct Drive
Materials Testing
Materials Science/Development
First Run
Second Run
IFMIF
Component Testing
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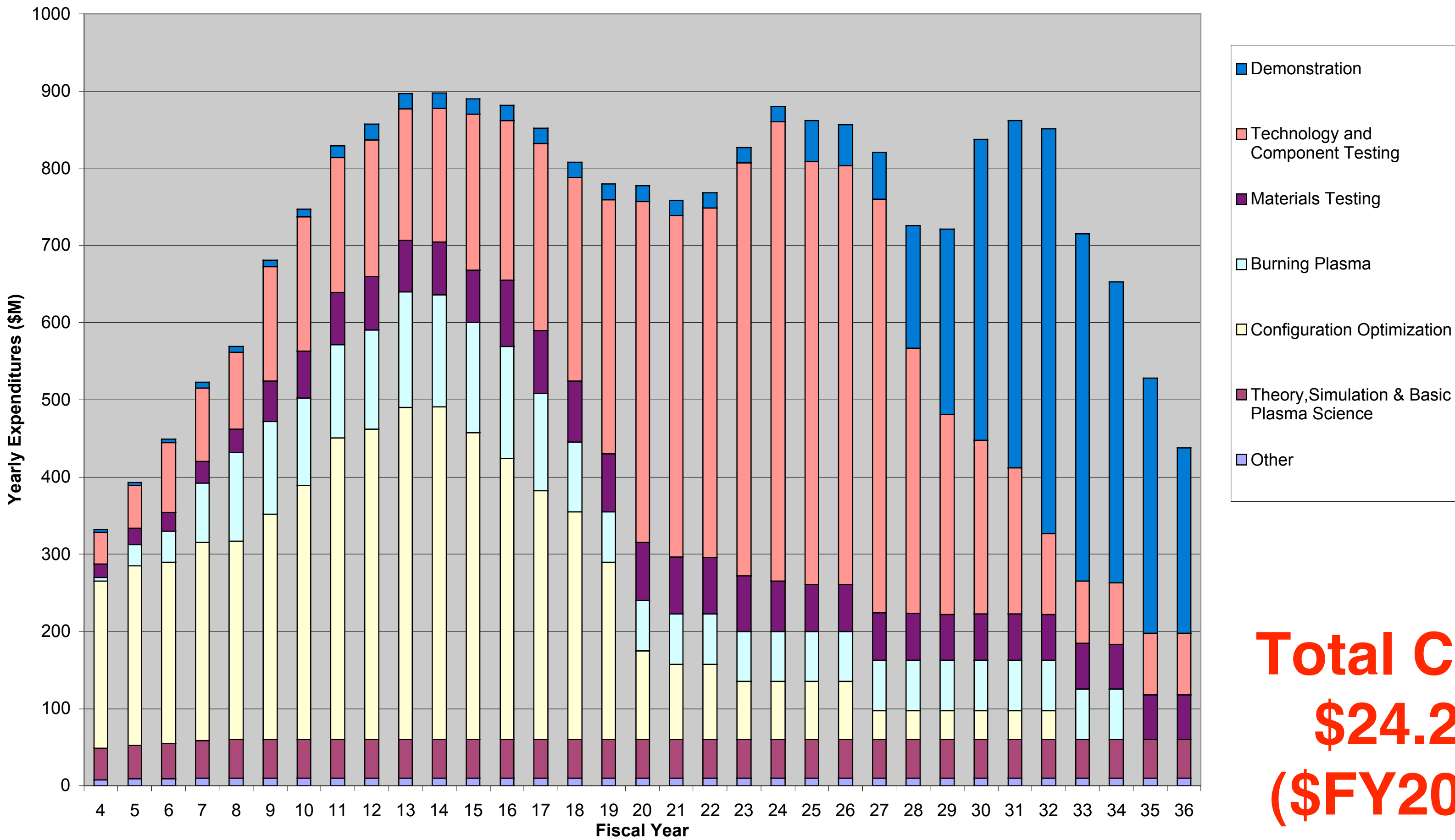
Cost Assumptions

