The National Academies of SCIENCES ENGINEERING MEDICINE

Final Report of the Committee on a Strategic Plan for

BURNING PLASMA RESEARCH

Download the report at ***nap.edu/25331***

Michael Mauel and Melvyn Shochet, Co-Chairs

The study is supported by funding from the DOE Office of Science.

#BurningPlasma

Committee Members Talking Today

Melvyn Shochet
University of Chicago

Michael Mauel
Columbia University

Brian Wirth
Univ Tennessee

Amy Wendt
Univ Wisconsin-Madison

Full Committee Membership and More Information can be found at: https://www.nap.edu/25331

The National Academies of Science, Engineering and Medicine

The National Academies produce reports that shape policies, inform public opinion, and advance the pursuit of science, engineering, and medicine.

The present report is carried out under the leadership of the Board on Physics and Astronomy (James Lancaster, Director). The BPA seeks to inform the government and the public about what is needed to continue the advancement of physics and astronomy and why doing so is important.

Committee on a Strategic Plan for U.S. Burning Plasma Research

The National Academies of Sciences, Engineering, and Medicine was asked by the U.S. Department of Energy to study the state and potential of magnetic confinement-based fusion research in the United States and provide guidance on a long-term strategy for the field.

The Department of Energy requested two reports.

The first, an **Interim Report**, was released on December 21, 2017 and presented the committee's assessment of the current status of United States fusion research and of the importance of burning plasma research to the development of fusion energy as well as to plasma science and other science and engineering disciplines.

For the second, the **Final Report**, the committee was asked to provide guidance on a strategic plan for a national program of burning plasma science and technology research given the U.S. strategic interest in realizing economical fusion energy in the long-term. Strategic guidance is to be provided in two separate scenarios, in which the United States is, or is not, a member in ITER.

(Full Statement of Task at: https://www.nap.edu/25331)

Committee on a Strategic Plan for U.S. Burning Plasma Research

The Committee's unanimous conclusion within its Final Report is …

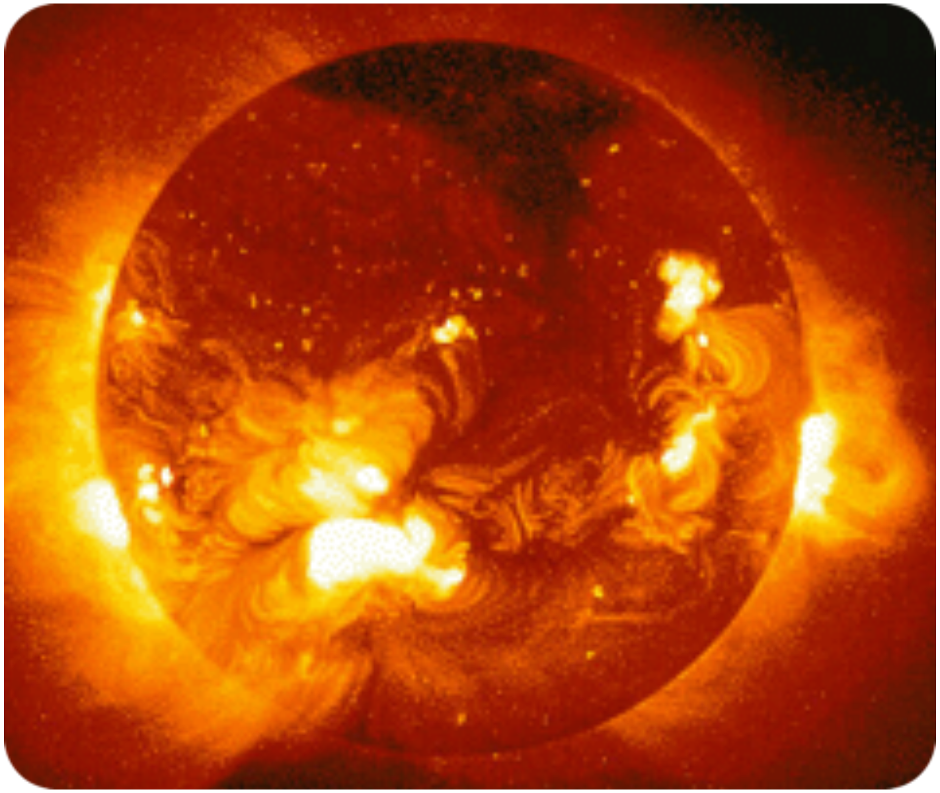
Now is the right time for the United States to develop plans to benefit from its investment in burning plasma research and take steps towards the development of fusion electricity for the nation's future energy needs.

