A Strategic Plan for U.S. Burning Plasma Research

Interim Report

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February 1, 2018

Meeting of the Fusion Energy Sciences Advisory Committee (FESAC)

Gaithersburg Marriott Washingtonian Center; Gaithersburg, MD 20878

http://nas.edu/fusion

Outline

- Study Origin

- ***Interim Report:***
  (1) Importance of burning plasma research, and
  (2) Status of U.S. program

- ***Towards the Final Report:***
  Long-term strategic guidance for U.S. fusion research, in ***two*** scenarios: (1) ***is*** and (2) ***is not*** an ITER partner

- Discussion

Study Origin

CONSOLIDATED APPROPRIATIONS ACT, 2016

PUBLIC LAW 114–113—DEC. 18, 2015

(129 STAT. 2410) That not later than May 2, 2016, the Secretary of Energy shall submit to the Committees on Appropriations of both Houses of Congress **a report recommending either that the United States remain a partner in the ITER project after October 2017 or terminate participation**, which shall include, as applicable, an estimate of either the full cost, by fiscal year, of all future Federal funding requirements for construction, operation, and maintenance of ITER or the cost of termination.

U.S. Department of ENERGY

U.S. Participation in the ITER Project
May 2016

Study Origin

United States Department of Energy
Washington, DC 20585

Message from the Secretary

- ITER remains the best candidate today to demonstrate sustained burning plasma, which is a necessary precursor to demonstrating fusion energy power.
- Having fully assessed the facts regarding the U.S. contributions to the ITER project, I recommend that the U.S. remain a partner in the ITER project through FY 2018 and focus on efforts related to First Plasma. …
- **The DOE will request that the National Academies perform a study of how to best advance the fusion energy sciences in the U.S.** …
- This study will address the scientific justification and needs for strengthening the foundations for realizing fusion energy **given a potential choice of U.S. participation or not in the ITER project,** and will develop future scenarios in either case.

Statement of Task: Two Reports

A committee of the National Academies … will be formed to **study the state and potential of magnetic confinement-based fusion research in the U.S. and provide guidance on a long-term strategy**…

✓ **Interim Report**:

- Describe and **assess the current status of U.S. research** that supports burning plasma science, including current and planned participation in international activities, and describe international research activities broadly.
- **Assess the importance of U.S. burning plasma research** to the development of fusion energy as well as to plasma science and other science and engineering disciplines.

➡ **Final Report:** *In two separate scenarios in which, after 2018,*

(1) the United States is a partner in ITER, and

(2) the United States is not a partner in ITER:

provide guidance on a long-term strategic plan (covering the next several decades) for a national program … which includes supporting capabilities and which may include participation in international activities, given the U.S. strategic interest in realizing **economical fusion energy in the long term**.

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, National Institutes for Quantum and Radiological Science and Technology

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

David Lang, NRC Study Director

https://www.nap.edu/catalog/24971/interim-report-of-the-committee-on-a-strategic-plan-for-us-burning-plasma-research

INTERIM REPORT OF THE COMMITTEE ON A STRATEGIC PLAN FOR U.S. BURNING PLASMA RESEARCH

Committee on a Strategic Plan for U.S. Burning Plasma Research
Board on Physics and Astronomy
Division on Engineering and Physical Sciences

A Consensus Study Report of
The National Academies of
SCIENCES • ENGINEERING • MEDICINE

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Contents

Background (1)

"Achievement of government consensus on rejoining ITER, along with broad support within the U.S. scientific community, was a major accomplishment over the past decade."

- (Dec, 2002) Interim Report of NAS Burning Plasma Assessment
- (Jan, 2003) President George W. Bush ITER announcement
- (2003; Updated 2007) U.S. DOE/OS lists ITER as **highest priority**
- (2006) Agreement to Establish ITER
- (2008) International Design Review
- (2010) **ITER construction begins**
- (2012) By French Order, ITER becomes "first of a kind" licensed basic nuclear fusion facility, defining strict compliance rules for procurement and construction

Background (2)

[*NRC BP Assessment* 2004, p. 39]: "once the [ITER] decision is made, fulfilling the international commitment to help construct the ITER facility and participate in the ITER program will necessarily become the highest priority in the program."

