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FUSION ENERGY ADVISORY COMMITTEE

Advice and Recommendations to the U.S. Department of Energy

In Response to the Charge Letter of September 1, 1992

April 1993

U.S. Department of Energy
Office of Energy Research

FUSION ENERGY ADVISORY COMMITTEE
Advice And Recommendations To
The U.S. Department Of Energy

In Response To The Charge Letter
Of September 1, 1992

Members of FEAC

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FEAC/93-I

March 1993

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Preface

This document is a compilation of the written records that relate to the Fusion Energy Advisory Committee's deliberations with regard to the Letter of Charge received from the Director of Energy Research, dated September 1, 1992.

During its sixth meeting, held in March 1993, FEAC provided a detailed response to the charge contained in the letter of September 1, 1992. In particular, it responded to the paragraph:

> "I would like the Fusion Energy Advisory Committee (FEAC) to evaluate the Neutron Interactive Materials Program of the Office of Fusion Energy (OFE). Materials are required that will satisfy the service requirements of components in both inertial and magnetic fusion reactors -- including the performance, safety, economic, environmental, and recycle/waste management requirements. . . . Given budget constraints, is our program optimized to achieve these goals for DEMO, as well as to support the near-term ITER program?"

Before FEAC could generate its response to the charge in the form of a letter report, one member, Dr. Parker, expressed severe concerns over one of the conclusions that the committee had reached during the meeting. It proved necessary to resolve the issue in public debate, and the matter was reviewed by FEAC for a second time, during its seventh meeting, held in mid-April, 1993.

In order to help it to respond to this charge in a timely manner, FEAC established a working group, designated "Panel #6", which reviewed the depth and breadth of the U.S. materials program, and its interactions and collaborations with international programs. The panel prepared background material, included in this report as Appendix I, to help FEAC in its deliberations.

Department of Energy
Washington, DC 20585

SEP 01 1992

Professor Robert W. Conn
University of California, Los Angeles
6291 Boelter Hall
405 Hilgard Avenue
Los Angeles, California 90024

Dear Bob,

I would like the Fusion Energy Advisory Committee (FEAC) to evaluate the Neutron Interactive Materials Program of the Office of Fusion Energy (OFE). Materials are required that will satisfy the service requirements of components in both inertial and magnetic fusion reactors -- including the performance, safety, economic, environmental, and recycle/waste management requirements. It is acknowledged that this will require a sustained effort over many years. Given budget constraints, is our program optimized to achieve these goals for DEMO, as well as to support the near-term ITER program?

The goal of the OFE fusion materials program is to develop the materials for all components of fusion reactors. Parallel activities focus on (a) meeting functional requirements, for the near-term applications in ITER, and (b) developing materials optimized for both functional requirements and environmentally attractive features needed for longer range applications. The FEAC evaluation should include the work on materials for structural components and on ceramics for insulators and other components in the high neutron flux reactor regions.

Your evaluation of the materials program should include consideration of balance. Is the balance appropriate between:

a. near-term (ITER) and longer range applications;
b. the several candidate materials for longer range structural applications;
c. structural materials and ceramic insulators; and
d. domestic and collaborative international programs?

The program relies heavily on the use of fission reactors for irradiation experiments that partially simulate the fusion environment. The need for a "fusion neutron source" is also widely recognized. Would you please comment on the following: adequacy of planning to maintain and use available facilities; development of new facilities (especially a fusion neutron source); and additional supporting facilities needed to conduct the complete program.

A major focus of the long-range materials program is the development of reduced activation materials (sometimes called low activation materials). Would you please review the evaluation criteria for materials activation used to direct this program. These criteria include considerations of environmental effects, safety, recycle potential, and waste management, in addition to performance requirements.

I would like to have the FEAC evaluation and recommendations on the Fusion Materials Program by February 1993. This will be important for decisions both on the inertial and magnetic fusion energy programs.

Sincerely,

William Happer

William Happer
Director
Office of Energy Research

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May 20, 1993

Dr. William Happer
Director
Office of Energy Research
U.S. Department of Energy
Washington, D.C.

Dear Will:

In your letter to me of Sept. 1, 1992, you asked the Fusion Energy Advisory Committee (FEAC) to evaluate the Neutron Interactive Materials Program of the Office of Fusion Energy (OFE). You inquired about many aspects of this program including whether, given budget constraints, the program is optimized to achieve the performance, safety, economic, environmental, and recycle/waste management requirements of a fusion demonstration reactor while supporting the near-term ITER program; whether the balance is appropriate a) between the several candidate materials for longer-term structural applications, b) between structural materials and materials needed for other applications, and c) between domestic and collaborative international programs; whether the planning and use of available irradiation facilities is adequate; and whether there are additional supporting facilities, especially a fusion neutron source, needed to conduct the complete program.

The FEAC formed a panel, Panel 6, to address the issues raised in your letter and to provide the Committee with background, findings and conclusions that form the basis of the recommendations in this letter to you. Panel 6 was chaired by Dr. Klaus Berkner, with Dr. Richard Siemon as vice-chair, and consisted of 19 people, 3 members of FEAC and 16 other people with technical expertise and experience relevant to the issues of your charge. Several people on the panel came from outside the fusion program and brought additional perspectives to the issues. The Committee is grateful to all the panel members for their extensive efforts over a period of several months. The panel provided the members of FEAC with a detailed report which will be published by the Department together with this letter.

The FEAC met on March 4 and 5, 1993 for two full days to consider the Panel 6 report and held additional discussion during our April 15 and 16 meeting to conclude our deliberations. We summarize first a set of panel findings which the Committee accepts and which are in direct response to a number of queries in your letter.

Regarding neutron irradiation facilities, testing in fission reactors is a vital component of fusion materials development. The program relies on both mixed- and fast-neutron-spectrum fission reactors. There is concern about the continued availability of such reactors. One fast reactor (FFTF) is no longer operating, and the availability of the sole remaining reactor (EBR-II) is not assured.

Regarding a fusion neutron source, a key finding is that preparation for building a DEMO requires that both ITER and a high-flux 14-MeV neutron source proceed on similar schedules. Two concepts have been proposed: a 35-MeV deuterium beam impinging on a liquid lithium target; and a 120-keV deuterium beam impinging on a magnetic-mirror-confined plasma target. [In this regard, FEAC recommends that the U.S. seek an international commitment for the design and construction of a high-fluence fusion neutron source facility with the aim of having initial operation shortly after the year 2000.] If the outlook for international construction of such a source is favorable, then funding the conceptual design of this facility as part of an international effort should have the highest priority within the materials program. The panel and FEAC conclude that the accelerator - based D-Li system is the preferred approach for this function.

Turning now to the materials program in the Office of Fusion Energy (OFE), the current funding level for the development of structural materials for fusion applications is about $10 million per year in its base materials and ITER programs combined. The panel and FEAC find that this is inadequate to ensure the availability of such materials on the time scale consistent with the operation of an attractive fusion demonstration reactor beginning around 2025. A prudent effort focused on low/reduced activation structural materials needs to grow to about twice the current level by 1996-97. Funding needs to grow thereafter to provide for U.S. participation in the international construction of a fusion neutron source.

Structural materials must meet a variety of requirements to function in a fusion reactor environment. Currently, the base program primarily supports work on three materials systems, each offering different mixes of benefit and risk. In order of decreasing support, these are ferritic steels, vanadium alloys, and SiC/SiC composites.

The panel and FEAC find that it is important that the longer term base materials program be protected against diversion of funds towards near-term, non DEMO-relevant materials development.

FEAC recommends that the base program focus on the development of low/reduced activation structural materials, with relatively smaller but still important efforts on neutron irradiation issues related to ceramic insulators, material coatings, and plasma-facing components. In the base program on structural materials, the FEAC recommends that priority be given to enhancing the vanadium alloy and SiC/SiC composites programs. Titanium alloys also represent a promising material not now under investigation and the OFE should consider whether or not a reassessment of this alloy system is warranted.

Finally, the next generation of fusion facilities will provide opportunities for fusion materials development. ITER is a crucial element in the component development program and will provide the environment for neutron irradiation tests, though not to the fluence levels of a demonstration reactor. The Tokamak Physics Experiment, TPX, while not a D-T device, will provide an important high-duty-factor, high-heat-flux plasma environment for testing the plasma-interactive properties of advanced materials. These facilities will begin contributing operational experience after the year 2000. FEAC notes that both the ITER and TPX projects are considering seriously the use of low/reduced activation materials in appropriate components. We strongly endorse these efforts both for the impetus they will provide and for the benefits that will be gained from large-scale practical experience with such materials in actual fusion machines.

Sincerely,

Bob Conn

Robert W. Conn
Chairman, on behalf of the Fusion
Energy Advisory Committee

Appendix I

The report to FEAC of Panel #6, dated April 7, 1993.

FUSION ENERGY ADVISORY COMMITTEE

PANEL 6

NEUTRON-INTERACTIVE MATERIALS (NIM) PROGRAM

Wednesday April 7, 1993

This report was prepared by a panel established by, and reporting to, the Fusion Energy Advisory Committee (FEAC). The report of this panel should not be construed as representing the views, official advice or recommendations of FEAC.

CONTENTS

EXECUTIVE SUMMARY

To be commercially accepted, fusion energy must be competitive with other energy sources, especially those producing electricity. Studies like ARIES suggest that direct economic advantages will be difficult to obtain, so we need to look at the broad array of energy source characteristics. Although we cannot know the precise competitive market in the first half of the next century, safety and environmental performance will surely receive very close attention both now and in the future. Fission energy's economic prospects and public acceptance have been hampered by safety and environmental concerns, especially radioactive waste and the feared potential for catastrophic health impacts from worst-case accidents. Other energy sources may also suffer from safety and environmental problems— fossil fuels produce chemical pollutants, and solar energy entails high use of land and generation of some toxic materials. Even conservation is sometimes not without problems, such as increased indoor air pollution due to reduced ventilation.

Fusion has very high potential for safety and environmental acceptability. However, several studies, notably ESECOM, have found that this potential will not be realized automatically. ESECOM went further and indicated that improved safety and environmental performance should translate into economic benefits via faster and more assured licensing and reduced need for safety-grade (N-stamp) components. In 1982, the Conn Panel suggested "low activation materials" as an explicit objective of the US structural materials program, focusing on near-surface burial (per 10 CFR 61) as the major quantified objective.

Low/reduced-activation materials offer the potential to improve the safety and environmental performance of fusion energy. Among structural materials, the US program includes austenitic steels, ferritic/martensitic steels, vanadium alloys, and SiC composites. Austenitic steels are only viewed as near-term materials; the other options are viewed for long-term commercial fusion application because they require a high activation element to stabilize the austenitic crystal structure: either manganese (increasing high decay heat and accident potential) or nickel (with long-term waste management concerns). Low-activation versions of austenitic steels do not appear likely; thus these steels are not attractive candidates beyond ITER. Suitable low-activation compositions of the other candidates have been identified.

The low/reduced activation structural materials present activation hazards that are one to several orders of magnitude lower than those of conventional materials and of conventional fission power reactors. As a result, fusion power offers the promise of a qualitatively (not just quantitatively) lower level of radiation hazard. The activation of non-structural elements, especially divertor materials, is also quite important and must be addressed as well in order to minimize the quantity of high-level waste. Progress towards the use of radiative/gaseous divertors in TPX and ITER should open the possibility of using low/reduced activation materials in this area as well.

To achieve these goals, designers of the magnetic- and inertial-confinement fusion energy (MFE and IFE) systems of the future must meet formidable challenges in materials science and engineering. Materials will be pushed close to their limits in many aspects of performance: not only temperature, stress, and chemical environment, but also exposure to large fluences of energetic neutrons (up to 14 MeV). The neutronics issues have implications for both the long term (a demonstration power system—DEMO—or its IFE equivalent, along with subsequent power systems) and the near term (the International Thermonuclear Experimental Reactor, or ITER, and other proposed experiments). Accordingly, the Office of Fusion Energy within the US Department of Energy (DOE) has conducted a Neutron

Interactive Materials (NIM) Program. Relevant research and development has also been carried out in other programs and agencies.

In a letter dated September 1, 1992, the Director of the DOE Office of Energy Research, Dr. William Happer, requested an evaluation of the NIM Program by the Fusion Energy Advisory Committee (FEAC). Dr. Robert Conn, the chairman of FEAC, established FEAC Panel 6 to review the program and to report its findings to FEAC.

Responsibility for neutron-interactive materials research within OFE is distributed among several program areas, including NIM. The primary distribution is between the ITER program (managed within the ITER and Technology Division) and the "base" program (managed within the Advanced Physics and Technology Division). However, the Plasma Facing Components, Magnet, Fusion Safety and Environmental, and Blanket programs have some activities that address neutron effects. The total budget for materials research in the Office of Fusion Energy for FY 1993 is estimated at $23M; of this, about $12M is devoted to neutron-irradiation issues. The OFE NIM Program is a $10M subset of the latter. Roughly half the NIM effort is aimed at near-term problems (primarily ITER), and about half at long-range development for DEMO.

The fragmentation of the materials organization makes it difficult for materials development issues to obtain adequate recognition and, consequently, proper emphasis.

For fusion energy to be successful, a materials program that is large in both magnitude and breadth will be required. The NIM Program, as defined by the DOE, only includes structural materials and ceramic insulators. However, neutron interactive material requirements apply not only to the structure, but also to plasma-facing surfaces, divertor, coolant, breeder, neutron multiplier, magnets, insulators, and diagnostic component materials. The Panel addressed the broader range of neutron interactive materials, but focused more upon the details of the NIM Program.

The Panel, as charged, looked at the balance within the NIM Program, and made the following observations:

- Near-term (ITER) vs. long-term. The ITER team is still evaluating various combinations of structural materials and coolants, and, depending on the outcome, ITER may require an unexpected increase in materials R&D effort. Other areas where expanded efforts may be needed in the near term include divertor materials, ceramics and diagnostic components, and magnet materials. The structural materials funding for long-term applications is about twice as large as the funding for ITER materials. The Panel found this balance to be appropriate, but increases in ITER needs for non-DEMO-relevant materials development should not be allowed to cut into the base program. If the ITER design incorporated either ferritic/martensitic steels or titanium alloys in high-fluence regions, then ITER development would also help identify good candidates for DEMO.

- Ferritic steels vs. vanadium alloys vs. SiC/SiC composites. Long-range materials work in fusion consists mainly of investigating these three candidate structural materials. (Titanium alloys may also be candidates, but there is currently no work being done on them.) The sizes of the efforts on these materials are roughly in the ratio of 4:1.5:1. Although the Panel found this balance appropriate, given current funding levels for the total program, these levels are insufficient to meet the aggressive needs and objectives of the long-term fusion program.

  As realized in the early 80's, these three candidates have increasingly desirable properties with respect to activation; the technology database, however, decreases in the above order.

On the basis of how materials have evolved in other technologies, the panel is persuaded that low-activation materials should be introduced in an evolutionary way, not a revolutionary way. As part of the testing program on ITER, and in future steps such as TPX along the path towards an attractive fusion system, development of optimum materials should proceed by introducing them gradually as increasingly large and critical elements of the system. In this context, ferritic/martensitic steels are seen as a strong candidate for the primary structural components at some stage in the development of fusion; if so, the emphasis on their development is warranted. The funding devoted to vanadium alloys supports only small development efforts. The current effort on SiC/SiC composites is only sufficient to track and evaluate progress in the field; this level of effort is not sufficient to adequately evaluate SiC/SiC composites for applications in fusion systems.

- Structural materials vs. ceramics and diagnostic components. The accumulated database for ceramics to date is very limited, and in comparison with structural metals, relatively little is known about their properties under irradiation. Although ceramics and diagnostic components make up a small percentage of the mass of a fusion core, their performance is likely to be critical for success of the system. In the last few years this situation has been recognized and funding for ceramic work has been increased through redirection of funding. The Panel found the increased effort and the change in emphasis appropriate. However, the current level of effort worldwide is probably not adequate to provide the nonstructural-ceramics data needed for ITER.

- Domestic vs. Collaborative International Programs. As in other elements of the fusion program, international collaborations play a key role in maximizing progress for the domestic dollars expended. The US materials program seems to be well integrated with the international effort. A major issue that is developing with regard to international collaboration involves the need for a 14-MeV neutron source, as described below.

- Neutron Irradiation Facilities. Testing in fission reactors is a vital component of fusion materials development, and the program relies on both mixed- and fast-neutron-spectrum fission reactors. HFIR and FFTF have been the primary irradiation facilities used by the fusion program. The future of HFIR depends on the remaining life of the pressure vessel; one fast reactor (FFTF) is gone and availability of the sole remaining one in the US (EBR-II) is not assured. Fission reactors are essential for irradiation testing, but they do not provide the neutron energy spectrum characteristic of fusion power plants. Hence the irradiation damage response is sufficiently different in such areas as helium production that a fusion neutron source is required for the final stages of materials development and for confirming predictions of performance at the high levels of damage that must be sustained in DEMO and in power systems.

  The next generation of fusion facilities will provide opportunities for irradiation tests. ITER is a crucial element in the component development program, and TPX will provide an important high-duty-factor, high-heat-flux tokamak plasma environment for testing the plasma-interactive properties of advanced materials.

  Preparation for building a DEMO requires that both ITER and a high-flux 14-MeV neutron source proceed on similar schedules. Two concepts have been proposed: a 35-MeV deuterium beam impinging on a liquid lithium target, and a 120-keV deuterium beam impinging on a mirror-plasma target.

  While the proposed accelerator technology for a D-Li neutron source will be challenging (especially if superconducting rf cavities are chosen), the beam current exceeds existing room-temperature cw systems by only a factor of two, and appears feasible. Although the design of the lithium target system will be difficult, much was accomplished in the earlier

FMIT Project to demonstrate the concept. The volume of high neutron fluence for a D-Li source is small but appears sufficient to support materials development when used in conjunction with fusion systems. This approach appears to be the most direct route to attaining the needed materials testing capability.

Additional plasma physics and significant fusion technology development would be required to implement a 14-MeV neutron source based on a mirror plasma target. This source might be able to provide a larger volume of high neutron flux in a single facility than would a 250-mA D-Li source. The neutron spectrum would not be that found at a fusion system's first wall, but it would not include the high-energy (>14 MeV) neutrons of a D-Li source.

The trade-off of cost vs. testing volume for either a mirror-plasma or a D-Li source has not been characterized.

- Criteria for Low/Reduced Activation Materials. The definition of, and criteria for, low/reduced activation materials require updating; the near-surface burial criterion no longer appears either necessarily required or sufficient. A committee chaired by Professor Weston Stacey of the Georgia Institute of Technology has been chartered by OFE to develop evaluation criteria for low/reduced activation materials. That committee has not yet completed its work, hence this Panel was not able to review those recommendations.

SUMMARY OF FINDINGS

Successful development of fusion energy requires a materials R&D effort of much larger magnitude and wider breadth than is currently in place. The Neutron Interactive Materials Program (NIM) Program, as defined by the DOE, only includes structural materials and ceramic insulators. However, neutron interactive material requirements include not only the structure, but also plasma-facing surfaces, divertor, coolant, breeder, neutron multiplier, magnets, insulators, and diagnostic component materials. The Panel addressed the broader range of neutron interactive materials, but with greater focus on structural materials. Its findings are summarized here.