The implementation of these plans should be guided by the committee's two main recommendations:

- *First, the United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant.*

- *Second, the United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant which produces electricity from fusion at the lowest-possible capital cost.*

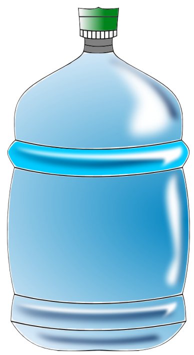
Burning Plasma is an Ionized Gas Like the Sun and Stars Heated by Fusion Reactions

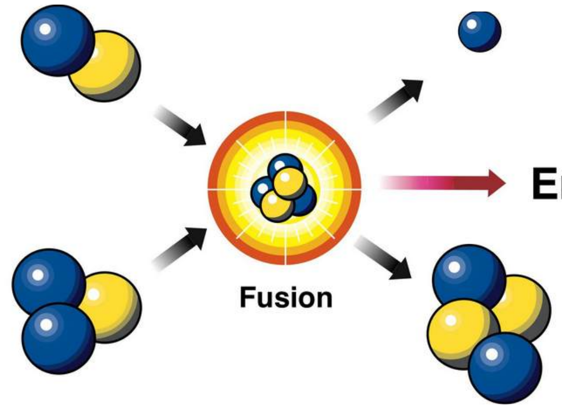


Every second the sun converts 600 million tons of hydrogen into helium and energy