- (2005, 2011, 2013) U.S. narrows research to support ITER burning plasma science
- (2014) ITER receives 40% of U.S. fusion program budget
- (2014) U.S. GAO and ITER Council review cost & schedule growth of ITER
- (2015) Benard Bigot becomes new ITER Director and implements management reforms
- (2015) DOE *A Ten-Year Perspective* to "build the scientific foundation needed to develop a fusion energy source"
- (2016) Resource-loaded plan to first plasma approved by ITER Council
- (2017) U.S. DOE approves project execution plan (SP-1) for U.S. contributions to ITER
- "Today, ITER construction and fabrication occurs throughout the 100-acre ITER site…"

Data Gathering for Interim Report

1. Government reports on U.S. participation in ITER.
2. Previous reports on burning plasma research and strategy for a burning plasma experiment (7 NRC Reports, 3 PCAST, 1 SEAB Report).
3. U.S. DOE fusion strategy reports
   - *A Ten-Year Perspective*, U.S. DOE/OS (2015)
   - Recent Workshops: *Computing at Extreme*, *PMI, and Transients*
   - Annual budget requests (FY2003-17)
   - *Many* FEAC/FESAC Reports
4. Community input
5. Physical and engineering sciences literature

and expertise of the committee's membership

Data Gathering (1):
U.S. Participation in ITER Project

- U.S. GAO, *Actions Needed to Finalize Cost and Schedule Estimates for U.S. Contributions to an International Experimental Reactor*, Report to Congress (GAO-14-499, June 2014).
- *Report* ITER Council Review Group (ICRG) Independent Review of the ULTS (April, 2016).
- U.S. Department of Energy, ***U.S. Participation in the ITER Project,*** Report to Congress (May 2016).
- *Project Execution Plan for the U.S. ITER SP-1* (Project: 14-SC-60), DOE/OS/FES (January 2017).
- Ned R. Sauthoff, "Perspectives from the U.S. ITER Project," presented to NAS Committee for a Strategic Plan for U.S. BP Research (August 29, 2017).

Data Gathering (2):
Strategy for U.S. Participation in BP Experiment

- *Pacing the U.S. Magnetic Fusion Program*, chair: Irvin White, National Academy Press (1989).
- *Realizing the Promise of Fusion Energy,* chair: Richard Meserve, Secretary of Energy Advisory Board (SEAB, August, 1999).
- ***Interim Report***, Burning Plasma Assessment Committee, (NRC, 20 December 2002).
- ★ *Burning Plasma: Bringing a Star to Earth,* chairs: John F. Ahearne and Ray Fonck, (NRC, Prepublication Release: September 2003).
- *A Review of the DOE Plan for U.S. Fusion Community Participation in the ITER Program,* chair: Pat Colestock (National Academies Press, 2008).

Data Gathering (3):
Fusion Strategy from U.S. DOE

- *Facilities for the Future - A Twenty Year Outlook*, U.S. DOE Office of Science (November, 2003; Updated 2007).
- U.S. DOE fusion annual budget requests (FY2003-17).
- *A Ten-Year Perspective*, U.S. DOE Office of Science, Report to Congress (2015); several DOE Workshops, *e.g. Computing at Extreme*, *PMI, Transients, …*

  "The overall mission of the FES program is to expand the fundamental understanding of matter at very high temperatures and densities and build the scientific foundation needed to develop a fusion energy source." - Dr. Patricia Dehmer
- More than a dozen FESAC Reports, including…
  - *Prioritization of Proposed Scientific User Facilities*, chair: John Sarff, (FESAC, 2013).
  - *Applications of Fusion Energy Sciences Research - Scientific Discoveries and New Technologies Beyond Fusion*, chair: Amy Wendt, (FESAC, 2015)

Data Gathering (4):
Community Input

- *Perspectives on U.S. Burning Plasma Research Strategy:*
  Edmund Synakowski (Former Associate Director of Science for FES),
  Emily Domenech and Adam Rosenberg (U.S. House Committee on Science, Space and Technology Science, Space, and Technology),
  Chuck Greenfield and Amanda Hubbard (U.S. Burning Plasma Organization),
  Ned Sauthoff, Bernard Bigot, Stewart Prager, and Tony Taylor
  David Maurer (University Fusion Association),
  Phil Ferguson (Virtual Laboratory for Technology).

