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DOE/ER/54508

Board on
Physics and Astronomy

Phone: (202) 334-3520
Fax: (202) 334-3575

November 18, 2002

U.S. Department of Energy
Dr. Steve Eckstrand
SC-55
19901 Germantown Road
Germantown, MD 20874-1290

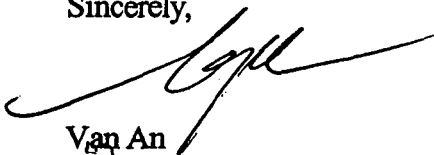
Reference: Grant No. DE-FG02-98ER54508

Dear Dr. Eckstrand:

Enclosed please find a final report for the grant mentioned above.

Should you have any questions related to this report, I can be reached at (202) 334-3563.

Sincerely,



Van An
Financial Associate

2002 NOV 22 AM 10:10
Cc: U.S. Department of Energy/ACQ
Chicago Operations Office
9800 South Cass Avenue
Argonne, IL 60439

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**NATIONAL RESEARCH COUNCIL
DIVISION ON ENGINEERING AND PHYSICAL SCIENCES
Board on Physics and Astronomy
FINAL PROGRESS REPORT
to the DEPARTMENT OF ENERGY**

I. Project Identification

Project Title: Assessment of the Fusion Energy Sciences Program
Agency Award No.: DE-FG02-98ER54508
Reporting Period: 9/15/1998 - 09/14/2002

II. Summary

The overall objective of this study is to prepare an independent assessment of the scientific quality of the Office of Fusion Energy Sciences program at the Department of Energy. The Fusion Science Assessment Committee (FuSAC) has been appointed to conduct this study.

III. Activities During this Reporting Period

The committee held a meeting for final input and discussion in Snowmass, CO as part of the fusion summer study, and completed work on the interim report while there. The interim report was delivered to the DOE on August 31, 1999.

The committee held three more meetings during the following months to gather more input from various stakeholders within the fusion community and to draft the main science chapters of the final report. These three meetings were (1) in conjunction with the APS/DPP meeting in Seattle, WA on Nov 17-18, 1999, (2) in Washington, D.C. on February 23-25, 2000, and (3) on May 8-9, 2000 in closed session at the NAS Beckman Center in Irvine, CA. The committee divided into three working groups to carry out the main writing functions, and a steering group to review the writing as it progressed.

The final writing, teleconference calls, and internal reviews by the full committee took place over the summer, and the report was submitted to formal NRC reviewer on September 21, 2000. The committee's detailed response to review was submitted to the NRC's Report Review Committee, and

official approval was received on October 18, 2000. Copies of the final report in prepublication were delivered to the fusion program personnel on October 20th. Committee member Bob Rosner briefed the fusion community during a public session at the Quebec City APS/DPP meeting on October 24th.

Dr. Rosner then briefed the Fusion Energy Sciences Committee (FESAC) on November 15th in Gaithersburg, MD, with committee chair Charlie Kennel participating via telephone. Dr. Kennel also briefed staff members at the Office of Science and Technology Policy and Office of Management and Budget on December 21st, 2000.

The final report was subsequently edited by NRC staff and released in final form in March 2001. Following the report's release a series of dissemination briefings were held in April 2001, including briefing to Congressional staff and staff at the Office of Management and Budget and the Office of Science and Technology Policy.

Attachments

- (1) FuSAC Membership Roster
- (2) Agendas of FuSAC meetings
- (3) Copy of the interim report
- (4) Copy of the final published report

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Fax: (202) 334-3575
Email: bpa@nas.edu

Fusion Science Assessment Committee Meeting

May 16-19, 1999

Hotel La Jolla

La Jolla, CA

Agenda*

Sunday, May 16

PLENARY SESSION

Room: Bistro

- | | |
|---------|---|
| 4:00 pm | Study Overview
<i>Charles Kennel, Committee Chair</i>
<i>Robert Rosner, Head, Theory and Computation Working Group</i>
<i>Claudio Pellegrini, Head, Experiment Working Group</i>
<i>James Drake, Head, Program Architecture Working Group</i> |
| 4:30 pm | Talk by and discussion with DOE
<i>John Willis, DOE</i> |
| 5:00 pm | WORKING DINNER -- Discussion |
| 5:30 pm | Overview of the goals of fusion theory and computation
and linkage with experiments
<i>Bill Nevins, Lawrence Livermore National Lab</i> |
| 6:00 pm | Discussion |
| 6:20 pm | Overview of Experimental Portfolio
<i>Mike Mauel, Columbia University</i> |
| 6:50 pm | Discussion |
| 7:10 pm | International standing of the US fusion physics experiment program
<i>Hiroshi Kishimoto, Japan Atomic Energy Research Institute, Japan</i> |
| 7:40 pm | Discussion |
| 8:00 pm | International standing of the US fusion physics theory program
<i>Predhiman Kaw, Institute for Plasma Research, India</i> |
| 8:30 pm | Discussion |