A Burning Plasma on Earth will use Heavy Hydrogen and Produce Abundant Energy

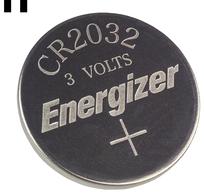
Deuterium in 3/4 Gallon Water





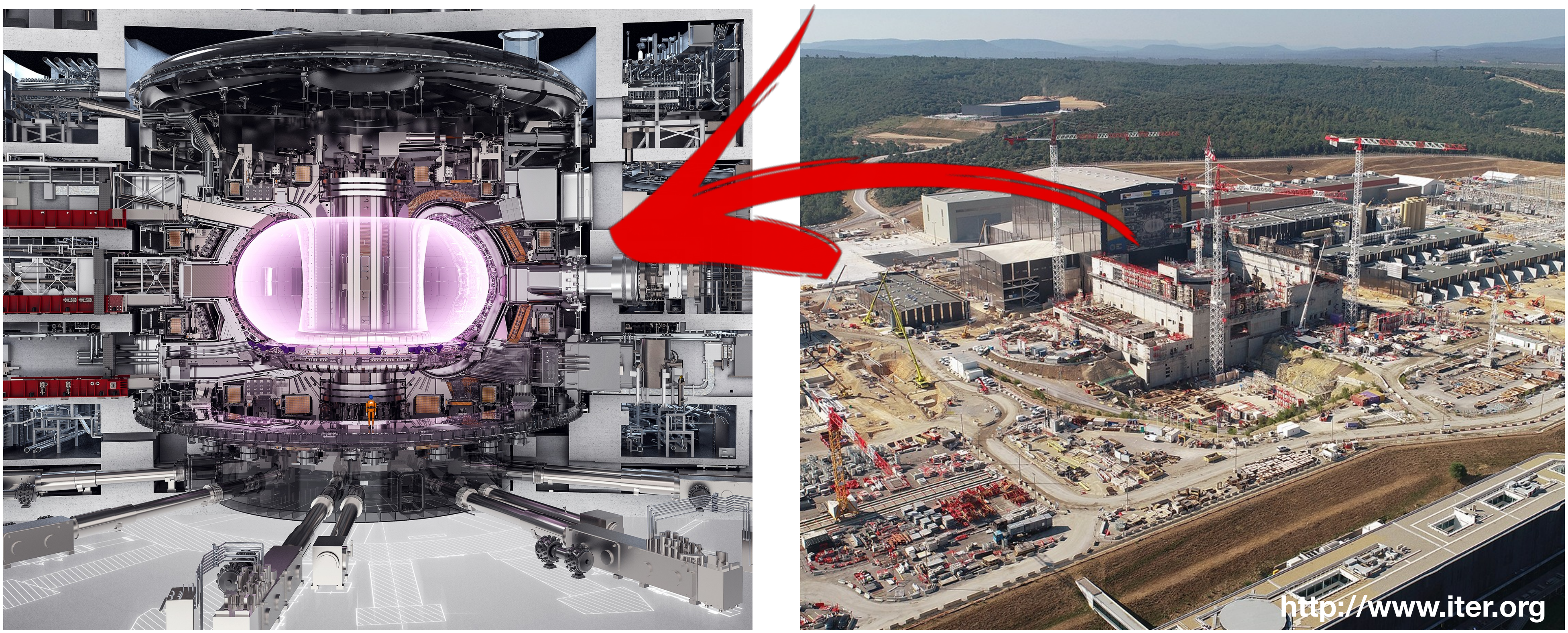
Energy Equivalent of 4 Barrels of Oil

Tritium made from 100 mg Lithium



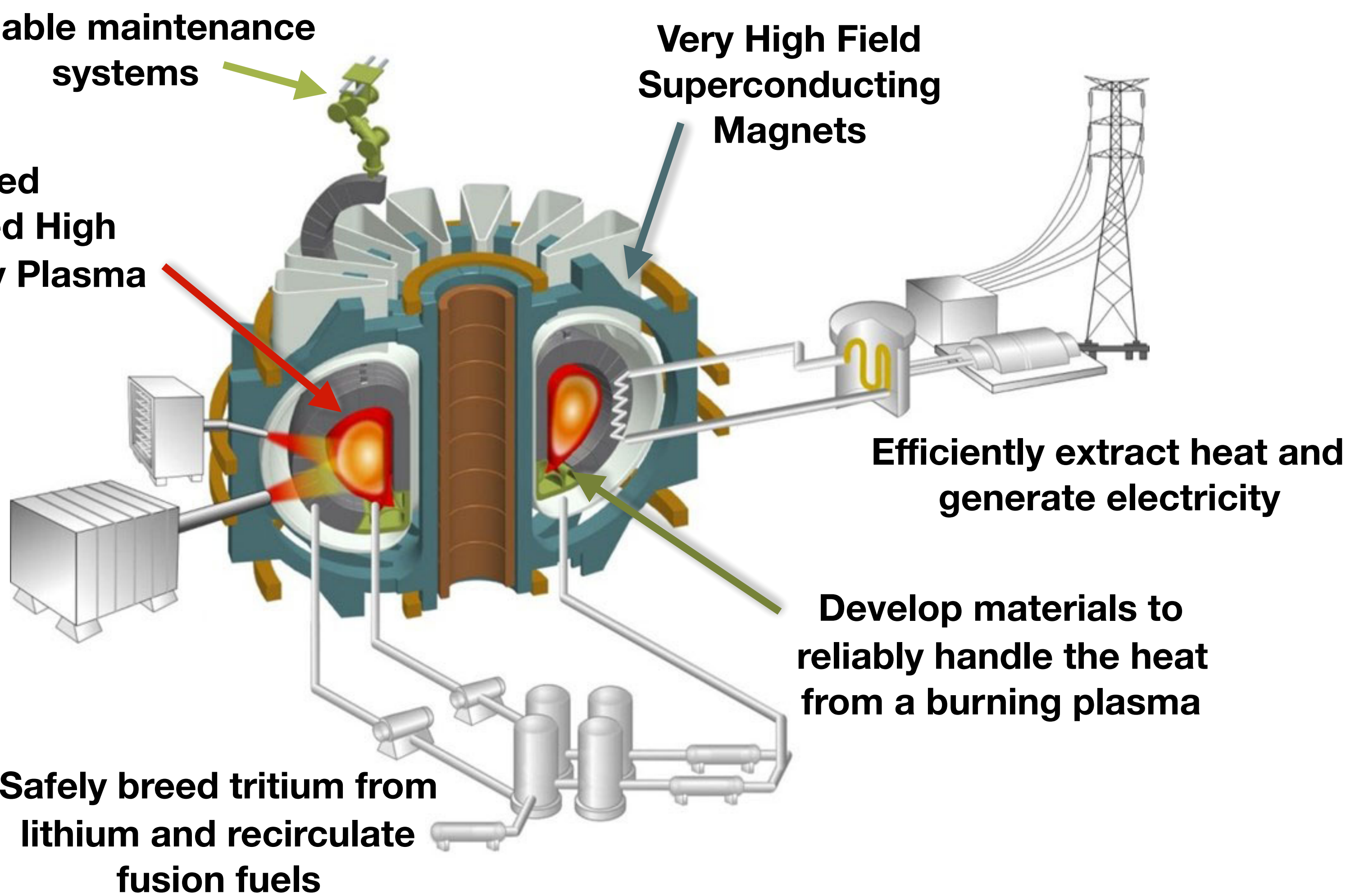
Although scientists have produced over 10 million Watts of fusion power, a sustained burning plasma has never been created on Earth.

ITER is an Ambitious International Project to Create, Study, and Control a Burning Plasma for the First Time



ITER construction began in 2010. First experiments are scheduled to begin within 10 years. When fully operational, ITER will demonstrate fusion power production. This will be scientific and technical achievement and a critical step towards delivering electricity from fusion energy.

In addition to a burning plasma experiment, further research is needed to improve and fully enable fusion electricity



Schematic Courtesy of South Korea's National Fusion Research Institute.

Research is needed to address science and technology challenges and demonstrate innovations that reduce the size and cost of fusion electricity.