- White papers to the Committee

- Community workshop on strategic directions for U.S. MFE research, University of Wisconsin-Madison (July 2017).

Data Gathering (5):
Physical and Engineering Sciences Literature

- Members of the committee referenced over 100 published journal articles
  49 *Nuc Fusion, Phys Plasmas*; 33 *Fusion Eng Des, Fus Sci Tech, J Nuclear Mat*
- Eight of the eleven *Nuclear Fusion* Awards were presented to United States scientists working on scenarios, transport, stability, transient control, boundary, and pedestal physics: Tim Luce (2006), Todd Evans (2008), Steve Sabbagh (2009), John Rice (2010), Pat Diamond (2012), Dennis Whyte (2013), Phil Snyder (2014), and Rob Goldston (2015).
- More than 1/3 all articles published in *Nuclear Fusion* have U.S. co-authors

Importance of Burning Plasma Research

"The committee reaffirms the importance of burning plasma research to the development of fusion energy, as well as to plasma science and other science and engineering disciplines."

1. Importance to the Development of Fusion Energy: Controlling a Burning Plasma

2. Importance to the Development of Fusion Energy: Fusion Technology

3. Importance to Plasma Science and Other Science

(1) Importance to the Development of Fusion Energy: Controlling a Burning Plasma

"A burning plasma experiment would address for the first time all of the scientific and technological questions that all magnetic fusion schemes must face. Such an experiment is the crucial element missing from the world fusion energy science program and a required step in the development of practical fusion energy."
[*NRC BP Assessment* 2004, p. 16]

- A burning plasma experiment will represent the first time that a confined fusion plasma is dominated by fusion-born alpha particles
- A burning plasma experiment advances understanding of plasma transport properties from the core to the boundary
- A burning plasma experiment enables critical tests to control plasma transients
- A burning plasma experiment advances divertor science necessary for a fusion power source
- A burning plasma experiment tests integrated scenarios that simultaneously test the requirements for stability, confinement, fuel purity, and compatibility with plasma-facing components needed for a fusion energy source

(2) Importance to the Development of Fusion Energy: Fusion Technology

"While burning plasma science has progressed since the 2004 NAS burning plasma assessment, significant advancements in fusion technology are needed for a burning plasma reactor."

- Fusion blanket design, tritium breeding, fuel processing
- Fusion safety, remote handling, and waste management
- Fusion materials science
- Plasma heating and current drive systems for fusion
- Integrated systems engineering for fusion

(3) Importance Plasma Science and Other Science

"The process of creating a fusion-based energy supply on Earth has led to technological and scientific achievements of far-reaching impact that touch every aspect of our lives."

- FESAC (2015), *Applications of Fusion Energy Research: Scientific and Technological Advances Beyond Fusion:* advances span a wide variety of fields in science and technology, for example…
- Mathematical theory of solitary waves in everything from plasmas to water waves to Bose-Einstein Condensates with applications in the fields of optics, fluid mechanics, and biophysics
- Chaos in Hamiltonian systems
- Important plasma processes like magnetic reconnection, kinetic turbulent processes in magnetized plasma, nonlinear wave-particle interactions and resonances, and multi-scale phenomena in space and astrophysical plasma
- Better understanding of irradiated materials
- "Burning plasma research acts as an important driver for the development of novel concepts and methods at the interface between plasma physics, materials science, applied mathematics, and computer science, with wide visibility and impact."

Status of U.S. Research that Supports Burning Plasma Science

"Since the NRC report in 2004, the U.S. has undertaken an enormous effort in experimental, theoretical, and computational research in support of burning plasma science. The U.S. research program motivated world-leading contributions to science and technology in support of ITER and other major international fusion experiments. However, the closure of domestic fusion research facilities and the failure either to upgrade or to start new medium-scale experiments, together with substantially decreased funding to fusion nuclear science and technology research, creates concern as to whether the United States will continue to be a scientific leader in the field."

