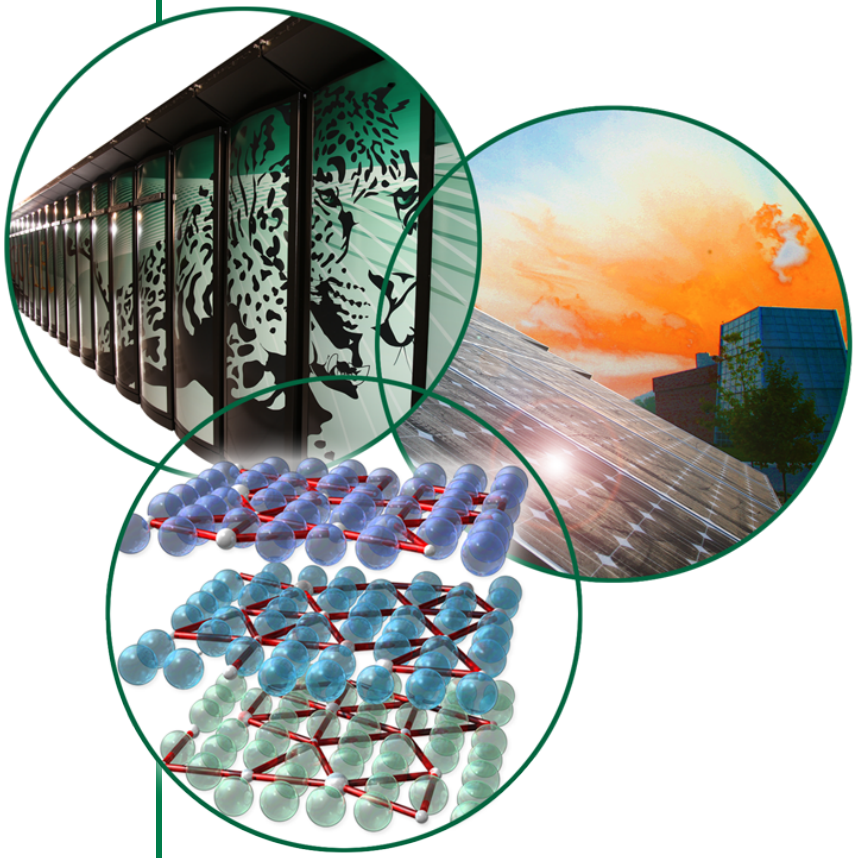
Fusion Engineering: Technology Gaps and ORNL Expertise

Arnold Lumsdaine



U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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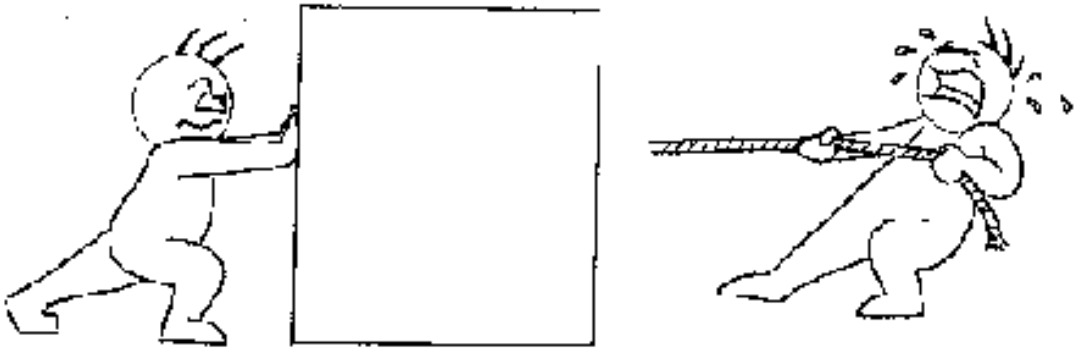
Fusion Engineering and Technology at ORNL

- Motivation
  - Strategic Hire
  - Feedback from FED
- Gaps in Fusion Engineering / Technology (pull)
- Expertise at ORNL / FED (push)
- Options for fusion technology program at ORNL (2-5 years)



Strategic Hire Program

- "The purpose of the strategic hire program is to add senior individuals to the ORNL staff that bring critical skills and can build and lead new research programs and areas. In general strategic hires will be established investigators, have demonstrated the ability to develop substantial programs, and/or be otherwise well qualified for substantial research or organizational leadership roles. Individuals of substantial promise at earlier stages in their careers and who bring expertise critical to major ORNL strategic thrusts may also be supported through this program."

Strategy (2-5 year)

- Goals:
  - To develop new world-class fusion engineer/fusion technology programs at ORNL.
  - To close technology gaps towards a commercially viable fusion power plant.
- Outcomes:
  - Substantial DOE funding.
  - Movement towards one or more facilities at ORNL.
  - Strong publication record.

Bio Sketch

UNIVERSITY OF MICHIGAN

Ford

UNIVERSITY OF MICHIGAN

UNIVERSITY OF MICHIGAN

UTPA

MTS

NANO INSTRUMENTS

Agilent Technologies

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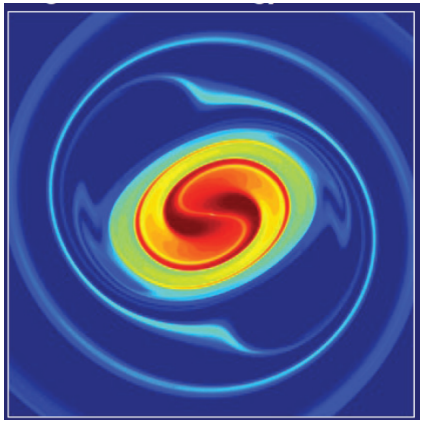
Bio Sketch

- Research / Experience
  - Structural Mechanics
  - Vibration Damping and Control
  - Finite Element Analysis
  - Design Optimization
  - Smart Structures and Materials
  - Energy Harvesting
  - Nanomechanics / Nanomaterials
  - New Product Development

Primary Sources of Info for Gaps

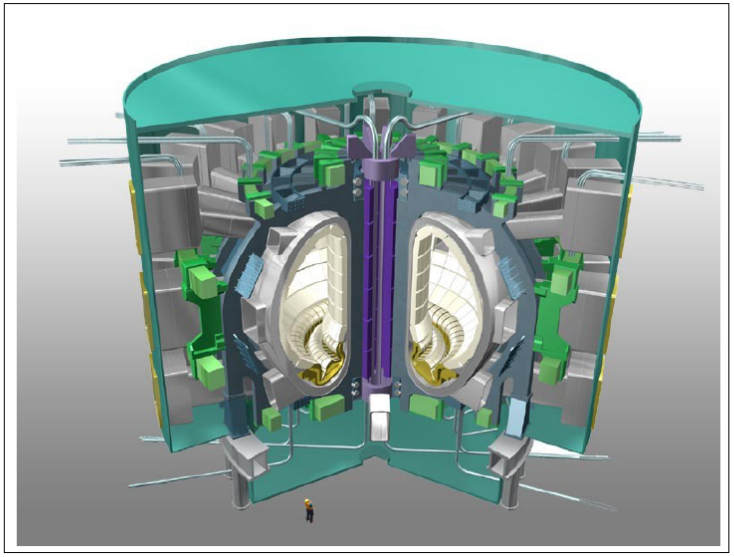
- FESAC Report (October 2007)
- ReNeW for Magnetic Fusion (June 2009)
- Marmar Panel Report (September 2009)

Priorities, Gaps and Opportunities:
Towards A Long-Range Strategic Plan For
Magnetic Fusion Energy