INTRODUCTION (SECTION 1)

- Low/reduced activation materials offer the potential to improve the safety and environmental performance of fusion energy.

- Austenitic steels are not an attractive long-term structural material for regions of high neutron and heat flux, given a mix of concerns about inadequate performance (such as thermal stress and fatigue) and the lack of compositions that have low long-term induced activation. However, they could be, and probably will be, used extensively in regions of low heat flux and low neutron exposure in DEMO.

- Preparation for building a DEMO requires that both ITER and the 14-MeV neutron source proceed on similar schedules.

- A fusion neutron source (sometimes referred to as a 14-MeV neutron source) is required for materials development for three reasons: (1) to confirm predictions of materials performance obtained from fission-reactor irradiation; (2) to complete the development of advanced materials, such as vanadium alloys and SiC/SiC composites, for which adequate damage simulation cannot be obtained in fission reactors; and (3) to extend engineering design databases on materials performance to the goals for fusion damage levels.

- Fission-reactor testing is a critical element of any viable strategy to develop neutron-interactive materials for fusion. Prior to having an operating 14-MeV neutron source, fission reactor testing is necessary to screen and select primary candidate options. However, the continued availability of fission reactors is in serious doubt, further motivating an early start on the 14-MeV neutron source; the loss of FFTF and the questionable operational future of EBR-II are significant concerns. The need for and priority of a fusion neutron source are thus increased.

- An examination of the materials development programs for fast fission breeder reactor fuel cladding, high-performance gas turbines, aircraft, and the National Aerospace Plane indicates that mission-oriented materials development programs require sustained efforts of tens of millions of dollars ($\approx$ 15% of total program budgets) for periods of a decade or more, exclusive of major testing facilities.

- The strategy employed in non-fusion programs is to use new materials first in small, less critical and risky ways, moving in an evolutionary way to progressively greater use. This strategy would be wise for fusion development and implies the need to incorporate some advanced materials in test machines like TPX and ITER to gain experience in an integrated fusion environment.

OFE ORGANIZATIONAL ISSUES (SECTION 2)

- The Panel observes with concern the distributed nature of the neutron interactive materials program within DOE Office of Fusion Energy. The structural materials program is split between the long-term and the ITER programs. Neither of these parts appears to be closely coordinated with other materials programs, such as divertors, magnets, blanket (coolant, breeder, neutron multipliers); safety and environment; and IFE issues.
- The fragmentation of the materials organization makes it difficult for materials development issues to obtain adequate recognition and, consequently, proper emphasis.
- Decreases in funding for materials R&D over the last decade have lead to the near elimination of the theory, modeling, and basic experiments that provide understanding of important phenomena occurring in materials in the fusion environment. Present facilities for experimentation in support of materials development reproduce only portions of the actual fusion environment. The ability to predict materials performance, to extrapolate to new parametric space, and to develop materials with composition and structure optimized for the desired properties is seriously compromised by lack of fundamental understanding. Also, the loss of basic research has a disproportionate effect on university research, which is the source of new-materials scientists and engineers for the future.
- It is likely that the ITER project will require substantially more work than is currently planned in structural materials, coolants supporting high temperature operation (bakeout/conditioning), nonstructural ceramics, and magnet materials. We base this finding on the cost for developing specific materials in other non-fusion projects, and we also note that some high-technology projects have failed because of inadequate materials work.
- If, in fact, more materials work is needed for ITER, and if the US increases its participation in ITER materials work, it is extremely important that the long-term base program in materials be protected against diversion from DEMO-relevant materials development to ITER. If ITER uses materials that have long-term potential, then this resource problem is lessened. If or where "off the shelf" materials are deemed inadequate for ITER, then any required materials development should, if possible, be focused on materials that have application beyond ITER. This approach would make more-efficient use of limited resources.

THE NEUTRON INTERACTIVE MATERIALS PROGRAM (SECTION 3)

Ferritic/Martensitic (FM) Steels

- Ferritic/martensitic steels with reduced activation compositions show high promise, providing lower activation levels and better performance than conventional ferritic steels with regard to ductile-brittle transition temperature (DBTT). There is a strong industrial database, but of course not with the exact fusion-relevant reduced activation compositions.
- The present ferritic/martensitic steel R&D program is focused on the most critical issues for this class of alloys, namely, the effects of fusion system damage levels on the DBTT and fracture toughness along with the development of a reduced activation alloy with

composition and microstructure optimized for strength and fracture toughness. Some concern still exists regarding the use of ferromagnetic materials in a magnetic fusion system.

Titanium

- Titanium alloys were dropped from the US materials program, mainly because of tritium inventory and hydrogen embrittlement concerns. The high temperature capability is also somewhat limited. If coatings could be developed to control the hydrogen/tritium retention problem, titanium alloys (which are a lower-activation alternative to ferritic/martensitic steels) may deserve another look, assuming that restrictions on ^{26}Al are relaxed.

- Titanium alloys are non-magnetic and a strong industrial database is available. For reduced activation, one would use Ti alloys without niobium or molybdenum, and perhaps without aluminum. Experience with titanium in TPX will dramatically increase the fusion Ti-alloy database.

Vanadium

- Vanadium shows the highest potential for low long-lived activation, promise for high engineering performance, and good waste management and recycling potential. While the tritium retention problem is lower for vanadium than titanium, tritium permeation is comparable for both metals, and surface barriers may be needed for both alloys.

- There are two key issues with vanadium in fusion applications. One is the DBTT shift and fracture toughness; the other relates to chemical compatibility. Also, industrial experience with vanadium is very limited.

- The near-term vanadium program is addressing the DBTT concern via the dynamic He charging experiment. There is currently no work aimed at resolving the chemical compatibility issues. Industrial experience must await a strong programmatic need for substantial amounts of vanadium.

SiC/SiC Composites

- Silicon carbide-fiber-reinforced silicon carbide-matrix (SiC/SiC) composites have been identified as the most attractive candidate fusion-system structural material in terms of accident safety (both short-term dose and decay heat) and environmental concerns (no activation, no recycling required). Although ceramic composites are enjoying renewed industrial attention as engineering materials, such applications do not address the key radiation-damage questions for fusion. Considering the infancy of SiC/SiC technology and the lack of databases on radiation performance and large-scale applications, a majority of us did not feel that a DEMO could be constructed fully of SiC/SiC by 2025 (a minority felt that 30 years would suffice for development). We also accepted that R&D will continue beyond ITER and DEMO, especially in the materials area. One might envision a helium-cooled DEMO with some combination of metallic alloys and SiC/SiC composites.

- The ARIES I study, which assumed SiC/SiC composites, highlighted an important aspect of the low/reduced activation issue: to minimize activation, not only the structure but also other neutron-interactive systems, such as the divertor, coolant, and neutron multiplier, must also be considered. ARIES IV (in progress) eliminates certain materials (e.g., tungsten, used as a divertor coating in ARIES I) and replaced lithium zirconate (the solid breeder in ARIES I) with lithium oxide. For low/reduced activation, appropriate candidates would include beryllium as the plasma facing material; lithium, lithium oxide, or perhaps fluorine/lithium/beryllium ("Flibe") or a 17Li83Pb eutectic material as coolants; and beryllium and perhaps lead as multipliers.

- The main incentive for investing in the development of fusion energy is the prospect of safety and environmental attributes significantly better than those of fission or coal. SiC/SiC composites are attractive in this respect, but because of their infancy as engineering materials, many feasibility issues, such as leak-tightness, joining, and large-scale manufacturing, have yet to be resolved. Further, SiC/SiC composites have not been extensively researched as fusion or fission materials, so their response to high radiation fluence must be further investigated. Much more intense effort, with concomitant support, is needed to optimize testing and ascertain suitability.

Non-structural Ceramics and Diagnostic Components

- The relatively small amount of data available regarding radiation effects upon non-structural ceramics and diagnostic components gives cause for serious concern in meeting the requirements for ITER. At low fluences (<1 displacement per atom) some candidate insulators appear to degrade markedly in resistivity, and the fused quartz normally used in windows and fiber optics becomes opaque.

- The proposed US ITER materials program is strongly integrated with the base materials program in terms of reactor facilities, post-irradiation testing, corrosion testing, and key personnel. If the ITER-credit assignments do not cover some of the proposed activities, some areas of the US materials program may become sub-critical and jeopardize our ability to sustain existing international cooperative programs and impact materials development for DEMO.

The US Materials Program for ITER

- The present ITER Materials Program has been based on the design and material choices made in the Conceptual Design Activity (CDA). Now, however, the Engineering Design Activity (EDA) may be heading in new directions. This may cause changes in the ITER Materials Program that cannot now be known; this uncertainty complicates the job of addressing the ITER Materials Program and how it fits into the entire fusion materials development effort.

- If or where "off the shelf" materials are deemed inadequate for ITER, then it is appropriate for materials to be selected that have application beyond ITER to make more efficient use of limited resources.

- The Panel notes the importance of having materials expertise integrated into the ITER Joint Central Team (JCT). Some high-technology projects have failed because of choosing the wrong material or not adequately developing the right one. The history of fission power suggests vigilance for unanticipated materials-related problems.

- There is no significant, long-term materials program for low/reduced activation divertors for DEMO. Funding in this area has been redirected towards ITER divertor development. This is appropriate given budget constraints, since the requirements for divertor materials are expected to evolve in response to divertor designs for, and experimental results from, TPX and ITER.

OTHER OFE MATERIALS PROGRAMS (SECTION 4)

Plasma Facing Components

- Neutron irradiation is known to degrade the thermal and mechanical properties of beryllium and graphite plasma-facing materials under consideration for ITER. Fission reactor irradiations are being used to screen candidate materials, but more work is needed to expand the design database.

- Of immediate concern for ITER is the lack of operating hot-cell facilities for thermal fatigue testing of activated ITER prototype divertor mock-ups in their irradiated states. The performance of a bonded duplex structure cannot be adequately assessed from the behavior of its individual irradiated materials.

Superconducting Magnet Materials Development

- The high reliability requirement of ITER superconducting magnets is a serious concern. The adequacy of structural alloys and welds and organic or inorganic insulation materials to operate at 4 K under ITER fluence conditions is uncertain.

Blanket Materials

- The US, until recently, had a strong solid breeder irradiation-testing program. The shutdown of FFTF in February 1992 resulted in the termination of the international BEATRIX II solid breeder program. Currently there is a lack of US nuclear testing facilities. The proposed EBR-II irradiation facility upgrade (BEATRIX III) is needed.

- Beryllium is an important component in solid breeder blankets. Tritium release behavior is critical for safety aspects and the large helium-generation rates affect thermal-mechanical properties. Significant testing and modeling remains to be done.

- Electrically insulating coatings inside the coolant channels are necessary to reduce MHD pressure drops in liquid-metal-cooled fusion power plants. High voltages developed during disruptions will challenge the insulating coatings, which may, therefore, need to be redeveloped *in situ*.

- The complexity of solid breeder blankets requires integrated testing, including in ITER, to determine synergistic effects between the different materials.

Safety and Environmental Program

- Numerous design studies have shown that the high safety and environmental performance of fusion is not achieved automatically.

TESTING FACILITIES (SECTION 5)

Introduction

- To have the option of using low/reduced activation materials in DEMO, the materials program needs (a) fission-reactor irradiation facilities; (b) testing of such materials in ITER and TPX, and (c) a high-fluence 14-MeV neutron source to complete development and develop engineering databases.
- Large-volume, lower-fluence neutron sources (tokamaks and tandem mirrors) have been proposed to augment the nuclear test program planned for ITER. The Panel did not hear presentations on these proposals.

Fission Reactors

- Testing in fission reactors is a vital component of fusion materials development. The fusion materials development strategy relies on both mixed- and fast-neutron-spectrum fission reactors. The HFIR at Oak Ridge provides a mixed thermal and fast neutron spectrum; its future is dependent on the remaining life of the pressure vessel. One fast reactor, FFTF, is gone, and availability of the one remaining facility, EBR-II, is not assured.

ITER

- ITER is an important element in the U.S. neutron-interactive-materials and component development program. Together with a high-flux 14 MeV neutron source, ITER, as conceived with two phases achieving a total fluence of 1 to 3 MW-year/m^2 on large material and blanket test modules, should provide the necessary testing and component development information for DEMO. It must be recognized, however, that fusion materials development will continue in DEMO and beyond.
- It is important that the ITER Project address the scope of ITER's module-testing capability, taking into account such issues as ferromagnetic effects and compatibility of coolants.
- TPX will provide an important high-duty-factor, high-heat-flux tokamak plasma environment for testing the plasma-interactive properties of advanced materials. The approach of testing new materials in non-critical applications in one generation of device for application in later generations is a necessary element of the fusion materials development strategy.

High-Fluence 14-MeV Neutron Source

- While the proposed accelerator technology for a D-Li neutron source is challenging (especially if superconducting rf cavities are chosen for the design), the beam current exceeds existing room-temperature cw systems by only a factor of two, and appears feasible. The design of the lithium target system will be difficult.

- The volume of high neutron fluence for a D-Li source is small but appears sufficient to support materials development when used in conjunction with fission reactors. This approach appears to be the most direct route to attaining the needed materials testing capability. Additional plasma physics and significant fusion technology development would be required to implement a 14-MeV neutron source based on a mirror plasma target. This source could provide a larger volume of high neutron flux in a single facility than would a 250-mA D-Li source. The neutron spectrum would not be exactly that found at a fusion system's first wall, but it would not include the high-energy (>14 MeV) neutrons of a D-Li source.

- The trade-off of cost vs. testing volume for either a mirror-plasma or a D-Li source has not been characterized.

IFE ISSUES (SECTION 6)

- Materials research within OFE is completely dominated by the needs of the magnetic fusion program. Little if any thought (and no funding) has been given to unique materials needs for inertial fusion.

- IFE benefits from some of the MFE materials work. However IFE also has some unique requirements, e.g., pulsed neutron effects on the final focusing element or the ion-beam delivery systems, and pulsed neutron effects in general.

EVALUATION CRITERIA FOR LOW/REDUCED ACTIVATION MATERIALS (SECTION 7)

- The definition and criteria for low/reduced activation materials require updating. In addition to waste management, there are several other safety and environmental criteria requiring attention: short-term accident dose potential, decay heat, ability to recycle/re-use materials, and biological hazard of other waste forms.

- The upcoming Stacey committee will re-integrate what is known about low/reduced activation criteria. If the definition for low/reduced activation materials changes, the priorities and appropriate compositions for specific material classes should change.

1. INTRODUCTION

The magnetic- and inertial-confinement fusion energy systems of the future will pose formidable challenges in materials science and engineering. Materials will be pushed close to their limits in many aspects of performance: not only temperature, stress, and chemical environment, but also exposure to large fluences of energetic neutrons (up to 14 MeV). For environmental and safety considerations, low/reduced activation materials are of particular importance. These neutronics issues have implications for both the long term (a demonstration MFE power system, referred to here as DEMO, or its IFE equivalent, and subsequent power systems) and the near term (the International Thermonuclear Experimental Reactor, or ITER, and other experiments proposed for the near future). Accordingly, the Office of Fusion Energy within the U.S. Department of Energy (DOE) has conducted a Neutron Interactive Materials (NIM) Program. Relevant research and development has also been carried out in other programs and agencies.

In a letter dated September 1, 1992, the Director of the DOE Office of Energy Research, Dr. William Happer, requested an evaluation of the NIM Program by the Fusion Energy Advisory Committee (FEAC). The charge letter is attached in Appendix A. Dr. Robert Conn, the chairman of FEAC, established FEAC Panel 6 to review the program and to report its findings to FEAC. The membership of Panel 6 is given in Appendix B.

The panel met three times: December 2-3, 1992, in San Francisco; January 13-15, 1993, in Dallas; and February 11-12, 1993 in St. Louis; the agendas are given in Appendix C. At these meetings the panel reviewed the various OFE programs that address materials issues, the numerous materials needs of current and future machines, and the design status of neutron sources for materials testing. The panel also heard from program managers of materials development efforts for the liquid-metal fast breeder program, for gas turbine engines, and for advanced aircraft; this input provided an appreciation for the levels of effort expended in other materials development programs. The results of the Panel's deliberations are presented in this report.

1.1. FUSION PROGRAM NEEDS

In 1981 David Rose[1] stated his belief that, following the demonstration of scientific feasibility of tokamaks, the development of fusion would be delayed for a decade or so because the performance of "...the entire wall-blanket-fuel handling will depend critically on properties of materials and material systems that are still only partly understood." In 1986, a comprehensive International Energy Agency report stated, "The present understanding of the behavior of materials and the associated databases are insufficient to guarantee the required performance and endurance of components for future fusion systems."[2] The numerous presentations on materials issues heard by this panel have convinced us that these observations remain true in 1993. In fact, the growing emphasis on safety and environmental

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1 D.J. Rose, "On international cooperation in fusion research and development," Nuclear Technology/Fusion, Volume 2 (July 1982), p. 474.

2 "Materials for Fusion," report to the Fusion Power Co-ordinating Committee by the Senior Advisory Panel, S. Amelinckx, chair, International Energy Agency (1986).

impact has made the selection of serviceable materials even more central to the success of fusion.

1.2. REQUIREMENTS ON MATERIALS FOR FUSION

In most energy systems, a wide choice of materials is available and materials research is mostly focused on improving economy or performance. Any realistic fusion system, by contrast, will push materials close to their limits in many aspects of performance: not only temperature, stress, and a harsh chemical environment, but also exposure to electromagnetic radiation and, in the most challenging aspect of all, large fluences of energetic neutrons (up to 14 MeV). Figure 1-1 illustrates the generic problem for fusion materials.

The vertical axis shows the end-of-life fluence requirement for materials near the first wall of present and future fusion systems. The units are displacements per atom (dpa), a dimensionless parameter for fluence that estimates the number of times each atom is displaced from its lattice position by the energetic neutrons. This parameter is found to correlate well with radiation damage effects such as swelling; generally, damage becomes significant when the parameter nears or exceeds unity. Between the conditions found in present machines and the conditions that will be experienced in ITER and subsequent systems, there is a gap of many orders of magnitude. This gives a measure of the progress that must be made in materials research.

The horizontal axis shows the wall heating per pulse, in megajoules per square meter, resulting from radiation and nuclear heating. (Here we show the relatively benign heat load on the walls and do not consider the highly stressed divertor region.) Given that steel 5 cm thick (one neutron mean free path) melts at 200 MJ/m^2, it is clear that ITER and other future systems to the right of the dashed line in Figure 1-1 will require active cooling, whereas present machines rely primarily on inertial cooling (that is, the machine cools off between pulses). In heat transfer (with the related temperature gradients and thermal stresses), just as in neutron fluence, there is an orders-of-magnitude gap between present and future systems. This is another one of the ways fusion materials are pressed to their limits of performance quite independently of radiation damage.

Divertor plasma-facing materials, such as beryllium and graphite, are exposed to the same high neutron flux as the first wall, but they are far more susceptible to neutron-induced degradation of thermal and mechanical properties than structural materials. Magnet coil structures receive significantly lower neutron fluence than the first wall, yet their organic or ceramic insulation suffers degradation of shear and dielectric strengths at extremely low fluences. The coil-case structural alloys also show deleterious changes in their mechanical properties at these low fluences due to neutron damage retention at liquid-helium temperatures.