CONCURRENT WORK GROUP SESSIONS (NEXT PAGE)

*Invited respondent: *Bruno Coppi, MIT*

Sunday, May 16 (Continued)

CONCURRENT WORK GROUP SESSIONS

Theory & Computation Working Group Session

Room: McKenzie

8:50 pm Contributions of fusion theory to other disciplines
Steve Cowley, UCLA

9:20 pm Discussion

9:50 pm ADJOURN

Experiment Working Group Session

Room: Ashley

8:50 pm Experimental Tests of Neoclassical Theory
Michael Zamstorff, Princeton

9:15 pm Turbulence and Transport - Understanding & Control
Michael Zamstorff, Princeton

9:40 pm Discussion

10:00 pm ADJOURN

Monday, May 17

PLENARY SESSION

Room: Bistro

7:00 am CONTINENTAL BREAKFAST

7:30 am Bias Discussion (CLOSED)

CONCURRENT WORK GROUP SESSIONS

Theory & Computation Working Group Session

Room: McKenzie

8:00 am	Development of computational models for understanding complex plasma dynamics <i>Bill Dorland, University of Maryland</i>
8:30 am	Discussion
9:00 am	Theory of electric field shear generation and its role in transport barriers <i>Patrick Diamond, UCSD</i>
9:30 am	Discussion
10:00 am	BREAK
10:30 am	The theoretical framework for fusion and plasma science <i>Liu Chen, UC Irvine</i>
11:00 am	Discussion
11:30 am	Magnetic reconnection and dynamos <i>Amitava Bhattacharjee, University of Iowa</i>
Noon	Discussion
12:30 pm	LUNCH
1:30 pm	Future directions for fusion theory and computation <i>Bill Tang, PPPL</i>
2:00 pm	Discussion
2:30 pm	CLOSED SESSION
5:30 pm	ADJOURN

Monday, May 17 (Continued)

Experiment Working Group Session

Room: Ashley

8:00 am	Ideal MHD <i>Tony Taylor, General Atomics</i>
8:20 am	MHD, Relaxation, Reconnection <i>John Sarff, University of Wisconsin</i>
8:40 am	Discussion
9:00 am	Burning Plasma Physics <i>Dale Meade, Princeton</i>
9:30 am	Discussion
10:00 am	BREAK
10:30 am	Wave Interaction with and Manipulation of Plasmas <i>Miklos Porkolab, MIT</i>
11:00am	Discussion
11:30 am	Facilities/Diagnostics Needs <i>Earl Marmor, MIT</i>
Noon	Discussion
12:30 pm	LUNCH
1:30 pm	Basic Plasma Experiments <i>Cliff Surko, UCSD</i>
2:00 pm	Discussion
2:30 pm	CLOSED SESSION
5:30 pm	ADJOURN

END OF CONCURRENT WORKGROUP SESSIONS

Room: T-29, Martin Johnson House, Scripps Institution of Oceanography

6:00 RECEPTION (Open)

7:00 DINNER (Open)

Tuesday, May 18

THE ENTIRE DAY IS CLOSED

Wednesday, May 19

THE ENTIRE DAY IS CLOSED

Fusion Science Assessment Committee
July 20-23, 1999 Meeting
Snowmass, CO
AGENDA

July 20 Carol Room, Snowmass Conference Center

5:30 pm Working Dinner to Discuss the Interim Report
10:00 pm Adjourn

July 21 Carol Room, Snowmass Conference Center

8:00 am Continental Breakfast
8:30 am Discussions with Members of the Fusion Community (Discussants
TBD)
Noon Lunch
1:00 pm Discussions with Members of the Fusion Community
5:30 pm Dinner

July 22 Terrace Room, Crestwood Condominiums

8:00 am Continental Breakfast
8:30 am Attend Summer Study Plenary Session
12:30 pm Working Lunch - discussion of plenary session
1:30 pm Attend Summer Study Plenary Session
5:00 pm Working Dinner - discussion of plenary session
7:00 pm Adjourn