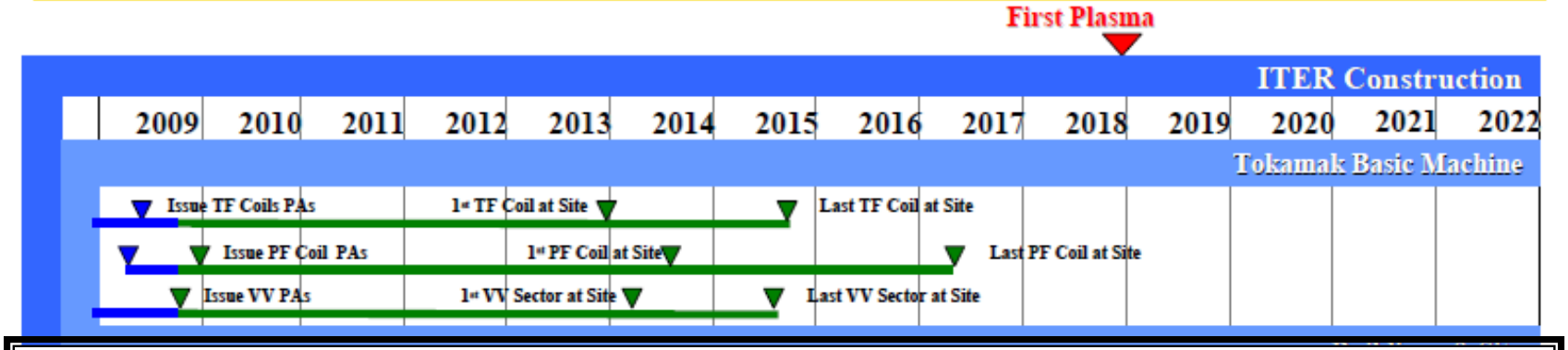


United States
Burning Plasma Organization

Report of the Burning Plasma Organization Panel
on
Planning for US Participation in ITER

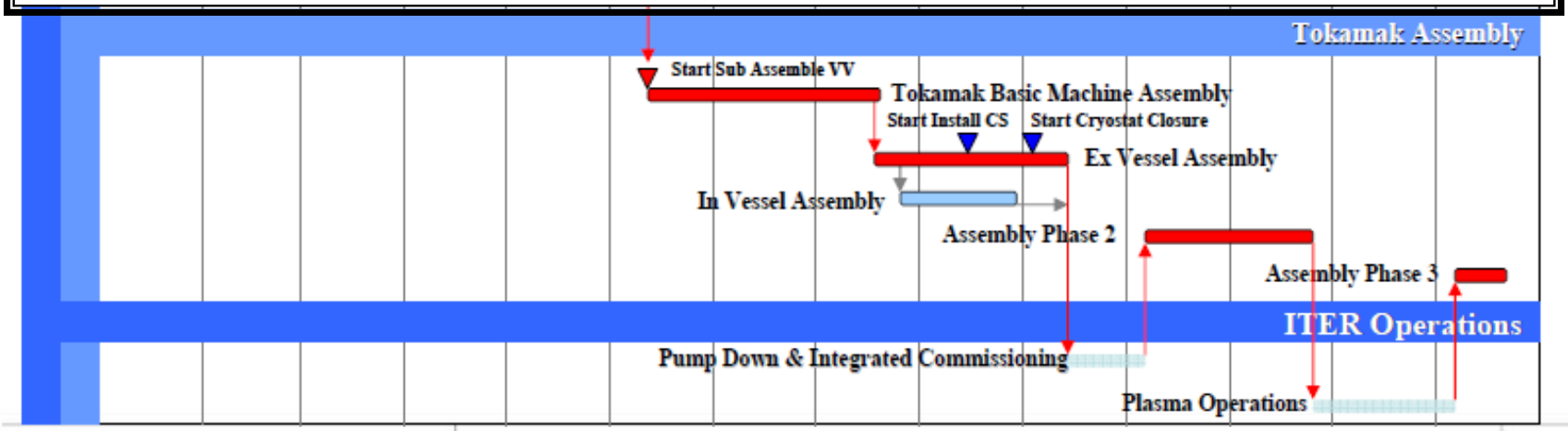


Updated Schedule



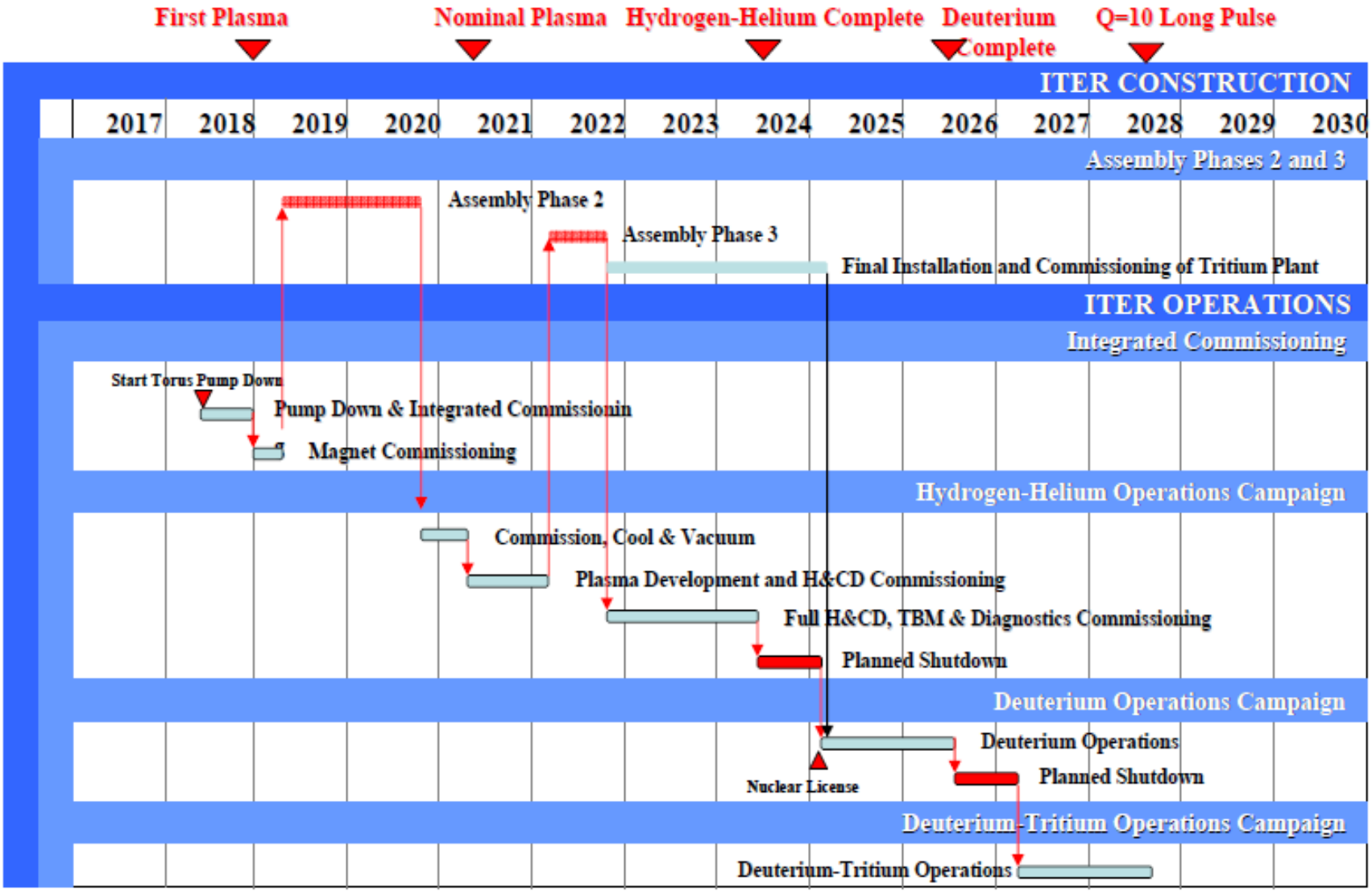
Depending on the optimism/pessimism reflected in the probability distribution for each activity in the schedule (in particular the higher risk items),