Committee Membership

Michael Mauel, Columbia University, Co-Chair
Melvyn Shochet (NAS), Univ Chicago, Co-Chair
Christina Back, General Atomics
Riccardo Betti, University of Rochester
Ian Chapman, UK Atomic Energy Authority
Cary Forest, University of Wisconsin, Madison
T. Kenneth Fowler (NAS), Univ of California, Berkeley
Jeffrey Freidberg, MIT
Ronald Gilgenbach, University of Michigan
William Heidbrink, University of California, Irvine
Mark Herrmann, LLNL
Frank Jenko, IPP Garching and University of Texas, Austin
Stanley Kaye, Princeton University
Mitsuru Kikuchi, Nat. Inst. Quantum Radiological Sci & Tech
Susana Reyes, LBNL
C. Paul Robinson (NAE), Advanced Reactor Concepts, LLC
Philip Snyder, General Atomics
Amy Wendt, University of Wisconsin, Madison
Brian Wirth, University of Tennessee, Knoxville
Chris Jones, David Lang, NRC Study Director

Members of Committee at General Atomics, San Diego, CA

Committee's Study and Report Process

Seven meetings and several teleconferences and several working groups

- **39 presentations from experts from around the world**; and more than **100 scientific white papers**.
- Two meetings for the Interim Report.
- Final five meetings were devoted to **the scientific and technical bases for the strategic elements under consideration** within the United States and the strategic plans for Europe, China, Japan, and the Republic of Korea.
- **Visits to the major fusion research facilities** within the United States, toured the superconducting magnet facility at Poway, CA where the large ITER central solenoid magnets are being manufactured, and learned first-hand of the European fusion energy strategy during a visit to the ITER construction site.
- Heard about fusion energy strategy from the two largest **privately-funded fusion ventures within the United States** from Dr. Bob Mumgaard, Chief Executive Officer of Commonwealth Fusion Systems (CFS) and Dr. Michl Binderbauer, President and Chief Technology Officer of TAE Technologies.
- Two weeklong community **Workshops on Strategic Directions for U.S. Magnetic Fusion Research**, hosted by the University of Wisconsin at Madison (July 2017) and by the University of Texas at Austin (December 2017).
- FESAC Report on ***Transformative Enabling Capabilities Toward Fusion Energy*** (February 2018). This report describes several "*revolutionary*" ideas that would dramatically increase the rate of progress through increased performance, simplification, reduced cost or time to delivery, or improved reliability and/or safety.

Main Message

Now is the right time for the United States to develop plans to benefit from its investment in burning plasma research and take steps towards the development of fusion electricity for the nation's future energy needs.

This conclusion is based on: (*i*) significant progress in predicting and controlling high-pressure plasma, (*ii*) ITER construction progress and mission confidence, and (*iii*) new technologies that make possible a less costly pathway to fusion electricity.

A national program of research and technology leading to the construction of a compact pilot plant at the lowest-possible capital cost will engage universities, national laboratories, and industry in the realization of fusion power.

Near- and mid-term research activities recommended by the report's strategic plan are:

- Understand the science, production, and control of a burning plasma with ITER,
- Demonstrate the science and engineering to sustain a magnetically confined plasma with the confinement and power-handling properties needed for a compact fusion pilot plant,
- Advance very high-field superconducting magnets for fusion,
- Expand research in fusion nuclear science, materials science, and tritium and blanket technologies needed to fully enable fusion electricity, and
- Promote promising innovations in burning plasma science and fusion engineering science.

Outline of Final Report

Front Matter

Preface

Executive Summary

- Chapter 1: Introduction
- Chapter 2: Progress in Burning Plasma Science and Technology
- Chapter 3: Extending the Frontier of Burning Plasma Research
- Chapter 4: Advancing Magnetic Fusion towards an Economical Energy Source
- Chapter 5: Strategic Guidance for a National Program for Burning Plasma Science and Technology
- Chapter 6: Comments on Organizational Structure and Program Balance

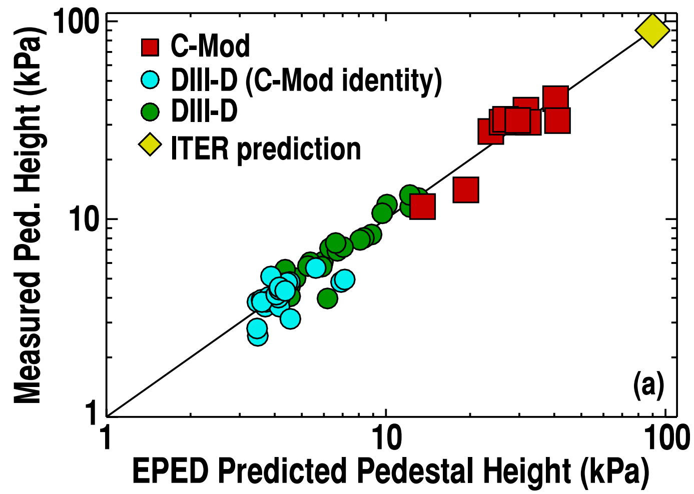
Appendixes: Statement of Task; Interim Report, Summary of Process and Input, History of Strategic Planning, Notional Budget Implications, Bios; Acronyms

Chapter 2

Progress in Burning Plasma Science and Technology

Fusion scientists in the U.S. and other nations have made advances in burning plasma science and technology that have substantially improved our confidence that ITER will succeed.