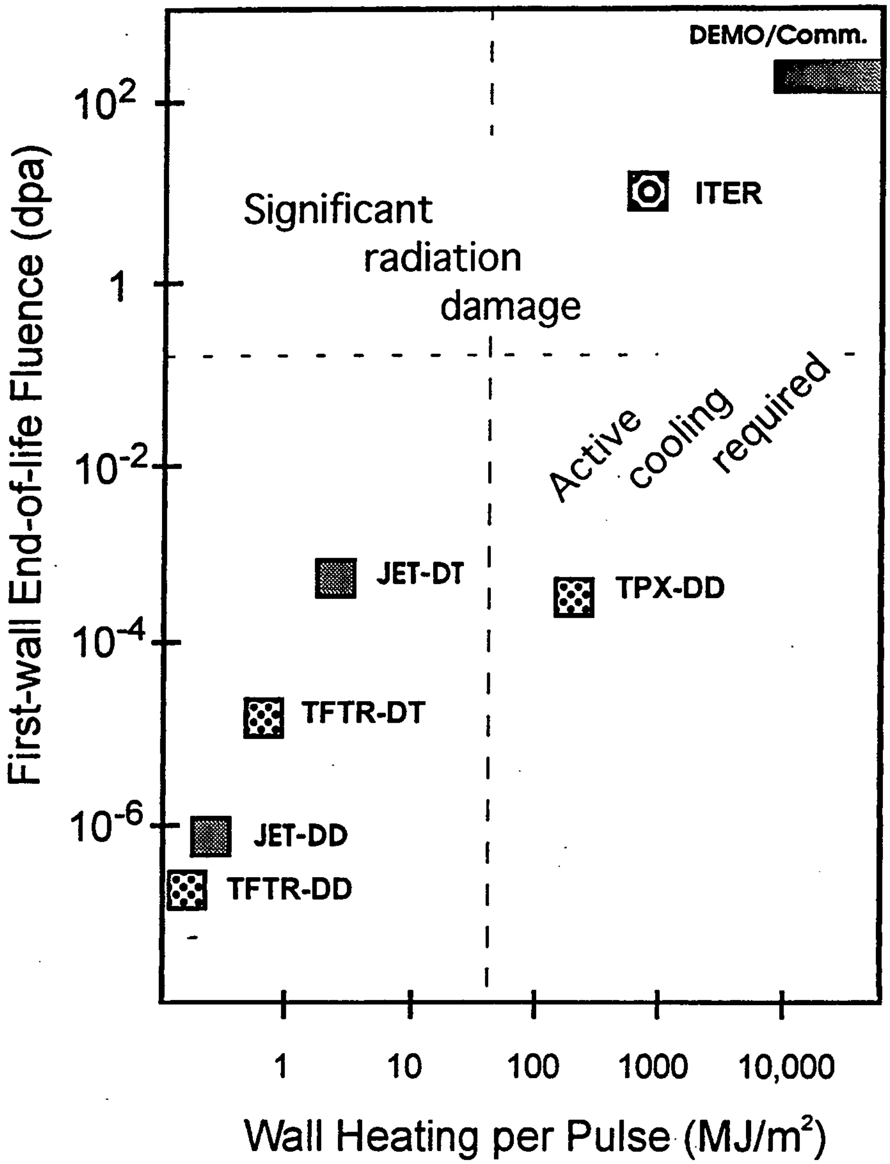

Figure 1-1. End-of-life fluence (dpa) and wall heating per pulse (MW-m2) are plotted for present-day and future fusion systems.

Neutron radiation effects must also be considered for such diverse materials issues as the compatibility of blanket coolants with structural alloys and the radiation hardening of plasma diagnostics. Tritium breeding materials must be tested for their radiation stability, and tritium permeation barriers must be tested in a radiation environment. Plasma diagnostics, with their active sensors, fiber optics cabling, etc., are extremely vulnerable to neutron-induced damage.

As a result of this widespread impact of neutron irradiation on various technologies, responsibility for neutron-interactive materials is distributed among many program areas.

> *Finding:*
> *For fusion energy to be successful, a materials R&D effort of large magnitude and wide breadth is required. The Neutron Interactive Materials Program (NIM), Program as defined by the DOE, only includes structural materials and ceramic insulators. However, neutron interactive material requirements include not only the structure, but also plasma-facing surfaces, divertor, coolant, breeder, neutron multiplier, magnets, insulators, and diagnostic component materials. The Panel addressed the broader range of neutron interactive materials, but with greater focus on structural materials.*

Safety and environmental protection impose another set of considerations, making low/reduced activation materials desirable. To be commercially accepted, fusion energy must be competitive with other energy sources, especially those producing electricity. Studies like ARIES suggest that direct economic advantages will be difficult to obtain, so we need to look at the broad array of energy source characteristics. Although we cannot know the precise competitive market in the first half of the next century, safety and environmental performance will surely receive very close attention both now and in the future. Fission energy's economic prospects and public acceptance have been hampered by safety and environmental weaknesses, especially radioactive waste and the feared potential for catastrophic health impacts from worst-case accidents. Other energy sources may also suffer from safety and environmental problems— fossil fuels produce chemical pollutants, and solar energy entails high use of land and generation of some toxic materials. Even conservation is sometimes not without problems, such as increased indoor air pollution due to reduced ventilation.

Several studies, notably ESECOM,[3] have found that fusion's very high safety and environmental potential will not be realized automatically. ESECOM went further and indicated that improved safety and environmental performance should translate into economic benefits via faster and more assured licensing and reduced need for safety graded (N-stamp) components. In 1982, the Conn Panel[4] suggested "low activation materials" as an explicit objective of the U.S. structural materials program, focusing on near-surface burial (per 10 CFR 61, the applicable part of the Code of Federal Regulations) as the major quantified objective.

> *Finding:*
> *Low/reduced activation materials offer the potential to improve the safety and environmental performance of fusion energy.*

Among structural materials, the U.S. program includes austenitic steels, ferritic/martensitic (FM) steels, vanadium alloys, and silicon carbide (SiC) composites. Austenitic steels, the type commonly in use today for structural applications in power systems, are only viewed as near-term materials, not suitable for long-term commercial fusion

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3 See J.P. Holdren et al., "Exploring the competitive potential of magnetic fusion energy: the interaction of economics with safety and environmental characteristics," Fusion Technology, Vol. 13, p. 7.

4 See "Report of the DOE Panel on Low Activation Materials for Fusion Applications" (R.W. Conn, chair), report PPG-728, University of California, Los Angeles School of Engineering and Applied Science (1983).

application. To stabilize the face-centered cubic austenitic phase, they require an element that happens to be highly activated by neutrons. This element is either manganese (increasing decay heat and thus accident potential) or nickel (causing long-term waste management concerns). Low-activation versions of austenitic steels do not appear likely, and thus these steels are not attractive candidates beyond ITER for high-fluence locations. The extensive database that has been developed for austenitic steels is aiding the fundamental understanding of neutron damage, and this program is phasing down. Suitable low-activation compositions of the other candidates have been identified, and research on these materials is the prime focus of the NIM Program.

Finding:
Austenitic steels are not attractive long-term structural materials for regions of high neutron and heat flux, given a mix of concerns about inadequate performance (such as thermal stress and fatigue) and the lack of compositions that have low long-term induced activation. However, they could be, and probably will be, used extensively in regions of low heat flux and low neutron exposure in DEMO.

It should be noted that the low/reduced activation materials offer a reduction in activation hazards—one or more orders of magnitude—as compared to conventional materials. (This improvement adds to the existing advantage that fusion has over fission in terms of radiation hazards.) However, the activation of nonstructural materials, especially the divertor and also the coolant, tritium breeder, neutron multiplier, etc., is nonetheless important and must be addressed to minimize the quantity of high-level waste. If these materials are not selected with activation hazards in mind, the advantage of using low/reduced activation structural materials could be substantially compromised.

Progress towards the use of radiative/gaseous divertors in TPX and ITER should open the possibility of using low/reduced activation materials in this area as well. In this context, certain materials like tungsten (for the divertor) and lithium zirconate (for the breeder) are undesirable. From the activation perspective, appropriate candidates would include:

- Beryllium as the plasma-facing material.
- Helium, lithium, and perhaps Flibe (fluorine-lithium-beryllium) or eutectic 17Li/83Pb as coolants.
- Lithium, lithium oxide, and perhaps Flibe or 17Li/83Pb as breeders.
- Beryllium and perhaps lead as multipliers.

1.3. HOW THE OFE PROGRAM IS MEETING THE NEEDS

Responsibility for neutron-interactive materials research within the Office of Fusion Energy (OFE) is distributed among several program areas.

Table 1-1 summarizes the Panel's estimates of funding allocations for fusion technology in FY 1993 to provide a context for examination of the materials component of the program. (OFE does not break down accounts in this manner; the assignments are Panel estimates based on discussions with program managers.) Some detail is included on the various candidates for structural materials, because this represents the largest budget category. In addition to the present funding levels, the table includes, in the rightmost columns, estimates of the portion of the present R&D that might be categorized as materials work ($23M), and of that, the portion devoted to neutron-irradiation issues ($12M). The OFE NIM Program is a $10M subset of the latter. A pie chart version of the last column of Table 1-1 is shown as Figure 1-2.

Table 1-2 gives in greater detail the present levels of funding for the specific materials issues related to neutron interactions, organized by the functions that various materials must perform. The table shows that many issues and materials need to be considered, and that many important topics are funded at a fractional FTE level.

The NIM Program examines two main categories of materials. One is structural materials—austenitic steels for near-term applications and ferritic/martensitic steels, vanadium alloys, and SiC/SiC composites for DEMO. (Work on titanium alloys, another class of candidate structural materials, is not currently supported.) The other category is non-structural ceramics, including optical fibers. Long-range applications (DEMO and beyond) are generally considered to be part of the NIM "base program," whereas near-term applications are primarily part of the ITER R&D program.

Table 1-1. *A summary of the US fusion technology budget, with all figures in FY 1993 $M. The two rightmost columns give estimates of the present R&D that might be categorized as materials work ($23M) and the portion of that work devoted to neutron-irradiation issues ($12M). The OFE NIM program is a $10M subset of the neutron-irradiation work.*

Program Component	ITER	Base	ITER + Base	Estimated materials R&D	Estimated neutron-damage research
Structural Materials and Ceramics					
Austenitic steel	1.3	1.6	2.9		
Ferritic/martensitic steel	0.3	2.4	2.7		
Titanium					
Vanadium	0.3	0.6	0.9		
SiC/SiC Composites		0.6	0.6		
Nonstructural ceramics	1.2	0.4	1.6		
Neutron-source design		0.7	0.7		
Subtotal	**3.10**	**6.3**	**9.4***	9.4	9.4
Plasma Facing Components					
Plasma Interactive Materials	7.9	1.3	9.2		
Structural Materials	0.6		0.6*		
Subtotal	**8.5**	**1.3**	**9.8**	5.6	1.2
Blankets/Shielding/Coolant	**6**	**1.1**	**7.1**	3	1.
Safety	**1.3**	**1.5**	**2.8**	0.8	
Magnetics	**8.9**	**1.3**	**10.2**	3	0.4
Heating and Current Drive	**4.8**	**5.2**	**10**	1	
Fueling	**2.2**	**1.8**	**4**	0.4	
Systems Studies		**2.5**	**2.5**		
ITER Design and Management					
Design	10.1		10.1		
Home Team management	2.4		2.4		
Co-Center	4.3		4.3		
Subtotal	**16.8**		**16.8**		
GRAND TOTAL	**51.6**	**21**	**72.6**	**23.2**	**12**

* Components of the OFE NIM Program

Table 1-2. *Structure and estimated FY 1993 radiation-effects funding level for the OFE NIM Program, which addresses structural materials and ceramics.*

Function of Material	Neutron Interaction Issues	Major Candidates	Potential Application		Est. FY93 Funding		Comments
			ITER	DEMO			
Structural	Swelling/ creep; strength/ ductility; weldability; corrosion; radioactivation	Austenitic steel (e.g., 316 SS)	Y	N	1.3	1.4	Limited DEMO relevance because of thermal/ physical properties at high temp. Largest database for ITER use at fluence up to 10 dpa.
			Y	Y	0.3	2.3	Reduced-activation alloys available. Design must allow for magnetic permeability. Largest database, most fabrication experience for ITER/DEMO.
		Titanium alloys	Maybe	Maybe	0	0	Reduced activation. Good manufacturing database. Small neutron database. Tritium solubility is an issue.
		Vanadium alloys	Module tests	Maybe	0.3	0.6	Significantly reduced activation. Modest database shows promise. Limited industrial experience and few commercial suppliers. Tritium solubility is an issue.
		SiC/SiC composites	Maybe module tests	Module tests	0	0.6	Lowest known activation. High-temperature properties appear promising. Radiation damage and performance feasibility not demonstrated. Unresolved cost, practicality.
Nonstructural ceramics (antennas, breeder components, etc.)	Structure issues; induced electrical conductivity; dielectric breakdown; optical absorption and luminescence	Ceramics	Y	Y	0.8	0.3	Relatively little data on neutron damage; possibly a major problem for ITER, beyond.
		Fused silica	Y	Y	0.3	0.1	Strong neutron-induced optical absorption requires that windows and fiber optics be highly shielded.
		Many, inc. mirror coatings	Y	Y	0.1	0	Little is known about neutron effects.
Breeder material and coolant	Tritium breeding ratio; degraded chemical compatibility	Flowing self-cooled Li or Li-Pb	Y	Y	0	0	Neutron interaction not among most critical issues.
		He-cooled Li ceramic	Module tests	Y	0	0.8	
Divertor/ plasma-facing components	Structure issues; degradation of thermal conductivity; embrittlement; tritium retention; duplex materials; structural integrity	Beryllium	Y	Y	0.1	0	Low activation. Design must allow for biological hazard. Operating experience from JET experiment.
		Graphite	Maybe	Unlikely	0.5	0	Low activation. Good thermal properties and considerable experience from existing experiments. Unresolved high-fluence issues.
		High-Z refractory metals	Maybe	Y	0	<0.1	Feasibility in plasma interaction not yet demonstrated.
		Cu and Ni	Y	Y	0.6	0.0	Substrate materials.
		SiC/SiC	N	Maybe	0	<0.1	No data to support this application.
Superconducting magnets	Critical-current reduction; insulation failure	NbTi, Nb_3Sn, Cu stabilizer	Y	Y	0.3	0	Neutron leakage to magnets—superconductors have low radiation tolerance.
		Cera. insulators	Y	Y	0.1	0	Cannot yet be specified with confidence.

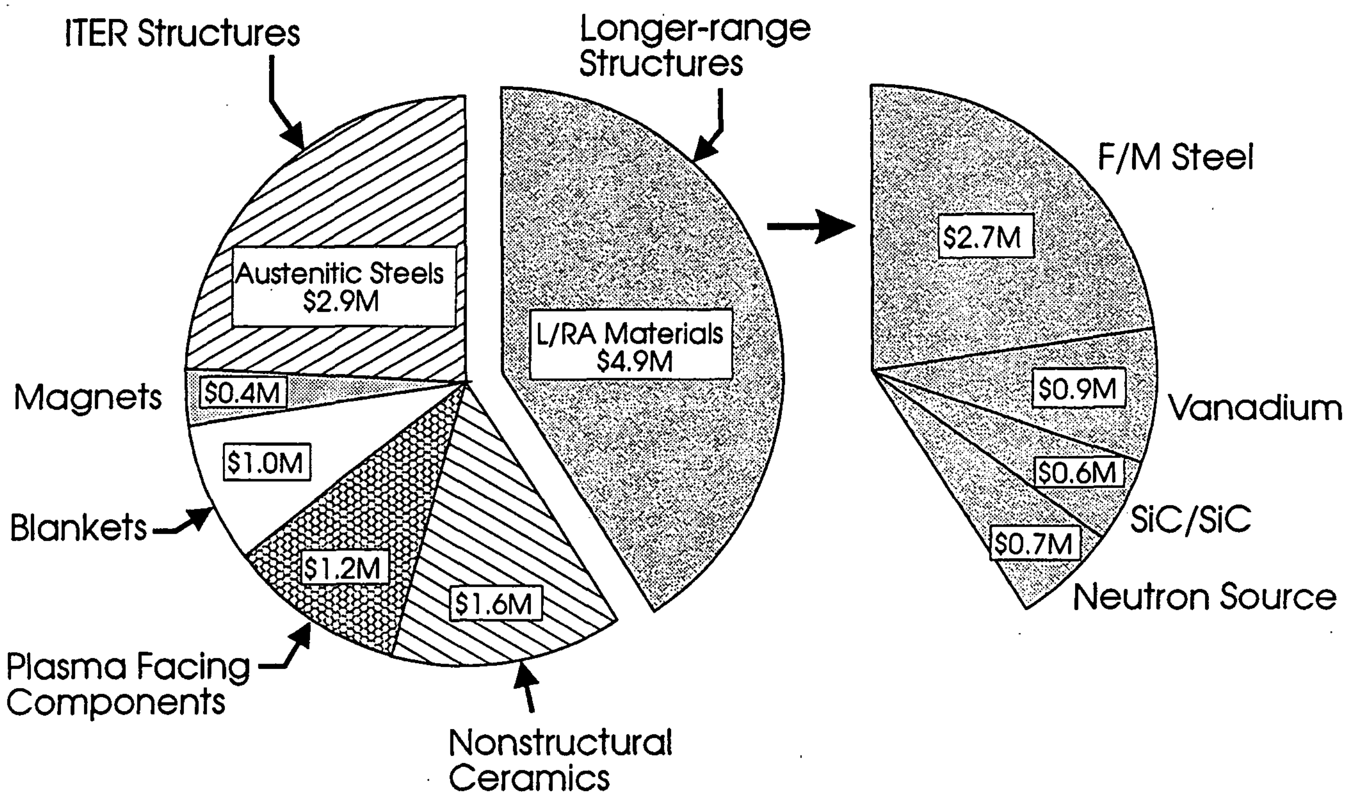


Figure 1-2. US NIM Program ($12M in FY 1993 as defined by Panel 6); after the last column of Table 1-1.

1.4. THE NEED FOR NEUTRONS IN THE MATERIALS PROGRAM

Fission reactors provide valuable means for simulating the atomic displacements of the fusion radiation environment, but not the significant effects exerted upon material properties by solid and gaseous transmutations. The simulations are not perfect because the neutron energy spectrum lacks a 14-MeV component and the ratio of gamma rays to neutrons is too high, but with care in interpretation, the results are generally useful. Another issue, which is causing more and more concern, is the shrinking number of fission reactors and associated capabilities for handling radioactive materials. For the time being, fusion is relying on other programs to carry the burden of operating the reactors, but the growing cost of operations in today's regulatory climate may impact the fusion program in the not-too-distant future. Note that the FFTF reactor has been shut down and that continued operation of EBR-II is not assured.