July 23 Terrace Room, Crestwood Condominiums

8:00 am Continental Breakfast

Working Group Session

8:30 am Attend Summer Study Plenary Session

Steering Group Session

8:30 am Discussion of Interim Report
12:30 pm Working Lunch -- Discussion with John Sheffield, Chair, FESAC
1:30 pm Adjourn

FUSION SCIENCE ASSESSMENT COMMITTEE

3rd Meeting

November 17-18, 1999

Westin Seattle Hotel, Blakely Room

1900 Fifth Avenue

Seattle, WA

Agenda

Wednesday, 17th

EXECUTIVE SESSION

7:30am Committee Status --Charlie Kennel, Chair
(Breakfast will be served in the meeting room.)

OPEN SESSION

8:30am The role of FESAC --Richard Hazeltine, UT-Austin

9:30am Break

10:00am Programmatic issues --Rob Goldston, PPPL

11:00am Energy Policy and Fusion --Richard Wilson, Harvard

Noon Lunch

1:30pm MFE-IFE synergy --Alan Wootton, LLNL

2:30pm DOE decision processes --John Willis, DOE
SEAB report

3:30pm Break

4:00pm Universities/Science @ OFES --John Cary, Colorado & Arnold Kritz, Lehigh

5:00pm Liquid walls --Farrokh Najmabadi, UCSD

--Mohamed Abdou, UCLA

--Leonid Zakharov, PPPL

--Mike Kotschenreuther, IFS-Texas (*not confirmed*)

6:30pm Adjourn

7:00pm DPP Banquet at the hotel

Thursday, 18th

MORNING AND AFTERNOON IN CLOSED SESSION

OPEN SESSION

Town Meeting: Cascade II (Mezzanine Level)

7:00pm	Introduction	--Kennel
7:30pm	Discussion with audience	--Kennel & other panel members
present		
9:00pm	Scheduled end on DPP program	

FUSION SCIENCE ASSESSMENT COMMITTEE

Agenda

February 23-25, 2000
National Academy of Sciences
Rooms 280, 250, 227, & 150
2100 C St., NW
Washington, DC

Wednesday, February 23, First Day

Closed Session

Convene (Room 280)

8:00am Status report; plans for the meeting
--Charlie Kennel, Chair

Open Session

Outside Input (Room 280)

9:00am Discussion on assessing the quality of the science in the program,
focusing
on the letter from Kenneth Gentle to Charlie Kennel
--Kenneth Gentle, UT-Austin

9:45am Follow-up discussion
(Jim Voytuk, NRC Office of Scientific and Engineering Personnel, will be
present to discuss what plasma physics personnel numbers are available.)

10:00am Break

10:30am Discussion of Office of Management and Budget views on the Fusion Program
--Michael Holland, OMB Fusion Examiner

11:00am Discussion of DOE/OFES views on the Fusion Program
--Anne Davies, Associate SC Director for Fusion Energy Sciences, DOE

11:30am Follow-up discussion

Noon Lunch

Wednesday, February 23, First Day (con't)

Closed Session

Working Group internal discussions (Rooms 280, 227, & 150)

6:30pm Dinner (Executive Dining Room)

Thursday, February 24, Second Day

All day Closed Session for report preparation

6:00pm Dinner (Executive Dining Room)

Friday, January 25, Third Day

All day Closed Session for report preparation

2:00pm Adjourn

Fusion Science Assessment Committee

Agenda

May 8-9, 2000
NAS Beckman Center, Board Room
100 Academy Drive
Irvine, CA

This meeting is closed in its entirety.

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August 31, 1999

Dr. Martha Krebs
Director
Office of Science
Department of Energy
Washington, DC 20550

Dear Dr. Krebs:

National Research Council Chair Dr. Bruce Alberts, in response to your letter requesting a judgement on the quality of the science in the program of the Office of Fusion Energy Sciences (OFES), has established the Fusion Science Assessment Committee (FuSAC). The committee's study will focus primarily on the science of magnetically confined plasmas and the programmatic strategy for long-term progress in this area. The Department of Energy's defense programs also sponsor major inertial-confinement research for stockpile stewardship purposes. Some of the plasma-science issues are common to both magnetic and inertial confinement, but the program structures are quite different. The committee does not directly address inertially confined plasmas in the attached interim report.

The committee prepared the interim report to fulfill the commitment to provide OFES with some initial comments on the quality of the science in its program in time for inclusion in OFES's plans for the next year. A final report will provide a more comprehensive assessment and will address long-term issues facing the field.