- **we end up between Dec 2018 and autumn 2019 (with 50% confidence)**

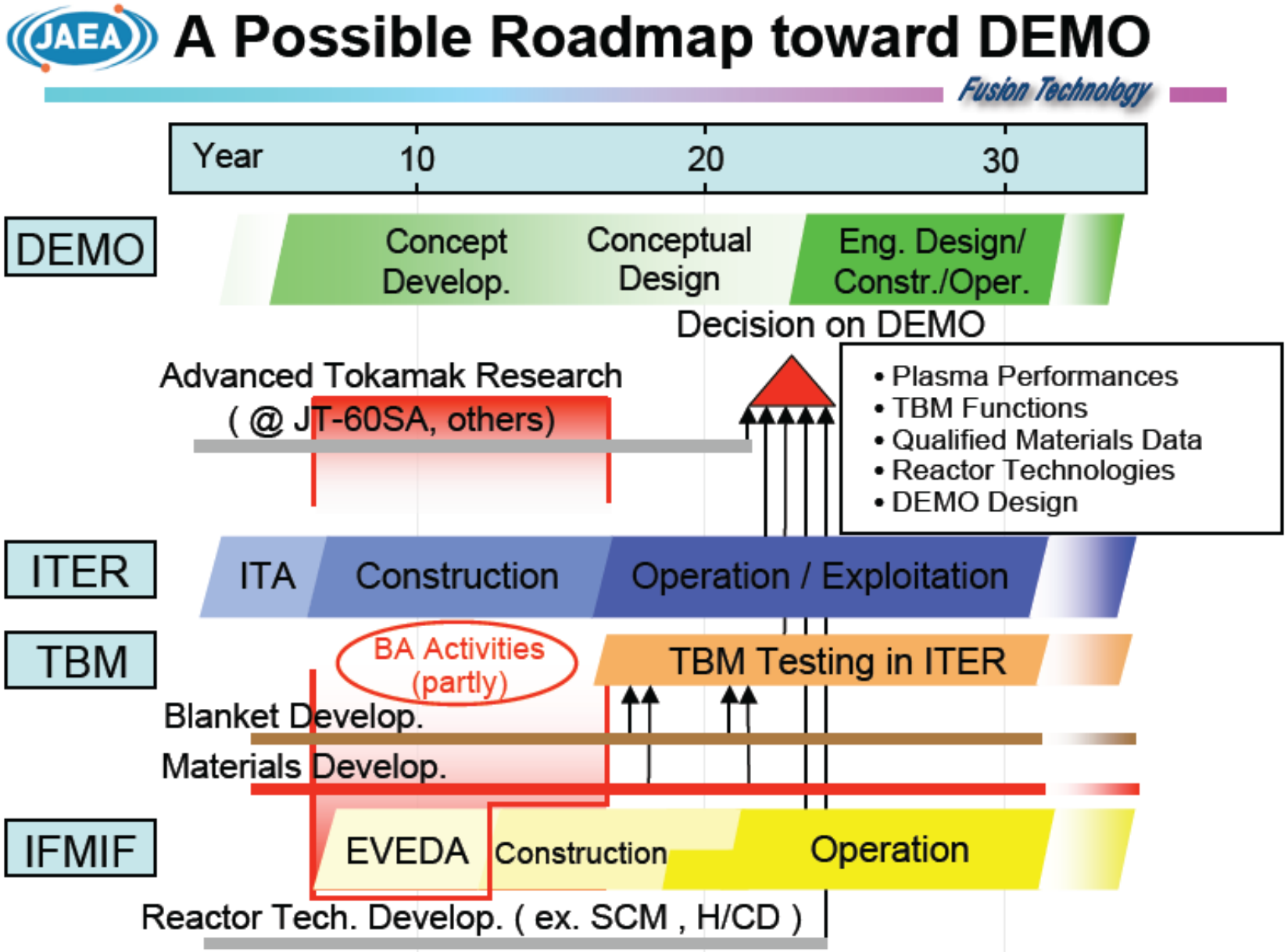


Approach to DT Operation

-First D-T Plasma foreseen at the end of 2026

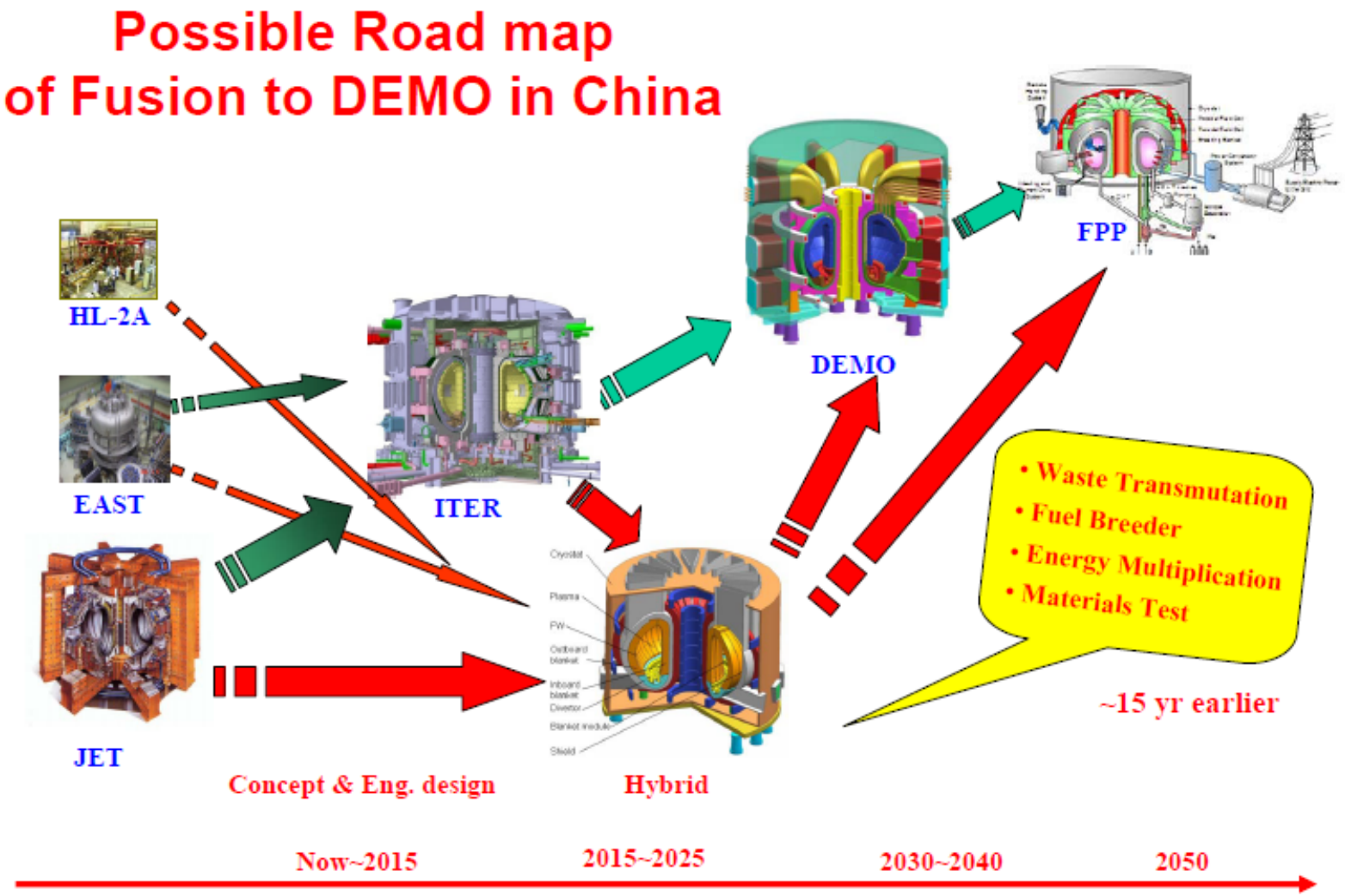


Path to DEMO – Japan



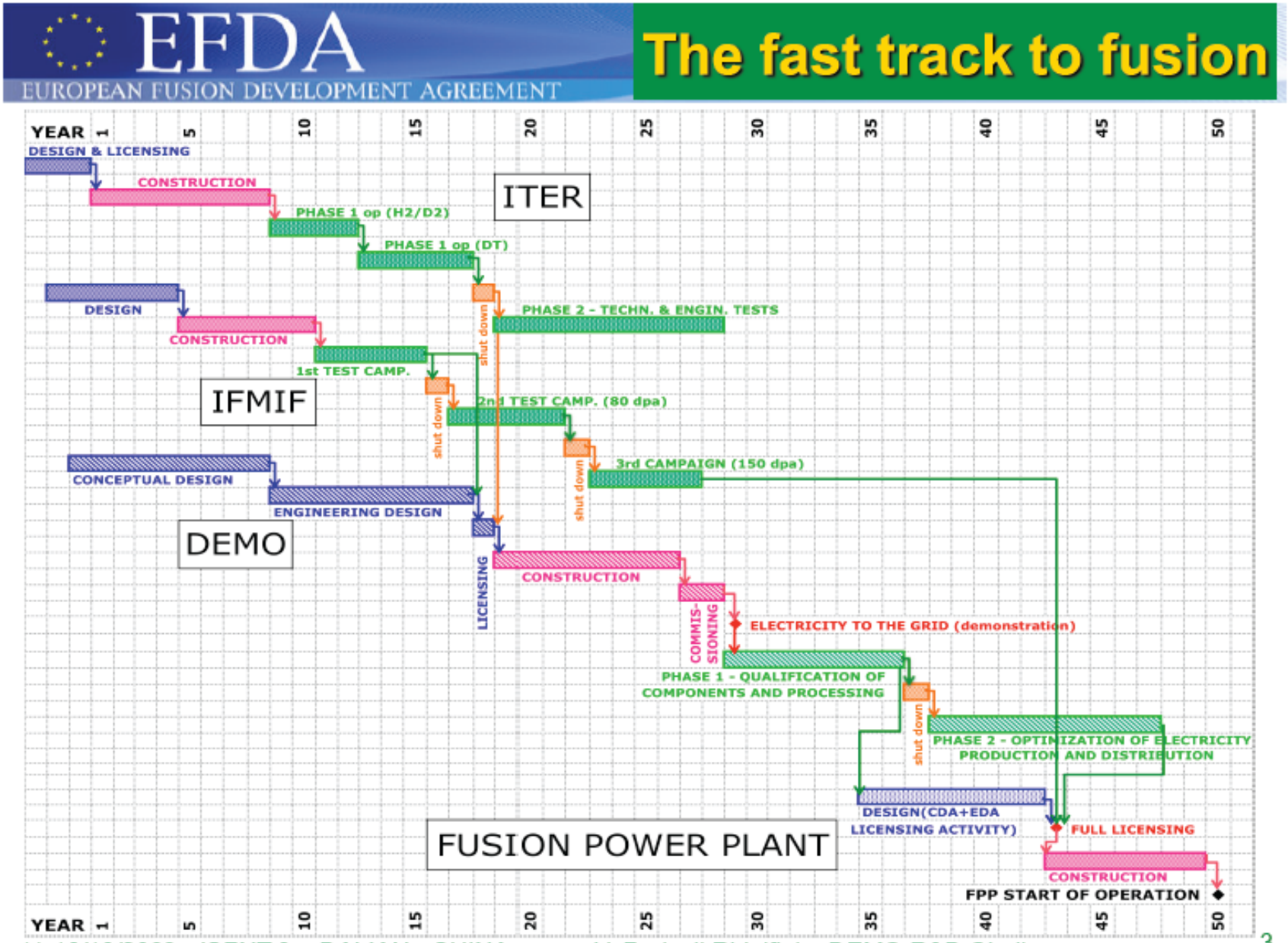
From "Recent Progress on Fusion Nuclear Technologies in Japan in Implementation of the ITER Program and the BA Activities," Hideyuky Takatsu, presented at ISFNT-9, Dalian, China, 2009.

Path to DEMO and FPP – China



From "Status and Strategy of Fusion Energy Development Towards DEMO in China," Yuanxi Wan, ISFNT-9, Dalian, China, 2009

Path to DEMO and FPP – EU



2007 FESAC Report

Priorities, Gaps and Opportunities:
Towards A Long-Range Strategic Plan For Magnetic Fusion Energy

- Technology Related Gaps to DEMO
  - G-6. Developments for concept free of off-normal plasma events
  - G-7. Reactor capable RF launching structures
  - G-8. High Performance Magnets
  - G-9. Plasma Facing Components
  - G-10. Fuel cycle
  - G-11. Heat removal
  - G-12. Low activation materials
  - G-13. Safety
  - G-14. Maintainability

2007 FESAC Report

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2007 FESAC Report – US Strengths and Opportunities

Priorities, Gaps and Opportunities:
Towards A Long-Range Strategic Plan For
Magnetic Fusion Energy

- US Leadership:
  - Measurement
  - Theory and predictive modeling
  - Control
- US Competitive:
  - Plasma-wall interactions
  - Integrated, sustained, high-performance plasmas
  - Safety/environment
- US Risk:
  - Measurement
  - Control