1. Burning Plasma Science
2. Fusion Technology and Engineering Science
3. U.S. Research and Participation in International Fusion Activities
4. Role of ITER in Today's U.S. Burning Plasma Research Activities

(1) Status of U.S. Research:
Burning Plasma Science

"U.S. fusion scientists and engineers have contributed a substantial number of new, innovative ideas to the study of burning plasma science."

- Theory and Simulation to Understand and Predict Burning Plasma Dynamics
  - U.S. scientists are recognized internationally as world leaders in basic theory and simulation.
- Medium-Scale Fusion Research Facilities
  - Significant accomplishments resulted from pioneering experiments conducted using medium-scale facilities, DIII-D, NSTX-U, and Alcator C-Mod.
  - A strength of the U.S. program is the close coupling between theoretical and experimental research.
  - The current U.S. research strategy has increasing focus on international participation in newer long-pulse experiments with superconducting magnets. "*However, presentations to the committee … did not foresee how international cooperation by itself will allow the U.S. fusion researchers to maintain a world leadership.*"

(2) Status of U.S. Research:
Fusion Technology and Engineering Science

"Many of the program contributions to burning plasma science are interrelated to advancements in fusion technology and engineering science."

- Fusion technology advances have been driven by ITER research needs and by next-step goals to fully enable the fusion energy system, e.g.
  - Fusion fuel cycle, fusion materials, fusion materials modeling, fusion plasma power handling, superconducting magnets, and liquid metals.
  - Progress in the definition of requirements for a Fusion Nuclear Science Facility (FSNF) for integrated testing of fusion components and in the understanding of lithium blanket concepts
- Although there have been significant advances in U.S. capabilities since the NRC Burning Plasma study in 2004, many research needs for fusion technology and engineering science remain unresolved, e.g.
  - Fusion plasma material interactions, fusion blanket materials, fuel cycle safety, breeding and fueling, and opportunities for advanced materials and manufacturing guided by new high performance computing tools

(3) Status of U.S. Research:
U.S. Participation in International Fusion Activities

"Fusion energy research is international. The U.S. participates actively in Europe and Asia, and international scientists from around the world participate in fusion experiments and research programs within the U.S."

- U.S. Participation in Fusion Activities in Europe (JET, ASDEX, TCV, MAST-U)
- U.S. Participation in Fusion Activities in Asia
  - The United States is actively playing a significant role in developing new fusion programs in Asia, notably in EAST (China), KSTAR (ROK), HL-2A (China), J-TEXT (Japan),…
- U.S. Participation in the International Tokamak Physics Activity
  - ITPA operates under the auspices of ITER and provides an international framework for coordinated fusion research. Presently, the United States chairs four of the seven ITPA Topical Working groups.
- International Participation in the U.S. Program
  - International collaboration with U.S. researchers in burning plasma science involves all parts of the program, including experimental facilities and theory, simulation, and modeling

(4) Status of U.S. Research: Role of ITER in Today's U.S. Burning Plasma Research

"DOE *Ten-Year Perspective* (2015) (p. 8), "the global magnetic fusion research community is focused primarily on the commencement of the 'burning plasma' era."

- Global focus on ITER is reflected in the U.S. fusion energy science research program
- DOE plan goals include "urgent scientific questions … required for ITER", "formulating ITER operational scenarios", and building "essential expertise for U.S. scientists who may participate in research operations on ITER and future burning plasma experiments."
- Research in support of ITER has facilitated enhanced multi-national collaborative activities through the ITER-sponsored ITPA Topical Groups
- Majority of U.S. ITER construction remains within the U.S. resulting in advancements in U.S. domestic industrial capabilities and capacities
- U.S. has been a key contributor towards the approval of ITER's construction license
- ITER plays a central role in today's U.S. burning plasma research activities, and participation in the ITER project provides formal mechanisms for U.S. scientists to take leading roles in the international effort to develop fusion energy.