- Plasma Confinement Predictions
- Plasma Stability and Operational Boundaries
- Energetic Particle Physics
- Mitigation of Transients and Abnormal Events
- Fusion Technology and Engineering Science



Example: Research from US DOE Joint Research Target FY11 identified the processes that control the H-mode pedestal structure (including C-Mod, DIII-D and NSTX and theory-based modeling codes) *Nuclear Fusion* **53** (2013) 093024.

"This provides a solid basis for predicting the maximum pedestal pressure height in ITER."

Chapter 2

Progress in Burning Plasma Science and Technology

Fusion scientists in the U.S. and other nations have made advances in burning plasma science and technology that have substantially improved our confidence that ITER will succeed.

ITER Construction **Then**

ITER Construction **Now**

Today, ITER is coming together. Construction is now more than half complete and ITER construction continues on track.

Chapter 2

Progress in Burning Plasma Science and Technology

Research Progress Beyond ITER towards Fusion Electricity

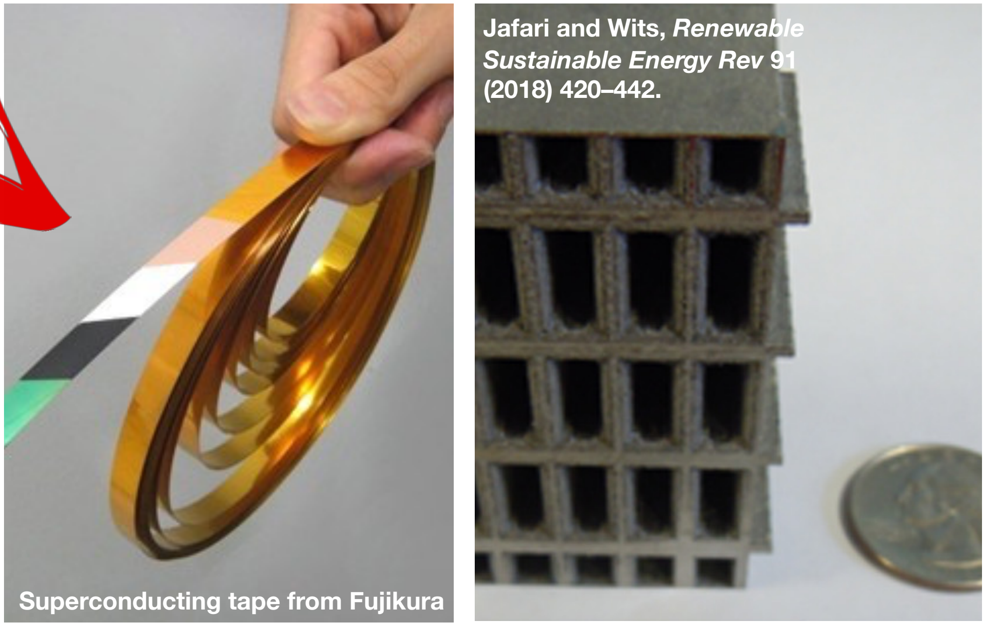
New technologies for fusion, **advances in understanding** and predictive modeling, **improved confidence** in the science and operation of ITER, and **engineering studies** conducted within the United States and by our international partners demonstrate a **readiness to undertake the research beyond ITER** needed to define the next step toward the demonstration of fusion electricity.

Transformative Enabling Technologies (FESAC 2018):

- Intelligent Control
- High-Field Superconductors,
- Advanced Materials and Manufacturing,
- Fusion Blanket Research and Tritium Cycle
- and more…