  - Antennas and launchers
  - Materials
  - Integrated, sustained, high-performance plasmas
  - Plasma-wall interactions
  - Plasma facing components
  - Safety
  - Magnets
- US Leadership with $$$
  - Plasma facing components
  - Materials

European View of Gaps

EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

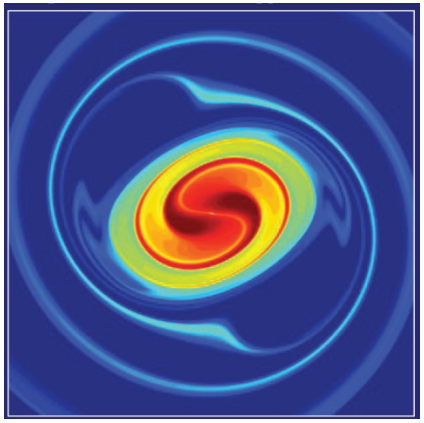
Areas for further R&D

Analysis of the present gaps

Table from "Input to the Facilities Review Panel" (EFDA 2008)

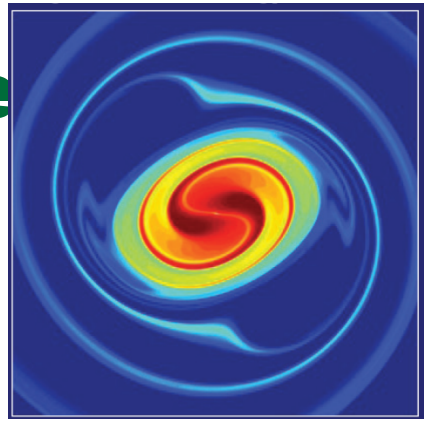
	Issue	Approved devices	ITER	IFMIF	DEMO phase 1	DEMO phase 2	Power plant		Contribution to the issue	colour
Plasma performance	Disruption avoidance	2	3	0	6	6	6		0 = NONE	
	Steady-state operation	2	3	0	5	5	5		1 = MAY HELP	
	Divertor preformance	1	3	0	6	6	6			
	Burning plasma (Q>10)	0	3	0	6	6	6			
	Start-up	1	3	0	6	6	6		2 = MAY SOLVE	
	Power plant plasma performance	1	3	0	5	6	6		3 = SHOULD SOLVE	
Enabling technologies	Superconducting machine	2	3	0	6	6	6			
	Heating current drive and fuelling	1	2	0	3	6	6		4 = MUST SOLVE	
	Power plant diagnostics & control	1	2	0	5	6	6			
	Tritium inventory control & proicessing	1	3	0	6	6	6		5 = SOLUTION DESIRABLE	
	Remote handling	1	2	0	6	6	6			
Materials, Component performance & lifetime	Materials characterization	0	0	3	6	6	6		6 = SOLUTION REQUIRED	
	Plasma-facing surfaces	1	2	0	3	4	6			
	FW/blanket/divertor/ materials	0	1	1	3	4	6			
	FW/blanket/divertor/ components	0	1	1	2	4	6			
	T self-sufficiency	0	1	0	3	6	6			
Final goal	Licencing for a power plant	1	2	1	3	4	6			
	Electricity generation at high availability	0	0	0	1	3	6			