Although fission reactors have been and will continue to be useful, the neutron energy spectrum is an important limitation. Helium production exhibits threshold-like behavior above 4 MeV or so, implying that, for a given neutron fluence or number of displacements, much more helium is produced in a fusion spectrum than in a fission spectrum. Figure 1-3 shows the significant increase in He production in candidate fusion materials that results from a fusion spectrum, as compared to a fission spectrum. Many material properties, such as swelling, are found to be influenced by the quantity of gas generated; thus, greater helium production is a key reason that a 14-MeV neutron source is considered so important for developing fusion materials. In current planning, as proposed in the Fusion Policy Advisory Committee Report of 1991, the programmatic need for a 14-MeV source will shift from "desirable" to "essential" in about the same timeframe as ITER construction.

Findings:

- *Preparation for building a DEMO requires that both ITER and the 14-MeV neutron source proceed on similar schedules.*
- *A fusion neutron source (sometimes referred to as a 14-MeV neutron source) is required for materials development for three reasons: (1) to confirm predictions of materials performance obtained from fission-reactor irradiation; (2) to complete the development of advanced materials, such as vanadium alloys and SiC/SiC composites, for which adequate damage simulation cannot be obtained in fission reactors; and (3) to extend engineering design databases on materials performance to the goals for fusion damage levels.*

In some cases, such as blanket materials, the spectral effects are less important.

The neutron source should provide more fluence per year than ITER, thereby permitting faster iterations of the tests, a characteristic needed for materials development. It should also provide a test volume large enough for testing many small samples at a time for radiation response. These capabilities would greatly facilitate the basic steps in developing optimum materials. The test program using the 14-MeV source would allow ITER to introduce new materials, in an evolutionary way, in both the plasma-facing components and the blanket test modules, as described elsewhere in this report. Similarly, it would enable DEMO designers to contemplate materials other than those used in ITER. Considering that DEMO will require materials with a greater fluence lifetime than those in ITER, and considering the significant challenge of finding suitable materials for fusion including the desire for reduced activation, the need for a high-flux 14-MeV test facility is compelling.

Finding:

Fission-reactor testing is a critical element of any viable strategy to develop neutron-interactive materials for fusion. Prior to having an operating 14-MeV neutron source, fission reactor testing is necessary to screen and select primary candidate options. However, the continued availability of fission reactors is in serious doubt, further motivating an early start on the 14-MeV neutron source; the loss of FFTF and the questionable operational future of EBR-II are significant concerns. The need for and priority of a fusion neutron source are thus increased.

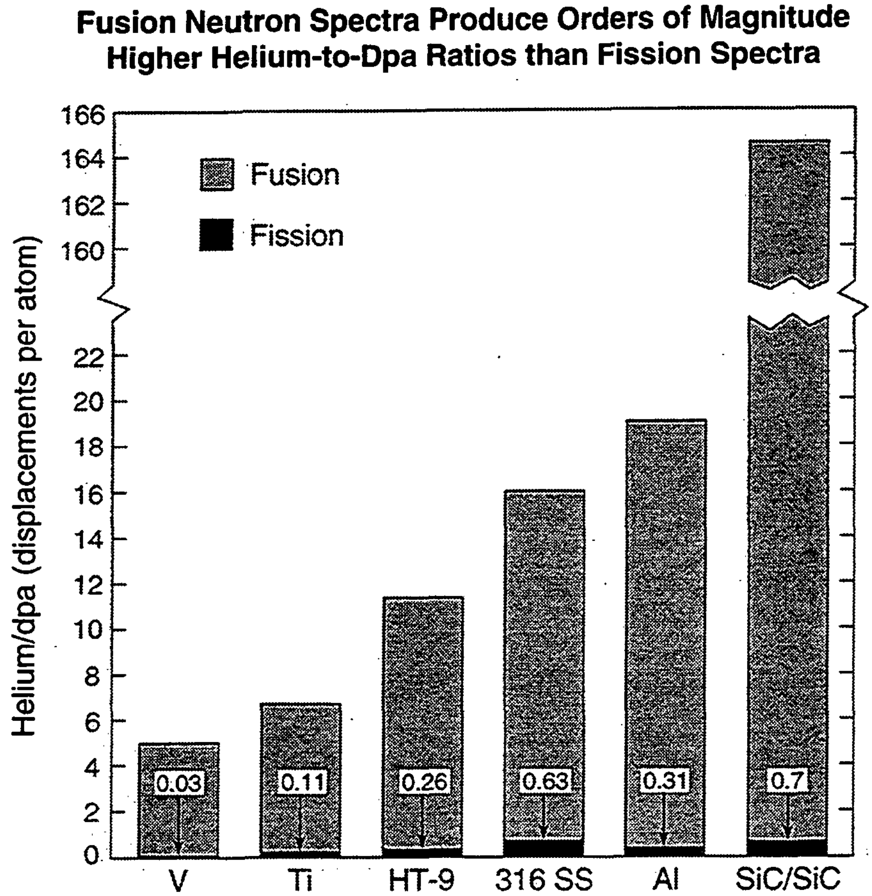


Figure 1-3. *Typical ratios of helium production to displacement damage for candidate fusion materials. The ordinate is the ratio of atomic parts per million (appm) of He to the displacements per atom (dpa) produced by neutrons. Shaded and solid areas are for fusion and fission neutron spectra, respectively.*

1.5. OTHER MATERIALS ISSUES

The ability to maintain functionality under high-fluence bombardment by fusion neutrons is, of course, the *sine qua non* of fusion-relevant materials. But survivability and low/reduced activation are not the only materials issues. Also important are issues such as joining, corrosion resistance, compatibility with coolants, gas permeation, industrial capability, and cost.

> *Finding:*
> *An examination of the materials development programs for fast fission breeder reactor fuel cladding, high-performance gas turbines, aircraft, and the National Aerospace Plane indicates that mission-oriented materials development programs require sustained efforts of tens of millions of dollars (≈ 15% of total program budgets) for periods of a decade or more, exclusive of major testing facilities.*

To obtain reference points for assessing the magnitude and time requirements for developing fusion materials, the panel heard presentations describing programs for developing the fuel systems (fuels, cladding, and ducts) for liquid-metal fast breeder reactors; materials for high-performance gas turbines used in aircraft propulsion; and materials for advanced aircraft such as the National Aerospace Plane (NASP).

Development of the breeder-reactor fuel system occurred over, approximately, 1965-1992 and cost approximately $1.1 billion. Escalated to 1993 dollars, the cost would be approximately $2.0 billion. This figure does not include the operational costs for large facilities such as reactors, large corrosion loops, fuel fabrication lanes, etc. Nor was this the total breeder materials-development program, for there was also a significant effort to develop the reactor vessel and core-support structural materials. In discussions with J.J. Laidler, who headed the breeder reactor advanced alloy development program, the clear consensus was that development of materials for the breeder fuel system was significantly easier than the development of materials for fusion breeder blanket systems will be.

The presentations on gas turbines and NASP emphasized the evolutionary introduction of new materials into these challenging environments. This implies that materials for early fusion power systems need to be tested in TPX, ITER, and DEMO.

Finding:
The strategy employed in non-fusion programs is to use new materials first in small, less critical and risky ways, moving in an evolutionary way to progressively greater use. This strategy would be wise for fusion development and implies the need to incorporate some advanced materials in test machines like TPX and ITER to gain experience in an integrated fusion environment.

2. OFE ORGANIZATIONAL ISSUES

Responsibility for neutron-interactive materials research within OFE is distributed among several program areas. The primary distribution is between the ITER program (managed within the ITER and Technology Division) and "base" program (managed within the Advanced Physics and Technology Division). However, the Plasma Facing Components, Magnetic, Fusion Safety and Environmental, and Blanket programs have some activities that address neutron effects.

Findings:

- *The Panel observes with concern the distributed nature of the neutron interactive materials program within DOE Office of Fusion Energy. The structural materials program is split between the long-term and the ITER programs. Neither of these parts appears to be closely coordinated with other materials programs, such as divertors, magnets, blanket (coolant, breeder, neutron multipliers) and IFE issues.*

- *The fragmentation of the materials organization makes it difficult for materials development issues to obtain adequate recognition and, consequently, proper emphasis.*

- *Decreases in funding for materials R&D over the last decade have lead to the near elimination of the theory, modeling, and basic experiments that provide understanding of important phenomena occurring in materials in the fusion environment. Present facilities for experimentation in support of materials development reproduce only portions of the actual fusion environment. The ability to predict materials performance, to extrapolate to new parametric space, and to develop materials with composition and structure optimized for the desired properties is seriously compromised by lack of fundamental understanding. Also, the loss of basic research has a disproportionate effect on university research, which is the source of new-materials scientists and engineers for the future.*

The NIM Program examines two main categories of materials. One is structural materials—austenitic steels for near-term applications and ferritic/martensitic steels, vanadium alloys, and SiC/SiC composites for DEMO. (Work on titanium alloys, another class of candidate structural materials, is not currently supported.) The other category is non-structural ceramics, including diagnostics. Long-range applications (DEMO and beyond) are generally considered to be part of the NIM "base program," whereas near-term applications are primarily part of the ITER R&D program.

The level of effort and nature of the programs carried out in the ITER category is expected to change, perhaps dramatically, since the tasks and level of effort devoted to those tasks will be determined by the ITER Joint Central Team. The U.S. has tentatively listed some programs under the ITER category that are unlikely to be funded by ITER, e.g., part of the vanadium-alloy development program.

Findings:

- *It is likely that the ITER project will require substantially more work than is currently planned in structural materials, coolants supporting high temperature operation (bakeout/conditioning), nonstructural ceramics, and magnet materials. We base this finding on the cost for developing specific materials in other non-fusion projects and the recognition that some high-technology projects have failed because of inadequate materials work.*

- *If, in fact, more materials work is needed for ITER, and if the US increases its participation in ITER materials work, it is extremely important that the long-term base program in materials be protected against diversion from DEMO-relevant materials development to ITER. If ITER uses materials that have long-term potential, then this resource problem is lessened. If or where "off the shelf" materials are deemed inadequate for ITER, then any required materials development should, if possible, be focused on materials that have application beyond ITER. This approach would make more-efficient use of limited resources.*

It is clear that the base program could productively accommodate a funding level 2 times the current level of effort. However, the rationale for the current effort is not tied to an agreed upon development schedule; hence it is difficult, if not impossible, to determine the necessary level of effort.

3. THE NEUTRON INTERACTIVE MATERIALS PROGRAM

The main elements of the OFE Neutron Interactive Materials (NIM) Program are:

1. The development of low-activation structural materials—ferritic/martensitic steels, titanium alloys (not currently funded), vanadium alloys, and SiC/SiC composites;
2. The study and minimization of radiation effects in non-structural ceramics and diagnostic components; and
3. Support of ITER materials needs.

In summary: There are four classes of candidate structural materials for low/reduced activation service in a fusion system. They are ferritic/martensitic (FM) steels, titanium alloys, vanadium alloys, and SiC/SiC composites. Research in all of these materials except titanium alloys (not currently funded) is supported by the NIM Program in DOE/OFE. In terms of manufacturing readiness and technical risk, the Panel ranks FM steels as the leading candidate, followed by Ti, V, and SiC/SiC, in that order. However, in terms of low/reduced activation characteristics, the Panel ranks them in the reverse order. It is, therefore, important to pursue development and neutronics studies of all four classes of materials.

3.1. FERRITIC/MARTENSITIC (FM) STEELS

3.1.1. Introduction

The major impetus for the use of FM steels in fusion devices is the promise of extended lifetime for the first-wall/blanket region. Martensitic steels have been actively investigated in the U.S. Liquid-Metal Fast Breeder Reactor (LMFBR) Program since 1974, but were not considered as candidate materials for the fusion program until 1978. The lateness was primarily due to the perception that their ferromagnetic nature would interfere with the high magnetic fields inherent in magnetically confined fusion devices. By 1978, though, a body of data had been accumulated indicating that martensitic and ferritic steels evidence little swelling under fast neutron and heavy-ion bombardment. These data, combined with the favorable physical and mechanical properties of martensitic steels, resulted in a closer look at the possibility of using ferromagnetic steels in a magnetically confined fusion device. Martensitic steels were subsequently added to the Fusion Reactor Materials Program.

The use of ferromagnetic materials in tokamak design has been examined only in a "systems" sense, and there is a concern that today's strict rules about field non-axisymmetry could result in severe restrictions upon the use of such materials. A related concern is the force exerted upon the FM steels by the electromagnetic fields. There is also a real concern about whether large-scale modules made of ferromagnetic materials can be tested in ITER because of the field errors that would result.

Two FM alloys were chosen as model alloys for initial investigations in the Fusion Materials Program. Table 3-1 lists the compositions of these alloys, which variously contain chromium, molybdenum, vanadium, tantalum, and tungsten as intentional alloying elements. The modified 9 Cr - 1 Mo steel is an alloy that was developed in the LMFBR Materials and Structures Program. The 12 Cr -1 Mo - 0.3 V steel is a commercial alloy composition marketed by, among others, Sandvik Steel Company (as alloy designation HT-9). FM steels have been used extensively in high-temperature applications, such as superheater and reheater tubing in fossil-fired and nuclear power plants, since the 1950s. These steels have also been used successfully in steam turbines, jet engines, and gas turbines. Extensive data are available on the production, fabrication, welding, and mechanical and thermophysical properties of FM steels over the temperature range of interest.

Thousands of technical papers have been written about the physical metallurgy of 9 to 12 Cr martensitic steels. When these alloys are cooled (quenched) from their austenitization temperature (1038 to 1050°C), their structure transforms from austenite (face-centered-cubic or fcc) to martensite (body-centered-tetrahedral or bct), hence the term martensitic steel. Both alloys are air-hardenable; that is, they transform to martensite when cooled in air. Occasionally small amounts of delta ferrite will remain in the cooled structure, but essentially the structure is untempered, highly dislocated martensite with a lath grain structure.

These steels are rarely used in the as-quenched condition due to their very poor toughness. Tempering at a high enough temperature causes recovery of the highly dislocated martensitic lath structure, forming subgrains of ferrite (bcc) within the laths, increasing toughness. In addition, precipitation of carbides at the prior austenite grain boundaries and lath boundaries also occurs. A tempering heat treatment of 700–870° C for 1–3 hours is commonly used for the martensitic alloys in the fusion materials program. Because these steels are almost always used in the overtempered condition, they are sometimes called ferritic steels despite the lath-like structure they retain.

Finding:
Ferritic/martensitic steels with reduced activation compositions show high promise, providing lower activation levels and better performance than conventional ferritic steels with regard to ductile-brittle transition temperature (DBTT). There is a strong industrial database, but of course not with the exact fusion-relevant reduced activation compositions.

Table 3-1. Chemical compositions of FM steel alloys used in early fusion materials research (i.e., before the emphasis on low activation).

	Nominal composition (percentage by weight)											
	C	Cr	Mo	W	V	Nb	Ni	Mn	Si	N	P	S
Sandvik HT-9 or 12Cr-1Mo-0.3V	0.20	11.5	1.0	0.5	0.30		0.50	0.55	0.40		0.020	0.020
Modified 9Cr-1Mo	0.10	8.5	0.95		0.21	0.08	0.10	0.40	0.20	0.05	0.020	0.020

3.1.2. Scope and Organization of US Effort

In 1979 a workshop was held to formulate a R&D strategy for the development of FM steels for fusion applications. The attractive characteristics of these alloys *vis-a-vis* austenitic stainless steels had been established:

- Higher thermal conductivity and lower thermal expansion than austenitic steels, giving better performance in designs having cyclic thermal stresses, such as pulsed machines.
- Low swelling at high dpa levels in fast reactor irradiation.
- Retention of mechanical properties—specifically, tensile strength and ductility—in fast reactor irradiation to high dpa levels.
- Improved liquid metal compatibility (Li and Pb-Li) compared to austenitic steels.

The 1979 workshop identified four critical questions on areas of concern that formed the focus of the initial R&D efforts:

- The effects of increased helium generation on irradiation response.
- The effects of fusion system damage levels on fracture properties.
- The ability to accommodate loads induced by the magnetic field on a ferromagnetic structure and the magnitude and effects of field perturbations caused by the ferromagnetic structure.
- Fabrication and welding and the need for post-weld heat treatment.

In 1983 the focus of the U.S. Fusion Materials Program changed to include the objective of developing reduced or low activation structural materials. With regard to FM steels the objective was development of an alloy that could be disposed of by shallow land burial under the guidelines of 10 CFR 61 (assuming this regulation would apply) and would meet requirements for engineered safety with some characteristics for intrinsic safety.

With the 9Cr and 12Cr FM steels that were under investigation in the program, the approach to a low/reduced activation steel was reasonably clear—two intentional alloying elements, Mo and Nb, were unacceptable from an activation standpoint. However, since these alloying elements had metallurgical functions, they could not simply be removed, but rather, had to be replaced with elements having similar chemical/metallurgical effects. Several approaches were investigated. Irradiation experiments were used to select 9Cr - 2WV as the most attractive low/reduced activation candidate. Research and development is now almost totally directed toward the low/reduced activation alloys, specifically 9Cr - 2WV. A small amount of effort continues with the initial 9Cr - 1Mo and 12Cr - 1Mo compositions to better understand the problems that are more or less generic to this class of alloys, such as the effects of helium and He/dpa on irradiation response and fracture characteristics.

Significant progress has been made towards the development of FM steels for fusion system structural applications. The program has addressed the critical issues and made significant progress towards a low/reduced activation alloy. With regard to the four critical issues:

- Experiments conducted to evaluate the effects of He on fracture properties have demonstrated a reduction in fracture strength.
- In irradiation producing high dpa levels with little He (i.e., a fast fission reactor neutron spectrum), excellent tensile properties are retained, fracture properties remain adequate, and swelling rates remain low.
- Analyses conducted to date suggest that the ferromagnetic properties can be handled in design, but this should be re-examined; skepticism will remain until such steels have been used in a real machine.
- Preheat, interpass temperature control, and post-weld heat treatment will be required.

Progress towards low/reduced activation FM steels has been substantial:

- Based on the near-surface-burial objective, W and V have been identified as substitutes for Mo, and V, T, and Ta have been identified as substitutes for Nb, in approaches to development of low/reduced activation martensitic steels.
- A wide range of alloys having base compositions in the range Fe -2Cr to Fe - 12Cr have been investigated.
- Results from these experimental alloys suggest that low activation compositions with properties comparable to the respective commercially available Fe-Cr-Mo alloys (2¼Cr - 1Mo, 9Cr - lMoVNb, and 12Cr - lMoVW) can be developed.
- The most promising compositions appear to be in the vicinity of 9Cr. The 2¼ Cr alloys offer attractive welding characteristics.
- Although data are very limited, the low/reduced activation 9C2WV FM steel exhibits the smallest shift in ductile/brittle transition temperature (DBTT) of any of the FM steels examined to date.

3.1.3. International Activity and Coordination

Within the international fusion materials community, the FM steels are considered the leading candidates as a structural material for DEMO; they are the only system of alloys for which there are significant R&D efforts in the United States, Japan, and the European Community. The Japanese program is similar to, or parallels, the U.S. program, focusing on low/reduced activation alloys in the 8-9Cr range using W, V, and Ta as carbide-forming elements. The EC program has a large effort on a 10Cr - 0.5MoVNbB steel (MANET), which is not a low/reduced activation alloy. The EC has recently initiated some effort on low/reduced activation FM steels. Within the international community there is a healthy exchange of information and the beginnings of a collaborative development effort. At a recent IEA Workshop in Ferritic/Martensitic Steels (Report of Travel of Ronald L. Klueh to Japan, October 1992, ORNL), it was proposed that leading candidate steels from Japanese, EC, and U.S. programs be irradiated together in the range 200–400° C so a direct comparison of their properties can be made. Also, Japan agreed to produce two 10- to 50-ton heats of two promising low/reduced activation compositions for a series of coordinated tests in the three countries.