Examples Transformative Technologies

(a) High-Field Superconductor **(b) Tungsten Heat Exchange**



Chapter 3

Extending the Frontier of Burning Plasma Research

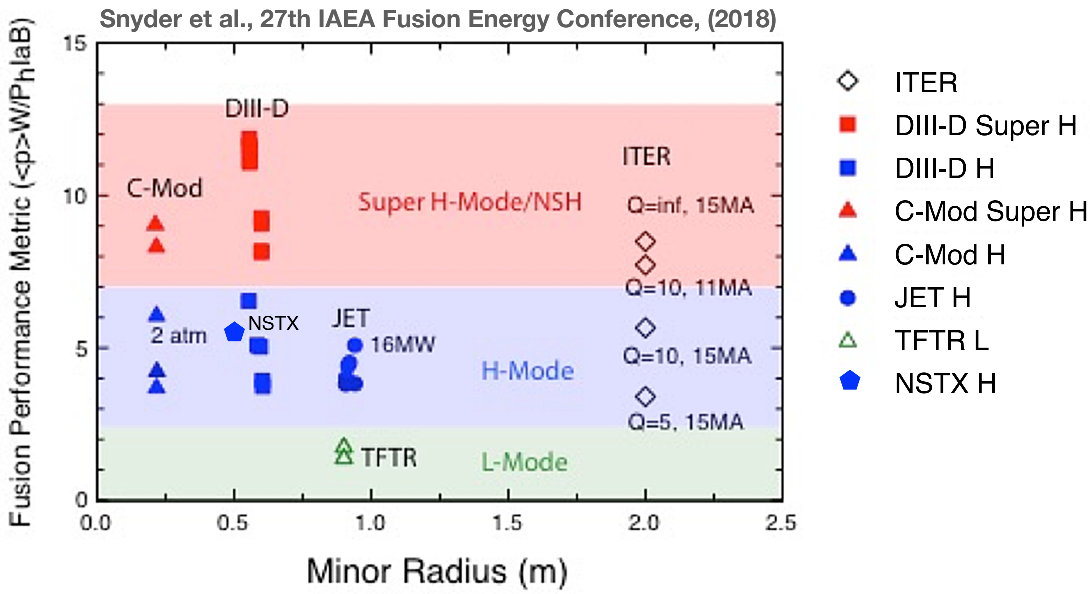
- The Importance of Burning Plasma Research
- The Importance of ITER to the U.S. Fusion Research Program
- Extending ITER Performance
- Developing an Alternate Approach without ITER Participation

Recommendation: Because the scientific and technical benefits from ITER are compelling and because ITER is the only existing project to create a burning plasma at the scale of a power plant, **the Committee recommends that the United States government fulfill its commitment to construct and operate ITER as the primary experiment in the burning plasma component of its long-term strategic plan for fusion energy.**

Recommendation: A near-term focus of the U.S. DOE OFES research program should **maximize the scientific and technical benefits from its partnership in a burning plasma experiment.**

Extending the Frontier of Burning Plasma Research

Extending ITER Performance



Finding: Advances in understanding toroidal magnetic confinement, plasma control, and integrated solutions to whole-plasma optimization point to improvements beyond the ITER baseline and show how careful design and simulation can be used to lower the cost and accelerate fusion energy development.

Recommendation: In the longer-term, the U.S. DOE OFES research program should encourage the development and testing of burning plasma scenarios on ITER that contribute to reliable operation of a compact fusion pilot plant.

Chapter 3

Extending the Frontier of Burning Plasma Research

Developing an Alternate Approach without ITER Participation

Finding: Without ITER, the United States would need to design, license, and construct an alternative means to gain experience creating and controlling an energy-producing burning plasma. The scale of research facilities within the United States would be more costly. The achievement of electricity production from fusion in the United States would be delayed.

Recommendation: Nevertheless, if the United States decides to withdraw from the ITER project, the U.S. DOE OFES should initiate a plan to continue research that will lead towards the construction of a compact fusion pilot plant. This should include the construction of an alternative means to study the burning plasma regime and an alternate method to engage in the international effort in the pursuit of its long-term objective for fusion demonstration.

Chapter 4

Advancing Magnetic Fusion towards an Economical Energy Source

- Previously Studied Pathways to Commercial Fusion Energy
- A Compact and Lower-Cost Pathway to Fusion Electricity
- The Technology Pathway to Economical Fusion Power
- Pre-Pilot-Plant Research Program for the Compact Fusion Pathway

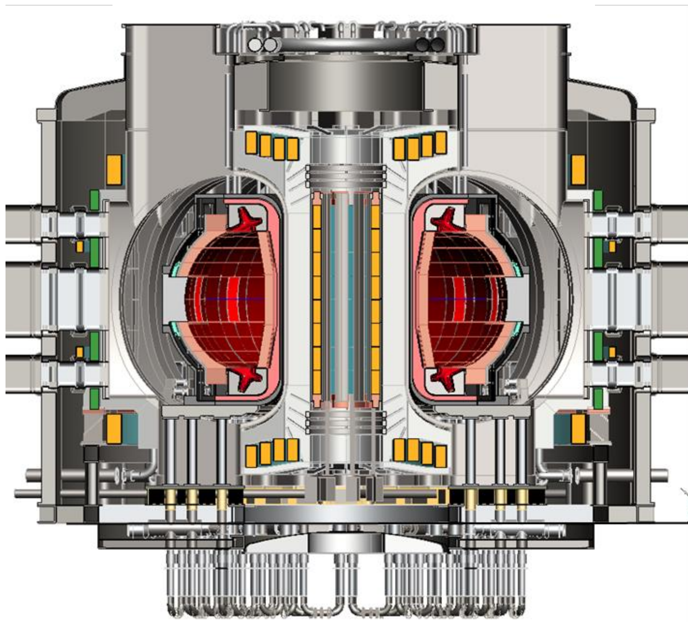
Recommendation: Along with participation in international fusion research, including the ITER partnership, the U.S. DOE OFES should start a national program of accompanying research and technology leading to the construction of a compact pilot plant, which produces electricity from fusion at the lowest-possible capital cost.