In response to congressional direction in 1996, OFES has shifted the focus of its program, emphasizing the effort to build the science and technological foundations for fusion energy and moving the energy technology development effort into the background. The redirection of funds into a broader range of science and technology issues, and to a broader community, is responsive to the report *Plasma Science: From Fundamental Research to Technological Applications*.¹ The committee finds that this new approach is enabled by recent advances in experiment, diagnostics, theory, and computational modeling.

FuSAC initiated its efforts with a meeting in mid-May 1999 that convened a number of experts on various aspects of the fusion research effort. Discussions with the experts on critical aspects of the program were followed by closed-session discussion by members of the committee about their impressions of the program. On the basis of that work, subsequent telephone conferences, and especially further community inputs and committee discussion at the July 1999 Snowmass meeting, the committee offers a number of observations about the science in the fusion program

¹ National Research Council, *Plasma Science: From Fundamental Research to Technological Applications*, National Academy Press, Washington D.C., 1995. A new decadal survey of physics entitled *Physics in a New Era* is now in progress; the *Plasma Science* report is part of the series.

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and about critical unresolved problems. These observations focus on the conceptual advances and the challenges in the program. The connections between experiment, computation, and theory will be discussed in greater depth in the final report.

The committee's final report will be based on an assessment of the past achievements, current strengths and weaknesses, and future prospects of the field. Development of the final report will be guided by broad questions such as: Does the program ask deep physics questions? What are the current role and future potential of a scientific predictive capability for advancing fusion energy? How does one guide the directions of a fusion energy science program if the ultimate goal is to develop a commercially viable fusion reactor? How can the connectivity of fusion science with other scientific disciplines be strengthened? What structural, programmatic, and institutional innovations and international initiatives might strengthen the scientific approach to fusion energy?

FuSAC's Steering Group joins me in transmitting the committee's interim report to you. The committee members have enjoyed interacting with and learning from the fusion community during the past few months. We look forward to continuing these fruitful interactions as we prepare our final report.

Sincerely,

A handwritten signature in black ink that reads "Charles F. Kennel". The signature is written in a cursive, slightly stylized font.

Charles F. Kennel
Chair, FuSAC

Cc: Anne Davies, Director, OFES
Bruce Alberts, Chair, NRC
Peter Banks, Co-Chair, CPSMA
Carl Lineberger, Co-Chair, CPSMA
Robert C. Dynes, Chair, BPA

Enclosures:

Interim Assessment
FuSAC Roster
May 16-19 Meeting Agenda and Attendance List

THE NATIONAL ACADEMIES

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National Academy of Engineering
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National Research Council

August 31, 1999

Fusion Science Assessment Committee Interim Assessment

The birth of modern plasma science

The development of a practical fusion energy source remains one of the most challenging scientific endeavors undertaken by mankind. The early predictions of tabletop-scale fusion energy machines based on "back of the envelope" calculations very quickly confronted the reality of the plasma state as a complex nonlinear medium. Early plasma experiments more often than not ended with the plasma splattered against the walls of the containment vessels rather than confined within the magnetic bottle as intended. The production of a fusion-grade plasma at a temperature of 100 million Kelvin required the development of the field of plasma science. Scientific tools had to be developed to describe plasma equilibrium, the balance between plasma pressure forces and the confining magnetic forces, and stability. Why do large-scale instabilities cause the plasma to break up and why do instabilities at small scale cause the energy to leak across the magnetic field? How do you heat an essentially collisionless plasma to the temperatures required for fusion and how do you accurately remotely diagnose the complex dynamics of the plasma at both large and small scales to test your understanding of the system? These questions and many more must be answered to establish the firm knowledge base required for the achievement of practical fusion energy production.

Fundamental scientific insights from plasma physics and their impact on other scientific disciplines and industry

The historical development of the fusion program has involved both basic physics and the applied and engineering sciences. Because of the explicitly applied goal of the fusion program, the larger scientific community can lose sight of the contributions the program has made to our understanding of fundamental physics. Basic plasma experiments elucidated the nonlinear properties of the plasma medium. As a consequence, a number of areas in modern nonlinear physics found some of their principal applications in fusion plasma science. In some of these cases, plasma scientists became leaders of these emerging fields—solitons, chaos, and stochasticity are noteworthy examples. Basic tools developed in the fusion program ranging from computer-based algebra to particle simulation techniques have found widespread applications in allied fields.