(1) Assessments:

Importance of Burning Plasma Research

- Burning plasma research is essential to the development of magnetic fusion energy and contributes to advancements in plasma science, materials science, and the nation's industrial capacity to deliver high-technology components.

- Construction and operation of a burning plasma experiment is a critical, but not sufficient, next step toward the realization of commercial fusion energy. In addition to a burning plasma experiment, further research is needed to improve and fully enable the fusion power system.

(2) Assessment:

Status of U.S. Burning Plasma Research

- The U.S. fusion energy science program has made leading advances in burning plasma science that have substantially improved our confidence that a burning plasma experiment such as ITER will succeed in achieving its scientific mission.

- Recent closures of domestic experimental facilities without new starts, as well as a reduction of fusion technology efforts, threaten the health of the field in the United States.

- Although our international partners have national strategic plans leading to a fusion energy demonstration device, the United States does not.

(3) Assessment:
Any Fusion Strategy Requires a Burning Plasma Experiment

- Any strategy to develop magnetic fusion energy requires study of a burning plasma.
- The only existing project to create a burning plasma at the scale of a power plant is ITER, which is a major component of the U.S. fusion energy program.
- As an ITER partner, the United States benefits from international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources
- A decision by the United States to withdraw from the ITER project could isolate U.S. fusion scientists from the international effort and would require the United States to develop a new approach to study a burning plasma.

(4) Assessment:
The U.S. Needs a Long Term Strategy

- If the United States wishes to maintain scientific and technical leadership in this field, the committee concludes that the United States needs to develop its own long-term strategic plan for fusion energy.

- In the development of the final report, the committee views the following elements as important to its guidance on a long-term strategic plan:

  - Continued progress towards the construction and operation of a burning plasma experiment leading to the study of burning plasma,
  - Research beyond what is done in a burning plasma experiment to improve and fully enable commercial fusion power,
  - Innovation in fusion science and technology targeted to improve the fusion power system as a commercial energy source, and
  - A mission for fusion energy research that engages the participation of universities, national laboratories, and industry in the realization of commercial fusion power for the nation.

Towards Completion of the Final Report

- February 1-2 (Cadarache):
  - Development and Status of EU fusion energy strategy
- February 26-28 (General Atomics):
  - Near and long-term vision of fusion energy research at General Atomics
  - Critical technologies to fully enable fusion power
  - Chinese, Japanese, ROK fusion energy strategies
  - Role and potential for private sector contribution to fusion
  - Further considerations for a U.S. fusion strategy
- April 11-13 (tentative) (PPPL):
  - Near and long-term vision of fusion energy research at PPPL
  - Technology innovations, including HTSC magnets
  - Further considerations for a U.S. fusion strategy
- May-June (T.B.D. NRC): Committee work
- September - October: **Final Report Released**

Towards Completion of the Final Report

- To the extent possible, the final report will include considerations of the health of fusion research sectors within the U.S., the role of international collaboration, the capability and prospects of private-sector ventures, the impact of science and technology innovations, and the research strategies that may shorten the time and reduce the cost required to develop commercial fusion energy.

- Anticipate the final report will present strategies that incorporate continued progress toward a burning plasma experiment, research beyond that done at a burning plasma experiment in order to improve and fully enable commercial fusion power, a focus on innovation, and participation of universities, national laboratories, and industry in the national program.

http://nas.edu/fusion

BOARD ON PHYSICS AND ASTRONOMY

Division on Engineering and Physical Sciences

A Strategic Plan for U.S. Burning Plasma Research

Call for Community Input

Community input is critical in developing a long-term strategy to support U.S. efforts in fusion energy. What are (i) the scientific and engineering challenges and opportunities associated with advancing magnetic confinement fusion as an energy source and (ii) the critical elements of a long-term strategy for the U.S. burning plasma science and technology research program? We invite you to share your thoughts. To upload comments or documents for the committee, please fill out our community input form.

The committee welcomes input in ***any*** form:
Just click…

Note: All input provided will become part of the committee's ***public record***.