Chapter 4

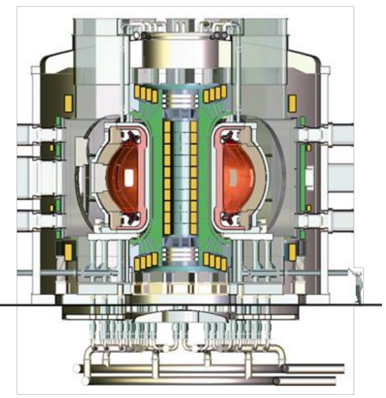
A Compact and Lower-Cost Pathway to Fusion Electricity

(An example from White Paper, Tom Brown, Fusion Engineer PPPL)

Korean DEMO 6.8m



PPPL 4.0m
Pilot Plant



Relative to previous pathways, a compact fusion pathway targets smaller device size, lower capital cost, and shorter development steps.

A research approach that includes the production of electricity motivates efforts to optimize overall systems efficiency as an essential part of the evaluation of the compact fusion pilot plant.

Although promising concepts exist, **additional research and engineering will be needed to identify the optimal approach.**

Chapter 4

New Near- and Mid-term Research Activities

Recommendation: In the near- and mid-terms, the U.S. Department of Energy should resolve critical research needs for the construction of a compact fusion pilot plant:

- Understand the **science, production, and control of burning plasma at the scale of a power plant** through participation in ITER. ← **Full benefit from ITER**
- Demonstrate the science and engineering needed to **sustain a magnetically confined plasma having the high-confinement property and compatible plasma exhaust system** that are needed for a compact fusion pilot plant. ← **New** **Steady-State High-Power Density Research Facility**
- Advance high-field, high-temperature superconductors and **demonstrate the ability to achieve high magnetic fields using large, fusion-relevant coils**. ← **New** **Fusion Magnet Research**
- **Expand significantly the U.S. research program in fusion nuclear technology, advanced materials, safety, and tritium and blanket technologies needed to fully enable fusion energy**. ← **New** **Fusion Nuclear Science and Technology**
- **Develop promising innovations** in burning plasma science, such as optimized stellarator configurations and innovative approaches for a low-cost fusion irradiation facility, and fusion engineering science that reduce the cost and improve the fusion concept as a source of electricity. ← **New** **Innovations in both burning plasma science and fusion technology**

Advancing Magnetic Fusion towards an Economical Energy Source

Recommendation: In recognition of the significant challenges that needs to be addressed for the construction of a compact fusion pilot plant facility capable of electricity production, the U.S. DOE OFES plan for a pilot plant should have a two-phase approach. These objectives of these two phases are:

- In the **first phase**, the pilot plant should be capable of demonstrating fusion electricity production for periods lasting minutes and establish the feasibility of electricity production in a compact fusion system including the assessment of plasma material interactions, tritium safety, pumping, recycling, breeding, and extraction.

- In the **second phase**, the pilot plant should be capable of uninterrupted operation for many days allowing fusion materials and component testing consistent with a commercial power plant, including full fuel cycle blanket testing.

Chapter 5
Strategic Guidance for a National Program for Burning Plasma Science and Technology

- ITER: Extending the Frontiers of Burning Plasma Science
- Beyond ITER: Setting the Nation's Fusion Energy Goal
- Towards Fusion Electricity: The Compact Fusion Pilot Plant
- 2020-2035: Removing the Barriers to Low-Cost Fusion Development
- Fusion Science Predictive Modeling and Exascale Computing
- Promoting Discovery in Fusion Energy Science and Technology
- Responding to a United States Decision to Withdraw from the ITER Project
- **Sustaining the National Program**
- **Budget Implications**

Chapter 5

Strategic Guidance for a National Program for Burning Plasma Science and Technology

Sustaining the National Program and Budget Implications

The committee was asked to consider the budget implications of its guidance. These cost and schedule estimates are necessarily approximate. Implementation of the committee's strategic guidance will require significant planning and thought by the fusion research community, involvement with international partners, and oversight by the U.S. Department of Energy. Additionally, the impact of unanticipated discoveries, breakthroughs, or technical setbacks that would influence the schedule and cost of the strategic plan could not be determined.

Using the baseline cost and schedule for U.S. contributions to ITER's first plasma subproject and estimates from recent reports of the U.S. DOE FESAC, the committee's strategic guidance **implies additional annual funding, rising to nearly $200 million beyond the presently enacted funding levels**.

About half of this additional amount is required to meet ITER commitments and the other half is needed to launch the science and technology supporting the research leading to a compact fusion pilot plant.

This funding would need to be sustained for several decades. Although the funding remains level, the research portfolio evolves in time and existing research facilities are phased out and new ones are implemented.