ReNeW for Magnetic Fusion



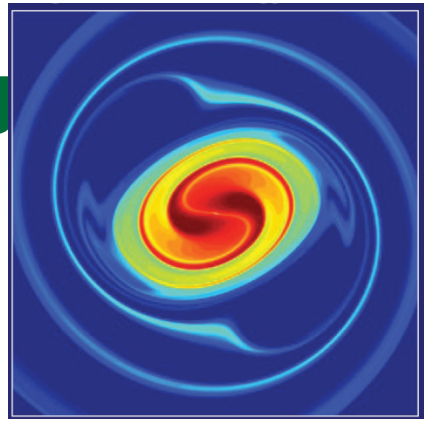
- Five "Themes" – two emphasizing technology issues
  1. Burning Plasmas in ITER
  2. Creating Predictable, High-Performance, Steady-State Plasmas
  3. Taming the Plasma-Material Interface
  4. Harnessing Fusion Power
  5. Optimizing the Magnetic Configuration

Thrusts for Theme 3 – Taming the Plasma-Material Interface



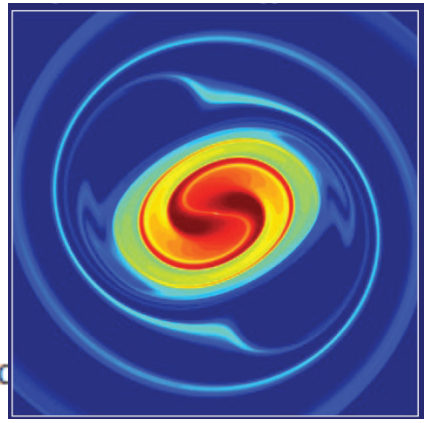
9. Unfold the physics of boundary layer plasmas
10. Decode and advance the science and technology of plasma-surface interactions
11. Improve power handling through engineering innovation
12. Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core

Thrusts for Theme 4 – Harnessing Fusion Power



13. Establish the science and technology for fusion power extraction and tritium sustainability
14. Develop the material science and technology needed to harness fusion power
15. Create integrated designs and models for attractive fusion power systems

Gap – Irradiated Structural Materials



The following seven gaps capture the essential elements of what is missing fro
sion materials research portfolio.

Gap: *The overarching scientific challenge facing successful development of a viable fusion power system is acquiring a firm scientific understanding and devising mitigation strategies for the deleterious microstructural evolution and property changes that occur to materials in the fusion environment.*

Although considerable progress has been made exploring the resistance of structural materials to neutron irradiation in fission reactors (to damage levels on the order of ~30 dpa), the current knowledge base for reduced-activation structural materials exposed to fusion-relevant irradiation conditions is almost nonexistent. In a fusion reactor structural (and other) materials will

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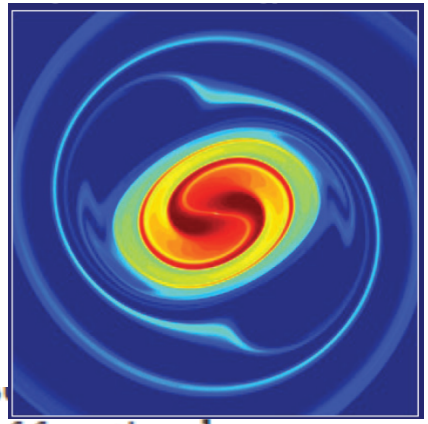
Gap – High Performance Alloys and Ceramics



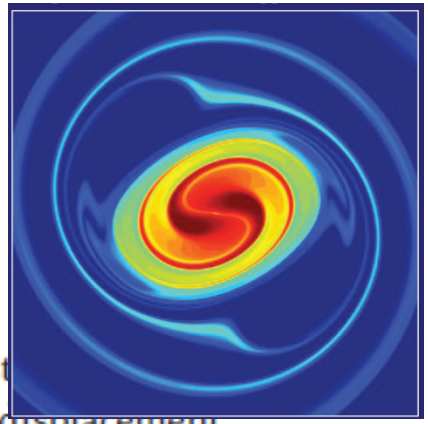
ket and W-alloys for the divertor), but also critical are other materials systems s

flux plasma facing components, breeding blanket materials, and a wide variety of functional materials essential for successful operation of a fusion power system.

Gap: *Development of high-performance alloys and ceramics, including large-scale fabrication and joining technologies, is needed.*

We anticipate that the current generation of reduced-activation structural materials may not provide adequate performance for a safe, environmentally sound and economically attractive fusion power system. There is a compelling need to evolve the next generation of candidate materials to increased levels of performance. We must seek breakthroughs in materials science and technology to discover a revolutionary class of high-performance materials for a fusion power system that fulfills safety, economic and environmental attractiveness goals. This can only be accomplished by implementing a full-scale alloy and ceramics development program. This includes the need to research large-scale fabrication and joining technologies for complex structures, including investigation of near-net-shape fabrication technologies that may provide substantially lower

Gap – Material Testing Facilities

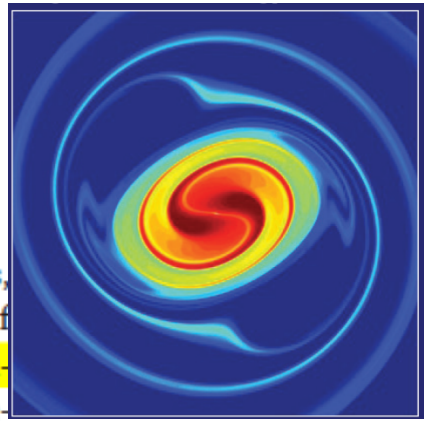


Research Needs

Critical research needs identified from the gap analysis are described below. The most is the capability to investigate the behavior of fusion materials under high levels of displacement damage while simultaneously producing helium and hydrogen. Consequently, a high-energy neutron source such as the International Fusion Materials Irradiation Facility is essential for developing and qualifying the full range of materials (first-wall, blanket, plasma facing components, functional materials, magnets, etc.) needed to construct a fusion power system.

There is also a compelling need for a suite of nonnuclear and nuclear facilities for testing materials, components and structures to investigate for potential synergistic effects not revealed in simpler single-variable experiments or limited multiple-variable studies. Such data is essential to refine and qualify predictive models of materials behavior, and provides essential reliability and failure rate data on materials, components, and structures to validate codes for designing intermediate step nuclear devices and a fusion power system. These facilities also provide a test bed to evaluate nondestructive inspection techniques and procedures as well as remote handing and maintenance technologies. Also included would be facilities for performing corrosion and