3.1.4. Program Goals and Timing

The near-term development of FM steels will focus on the effects of irradiation on their ductile-brittle transition temperature (DBTT) and fracture properties. Further testing in fission reactors is needed to fully determine their DBTT behavior. Initial experiments suggest that the He/dpa ratio of a fusion system is much more damaging than the lower He/dpa ratio of a fission reactor. This is a question of highest priority. Alloy development must also focus on optimization of composition and microstructure for improved fracture properties. Likewise, it is important to obtain sufficient engineering data on representative low/reduced activation FM steels to support self-consistent conceptual system design studies. This near-term activity, if funded at ~$3 million per year, will obtain results in a period of 6–8 years.

Finding:
The present ferritic/martensitic steel R&D program is focused on the most critical issues for this class of alloys, namely, the effects of fusion system damage levels on the DBTT and fracture toughness along with the development of a reduced activation alloy with composition and microstructure optimized for strength and fracture toughness. Some concern still exists regarding the use of ferromagnetic materials in a magnetic fusion system.

3.1.5. Irradiation Needs

A source of fusion neutrons will be needed to confirm or adjust performance predictions and to conduct final optimization for fusion damage levels. When any particular material is selected for DEMO, development of an engineering database, involving further use of this and other facilities, will be needed to support design performance analysis, licensing, etc.

3.2. TITANIUM ALLOYS

Early in the fusion materials program, titanium was of interest because of its large unirradiated material property database, mature supplier/fabrication industry, low cost, large resources, and low long-term radioactivity.

The impact of reduced waste-storage requirements and of titanium's potential for reuse was addressed in a series of studies conducted at the University of Wisconsin, which culminated with the design of an all-titanium reactor called NUMAK. While titanium appeared to offer a number of advantages to fusion, there was concern about using it in the first wall of a reactor, primarily because of a lack of an irradiation database and the potential for hydrogen embrittlement.

To answer these questions, experiments and studies were initiated both in the U.S. and Japan. In the U.S. these studies were under the auspices of the OFE Alloy Development for Irradiation Performance (ADIP) program and to a lesser extent the Damage Analysis and

Fundamental Studies (DAFS) programs. The ADIP program, which was the primary focus of the titanium work, initiated a series of scoping studies to develop an understanding of the influence of alloy phase (alpha and beta) and the effect of heat treatment (mill annealed, duplex anneal, and beta anneal) on the irradiation resistance. While the irradiations were at 394, 450, and 550° C in EBR-II for fluences up to 24 dpa, only the 450 and 550° C irradiations were examined.

The results of these studies indicated that void formations were observed in both the 450° and 550° C irradiations. However, the voids appeared to be segregated to the alpha phase and appeared to be formed as a result of transforming beta phase to alpha; they did not result in unacceptable degradation of material properties. This transformation occurred at a lower temperature than expected from the phase diagram. While immersion density measurements indicated that swelling did occur, it was unclear if the swelling was a result of phase change since the amount of swelling was within the sensitivity of the measurements. The 394° C specimens were not examined; however, ion irradiations at temperatures indicated that, for temperatures below 450° C, voids were not observed. While the results of the irradiation experiments are inconclusive for the alloys studied, the fact that voids were observed in these specimens is an area of concern for first wall applications where titanium would experience temperatures >450° C and fluences >50 dpa.

The second area of concern regarding titanium was hydrogen embrittlement. Studies conducted for DOD and NASA and at various aerospace companies indicated that, for internal hydrogen concentrations in excess of 1000 wppm, hydrides and hydrogen embrittlement was not observed in the near alpha, alpha+beta, and beta alloys. Flaw growth studies conducted at McDonnell Douglas showed no appreciable change in the flaw growth rate of near-alpha and alpha-beta titanium allows when in a hydrogen gas at pressures up to 1 torr and internal hydrogen concentrations of 50 and 500 wppm over the temperature range of room temperature to 200° C. Because hydrogen is more soluble in titanium than in iron- or nickel-based alloys, tritium permeation and inventory will likely be an issue.

Permeation studies conducted by Argonne indicate that the permeability of near-alpha and alpha-beta titanium alloys is roughly a factor of 5 times greater, however this permeation can be reduced significantly with barrier coatings such as TiN, TiB_2, and TiO_2. For experimental machines that use glow discharge types of cleaning it is likely that barrier coatings will be required to prevent surface hydrides from forming during the cleaning operation. The final issue is the tritium or hydrogen inventory. The specific inventory in titanium will be difficult to determine because of components within the vacuum chamber, such as carbon or beryllium, that compete for hydrogen, and because the different types of coolant—water, lithium, or helium—have different effects. While the inventory will in all cases be higher than that of iron- or nickel-based alloys, it will be design-dependent.

There has been little fusion-related titanium research in recent years. During a time of declining fusion budgets in the early 1980's, titanium was eliminated as an option because of its probable low operating temperature (≤450° C) and because the higher tritium inventory in comparison to stainless steels and ferritic steels, increased the requirement for tritium breeding. Low activation was not yet perceived as the strong requirement that it is today.

Aluminum is a commonly used (though not required) alloying element; most commercial titanium alloys contain it. Titanium's claim to "reduced activation" therefore depends on either low/reduced activation criteria that are more tolerant of ^{26}Al than is 10 CFR 61 as currently adapted by the fusion community, or else development of new alloys.

Findings:
- *Titanium alloys were dropped from the U.S. materials program, mainly because of tritium inventory and hydrogen embrittlement concerns. The high temperature capability is also somewhat limited. If coatings could be developed to control the hydrogen/tritium retention problem, titanium alloys (which are a lower-activation alternative to ferritic/martensitic steels) may deserve another look, assuming that restrictions on ^{26}Al are relaxed.*
- *Titanium alloys are non-magnetic and a strong industrial database is available. For reduced activation, one would use Ti alloys without niobium or molybdenum, and perhaps without aluminum. Experience with titanium in TPX will dramatically increase the fusion Ti-alloy database.*

In summary, from a low-activation-materials and waste-management standpoint, titanium alloys offer an off-the-shelf solution to a very difficult issue. Titanium alloys may be suitable for the first wall; certainly they should be considered for other components, such as shielding and support structures.

3.3. VANADIUM ALLOYS

3.3.1. Introduction

Vanadium-base alloys have been identified as a promising class of candidates for the first-wall/blanket structure of a fusion reactor. The vanadium-base alloys exhibit favorable physical and mechanical properties, Thus they offer the potential for high performance; apparent radiation damage resistance with a potential for long lifetime; and low long-lived-activation characteristics that provide favorable safety and environmental benefits. A significant database has been developed as part of the fusion materials program and earlier work in support of the fast breeder reactor program.

Vanadium-base alloys have been selected in several fusion system design studies. The ARIES-II study (in progress) is showing them to have attractive characteristics in theory. A joint US-British team is currently looking at their recycling potential. Most of the feasibility issues have been resolved in the scoping studies conducted to date and the key issues requiring further development have been identified.

Finding:
Vanadium shows the highest potential in three respects: low long-lived activation, promise for high engineering performance, and good waste management and recycling. While the tritium retention problem is lower for vanadium than titanium, tritium permeation is comparable for both metals, and surface barriers may be needed for both.

3.3.2. Scope and Organization of US Effort

The U.S. vanadium-alloy development program is integrated as a specific task under the Neutron Interactive Materials Program of the Office of Fusion Energy. The vanadium alloy program is one of the three elements of the long-range structural materials programs focused on the development of low-activation structural materials. The current program is a broad-based program with modest funding for subtasks on

1. Preparation/fabrication/joining.
2. Baseline properties/performance characterization.
3. Chemical compatibility.
4. Radiation effects.
5. Safety and environmental studies.

The vanadium-alloy development program is coordinated by Argonne National Laboratory and a major fraction of the effort is conducted there. The current program includes the efforts shown in Table 3-2.

Table 3-2. Vanadium-alloy efforts in the US.

Organization	Subtasks (see page 2-1)	Comments
ANL	1, 2, 3, 4, 5[a]	
PNL/WEC	4	FFTF/EBR-II Irradiations & Dynamic Helium Charging Experiment (DHCE)
ORNL	3, 4	HFIR Irradiation, He Corrosion
INEL	5[b]	Safety, Volatility, Recycle
Universities	2, 3, 4	University Of Illinois, Illinois Institute of Technology, Purdue University
Industry	1	Alloy Preparation, Fabrication

[a]Subtasks on compatibility funded by Blanket Technology Program.
[b]Funded by Safety Program.

The budget for vanadium alloy development has been ~10% of the Neutron Interactive Materials Program for the last few years, with a moderate increase in FY 1993 funding. In addition, more modest but important funding has been provided by the Blanket Technology and Safety programs. The current funding level includes:

Neutron Interactive Materials Program	$0.9 M
Blanket Technology (Compatibility)	$0.2 M
Safety (Volatility/Recycle)	$0.2 M

This funding does not include funds for either subassembly fabrication or reactor operation for the irradiation program.

3.3.3. International Activity and Coordination

The international efforts on vanadium base alloys are considerably smaller than the U.S. effort. The largest of these efforts is the Japanese "Monbusho" program conducted as part of the U.S./Japan collaboration. This program is focused primarily on fundamental irradiation studies. The European Community has contributed to the safety and irradiation effects areas, but this effort is quite small. The Russian effort is also very small. Table 3-3 summarizes these activities.

Table 3-3. Vanadium-alloy efforts internationally.

Organization	Subtasks (see page 2-1)	Comments
Japan (Monbusho)	2, 4	Collaboration on DACE
UK	5	Activation/Recycling (with INEL)
Russia	1, 4	Includes Planning Collaboration

3.3.4. Program Goals and Timing

The objective of this program is to develop improved vanadium base-alloys for first wall/blanket structural applications in a DEMO fusion system and to provide the required database on a time frame consistent with the U.S. strategy for development of a DEMO and the schedule for blanket testing in ITER.

The program strategy is to conduct a balanced, broad-based program that includes investigation of all major issues. Emphasis is placed on resolution of the critical issues identified in the design studies. The aims of the program are (1) to provide sufficient understanding to predict the behavior of candidate alloys under projected operating conditions and to guide in the development of improved alloys, and (2) to provide the required database on selected alloys for actual use in a DEMO system.

A three-phased approach (each phase ~6-7 years) to the development of vanadium alloys would include the following goals.

- Phase I includes development of scoping data on a range of alloys with emphasis on all identified critical issues. This phase is nearly complete.
- Phase II - Conduct detailed evaluation and develop a design database on a few selected alloys.
- Phase III - Select a reference alloy and develop the engineering database required for DEMO applications.

In Phase I, a systematic approach is being used to develop improved alloys with a focus on the Vanadium-Chromium-Titanium-Silicon (V-Cr-Ti-Si) alloy system with compositional variations of (0-15%) Cr, (0-20%) Ti and (0-1%) Si. The effects of nonmetallic elements (O, N, C and H) and thermomechanical treatment (TMT) on the properties and performance characteristics are also being evaluated.

<u>Status of Database</u>. The Phase I scoping database on a range of alloys of the V- Cr-Ti-Si system is nearly complete. Selected properties of six V-Ti binary alloys, eight V-Cr-Ti ternary alloys, and three V-Ti Si alloys have been evaluated. On the basis of these results, the compositions of candidate alloys for Phase II have been tentatively selected. Final selection of the Phase II candidate alloys will be made with additional results expected within one year. The candidates have been narrowed to a composition range of 4–7% Cr, 3–5% Ti, and <0.1% Si. The status is summarized as follows:

Preparation/Fabrication/Joining

- Vanadium resources are adequate, and costs, although higher than those of steel and Ti alloys, appear acceptable.
- Procedures for alloy preparation and secondary fabrication have been demonstrated and preliminary characterization of weldments has been initiated.
- Scale-up of production appears feasible but must be demonstrated.

Baseline Properties

- Physical properties are relatively insensitive to compositional variations of interest and are reasonably well established.
- Tensile properties as a function of alloy composition have been determined to 700° C.
- The effect of composition on the DBTT has been determined. A range of alloys exhibit DBTT's over 100° C below room temperature. These results are a dominant influence in the selection of leading candidate alloys. Alloys containing 5-7% Cr and 3-5% Ti are optimal.
- Creep and fatigue data are still limited. Use of Cr enhances the creep strength.
- Compositions with attractive low/reduced activation characteristics appear to have good baseline properties.

Chemical Compatibility

- Limited data indicate that vanadium alloys are resistant to pure alkali metals.
- Nitrogen and carbon concentrations in lithium must be controlled.
- Hydrogen embrittlement and/or tritium inventory in V alloys exposed to lithium do not appear to be problems.
- The acceptability of vanadium alloys for helium coolant is yet to be demonstrated.
- Additional corrosion studies are required to establish purity requirements and corrosion kinetics.

Radiation Effects

- Titanium additions (3-5% Ti) effectively suppress swelling to neutron fluences of at least 100 dpa in low-He-generating fission spectra.
- Tensile properties of several alloys irradiated at 400-600°C to ~100 dpa show saturation of hardening at ~40 dpa and high residual ductility (7-12% uniform elongation).
- The DBTT shift in V alloys after irradiation is strongly influenced by the chromium concentration. A Cr concentration of ≤ 7% is beneficial, again in low-He-generating fission spectra.
- The Dynamic Helium Charging Experiment has been developed to approximate the fusion relevant helium generation rates in neutron irradiated alloys. Successful completion of this type of experiment is highly important to the evaluation of vanadium alloys. First results are expected near the end of FY 1993.

Critical Issues. The critical issues in the development of vanadium-base alloys for fusion system applications include:

- Scale-up of fabrication capability and demonstration of fabrication/joining methods.
- Development of adequate baseline database to meet design code requirements
- Demonstration of compatibility limitations under prototypic conditions
- Continued optimization of alloys for irradiation performance including effects of fusion relevant He/dpa ratios.

> *Finding:*
> *There are two key issues with vanadium in fusion applications. One is the DBTT shift and fracture toughness; the other relates to chemical compatibility. Also, industrial experience with vanadium is very limited.*

Schedule for Completion. The Phase I scoping test phase should be completed by the end of 1993. Selection of candidate alloys for Phase II investigations will be conducted in FY 1994. A design database for three candidate alloys could be built in 6-7 years with increased funding to ~$3 M per year. Selection of a reference alloy and development of a design database would be accomplished in a 6-7 year Phase III effort.

3.3.5. Irradiation Requirements

The primary facility requirements in the near term (Phase II) are fission reactors, primarily fast breeder reactors (EBR-II or FFTF). High fluence (to >100 dpa) irradiations can be accomplished in ~3 years of operation. The Dynamic Helium Charging Experiment approach for investigating fusion-relevant He/dpa effects is very important in the development schedule. Low temperature (<400°C) irradiations will be performed in HFIR. A high-flux 14

MeV neutron source (IFMIF) is needed to verify the irradiation properties in Phase III, especially the influence of high He production on DBTT shift and fracture toughness.

Corrosion test loops of both modest and large size will be required to demonstrate acceptable corrosion performance and control of tritium permeation in candidate coolants. Incorporation of V alloys in large fusion devices should be conducted to demonstrate compatibility with the plasma.

Finding:
The near-term vanadium program is addressing the DBTT concern via the dynamic He charging experiment. There is currently no work aimed at resolving the chemical compatibility issues. Industrial experience must await a strong programmatic need for substantial amounts of vanadium.

3.4. SiC/SiC COMPOSITES

3.4.1. Introduction

The main incentive for investing in the development of fusion energy is the prospect of safety and environmental attributes significantly better than those of fission or coal. Silicon carbide-fiber-reinforced silicon carbide-matrix (SiC/SiC) composites have been identified as the most attractive candidate fusion-system structural material in terms of accident safety (both short-term dose and decay heat) and environmental concerns (no activation, no recycling required).

SiC/SiC has high operating-temperature capabilities (above 1000° C), excellent thermal-shock resistance, and good chemical stability. The safety and environmental prospects of SiC exceed those of other materials because of low activation and low afterheat. The relative slowness of diffusion processes in SiC minimizes the volatilization of radionuclides. Saturation of small dimensional changes (swelling) in bulk SiC ceramics at high fast-neutron fluences and high temperatures indicate an apparent radiation-damage stability. However, the effects of high-energy neutron transmutation products (H, He) are not known.

Because of their technological infancy—they have only been developed over the past 5–10 years, primarily for high-temperature aerospace applications—SiC/SiC composites have only recently been investigated as fission and fusion materials. Therefore they have the lowest technological-feasibility assurance. However, because of their potential for attractive safety and environmental features, there is a need for an effort to develop a fusion-relevant data base as part of the fusion materials program.

The database on the unirradiated behavior of SiC/SiC composite materials is very sparse, although there are some data on most properties of interest to the fusion program. There is a moderate amount of information on the mechanical properties of a few specific composites; however, there are a large number of variations in fiber type, architecture, volume fraction, interface type and thickness, and matrix production method, so the amount of information focused on any one material is smaller. Properties that are needed by the fusion program, but for which there are few data, include thermal conductivity, hermetic properties, chemical compatibility, thermal fatigue, thermal shock, fatigue crack growth, and creep.

Finding:
Silicon carbide-fiber-reinforced silicon carbide-matrix (SiC/SiC) composites have been identified as the most attractive candidate fusion-system structural material in terms of accident safety (both short-term dose and decay heat) and environmental concerns (no activation, no recycling required). Although ceramic composites are enjoying renewed industrial attention as engineering materials, such applications do not address the key radiation-damage questions for fusion. Considering the infancy of SiC/SiC technology and the lack of databases on radiation performance and large-scale applications, a majority of us did not feel that a DEMO could be constructed fully of SiC/SiC by 2025 (a minority felt that 30 years would suffice for development). We also accepted that R&D will continue beyond ITER and DEMO, especially in the materials area. One might envision a helium-cooled DEMO with some combination of metallic alloys and SiC/SiC composites.

The irradiated database for SiC/SiC composites is virtually nonexistent. There is a small amount of information available from a restricted-distribution program at Pacific Northwest Laboratories, and some data are being generated by the fusion programs at PNL and Oak Ridge National Laboratory, but these are at limited temperatures, neutron fluences, low He production rates, etc. There is a moderate amount of radiation data on monolithic SiC; these data are useful for understanding radiation damage processes in SiC/SiC composites but are not directly applicable for assessing the radiation stability of SiC/SiC.