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

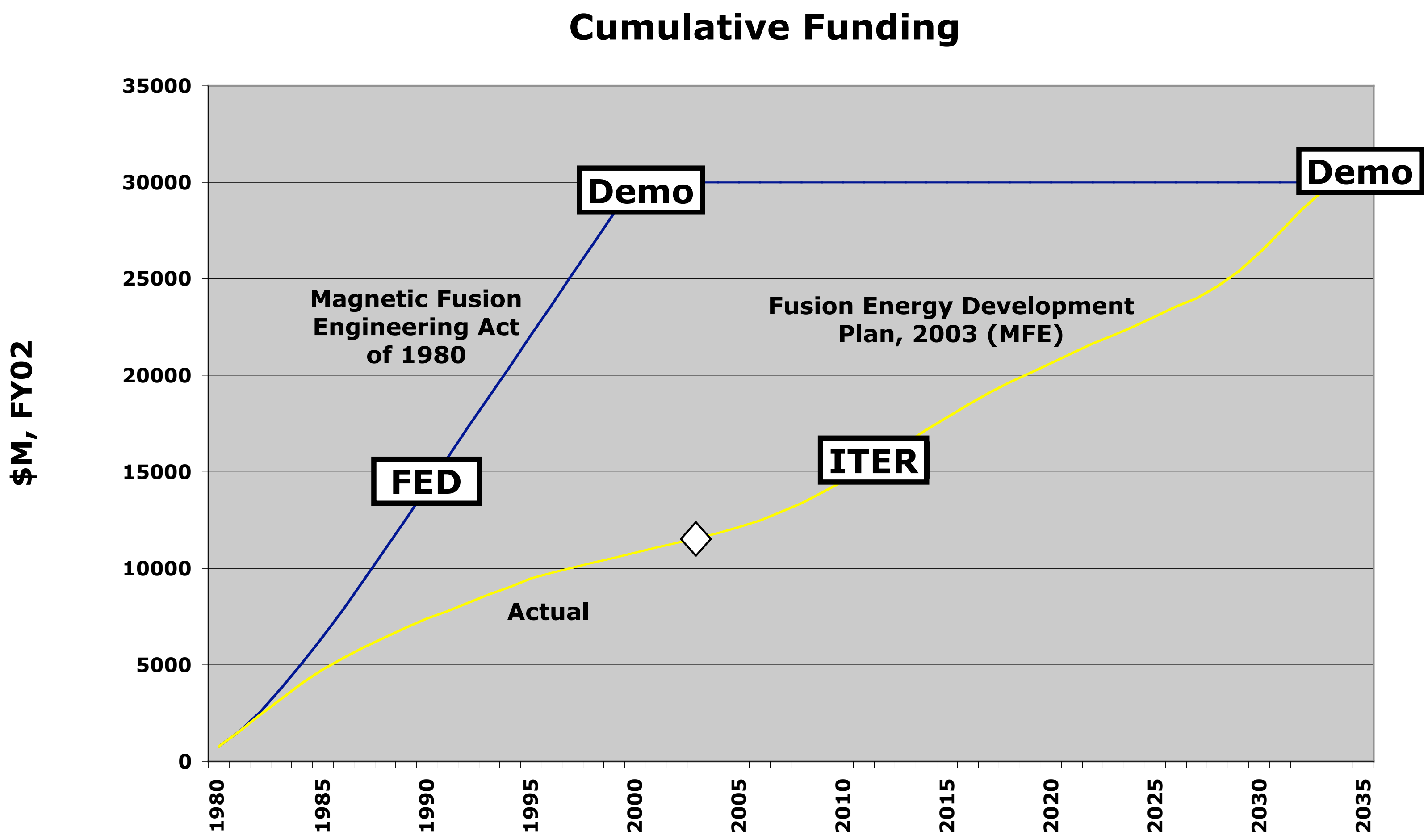
The U.S. fusion energy sciences program is ***still suffering from the severe budget cuts of the mid-1990's and the loss of a clear national commitment to develop fusion energy.*** The result is that despite the exciting scientific advances of the last decade it is becoming difficult to retain technical 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.