Gap – Plasma Facing Materials



Advanced Materials for Fusion Devices and Relation to Materials in Thrust 14

The material systems comprising the plasma facing components of present-day fusion devices, and those envisioned for ITER, share a common limitation. Given our current understanding of the extreme irradiation environment of next-generation reactors, none appear capable of withstanding the extraordinary combination of ion fluence and bulk neutron damage expected. Moreover, the plasma-surface boundary plays a key role in fusion performance of the core plasma by the self-consistent recycling of particles. Therefore, materials must address two primary design constraint
a viable pl
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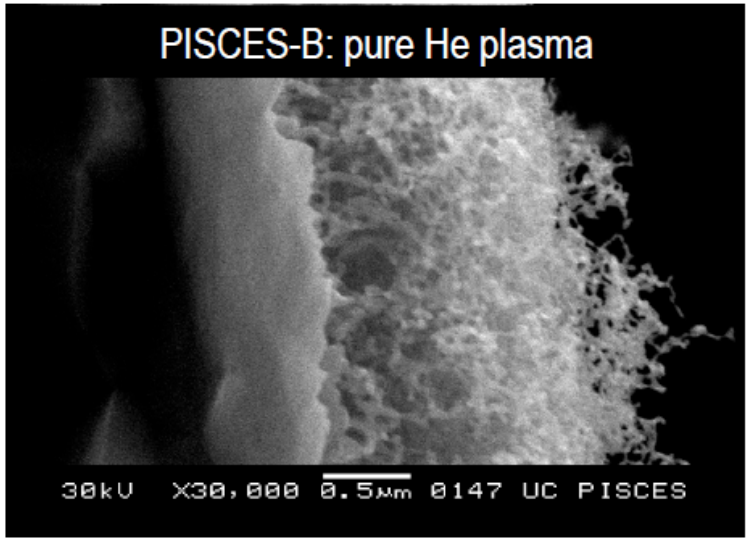
As an example, if one considers the three candidate materials typically considered for structural and plasma facing application — graphite, beryllium, and tungsten — each has a finite lifetime based on either PMI compatibility or structural integrity dictated by plasma-surface coupling, neutron exposure and operating temperature. In the case of graphite, anisotropic crystal growth leads to unavoidable materials disintegration. In turn, graphite suffers from hydrogen-dominated chemical erosion with strong temperature dependence. Neutron-irradiation-induced low-temperature embrittlement or high-temperature swelling limits beryllium as does its high hydrogen retention properties. In the case of tungsten, locked defects are created directly within the neutron cascade which, at least at moderate temperatures, leads to severe embrittlement and causes fracture toughness and flaw tolerance to plummet. Furthermore, edge alpha-induced surface morphology protrusions (e.g., "fuzz") can introduce intolerable high-Z amounts into the boundary plasma, leading to poor confinement.

To this point, research and development for both the plasma facing materials and the divertor structure have been somewhat limited to the issues relevant to current machines. To address the significant challenges of future fusion power devices, a more robust coupling of fundamentally

Summary – Causes of Material Degradation

- Heat from normal plasma operation
- Heat from abnormal plasma operation (ELMS, disruptions, vertical displacements)
- Runaway electrons
- Neutron bombardment
- Ion impingement
  - Heating
  - Erosion/redeposition
- EM loading
- H/He/D/T permeation
- Coolant interaction

Baldwin, Nishijima, Doerner, et. al, courtesy of Center for Energy Research, UCSD, *La Jolla, CA*



ORNL Fusion Technology Strengths

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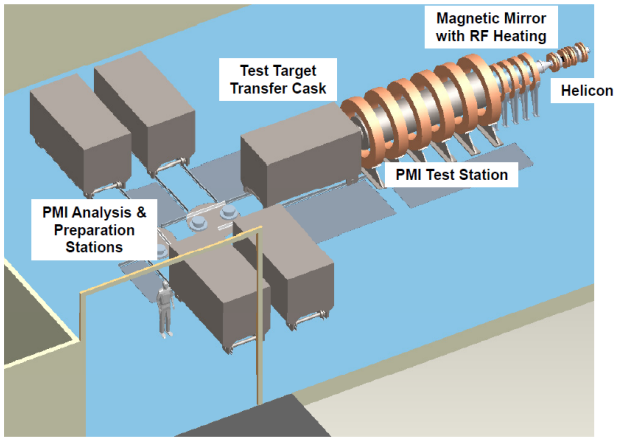
- Within FED
  - Plasma diagnostics
  - Pellet injection
  - Superconducting magnets
  - RF antenna
  - Electron cyclotron heating
- Beyond FED
  - Material diagnostics
  - Structural materials / irradiation
  - Supercomputing
  - Remote handling

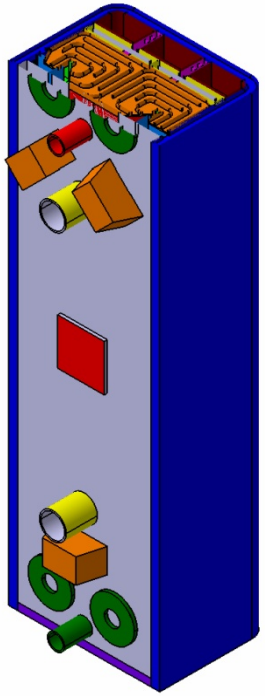
Potential Development Areas (2-5 Years)

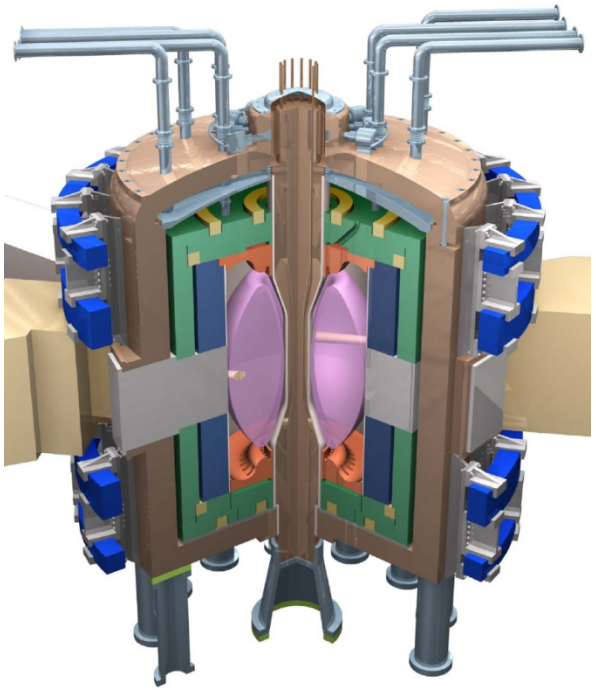
- Technologies
  - HT superconducting magnets
  - Instrumentation (i.e. sensor for blanket, TBM)
  - Design of plasma facing components (i.e. RF antenna)
  - 3D magnet design / fabrication
- Expertise
  - Integrated design engineering (multiphysics)
  - Plasma material interaction
  - Irradiated materials
  - Fabrication and joining technology
  - Remote handling
  - Codes / regulations / licensing

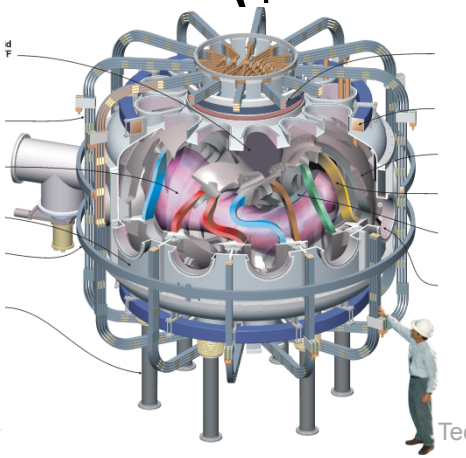
Possible Facilities / Major Projects

- PMIF – O($20M)
- TBM – O($100M)
- FNSF – O($3B)
- Stellarator – O($50M)
- RF Facility – O($10M)
- Hybrid Reactor – O($?????)