Findings:

- *Silicon carbide-fiber-reinforced silicon carbide-matrix (SiC/SiC) composites have been identified as the most attractive candidate fusion-system structural material in terms of accident safety (both short-term dose and decay heat) and environmental concerns (no activation, no recycling required). Although ceramic composites are enjoying renewed industrial attention as engineering materials, such applications do not address the key radiation-damage questions for fusion. Considering the infancy of SiC/SiC technology and the lack of databases on radiation performance and large-scale applications, a majority of us did not feel that a DEMO could be constructed fully of SiC/SiC by 2025 (a minority felt that 30 years would suffice for development). We also accepted that R&D will continue beyond ITER and DEMO, especially in the materials area. One might envision a helium-cooled DEMO with some combination of metallic alloys and SiC/SiC composites.*

- *The ARIES I study, which assumed SiC/SiC composites, highlighted an important aspect of the low/reduced activation issue: to minimize activation, not only the structure but also other neutron-interactive systems, such as the divertor, coolant, and neutron multiplier, must also be considered. ARIES IV (in progress) eliminates certain materials (e.g., tungsten, used as a divertor coating in ARIES I) and replaced lithium zirconate (the solid breeder in ARIES I) with lithium oxide. For low/reduced activation, appropriate candidates would include beryllium as the plasma facing material; lithium, lithium oxide, or perhaps fluorine/lithium/beryllium ("Flibe") or a 17Li-83Pb eutectic material as coolants; and beryllium and perhaps lead as multipliers.*

3.4.2. Scope and Organization of US Effort

Funded participation in the U.S. SiC/SiC effort is associated with direct DOE Office of Fusion Energy funding of the Neutron Irradiated Materials Safety (NIMS) program at PNL and ORNL. The combined NIMS budget and effort for this work at ORNL and PNL, including irradiation costs, is 0.5 FTE and $300k in FY 1992, and 1.5 FTE and $600k in FY 1993. Students at the University of California-Los Angeles and Renesslaer Polytechnic Institute are working on this program. There is also ARIES-funded reactor-studies work at UCLA and General Atomics, as well as internally funded activity at GA.

Current regulations would limit an SiC/SiC composite first wall to an exposure of about 13 MW-year/m^2 if it were to qualify for shallow burial as a Class C waste.

Role of Non-Fusion-Funded Commercial Participation. Commercial participation will be very important to the development of SiC/SiC for fusion applications. There already exists the capability in the US to produce commercial SiC/SiC composite components with sizes up to 4.5 feet in diameter and 7 feet in height (Du Pont).The fusion program has chosen to invest in issues related directly to fusion, such as radiation stability and design, while non-fusion commercial developments play other crucial roles. These roles will involve the development of new fibers, composite processing and fabrication methods, joining methods and design criteria. Also, the fusion program will rely on commercial production capability. There is currently a sufficiently active ceramic composite development capability in the U.S. to assist this program, but a projection of the availability of production capability 10–20 years hence has not been attempted. Examples of other ceramic composite development programs that will benefit the fusion program include the $110 M engine combustor development effort of the High Speed Civil Transport program to develop SiC/SiC turbine engine components.

The Continuous Fiber Ceramic Composite (CFCC) program is a DOE-funded effort to support the development of ceramic matrix composites in general, including SiC/SiC. Funding of this project is $6.9M in 1992; $6.9M in 1993; projected $10.9M in 1994; $13M in 1995, and $13–15M/year in 1996–1998. In addition, there is an overall 25-40% cost sharing by industry, which brings the total expenditures to more than $100M for the 6–7 year period.

Informal collaborations exist between the Fusion SiC/SiC program and other programs, and there are various forms of interaction with industry. To summarize:

- A DOE Office of Basic Energy Sciences program at PNL evaluating the subcritical crack growth of SiC/SiC at elevated temperatures.
- OBES and OFE programs at ORNL involved in the development of chemical vapor infiltration (CVI) processing of SiC/SiC.
- Materials for irradiation studies have been supplied by GA, NASA, Dow-Corning, DuPont, and DuPont-Lanxide Composites Inc.
- A DOE Small Business Innovative Research (SBIR) contract is in place at MER Corporation to develop radiation-resistant materials.
- Discussions have been held with representatives of several companies that produce ceramic composites, including DuPont-Lanxide Composites, MER Corporation, Amercom, Dow-Corning, and NASA.

To help guide the SiC/SiC program, two workshops were held — May 1990 at the University of California-Santa Barbara and December 1991 at ICFRM 5 in Clearwater, Florida. A draft program plan, completed in September 1992, has been circulated to program participants in the organizations listed above.

3.4.3. International Activity and Coordination

Japan has an active research program evaluating both metal and ceramic matrix composite materials for fusion applications. Results on Al/SiC have been published. SiC/SiC samples have been irradiated in the FFTF/MOTA and are being irradiated in the EBR II COBRA 1A experiment by the Japanese Monbusho program. Fundamental research on radiation damage in SiC and evaluation of SiC as a low-activation material are active research subjects. Japan has a very active fiber development program and a smaller composite-materials development and evaluation program that are not related to the fusion program.

Europe has some research in SiC/SiC but the details are not known to this panel. There is work underway to evaluate the activation of polymer-derived SiC/SiC, along with some effort in engineering database evaluations.

There are no official collaborations between the U.S. and other countries on the subject of SiC/SiC for fusion. An informal agreement exists between the U.S. and Japan through the MONBUSHO program to share irradiation space and to test materials in a common facility. Nor is there official coordination of work between the U.S. and other countries on the subject of SiC/SiC for fusion, although there is informal cooperation in MONBUSHO.

3.4.4. Program Goals and Timing

At the current funding level, the goal is to evaluate feasibility issues associated with the use of SiC/SiC in fusion systems and to begin preparations for blanket tests in ITER. The major milestone ahead is a complete assessment of feasibility issues in FY 1998. It should be possible to complete the feasibility assessment (of composites developed by and for other programs) with the current level of funding, except for 14-MeV neutron effects, for which a new source is required.

At an enhanced funding level, the program could develop radiation-resistant SiC/SiC materials for fusion structural applications, and could prepare for blanket tests in ITER. The three phases of the plan are detailed below.

Phase I: Complete scoping study to identify methods to produce radiation resistant materials: 5 years, $12.5M (total).

Phase II: Complete evaluation of several prime candidate materials: 9 years, $22.5M (total).

Table 3-4. Approximate budget breakdown for both Phases I and II. Budgets are on a per-year basis throughout both phases.

Area of investigation	Approximate annual budget (FY 1992 $k)
Materials development	500
Hermetic Properties	75
Thermal Conductivity	75
Radiation Stability (irradiation costs not inc.)	500
Chemical Compatibility	200
Joining/Brazing Development	100
Thermal Fatigue/Shock	100
Design Criteria	50
Displacement/Transport	200
Baseline Properties	300
Impurity Effects	200
Plasma/First Wall	200
Reactor Safety	25
Total	**2525**

It may be seen that completion of Phases I and II will require an additional $2.5M/year in funding, above and beyond current funding, for the materials program.

Phase III: Complete prototype development. A schedule and budget have not been developed for this phase. Phase III does not need to follow Phases I and II; it could be initiated early to meet the ITER test module development schedule.

Finding:
The main incentive for investing in the development of fusion energy is the prospect of safety and environmental attributes significantly better than those of fission or coal. SiC/SiC composites are attractive in this respect, but because of their infancy as engineering materials, many feasibility issues, such as leak-tightness, joining, and large-scale manufacturing, have yet to be resolved. Further, SiC/SiC composites have not been extensively researched as fusion or fission materials, so their response to high radiation fluence must be further investigated. Much more intense effort, with concomitant support, is needed to optimize testing and ascertain suitability.

3.4.5. Irradiation Needs

The primary irradiation need is for a 14-MeV neutron source so that solid and gaseous transmutation effects can be evaluated.

The second irradiation need is for a temperature-controlled irradiation facility for high fluence irradiation to study radiation damage effects. The loss of the FFTF/MOTA has restricted the materials program to use of HFIR and non-instrumented assemblies in EBR II. A temperature control vehicle called MITA is being considered for EBR II but completion will require several years and the funding is uncertain.

3.5. NON-STRUCTURAL CERAMICS AND DIAGNOSTIC COMPONENTS

3.5.1. Introduction

A number of ceramic materials must be developed for fusion systems; they serve as electrical insulators, rf antennas, vacuum windows, and various diagnostic components. Although relatively little effort has been applied in past years towards meeting this need, these components may ultimately prove to be the most critical with respect to reliable operation of a fusion system. In part, this lack of effort has been attributable to a perception that many issues may be solved by design accommodation. A sufficiently complete program to deal generically with all the issues appears too expensive and intractable. However, work is needed to develop a fundamental understanding of behavior in various radiation environments in order to know if certain concepts are feasible.

Work in the ceramics area has increased in the last two years in recognition of ITER needs, but the level of effort is still "subcritical" and needs to be expanded, both to address near-term ITER problems and, especially, to develop a better fundamental understanding of radiation effects in nonmetallic materials.

3.5.2. Scope and Organization of US Effort

Ceramics R&D comprises about $1.2M in ITER-directed research and $400K in the base program in FY 1993. Of the ITER funds, LANL has $450k, ORNL $510k, and the Naval Research Laboratory $100k. LANL has the $300k from the base program. The overall program has grown considerably from a low of about $300k in FY 1991, primarily because of anticipated ITER needs.

LANL leads the program, working in close collaboration with ORNL and NRL. LANL's focus is the entire range of insulators and diagnostic materials. ORNL's focus is ICH insulators. NRL's participation is focused on radiation effects in fiber optics. All the labs communicate well with each other. Some outreach to other parts of the program is occurring, especially in blanket insulators and to some extent with magnet insulators. Other areas, such as materials for electron cyclotron resonance heating, divertors, and current breaks, are less well integrated.

The goals of the program are to determine the limits of performance in commercial ceramic insulators for ITER applications, and to develop improved materials for DEMO. Because of the current dearth of data, most of the ongoing work is directly relevant to ITER problems. Both prompt and long-term effects of irradiation are important.

The prompt effect, Radiation Induced Conductivity (RIC), decreases the electrical resistivity of ceramics during ionizing radiation and is directly proportional to the ionization part of the radiation flux. For fusion-relevant fluxes, this effect generally does not decrease the resistivity below 10^4 Ω-m. For most fusion applications, this is adequate performance, so present work concentrates on the long-term effects, including Radiation-Induced Electrical Degradation (RIED).

RIED has been observed in several important candidate ceramics at fluences much less than 1 dpa. The effect is a rapid, permanent increase in conductivity following an incubation period. The conductivity appears to be a runaway condition that would have very serious consequences for ITER applications. The effect depends on temperature, applied electric field during the irradiation, and, with present understanding, the relative fluxes of ionizing and atom-displacing radiation. With electron irradiation, the degradation begins at about 10^{-5} dpa; with protons at about 10^{-3} dpa, and with a fission-neutron spectrum at $>10^{-2}$ dpa, if at all.

Finding:
The relatively small amount of data available regarding radiation effects upon non-structural ceramics and diagnostic components gives cause for serious concern in meeting the requirements for ITER. At low fluences (<1 displacement per atom) some candidate insulators appear to degrade markedly in resistivity, and the fused quartz normally used in windows and fiber optics becomes opaque.

3.5.3. International Activity and Coordination

There is some activity outside the U. S., particularly in Japan. The Japanese have a large effort on basic aspects of radiation effects in ceramics under the Monbusho program. England, Spain and Germany have small efforts. The international programs are coordinated by an International Energy Agency subcommittee, managed by F.W. Wiffen of the DOE, which meets approximately yearly at opportune times. In addition, there is a U.S./Japan collaboration under the current DOE/Monbusho agreement. In November 1992, a workshop was held in Santa Fe, NM on "Dynamic effects of Irradiation in Ceramics"; participants from the U.S. and Japan attended.

3.5.4. Program Goals and Timing

Fission-reactor experiments have not gone beyond 10^{-1} dpa and indications of the presence of the effect have been equivocal. Collaborative experiments between LANL, ORNL and Japan are being planned. The aim of the experiments is to quantify the effect for ITER applications and to identify the temperature and flux conditions that are most serious. However, each program is about a 1- FTE effort, money for the experiments is very short, and *in-situ* experiments are much more expensive than previous irradiation experiments. Therefore, progress in this area has been very limited and the availability of sufficient data to predict the performance of insulators for many ITER applications is doubtful with current ITER funding.

A neutron irradiation of the best commercially available fiber optic materials was conducted by LANL and NRL at the Los Alamos Spallation Radiation-Effects Facility (LASREF) at the Los Alamos Meson Physics Facility (LAMPF) during the summer of 1992. These experiments had considerably higher fluence than any previous fiber optic irradiation. The results included luminescence and strong absorption at visible wavelengths, making even the best fibers unusable for fusion diagnostic applications at fluences greater than 10^{21} n/m^2 (about ten minutes of ITER operation near the vacuum vessel wall). There was some indication that more-radiation-resistant fibers could be developed, but many of the effects are generic to fused quartz. The current data have very serious implications for shielding of ITER fibers, windows, and other diagnostic components.

3.5.5. Irradiation Needs

A 14-MeV neutron irradiation source is essential for assuring that ceramic insulators will perform as expected in fusion systems. However, the critical nature of these issues for ITER demands that interim sources be used. *In situ* neutron-irradiation experiments have been conducted in the JMTR reactor in Japan and in LASREF. The considerable advantage provided by LASREF is its very large irradiation volume that allowed 18 instrumented, in situ experiments to be fielded simultaneously in the summer of FY 1992. A disadvantage of LASREF is the limited fluence (about 0.1 dpa/cycle) that can be achieved during the 2000-hour LAMPF annual run cycle. A tenfold increase of flux by redesign of the beam stop is possible for about $2M, but such funds are not currently in the program. An instrumented, temperature-controlled facility is being built at HFIR (ORNL), which will require about $250k of additional funds.

3.6. THE US STRUCTURAL MATERIALS PROGRAM FOR ITER

3.6.1. Introduction

It must be recognized that the ITER nuclear environment falls outside current fission reactor experience in nuclear materials technology. Compared to light water or liquid metal cooled reactors, the ITER environment is more aggressive in terms of: (a) high heat fluxes coupled with cyclic loading, (b) the frequency of large disruptive loads, and (c) the generation of hydrogen and helium via the 14 MeV component of the neutron spectrum. In addition, because of the difficulty of making in-situ repair and the daunting cost of removing and replacing failed components, the requirements for structural materials integrity and reliability are exceptionally high. The ITER environment also presents a difficult challenge to ceramic materials engineering. Ceramic applications occur in RF system feedthroughs, windows, standoffs, current breaks, and in diagnostic systems. The combination of ionizing and displacement damage and applied electric fields seriously degrade electrical properties; thermal and optical properties are also degraded by displacement damage.

During the initial stages of design (the current status of the ITER effort), the materials program has two main functions. First, it must provide designers with information on commercially available materials that includes fabrication and joining, corrosion behavior in various media, and physical and mechanical properties. Second, the program must provide enough data on irradiation behavior to define the regimes of temperature and fluence In which materials can operate without serious degradation of mechanical and physical properties. To validate materials selections it is necessary to carry out reactor irradiation experiments that simulate the ITER nuclear environment as closely as possible.

Once a concept has been chosen that incorporates viable materials engineering solutions, a materials program must generate the information needed to carry out a detailed engineering design. To support concurrent design activities at various sites, a consistent set of pedigree materials data is required for commercially produced, code qualified, prototypic materials. This database must be developed using well-defined and documented parameters. Internationally agreed standards must be adopted to define fabrication, welding, and microstructure parameters, reactor irradiation conditions, corrosion loop conditions, and the methodologies for determining physical and mechanical properties. A statistical distribution of materials properties is required to support a probabilistic approach to the determination of reliability.

3.6.2. Scope and Organization of US Effort

During the six-year period of the ITER Engineering Design Activity (EDA), the U.S. fusion program is committed to spending about $200M for ITER R&D activities. The technology program currently embraces ten tasks, which are prioritized to reflect the technical areas in which the U.S. has greatest interest in obtaining ITER credits from the Joint Central Team. Almost 80% of the U.S. interest (and current program interest) is focused in four areas: Magnets (27%), Plasma Facing Components (22%), Heating and Current Drive (10%), and Blanket and Shield (13%).

In the ITER technology program, materials R&D is not treated as a separate task area. Programs on structural materials form part of the tasks on Plasma Facing Components. Blanket and Shield, Heating and Current Drive, and Diagnostics. The total funding for the structural materials work ($3.7 M) is ~10% of the overall technology budget for FY 1993. The division of funds between the various subtasks is shown in Table 3-5.

Table 3-5. Distribution of FY 1993 ITER Materials R&D funds.

Subtask	Technical Areas	Labs	$k
Austenitic stainless steels for FWB/S	• define composition • irradiated properties database • welding irradiated material • Aqueous stress corrosion	ORNL PNL ANL	1500
Advanced blanket modules	• low activation ferritic steels • vanadium alloys	ANL ORNL PNL	500
Plasma facing components	• oxide dispersion strengthened copper alloys • Niobium alloys • Beryllium	ORNL PNL ANL	750
Diagnostics	• radiation effects in insulators and optical materials	LANL ORNL NRL	800
Ion cyclotron heating/current drive	• radiation effects on breakdown strength	ORNL LANL	400

The subtasks in the table reflect the areas where the U.S. has unique facilities and capabilities; these are the areas where the U.S. fusion materials program wishes to play a leading role. When the EDA Joint Central Team (JCT) is fully in place, potentially making new material selections, and directing the world ITER materials program, changes may be necessary that will have "knock-on" effects upon the base materials program. If the US is not granted ITER credits at the level and scope of work proposed, it is possible that the overall

(ITER + base) materials program budget would decrease as ITER funding was redirected to those R&D areas that did receive ITER credits.

> *Finding:*
> *The proposed US ITER materials program is strongly integrated with the base materials program in terms of reactor facilities, post-irradiation testing, corrosion testing, and key personnel. If the ITER-credit assignments do not cover some of the proposed activities, some areas of the US materials program may become sub-critical and jeopardize our ability to sustain existing international cooperative programs and impact materials development for DEMO.*

Depending on the choices made, the resource picture could improve or worsen. For example, if ferritic steels are selected for the first wall, blanket, and shield, and if titanium is selected for the vacuum vessel, then there would be no ITER credits for austenitic steels. In such a case, the austenitic steel program might appropriately disappear, given the earlier finding that austenitic steels are not attractive DEMO candidates. Then present austenitic steel funding could be devoted to ferritic and titanium alloys useful for both ITER and DEMO. However, in other cases, selections could be detrimental to resource needs. For example, if Mo alloys rather than vanadium were selected for the divertor, the present U.S. proposal for ITER credits for vanadium would be disallowed, putting the overall (ITER + base) vanadium program in serious difficulty.

Current U.S. ITER-Related Program. Because of the delays in putting together the ITER Joint Central Team, there have been no moves to put together a coordinated international effort to address the serious materials engineering issues confronting the project. International discussions on materials issues were held during the Conceptual Design Activity, which produced a set of materials selections for the conceptual design. Since then, the U.S. materials program has continued with collaborative irradiation programs with both Japan and Russia designed to increase the irradiation database of austenitic stainless steels and on copper alloys. The tasks currently being pursued with the U.S. program are as follows:

First Wall Blanket and Shield
- Irradiated properties of austenitic stainless steels.
- Environmentally assisted crack growth.
- Welding irradiated materials.

Divertor
- Irradiation behavior of ODS copper alloys and beryllium.
- Assessment of niobium alloys.