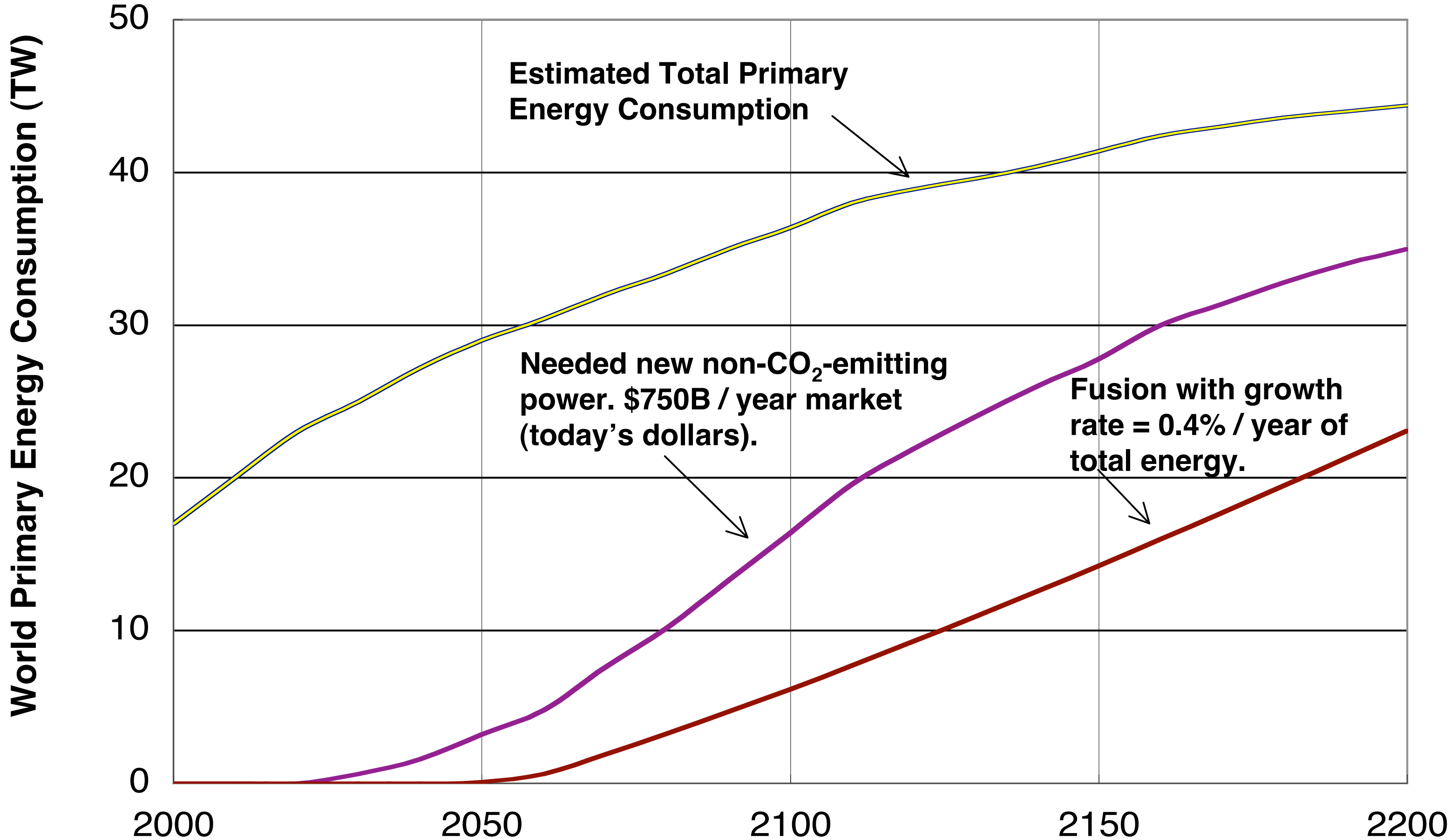
It is the judgment of the Panel that the plan presented here can lead to the operation of a demonstration fusion power plant in about 35 years, enabling the commercialization of attractive fusion power by mid-century as envisioned by President Bush.

The Estimated Development Cost for Fusion Energy is Essentially Unchanged since 1980



Fusion Development is on Budget.

The Value of Fusion-Produced Energy is $300T, in $FY2002



ROI and Real Options analyses are very favorable.

The Fusion Opportunity is Worth ~$660B
Discount Analysis

- **Fusion is a unique investment opportunity**
  - **Too large an investment for any corporation or consortium.**
  - **Intellectual property does not last long enough for investment.**
  - **Compare with Federal alternative: not borrowing the money.**
  - **Assume inflation rate of 3%, discount/interest rate of 5%.**
  - **Net Present Value of fusion development cost (MFE + IFE) = $17.5B.**
- **The value of energy in the future is very hard to estimate.**
  - **Assume same inflation rate of 3%, discount rate of 5%.**
  - ***This assumes that energy will not become relatively more expensive in the future, despite Hubbert's Peak, CO_2 concerns.***
  - **It also ignores spillover benefits such as computer chip processing.**
  - **Net Present Value of fusion-produced energy = $19.7T**
- **Fusion research does not provide the energy, but the opportunity for it.**
  - **Assume fusion energy is 20% "better," for its market share.**
  - **Assume the odds of achieving this advantage are 50:50.**
  - **Assume 1/3 of benefit accrues, directly and indirectly, to the U.S.**
  - **Net Present Value of opportunity for fusion is $657B**
- **Return on Investment in Fusion Energy Development is about 40:1**
  - ***Assumption on value of energy is very conservative.***