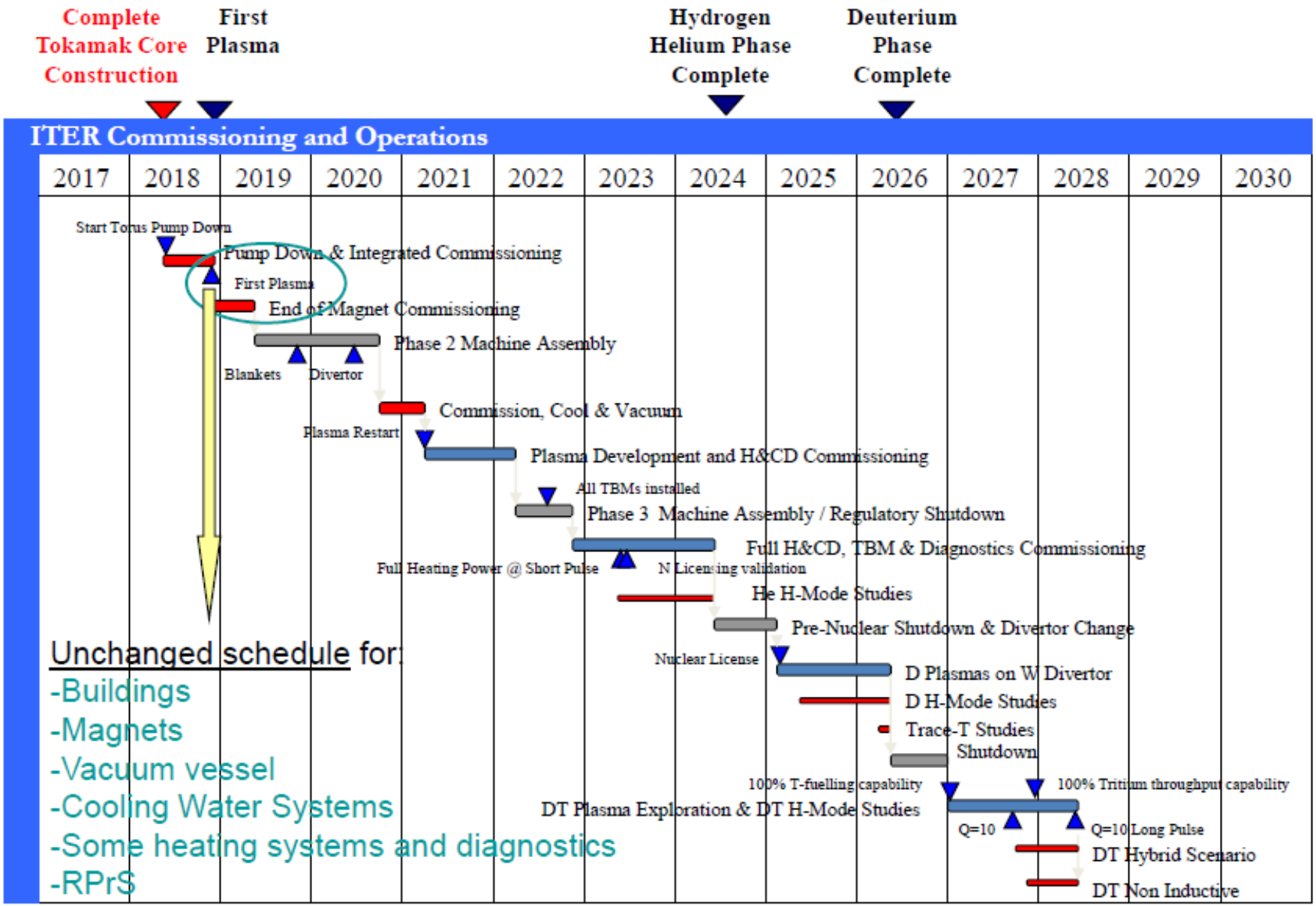
Discussion

- Today – quick questions / feedback

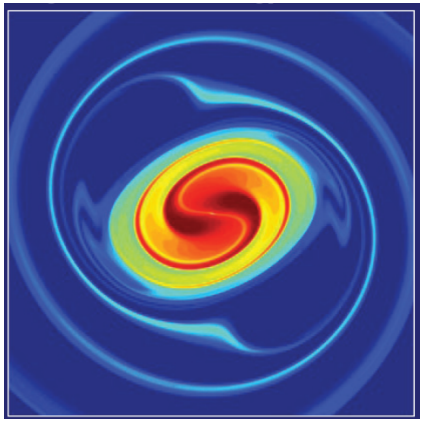
- Next few days – seeking input

Backup Slides

ITER Updated Schedule



Gap – Concurrent Development, Design, and Testing

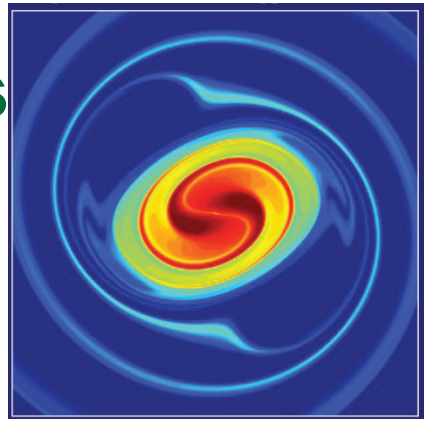


- **Pg 156**

Establishment of an alloy and ceramics development program to improve the performance of existing and near-term materials, while simultaneously pursuing breakthrough approaches to create materials with revolutionary performance characteristics (e.g., high strength, high toughness, high resistance to radiation damage and gases, exceptional thermo-physical properties, etc.). Couple this with a substantial effort on large-scale fabrication and joining technologies.

- An important crosscutting activity is the establishment of an integrated, concurrent materials-component-structure development, design and testing approach to fusion power systems. This activity begins with materials selection and ends with the qualified materials, components, structures and validated codes to describe the full range of behavior in the fusion environment.
- Extensive computational resources will be needed at all phases of fusion materials development to support model development. In particular, large-scale structural damage

Need for New Devices / Machines



- **Pg 311**

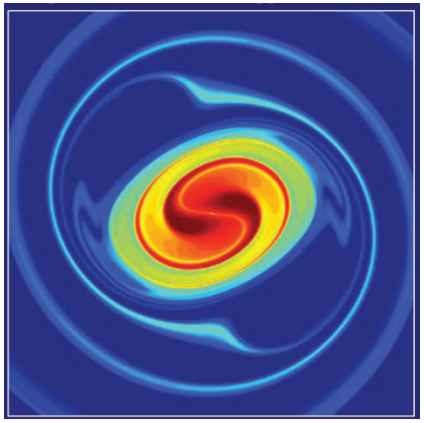
Thrust 10: Decode and advance the science and technology of plasma-surface interactions

Plasma-surface interactions define the boundary condition for any magnetically confined plasma. Many improvements in core plasma performance have resulted from changes in the way the material surface responds to the incident plasma. Improvements in wall preparation techniques have optimized performance in present-day confinement devices, but the reasons for this success are poorly understood. Extrapolation of plasma-surface interactions from today's pulsed devices to future steady-state machines (i.e., with hot surfaces under intense plasma and neutron flux) provides little confidence in predictions of future core plasma performance.

Key Issues:

- Plasma-surface interactions vary by orders of magnitude depending on temperature, incident species, surface material and exposure time. *Can we reliably extrapolate conditions at the wall of today's pulsed confinement machines to future steady-state reactors?*

New Test Facilities

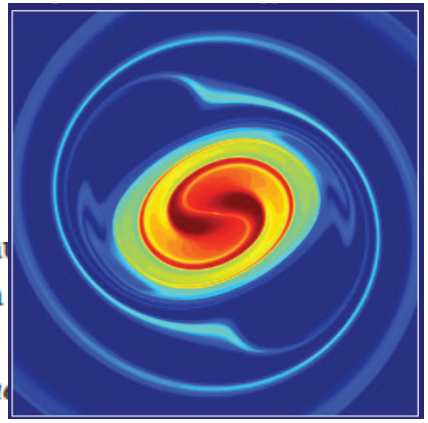


- **Pg 316-317**

can be used for integrated effects, model verification, and demonstration of fully reliable IC components.