Advanced blanket modules
- Irradiation behavior of low activation ferritic steels.
- irradiation behavior of vanadium alloys.

Diagnostics and plasma heating
- In-situ electrical property measurements.
- Study of in-situ and post-irradiation optical properties.

These tasks were defined on the basis of the ITER concept that evolved from the conceptual design activity. However, this concept is being seriously reconsidered and it is probable that there will be radical design changes, and that some of these materials tasks will no longer be appropriate. For example, the CDA blanket/shield concept was based upon a solution annealed AISI 316L stainless steel structure with water as a coolant at an inlet temperature of ~100° C. New physics-based criteria may require that the first wall be maintained at >280° C, which would preclude the use of water as a coolant. Consideration is being given to alternative coolants (Li, He, Ga, Na, and NaK) and to higher strength structural alloys (high nitrogen super-austenitics, Ni-based alloys, titanium, and ferritic-martensitic steels). Only the 9Cr to 12Cr ferritic/martensitic steels appear to have an adequate database to support this new direction.

The dilemma is that, for most of the higher-strength alloys being considered, the irradiation performance database is not sufficient to support a reliable selection. Depending upon the choice of coolant, the compatibility database may also need to be expanded to validate the concepts currently being considered.

Findings:

- *The present ITER Materials Program has been based on the design and material choices made in the Conceptual Design Activity (CDA). Now, however, the Engineering Design Activity (EDA) may be heading in new directions. This may cause changes in the ITER Materials Program that cannot now be known; this uncertainty complicates the job of addressing the ITER Materials Program and how it fits into the entire fusion materials development effort.*

- *If or where "off the shelf" materials are deemed inadequate for ITER, then it is appropriate for materials to be selected that have application beyond ITER to make more efficient use of limited resources.*

For example, as noted above, austenitic steels are not considered attractive materials for first-wall or plasma facing components of DEMO or fusion power plants. However, it is quite probable that austenitic steels will be used for shields, coolant pipes, heat exchangers, support structures, etc., even if the vanadium or SiC/SiC materials are chosen for areas of high neutron wall loading or high heat flux. Ferritic steels or titanium alloys may be attractive DEMO materials. Thus, if ITER were to use one or both materials, then ITER development would also help provide a good candidate for DEMO. The basic points hold for higher-temperature coolant options like liquid metals and helium, which are prime coolant options for DEMO, as opposed to the low-temperature water coolant that was specified in the CDA and cannot serve as a coolant in an electricity-producing DEMO.

3.6.3. International Activity and Coordination

Finding:
The Panel notes the importance of having materials expertise integrated into the ITER Joint Central Team (JCT). Some high-technology projects have failed because of choosing the wrong material or not adequately developing the right one. The history of fission power suggests the potential for unanticipated materials-related problems that will require vigilance. Internationally, ITER effort comparable in level to the US program is underway on austenitic stainless steels, while generally smaller levels of effort in the other technical areas are being pursued by the European Community, Japan, and Russia.

When the Joint Central Team is in place, probably late in 1993, decisions will be made regarding the distribution of funds between the various tasks and which institutions will be involved. If ITER credits were not allocated to the US at the proposed 1993 level of $3.9M, then it is possible that the materials program budget would decrease as funds were redirected to those technology areas that have received ITER credits. The U.S. ITER materials program is strongly integrated with the base program in terms of reactor facilities, post-irradiation testing and corrosion testing facilities, and key personnel. Such a policy of redirecting funds would render many areas of the US base program "sub-critical" and jeopardize our ability to sustain the existing collaborative programs with Japan and other countries.

4. OTHER OFE MATERIALS PROGRAMS

Materials issues are addressed throughout the fusion development effort. Specific materials programs that are not part of the neutron interactive materials program are Plasma Facing Components, Superconducting Magnets, Blanket Development, and Safety and Environmental Protection.

4.1. PLASMA FACING COMPONENTS

4.1.1. Introduction

Plasma Facing Components (PFCs), such as divertors and limiters, are the interface between the plasma core and the reactor structure. As a result, their plasma interactive materials must do "double duty." They must be compatible with plasma performance and be able to withstand plasma interactions such as deposition of high heat flux, sputtering, disruption erosion, and runaway electron damage. In addition, these materials and components must maintain structural integrity during thermal cycling in an intense neutron irradiation environment, and must be compatible with their coolants. The many conflicting requirements placed on PFCs has led most designs to focus on duplex structures. In these, a plasma facing material with low atomic number (to avoid plasma radiation losses from eroded atoms) is bonded to an actively cooled high-conductivity substrate material. The DOE ITER & Technology Program for Plasma Interactive Materials has been established to develop the required materials, components, and high-heat-flux and plasma-interactive database for the successful design and fabrication of PFCs. The program encompasses plasma-edge diagnostics in magnetic confinement devices, extensive modeling of the plasma edge and PFC surfaces, and design and fabrication of advanced prototypical components.

4.1.2. Scope and Organization of US Effort

The Plasma Interactive Materials Program consists of two parts: a base program and an ITER-related program. The base program supports existing US confinement devices such as TFTR and DIII-D. The ITER R&D program focuses on concept improvement to reduce the plasma interaction through innovative plasma techniques, as well as performance maximization through improved materials and heat removal technology. Operating funds in this area are approximately $9.8 M in FY 1993, with 85% devoted to ITER R&D. The program is distributed over a number of national laboratories and universities, with main test facilities at Sandia National Laboratories and UCLA. There is also a strong DOE-supported SBIR program in PFC development that includes approximately $1M of industrial research focused on innovative materials, bonding technology, and heat removal concepts. To transfer technology from the DOE program to industry, an ITER PFC Industrial Contract has recently been awarded to an industrial team headed by McDonnell Douglas Aerospace.

> *Finding:*
> *There is no significant, long-term materials program for low/reduced activation divertors for DEMO. Funding in this area has been redirected towards ITER divertor development. This is appropriate given budget constraints, since the requirements for divertor materials are expected to evolve in response to divertor designs for, and experimental results from, TPX and ITER.*

4.1.2. International Activity and Coordination

There are a number of international bilateral agreements in the PFC area. The US program provides plasma-material interaction support studies for a number of foreign tokamaks such as JET and JT-60U, and conducts fundamental laboratory measurements in collaboration with European Community, Japanese, and Russian laboratories. These exchanges have provided the US with important databases and understanding on such topics as beryllium performance in JET, heat removal technologies in Japan and Russia, and disruption vapor shielding using Russia's plasma gun simulations. The exchanges with Japan have given the US direct access to both the MOE and JAERI branches of Japanese fusion research. The exchanges have also allowed the countries to interact with each other and build trust prior to entering the more formalized ITER Engineering Design Activity.

4.1.3. Program Goals and Timing: Relevance to ITER and Beyond

Neutron irradiation of plasma interactive materials can degrade material properties such as thermal conductivity, mechanical strength, and bond interfaces. It can also lead to significant increases in in-vessel tritium inventory by radiation damage trapping. Component integrity and lifetime, especially for duplex structures, can be seriously degraded by mechanisms such as differential swelling of the various materials. An ITER PFC must be able to survive a very challenging neutron fluence, on the order of 1 dpa; for a DEMO fusion system the fluence lifetime will have to be raised by more than one order of magnitude in order to be cost-effective.

> *Finding:*
> *Neutron irradiation is known to degrade the thermal and mechanical properties of beryllium and graphite plasma-facing materials under consideration for ITER. Fission reactor irradiations are being used to screen candidate materials, but more work is needed to expand the design database.*

4.1.4. Irradiation Needs

There is very little work being done on potential advanced divertors with the performance and safety characteristics appropriate for fusion power plants. This is true even though studies such as ARIES have shown that divertors may dominate the safety characteristics of fusion power plants and need to be made of low/reduced activation materials. With the exception of a small base-program study on silicon carbide, all research on the effects of neutron irradiation on plasma facing materials and components is directed towards ITER. Approximately $600k in FY 1993 is being spent on the development and characterization of radiation-damage-resistant carbon-fiber composites and beryllium. These programs are conducted with fission reactor irradiations in FFTF and HFIR, which, unfortunately, do not provide a good simulation of the He/dpa ratio that will occur in a fusion system.

Since these low-atomic-number plasma facing materials have high (n, alpha) cross sections, the lack of a true 14-MeV neutron spectrum must be considered as a major liability of the PFC testing program. For example, beryllium is especially prone to loss of ductility from the formation of irradiation defects such as helium bubbles at grain boundaries. The present test program can provide qualitative materials selection information, but it cannot be considered as a realistic validation test for the environment found in ITER. In effect, the testing of plasma-facing materials in the combined neutron and plasma environment is part of the mission of ITER.

There are no suitable test facilities for the high-heat-flux testing of activated duplex structures and divertor mock-ups. The performance of a complicated divertor structure cannot be adequately assessed from the thermomechanical properties of its individual irradiated materials. Today there is no hot-cell facility with a high-heat-flux test capability in the US. An effort is underway to arrange a collaboration with KFA Juelich (Germany) for testing of samples in their JUDITH hot cell electron beam facility, which is currently in the German government's licensing process.

Finding:
Of immediate concern for ITER is the lack of operating hot-cell facilities for thermal fatigue testing of activated ITER prototype divertor mock-ups in their irradiated states. The performance of a bonded duplex structure cannot be adequately assessed from the behavior of its individual irradiated materials.

4.2. MATERIALS FOR SUPERCONDUCTING MAGNETS

4.2.1. Introduction

The key issue for the design of the ITER superconducting magnet is the design requirement of a very low probability of failure over the ITER lifetime of 25 years. The possibility of meeting this high reliability requirement is uncertain, since we have no experience in operating magnets at 4 K and under high fast-neutron irradiation. The situation is made worse by large shear/ compressive loads and by operating under cyclic conditions.

The levels of radiation damage at 4 K to be tolerated during the operational life of the magnet systems for the superconductor (NbTi or Nb_3Sn) and stabilizer (Cu) have not been changed between the design that was current in 1990 (Conceptual Design Activity) and the present understanding. The design damage levels for superconductor and stabilizer are 1×10^{23} n/m^2 (>0.1 MeV), and 6×10^{-3} dpa, respectively.

For the structural alloys and welds associated with the superconducting magnets, such as Fe-Cr-Ni-Mn-N alloy, 316LN, and Incoloy 908, the critical properties are fracture toughness and fatigue crack growth rate at 4 K. R&D will be required to determine the level of radiation that this material can tolerate.

Similarly, for organic or inorganic insulations, the critical properties are shear strength and dielectric strength. The CDA design level is 5×10^7 Gy. More R&D will be required in this area as well.

The National Institute of Standards and Technology has performed a review of irradiation effects on organic-matrix insulation and concluded that there are no high-fluence ($>10^{18}$ n/cm^2) data following irradiation at 4 K. Higher-temperature (e.g., 77 K) irradiation data are available, but the extrapolation to 4 K is too uncertain for design decisions.

> *Finding:*
> *The high reliability requirement of ITER superconducting magnets is a serious concern. The adequacy of structural alloys and welds and organic or inorganic insulation materials to operate at 4 K under ITER fluence conditions is uncertain.*

4.2.2. Scope and Organization of US Effort

There are five elements in the US program.

1. The development and screening of suitable insulation material,
2. Property measurement of candidate materials,
3. Evaluation of irradiation effects for materials after irradiated in the 4 K Garching reactor,
4. Nondestructive inspection of material, and
5. Prototype fabrication and testing.

The insulations being developed fall into two categories: hybrid systems and inorganic insulations. The hybrid systems being developed are vacuum-pressure impregnation epoxies, like DGEBA, TGDM, S2-glass weaves, mica and coating; and prepregnated epoxies, like polyimides, S2-glass weaves, mica and coatings. The inorganic insulations are plasma-sprayed coating (ZrO_2/Y_2O_3), porcelain-enamel coating, mica barrier (splittings, paper), machinable glass ceramics, swaged-packed powder (Al_2O_3, MgO), castable ceramic (Ca aluminate) and ceramic prepreg (Ca-Ti aluminate).

4.2.3. International Activity and Coordination

There are various international investigations in low-temperature irradiation testing. European Community researchers are going to do an in-situ shear test at 4 K, following irradiation at 4 K at the Garching reactor. ASEA Brown Boveri (ABB) has prepared samples of Olitherm resin, R-glass reinforcement and plasma-sprayed coating and Kapton barriers. Samples of plasma-sprayed Zr-Y coating on 316LN are being prepared and will be shipped to the U.S.

The Russians plan to characterize shear/compression properties, develop vacuum-impregnation techniques for large volumes and long gaps; design, fabricate and test prototypes; and perform nondestructive evaluation, all at 77 K in the Sverdlovsk reactor. Currently, they are studying polyimide-glass prepregnated with epoxy/polyimide binders, mica-glass tape with Al-Cu-phosphate binder and glass/epoxy compositions.

There is no Japanese program at this time.

4.2.4. Irradiation Needs

The radiation facilities needed for this research—fission reactors and exposure to the 14-MeV source—are also required for the other materials programs. However, this program requires a low-temperature (4 K) sample-handling capability.

The neutron fluence requirements for magnet materials are considerably lower than those of the first wall and should be easy to achieve with a number of existing sources. However, the only source we are aware of with the necessary low-temperature testing capability is the aging FRM fission reactor in Garching, Germany. It has cryostat facilities where in-situ lap-shear experiments can be performed with a single specimen at 4 K. This facility can only be accessed by the Next European Torus team (ITER program) for 4 months per year, and only 1 specimen per week can be irradiated at 4 K and tested at 4 K. To get a dose of 1×10^{23} n/m^2 will take 90 hours. The current working rule only allows 30 hours of irradiation per run. This old facility may be shut down for extensive maintenance in 1994.

In principle, the approximate neutron spectrum and fluence required could be achieved for the in-situ tests by building a low-temperature facility at one of a number of existing accelerators, but there are no plans or funding devoted to this purpose at present. The need for a low-temperature in-situ test capability is growing.

4.3. BLANKET MATERIALS

4.3.1. Introduction

The blanket serves three primary functions: it breeds tritium, converts neutron energy to thermal power, and provides much of the neutron shielding for other components. Two types of blankets are being pursued: a solid breeder blanket and a liquid-metal blanket. In the former, the breeding material is a ceramic, while in the latter, the liquid metal serves as both the breeding material and coolant. Although both blanket concepts have their advantages and disadvantages, recent irradiation testing has focused on the solid-breeder blanket concept.

4.3.2. Solid (Ceramic Blanket) Breeding Materials

Candidate lithium-ceramic breeding materials have been identified over the past decade. These include: Li_2O, Li_4SiO_4, Li_2ZrO_3, and $LiAlO_2$. To provide a basis for selection, significant R&D is required to determine their tritium release and other performance characteristics. ITER breeder-materials testing could be accomplished in low-flux thermal reactors; however, DEMO breeding materials would require testing in high-flux, fast-neutron reactors, e.g., EBR-II. Interactions between ceramic breeders and their transmutation products with other blanket constituents can only be determined with integrated blanket tests.

Scope and Organization of US Effort in Solid Breeding Materials. Participants directly funded by DOE are shown in Table 4-1 below. The total U.S. budget for FY 1993 is $1810k, not including IEA funds.

Table 4-1. US research funding in blanket materials.

Research area	FY1993 budget ($k)
In-reactor testing (PNL)	585
Non-nuclear testing/modeling (ANL/UCLA)	720
Neutronics (UCLA/LANL/ANL)	420

International Activity and Coordination in Solid Breeding Materials. Currently, a survey of international programs indicates that different countries are concentrating on different approaches to developing a lithium ceramic breeder. Japan is concentrating on Li_2O, France on Li_2ZrO_3, Italy on $LiAlO_2$, Germany on Li_4SiO_4, Canada on Li_2ZrO_3, and the U.S. on both Li_2ZrO_3 and Li_2O. A strong international irradiation-testing program, BEATRIX-I, was started in 1985, with the U.S. irradiating samples provided by Japan, the UK, Germany, France, Italy, and Canada. The program was not completed because of a lack of U.S. funding. A second international program, BEATRIX-II, began in 1990. Phases I and II addressed major issues on Li_2O and some on Li_2ZrO_3. Phase II was terminated early with the shutdown of FFTF in March 1992. Total joint funds for Phase I and II were above $6 M (Canada, Japan, and U.S.). Phase III of BEATRIX-II in EBR-II has been proposed at over $8 M; however, it is still unfunded.

Finding:
The US, until recently, had a strong solid breeder irradiation-testing program. The shutdown of FFTF in February 1992 resulted in the termination of the international BEATRIX II solid breeder program. Currently there is a lack of US nuclear testing facilities. The proposed EBR-II irradiation facility upgrade (BEATRIX III) is needed.

Program Goals and Timing in Breeding Materials. To develop ITER blanket test modules by the year 2010, solid breeder development calls for starting Phase III of BEATRIX-II immediately, but it will also require efforts to begin developing integrated fusion testing and volumetric 14-MeV neutron testing in ITER.

4.3.3. Tritium Barrier Coatings

Tritium contamination of coolant systems, particularly water, will require radiation-damage-resistant tritium-diffusional-barrier coatings. Recent advances in coatings have shown to provide a 10 000-fold decrease in tritium permeation through stainless steels. No program within OFE is in place to look at the behavior of coatings under neutron irradiation.

4.3.4. Neutron Multipliers

In lithium-ceramic breeders, parasitic neutron capture by fusion-power-core (FPC) structural materials requires neutron multiplication inside the blanket. The primary candidate is for solid breeder blankets is beryllium. The two significant transmutation products in Be are tritium and helium. Tritium release behavior is critical for safety aspects of the FPC, and the large helium-generation rates cause swelling and affect the thermomechanical properties of Be. Modeling of the tritium-release characteristics of Be is continuing.

Currently, irradiated Be samples from FFTF and EBR-II are available. However, FY 1993 funds are not sufficient for an irradiation-effects R&D program.

The radiation damage parameters and ratios, such as dpa, He/T, and He/dpa, depend on the neutron energy spectrum. For example, typical radiation-damage parameters for Be are shown in Table 4-2.

Table 4-2. Typical Be radiation-damage parameters in three scenarios.

Reactor	He/T Ratio	He/dpa ratio
ITER (fusion)	100–500	600
FFTF (fast fission)	3000	100
ATR (thermal fission)	10	400

These damage parameters determine the thermomechanical properties and tritium release characteristics of Be. Significant testing and modeling remain to be done.

Finding:
Beryllium is an important component in solid breeder blankets. Tritium release behavior is critical for safety aspects and the large helium-generation rates affect thermal-mechanical properties. Significant testing and modeling remain to be done.

Scope and Organization of US Effort in the Neutron Multiplier Program. PNL and INEL are the primary institutions in the U.S. with R&D efforts on Be. Actual funding for FY 1993 is $85k. Requested funding for FY 1994 is $420k to progress in a reasonable manner to ITER goals. Irradiation effects on mechanical integrity of Be are being investigated in the U.S. by EG&G Idaho and PNL, with ANL doing most of the modeling.

International Activity and Coordination in the Neutron Multiplier Program. Currently there are no funded international collaborations between the U.S., EC, and Japan. However, there is consensus that, although the U.S. has the largest and most advanced Be industrial base, development of Be multiplying materials could become a purely Japanese venture, if national funding of R&D programs for Be do not significantly increase.