Chapter 6
Comments on Organizational Structure and Program Balance

- **Organizational Structure and Program Management**
  - Expanding the OFES Organization to Meet Program Needs
  - Adopting a Long-term Strategy Towards a Fusion Energy Goal
  - Strengthening Community Organization and Input
- **Further Strengthening of United States Fusion Research**
  - Setting Safety and Licensing Standards for Fusion Energy Research Facilities
  - Health of the U.S. Fusion Program
  - International Partnerships
  - Private Sector
  - Relationship Between Private Sector and National Goals
  - Linkages to Other Science and Technology Disciplines
  - Public outreach

Five **Findings** and seven **Recommendations** aimed to guide implementation of an expanded U.S. DOE/FES research program and strengthen community participation in burning plasma science, materials science, fusion nuclear science, and engineering science.

Chapter 6

Comments on Organizational Structure and Program Balance

Recommendation: The committee recommends **a new division within U.S. DOE/FES** to manage and organize research in developing technologies needed to improve and fully enable the fusion power system.

Recommendation: The U.S. DOE/FES should establish a formal strategic planning process by which, at regular intervals, respected scientific and technical leaders review progress on short- and long-term goals. This should include consideration of upgrades and new U.S.-based research facilities needed to advance science and technology in support of fusion energy. **Community input should be an essential element of this process.**

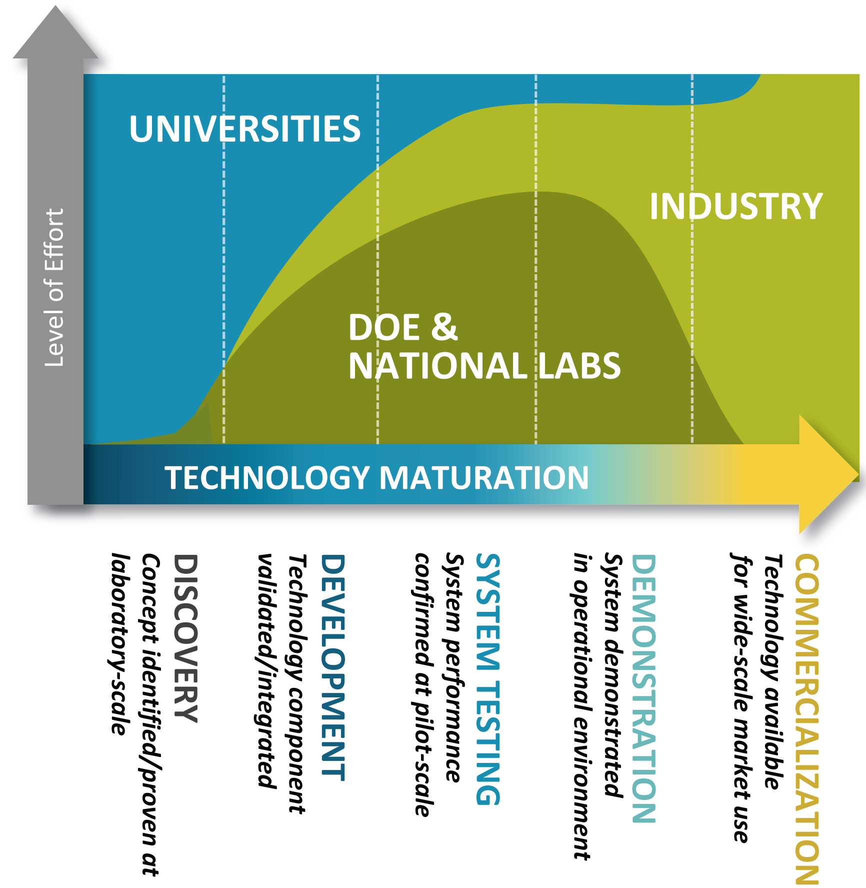
Recommendation: It is recommended that the DOE Fusion Safety Standards be reviewed for consistency with current regulations, and updated to incorporate the community's increased knowledge of the performance of fusion systems and current fusion program needs [and] a licensing strategy should be developed that includes transition from DOE to NRC regulatory authority to ultimately allow for commercialization of fusion power.

Chapter 6
Comments on Organizational Structure and Program Balance

Finding: Opportunities exist to encourage and support private investment in fusion energy development and the focused, goal-oriented approach from U.S. industry, which is beneficial to fusion energy development.

Recommendation: The U.S. DOE OFES should define mechanisms to manage assignment of intellectual property as a means to encourage both private and publicly funded researchers to establish mutually beneficial partnerships.

Recommendation: The U.S. DOE OFES should conduct outreach initiatives that engage the fusion research community and inform the nation. Public awareness is a critical element in maintaining support.



The institutional balance of science and technology research evolves with maturity and technical readiness of the technology. From the 2017 *Annual Report on the State of DOE National Laboratories.*

Main Message (again)

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Questions and Answers

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University of Chicago

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