A dedicated high flux linear facility can be used to validate many IC design issues, including thermal stresses at the joints subjected to high heat and neutron fluxes, cracking due to voids in brazes, tritium transport, erosion of coatings, insulator performance, and similar issues. A dedicated radiofrequency test facility can be used to develop and validate antenna performance issues and radiofrequency sheath formation. Arcing and breakdown issues can be addressed where multiple parameters can be controlled and tested for long-pulse operation. Other issues that can be addressed include simulation of the antenna interaction with the SOL, including radiofrequency sheath dynamics, antenna phasing effects, hot spot formation, localized erosion, transport along and across magnetic field lines, and wave-particle interactions. Many aspects of edge modeling can be tested and validated. A dedicated radiofrequency test facility will allow for easy access and rapid changes in antenna and launcher geometry or test conditions, and can be used to develop

Design Tools, Rules, and Codes



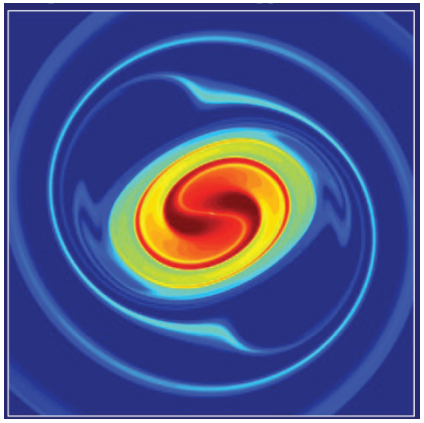
mance and lifetimes must be established, so that benchmarking in the nonnuclear and n
cilities can be translated into a meaningful basis to design the next generation of fusion

Implement an integrated design and testing approach for developing materials, compon
structures for fusion power plants.

Design of fusion power systems faces a significant challenge in that neither the materials property database, nor the requisite computational tools, nor the fusion-relevant design rules and codes currently exist for reliable integrity and lifetime assessments of fusion reactor components and structures. Existing thermo-mechanical property data and high-temperature design methodologies are not adequate to permit even preliminary designs of a fusion power system. Development of fusion relevant design rules and tools are needed. Successful design of a fusion power system will require close integration between materials development activities and system design processes. The commonly used "function-oriented" material design process must be replaced with a concurrent material-component-structure design process.

Fusion energy clearly presents an enormous materials-structural engineering challenge given the unprecedented requirements of an attractive power system. For example, new design and in-service performance computational tools must be developed to replace simplistic high-temperature design and operational rules. These tools must ultimately be incorporated in design codes and

Thrust 14 Costs, Scope

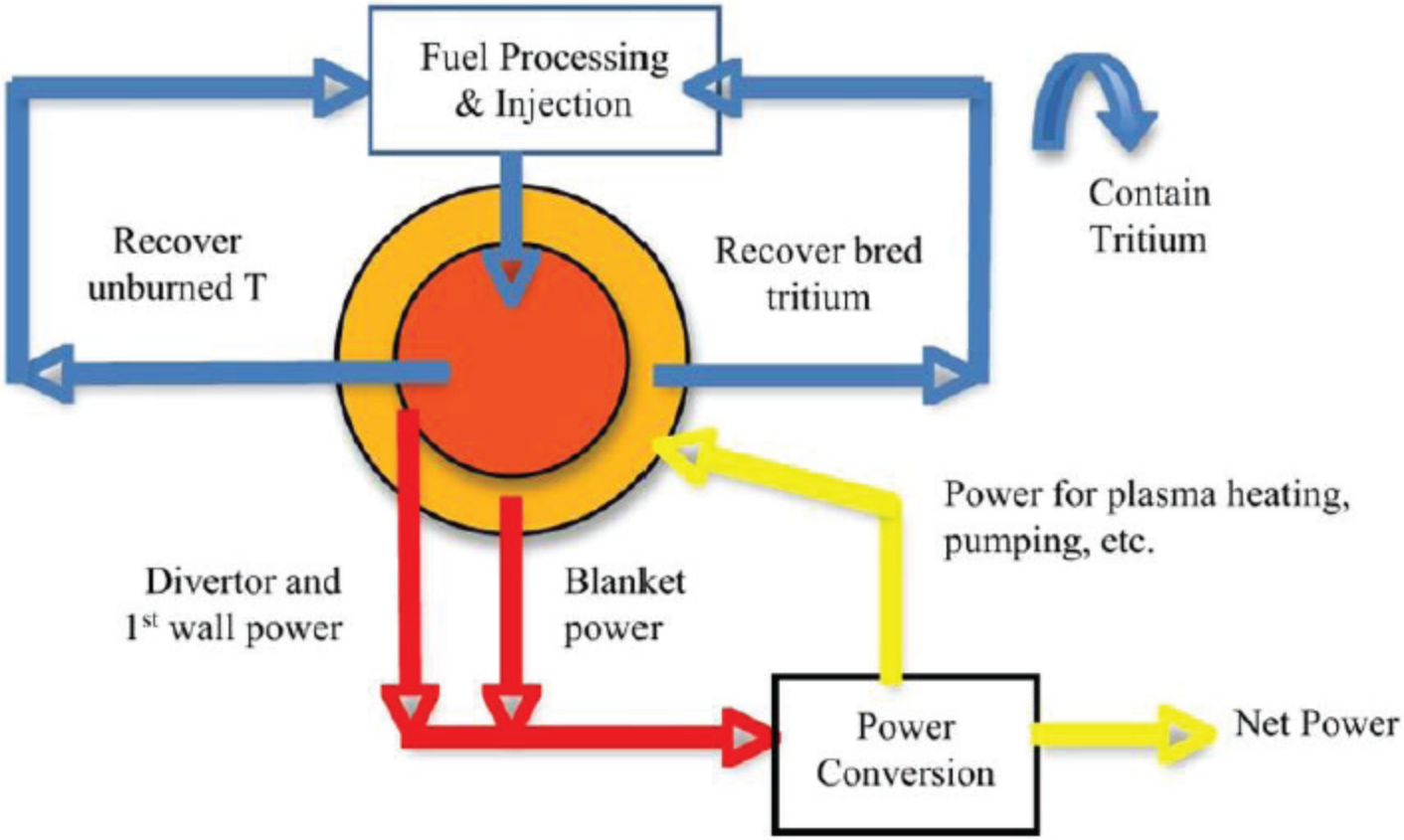


present planning activity, an order of magnitude level of effort can be obtained by examining previous cost estimates prepared for a similar planning effort. The 2003 Fusion Energy Sciences Advisory Committee Development Plan estimated about $1,600M would be required for materials research and development over 35 years (not inflation adjusted) and would involve approximately 60 full-time scientific and technical staff at peak activity.

It is also instructive to look at efforts to develop high-performance materials for other demanding applications. For example, a worldwide effort involving hundreds of scientists over a period of 20 years overcame several major technical hurdles to successfully develop Ni_3Al intermetallic high-temperature alloys with sufficient ductility and fabricability for commercial applications in 2003. Similarly, a dedicated science-based 14-year, $175M effort recently developed four successfully improved generations of Si_3N_4 ceramics with a resultant four-fold increase in high-temperature strength. This development enabled monolithic ceramics to become reliable structural materials for certain low-stress applications. The historical precedent for development of structural materials ranging from aircraft turbine components to pressure vessel materials is that a period of 10-20 years with $150-200M budgets are required for successful development. The development challenges for these materials systems pale by comparison to that for fusion materials, which could be the greatest materials development challenge in history. The combination of high temperatures, high radiation damage levels, intense production of transmutant elements (in particular, He and H), high thermo-mechanical loads that produce significant primary and secondary stresses, and time-dependent strains for which no high-temperature design codes exist requires very high-performance materials. Consequently, it is imperative to initiate a robust materials science program now so that the needed information will be available at the appropriate time.

Other Scientific Benefits

Many of the materials science questions facing fusion energy are universal in scope and fundamental in nature with potential broad applications in fields beyond fusion energy. As mentioned, the thermo-mechanical demands being placed on fusion materials are at the limits of today's ma-


Fuel Processing
& Injection
Contain
Tritium
Recover
unburned T
Recover bred
tritium
Power for plasma heating,
pumping, etc.
Divertor and
1st wall power
Blanket
power
Power
Conversion
Net Power

"I'm OK . . . just a little too much 'push' technology."

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