One measure of the quality of a scientific field is its impact on and acceptance by other fields. Some examples of important topical areas that have had a broad impact on the broader scientific and industrial community include:

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Stability: The understanding of the complex plasma dynamics observed in early plasma experiments was initiated with the development of powerful energy principles and eigenmode techniques to explore the linear stability of plasma equilibria. The wide variety of instabilities in plasma with an enormous range of spatial scales serves to define the richness of the plasma medium and the challenge to understand its dynamics. Predictions for the thermal pressure beyond which the plasma will disassemble have been confirmed in experiments in which the temperatures of the plasmas are in excess of those found on the surface of the Sun. In addition, experimental explorations have led to the development of methods that significantly increase the plasma pressure limits set by stability. Many of these stability analysis techniques are now essential tools not only in the field of plasma science but also in allied fields such as astrophysics and solar, ionospheric, and magnetospheric physics.

Stochasticity and chaos: The effort to understand how the magnetic surfaces that confine hot plasma in fusion experiments break up led to the development of the standard map, which allowed the generic exploration of the onset of stochasticity. Understanding of the onset of stochasticity in velocity space was also intrinsic to modeling heating in essentially collisionless plasmas. Finally, senior scientists trained in the physics of plasmas developed the first published method for controlling chaos.

Reconnection, field topology, and magnetic dynamos: A three-decade challenge of plasma physicists has been to explain the very short time scales that characterize the release of magnetic energy in the solar corona, in planetary magnetospheres (including Earth's), and in fusion experiments. Classical collisional dissipative processes are orders of magnitude too weak to explain the time scales observed. The difficulty lies in the extreme range in the spatial scales, from the macroscopic to the microscales associated with kinetic boundary layers, and in the necessity to include kinetic processes to provide collisionless dissipation. An emerging understanding based on theory, computation, and basic experiments is linked to the mediating role of dispersive waves, which act at the small scales where the "frozen-in" condition is broken. For the first time the predictions of energy release rates in fusion experiments are consistent with observations. A consequence of the fast release of magnetic energy associated with magnetic reconnection in some fusion experiments is the evolution to a minimum energy state where the magnetic field is partially self-generated by the plasma. The resulting "dynamo" action is related to magnetic dynamo processes in astrophysical systems such as the Sun and the planets. These fusion-sponsored experiments remain among the few laboratory demonstrations of a turbulent dynamo.

Wave dynamics: The plasma state is unique in the rich variety of waves that are supported by the medium. Waves in plasmas not only appear spontaneously as a consequence of instabilities, but also can be generated to control plasma temperature and currents. Understanding how waves propagate and are absorbed in nearly collisionless plasma was a scientific challenge. Building on Landau's idea of the wave-particle resonance as a mechanism for collisionless dissipation, fusion scientists developed models to describe the absorption of high-power radio frequency waves and benchmarked the predictions in fusion experiments. Waves could then be used to engineer the phase space of particle distribution functions. Waves can now be excited in plasmas to generate intense current or to accelerate particles to high energies—a

technique that can be applied to the next generation of high-energy accelerators. The nonlinear behavior of waves has also been an intrinsic component of the science of plasma wave dynamics, and knowledge of this phenomenon has spread widely to many other branches of physics. Indeed, such ubiquitous concepts as absolute and convective instabilities, solitons (nonlinear waves that persist through collisions), and parametric instabilities saw extensive development in the fusion context. Important industrial applications include the use of radio frequency technologies for plasma processing in semiconductor manufacturing. Finally, plasma physicists introduced the idea of using solitons in commercial high-speed communications.

Turbulent transport: Understanding transport driven by turbulence is critical to solving such important problems as the accretion of matter into black holes, energy transport in the solar convection zone, and energy confinement in fusion experiments. Gradients in pressure, angular momentum, or other free energy sources drive small-scale turbulent flows that act to relax the gradient. This "anomalous transport" process should be contrasted with classical transport, which arises from two particle coulomb interactions in magnetic fusion plasmas and can include photon diffusion in astrophysical systems. The identification of anomalous transport in fusion experiments (and the corresponding theoretical work) sparked the recognition of its importance in space science and astrophysics, fields in which concepts such as anomalous transport and heat flux inhibition are now common language. Because of its fundamentally nonlinear and turbulent nature, understanding anomalous transport has been one of the significant scientific challenges of the fusion program. Diagnostics to remotely measure turbulent fluctuations as well as computer codes to describe the nonlinear dynamics of small-scale flows in a collisionless medium were developed. Experimental work in fusion has shown that turbulence can be spontaneously suppressed and a transport barrier formed, and that the mechanism was linked to the development of local zonal flows, which shred the vortices driving transport. The dynamics of this process parallels that of zonal flows in Jupiter's atmosphere.

Outstanding problems

In its preliminary discussions, the committee has begun to identify critical unresolved problems in fusion science. The following includes some examples.

Turbulence and transport: Despite the scientific success in understanding the turbulent transport of ion thermal energy in magnetic containers, formidable challenges remain. The mechanism by which particles and electron thermal energy are lost from magnetic containers has not yet been clearly identified. This is a key issue for an energy-producing plasma, in which high-energy alpha particles produced during fusion deposit their energy in electrons. A paradox is that the electron energy-loss rate appears to be greatest in the core region of tokamak plasmas where theories based on linearization of equations for small-amplitude disturbances predict no linear instabilities. The source of the turbulence driving transport remains a mystery. The present experiments in tokamaks are in a regime in which magnetic field fluctuations associated with small-scale vortices driving transport are important, yet progress has been slow in developing the computational and diagnostic tools required to include these effects. The exploration of the role of magnetic fluctuations is especially critical for modeling experiments in the innovative magnetic containers now coming on line. Predictions of performance in proposed magnetic confinement experiments have traditionally been based on scaling laws deduced from

existing and previous experiments rather than from first-principles theories of turbulent transport. The reliance on this approach over the long term, though previously grounded in necessity since there were no reliable theories of transport, should be re-evaluated in light of the new developments in theory and computation and the emergence of control techniques for manipulating transport. Finally, the role of alpha particles in turbulence and transport, which will be an important issue for burning plasmas, is not well understood.

Energy density limits: The success in understanding pressure limits in confined plasma has been based largely on the ideal (dissipation-free) magnetohydrodynamic description. There is now substantial experimental evidence that, under some circumstances, the plasma pressure can be limited below these "ideal" limits by instabilities whose growth is facilitated by resistive or kinetic effects. Nonlinear instabilities, which self-sustain only when their amplitudes exceed a threshold value, are being studied as a possible mechanism for such limits. A major challenge for the field is to develop the computational tools to study the macroscopic nonlinear development of instabilities that constrain the global pressure of a system and that at the same time resolve the small time and space scales required to describe critical kinetic features. Until this challenge is met, numerical models of the large-scale plasma dynamics will be subject to the criticism that they are too primitive to fully describe the high-temperature regime of present and future fusion-grade plasmas. The duality of a medium that behaves like a continuum fluid at large scales and yet displays the effects of discrete particles at small scales is a recurring theme of plasma science.

Integrated physics of self-heated plasmas: While the past DT tokamak experiments that produced weakly burning plasma were a milestone, a broad range of scientific and technological issues nevertheless remain to be explored in the strong self-heating regime, where the local energy deposited by fusion-produced alpha particles exceeds the energy from external sources. Key scientific questions concern the stability of the profiles, including transport barriers, in the self-heating regime. As the plasma pressure exceeds stability limits because of self-heating, will transport rise to balance the source in a benign manner or will large-scale instabilities lead to a loss of global confinement? Will a high density of energetic alpha particles destabilize waves and degrade alpha confinement so as to reduce the efficiency of alpha particle heating? Will helium ash accumulation continue to be minimal? On the positive side, will ideas for channeling alpha-particle energy directly into ions rather than electrons be successful and therefore ultimately lead to a more attractive fusion energy source? Conclusive answers to such questions will require experiments in the burning plasma regime.

Summary

The worldwide fusion energy program, with vigorous U.S. participation in all areas and leadership in many, has achieved much in its 40-year history. The fusion energy goal also has driven the development of the modern phase of plasma science. Plasma science, in turn, has contributed to many fields of science and technology during this time.

The reorientation of the U.S. fusion program in 1996 had as its aims the stimulation of innovation and the strengthening of the scientific focus of the program. The extent to which the full promise of this approach has begun to be realized will be addressed in the committee's final report.

FuSAC can say with confidence now that the technology needed to create, diagnose, and model sophisticated experiments on fusion-grade plasmas has been developed. The critical materials science issues of fusion energy have been scoped. The progress can be measured in other ways as well: The first preliminary fusion-burning experiments were recently completed. Scientific and engineering understanding of the concepts required for future fusion energy systems is being continually deepened. Nonetheless, the distance to the ultimate goal remains large.