4.3.5. Liquid-Metal Program

The primary candidates for liquid-metal breeding materials are lithium and lithium-lead eutectic (17Li/83Pb). Corrosion effects are the main materials-related R&D issues. From the point of view of thermal hydraulics, electrically insulating coatings inside the coolant channels are necessary to reduce MHD pressure drops. Compatibility studies have to address both the chemical and mechanical effects of liquid breeders on the structure.

Electrically insulating coatings are being developed to reduce the MHD pressure drops. While the use of fission reactors may be adequate during the development phase of these coatings, a 14-MeV neutron source is desirable to confirm their performance.

> *Finding:*
> *Electrically insulating coatings inside the coolant channels are necessary to reduce MHD pressure drops in liquid-metal-cooled fusion power plants. High voltages developed during disruptions will challenge the insulating coatings, which may, therefore, need to be redeveloped* in situ.

Scope and Organization of US Effort in the Liquid-Metal Program. ANL leads the U.S. liquid-metal-corrosion R&D work, with ORNL contributing to this effort. Liquid metal R&D is funded jointly by the NIM and Blanket Technology programs. The ANL liquid metal activity funding will be $0.3 M for FY 1993.

International Activity in the Liquid-Metal Program. Currently, collaborations are primarily between ANL and KfK (Germany), and between ANL and EFREMOV (Russia). Furthermore, an IEA implementing agreement on fusion nuclear technology is to be signed.

4.3.6. Integrated Blanket Testing Program and Irradiation Needs

Because the blanket performs multiple functions, integrated testing of the system as a whole is needed. A 14-MeV-neutron source volume of 2 liters is required to do integrated blanket testing. While ceramic breeder materials and liquid metals may not require R&D in a 14-MeV-neutron environment, blanket structural materials, electrical insulating coatings, and tritium-diffusion barrier coatings do. The technology phase of ITER will provide a capability for integrated blanket testing.

The ITER terms of reference call for the testing of DEMO-relevant blanket modules when DT operation in ITER begins in about 2010. Therefore, an integrated blanket testing program with a 14-MeV neutron source should be underway shortly after the turn of the century. Prior to the tests with the 14-MeV source, both in-reactor (fission) and out-of-reactor integrated tests are required. An enhanced blanket development program should be initiated immediately to meet the schedule goals of these in-reactor and out-of-reactor tests and of the 14-MeV tests.

Finding:
The complexity of solid breeder blankets requires integrated testing, including in ITER, to determine synergistic effects between the different materials.

4.4. SAFETY AND ENVIRONMENTAL PROTECTION

Fusion energy has excellent potential for being safe and low in environmental impact. However, numerous studies for more than a decade have shown that this potential will not be realized automatically. Furthermore, it is clear that society is currently quite risk-averse with regard to safety and environmental concerns, especially nuclear ones. Accordingly, DOE has a safety and environmental program in order to be proactive in identifying, assessing, and solving safety and environmental concerns as early as possible in the fusion energy development program.

Many of the safety and environmental issues relate strongly to the choice of materials, especially neutron interactive materials. Material choice essentially determines the radioactivity inventory for a fusion facility and thus can decouple the hazard inventory from the output power level. By contrast, in fission reactors the radioactivity inventory is basically fixed by the output power level—fission gives fission products regardless of material choices. D-T fusion gives neutron activation products that are functions of the materials absorbing the neutrons. This is the motivation for low/reduced activation materials, namely, to define, select, and develop materials that have lower induced radioactivity, thereby taking advantage of this fundamental advantage of fusion.

Finding:
Numerous design studies have shown that the high safety and environmental performance of fusion is not achieved automatically. In conjunction with other technology programs, the fusion safety program is addressing the definition of low/reduced activation materials, the safety and environmental performance potential of advanced neutron interactive materials, and how advanced materials can be used in conceptual fusion power plants.

More broadly, the safety and environmental issues directly associated with materials include activation level (accident dose potential, decay heat, waste management, recycling potential), tritium permeation, tritium inventory, and chemical reactivity (chemical energy) in addition to traditional engineering performance characteristics like strength and fatigue resistance. The accident dose potential is perhaps the most important, but is also the most difficult to assess because the activation inventory (provided by design teams) must be combined with offsite dose calculations and mobilization pathways like oxidation-driven volatility. Chemical energy concerns include metal-water reactions for structural materials as well as liquid lithium and 17Li/83Pb reactivity with air, water, and concrete. The safety and environmental program addresses these various materials issues, focusing on the radioactivity and chemical energy inventory items mentioned here.

Material selection and characteristics have a profound effect on fusion safety and environmental performance. Accordingly, it is important for the associated radioactivity and chemical energy issues to be defined, assessed, and solved. This is being done by fusion safety personnel. In particular, the safety experts continue working to define the criteria for "low or reduced activation" materials.

The Fusion Safety and Environmental Program consists of two main parts: the Fusion Safety Program (FSP) at INEL, and direct DOE funding of the University of California at Berkeley (Profs. Holdren and Fowler) and MIT (Prof. Kazimi). The FSP includes subcontractors at the University of Wisconsin (Prof. Corridini), MIT, PPPL, and SAIC. Total DOE fusion safety and environmental funding is about $3M in FY 1993, with almost all from the ITER and Technology Division ($1.25M ITER R&D, $0.3M ITER design support, $1.6M base), and small funding from the Advanced Physics and Technology Division for development of a draft DOE Order for fusion test facilities. Something like $0.8M is directly associated with safety aspects of neutron interactive materials. There is also some small direct funding from PPPL for TFTR and TPX safety support and safety documentation.

The main experimental programs include the following:

1. Tests of oxidation-driven volatility in the VAPOR (volatilization of activation product oxides reactor) apparatus at INEL where prototypical materials (steel, V, Cu, W, Nb) are subjected to high temperature oxidizing environments.

2. Tests of implantation-driven permeation at INEL.

3. Liquid-metal chemical reactivity tests. Historically, this has included larger scale tests at Hanford with small-scale reaction kinetics tests at MIT and UW. Since most questions relating to Li and 17Li/83Pb have been answered to the degree needed for now, the liquid metal portion has shrunk to only UW, which continues liquid metal-water studies as well as some scoping studies with liquid metals now being considered for ITER, namely Ga.

These efforts are strongly coordinated internationally through ITER, IAEA fusion safety technical meetings, an IEA umbrella agreement on fusion safety and environment, and bilateral cooperation with Canada, Russia, Japan, and the EC. The IEA agreement has 7 specific tasks, 3 of which are coordinated by FSP personnel. FSP-generated fusion safety analysis computer programs are in use in several countries.

5. FACILITIES

5.1. INTRODUCTION

Fission reactors provide a valuable means of simulating the fusion radiation environment. The neutron energy spectrum lacks a 14-MeV component, and the ratio of gamma rays to neutrons is too high, but with care in interpretation of results, the simulations are generally useful. Of more and more concern is the shrinking number of fission reactors and associated capabilities for handling radioactive materials. For the time being it appears that fusion can continue to rely on other programs to carry the burden of operating the reactors, but the growing cost of operations in today's regulatory climate may soon affect the fusion program.

The TPX device will serve as an important test-bed for the introduction of subsystems made of low/reduced activation materials. ITER will complement it by functioning as a key element for testing materials and components in a neutron environment.

A 14-MeV neutron source that provides significantly more fluence per year than ITER and enough volume to test large numbers of small samples is required for developing any of the known candidate materials for roles in the high-flux region of a fusion system. Representing a necessary complement to ITER, the high-fluence 14-MeV source would allow important confirmation of present thinking derived from lower-energy fission irradiations. More important, it would enable an iterative campaign of fusion-relevant irradiations, thus allowing the first step towards qualifying improved materials for DEMO.

> *Finding:*
> *To have the option of using low/reduced activation materials in DEMO, the materials program needs (a) fission-reactor irradiation facilities; (b) testing of such materials in ITER and TPX, and (c) a high-fluence 14-MeV neutron source to complete development and develop engineering databases.*

Fundamental Reasons Why a Neutron Source is Needed. As noted in the Introduction, materials respond differently to the energetic neutron spectrum of fusion than to the softer spectrum of fission. Figure 5-1 shows the neutron spectra for the two types of sources, along with the most important cross sections for reactions that alter the properties of materials.

The fusion spectrum in the top curve, which depends in detail upon the materials used in the blanket and shield, was taken from the ANL Starfire reactor study. The delta function at 14.1 MeV corresponds to Starfire's plasma-generated, unscattered neutrons, which produced a wall loading of 3.6 MW/m^2. The first-wall environment also includes scattered neutrons, as shown in Figure 5-1, with a flux, integrated over energy, about 10 times as large as the primary 14.1-MeV flux. On the path from the first wall through the shielding to the superconducting magnets, this ratio of scattered to 14.1-MeV neutrons increases to about 1000.

The fission spectrum shown in Figure 5-1 is for 100-MW operation of HFIR, a reactor at ORNL, supported by DOE's Office of Basic Energy Sciences, that is currently being used for fusion materials studies.

The middle graph of Figure 5-1 gives the damage cross section in barns for four elements of interest. The displacements per atom (dpa) figure is equal to the integral of flux times the damage cross section. For comparison, the total scattering cross section for Fe at 14 MeV is 2.6 barns. The damage-to-scattering ratio of about 1000 represents the number of lattice displacements generated by recoil ions; the number depends on a model for ion-stopping.

The bottom graph of Figure 5-1 is the (n, alpha) or helium-production cross section. The atomic parts per million (appm) of He equals the integral of this cross section times flux times 10^6. Other transmutants such as H can be important, but He is often found to cause major damage because it does not readily combine chemically. Typically, He bubbles accumulate and cause swelling.

As explained in the Introduction, there is a cross section threshold for He production at about 4 MeV, meaning that, for a given number of displacements, a fission spectrum produces far fewer He transmutations than a fusion spectrum. This difference, in light of the established importance of He, is the major reason why an intense 14-MeV source is needed for fusion-materials studies. Also, the distribution in energy of recoil ions is generally different for fusion, causing concern about the interpretation for fusion of damage studies done with fission. An intense 14-MeV source, although not a perfect simulation, will allow critical comparisons between fission and fusion-like damage; these comparisons are essential for validating the existing data base.

Thus a source of 14-MeV neutrons dedicated to materials development is considered an essential step toward DEMO and should be constructed in parallel with ITER. Two concepts have been proposed. In one, a 35-MeV deuteron beam impinges on a liquid lithium target. In the other, a neutral deuterium beam is injected into a low-Q, mirror-confined plasma target. An accelerator based system (35-MeV deuteron beam on liquid lithium) appears to require the smallest extrapolation and therefore the least technical risk. A neutral-beam-injected low-Q mirror-confined plasma target offers the advantage that the spectrum would perhaps be more fusion-like. (The neutron spectrum would not be exactly that found at a fusion system's first wall, but it would not include the high-energy (>14 MeV) neutrons of a D-Li source.)

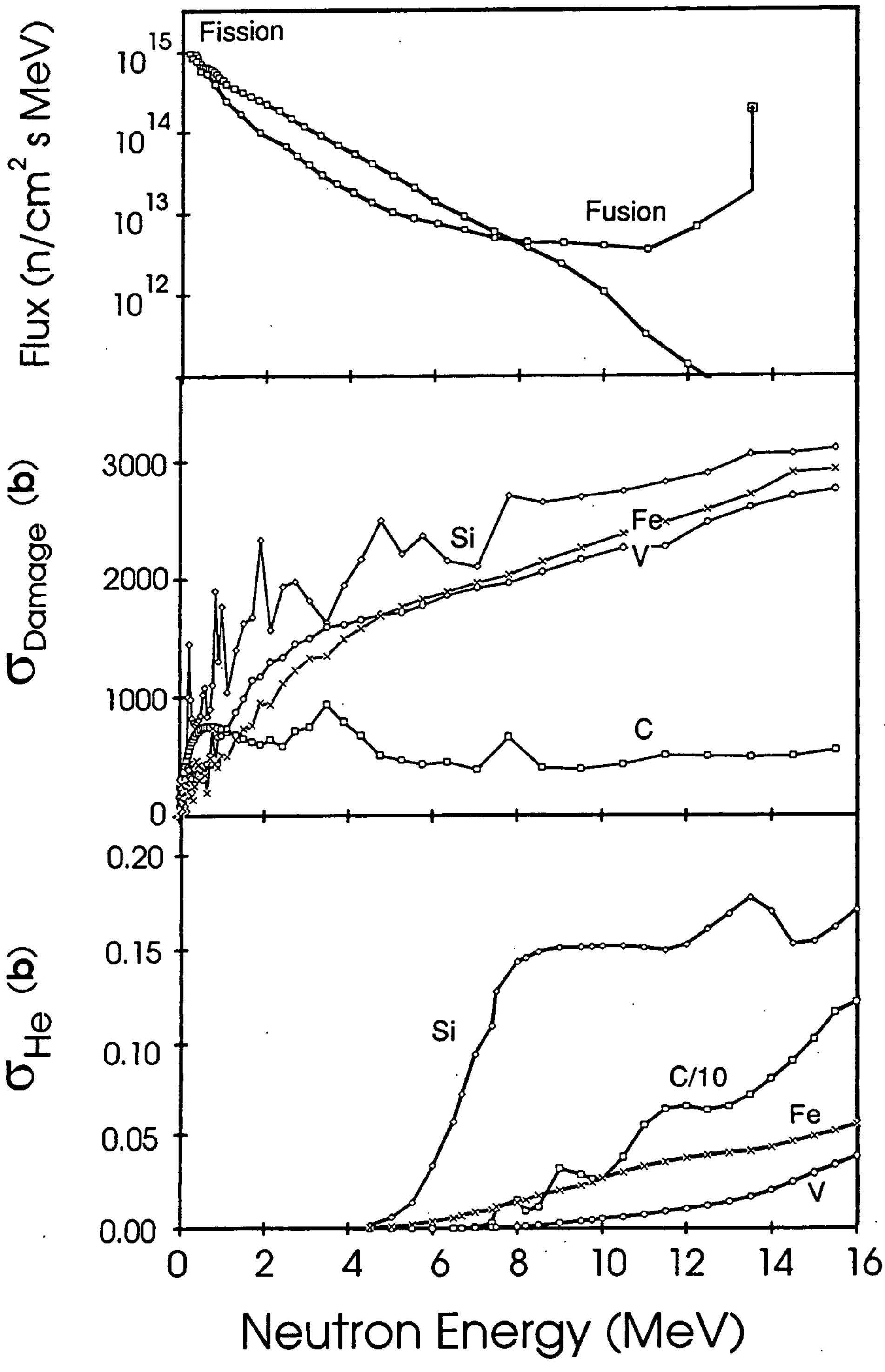


Figure 5-1. Neutron Damage and Helium Production Cross Sections. *Cross sections (barns) for neutron damage and for helium production as a function of neutron energy for materials of interest to fusion. Damage cross sections are large compared to scattering cross sections (typically a few barns) because many displacements result from each neutron scattering event. Also shown are the neutron energy spectra for a fission reactor and the first wall environment of a fusion reactor. The data were provided by L. Greenwood (PNL); the issues were explained to the panel by D. Doran and other speakers.*

The magnetic mirror system might also provide a larger test volume (issue of cost vs. size not resolved), but the technical risk appears to be larger with the magnetic mirror because the plasma confinement system must survive its own flux. Costs for either system are not well established, but would probably be of the order of $500M depending on specifications for flux and volume. For the D-Li approach, the accelerator component can be estimated reasonably well because the design resembles other well-studied systems. However the target design and tradeoffs in terms of achievable flux and test volume are still evolving.

> *Finding:*
> *Large-volume, lower-fluence neutron sources (tokamaks and tandem mirrors) have been proposed to augment the nuclear test program (primarily component testing) planned for ITER. The Panel did not hear presentations on these proposals.*

5.2. FISSION REACTORS

The FFTF materials open test assembly (MOTA) and the High Flux Irradiation Facility (HFIR) have been the primary irradiation facilities used by the fusion program for a number of years. With its 5 l of sample volume and ± 5° C of temperature control, FFTF/MOTA has been a high-quality irradiation facility. However, the FFTF was placed on hot standby in March 1992 and is currently unavailable to the fusion program. Transfer of the temperature-control capability to the EBR-II in Idaho was promised by the Nuclear Engineering division of DOE. After this change, EBR-II will be able to provide about 1/10 the sample volume of MOTA, but with similar temperature control. Uninstrumented irradiation vehicles are also being used in EBR-II by the fusion program.

The HFIR is a reactor that provides a mixed thermal and fast neutron spectrum. The thermal spectrum can be used to advantage when studying He effects in ferritic steels, but generally this portion of the spectrum is not advantageous. This reactor was shut down for several years to assess the state of the pressure vessel, but has been running for the last two years.

The operating costs of these reactors (many tens of millions of dollars per year) have been borne by other programs. It is not assured that the fusion program will continue receiving free reactor time.

The future of the HFIR, operated by the DOE Office of Basic Energy Sciences, is dependent primarily upon the remaining life of the pressure vessel, whereas the future of EBR-II depends on funding from the primary user, the Integral Fuel Reactor program. The uncertain availability of fission reactors for irradiation studies of fusion materials places the US fusion materials program, and perhaps the fusion program as a whole, in jeopardy. Without reactor space to provide the irradiation data needed for developing and qualifying materials, the fusion program could be left without an adequate materials database for materials selection and reactor design. This situation could lead the US to rely heavily on reactors in other countries and hence to become a secondary contributor in materials development and qualification for fusion. (Note that the availability of fission reactors in Europe for doing materials studies is also in question.)

Development of such a source could place fusion in control of its own destiny independent of fission-reactor availability, and would allow the US to stand as an equal partner in the materials development and qualification process.

Hot cells are available for materials testing at ANL, ORNL, PNL, and LANL. These facilities are coming under increasing scrutiny, such as the recent tests for radiation streaming; however, there does not appear to be a serious threat to their availability. For instance, at PNL there are six hot cells under the control of the fusion materials program; they will remain viable as long as the PNL fusion program exists. The central hot cells are under the control of another organization within PNL, and their viability is moderately stable at this time because of Hanford Works waste processing and other programs.

Finding:
Testing in fission reactors is a vital component of fusion materials development. The fusion materials development strategy relies on both mixed- and fast-neutron-spectrum fission reactors. The HFIR at Oak Ridge provides a mixed thermal and fast neutron spectrum; its future is dependent on the remaining life of the pressure vessel. One fast reactor, FFTF, is gone, and availability of the one remaining facility, EBR-II, is not assured.

5.3. THE ROLES OF ITER AND TPX IN MATERIALS TESTING

The ITER Council has adopted a set of Technical Objectives for the ITER EDA. These include "a few thousand hours of integral burn time, in parallel with the physics program, including test campaigns of 3-6 days at a neutron wall loading of about 1 MW/m^2" during the first decade of operation (~2007–2017). This corresponds to a fluence of ~0.4 MWa/m^2. At the same time "the design of the permanent components of the machine should not preclude achieving fluence levels of up to 3 MWa/m^2."

While ITER will not be able to achieve fluences corresponding to those required in DEMO, key testing of neutron-interactive materials will nevertheless be possible. A central lesson from other materials development programs has been that materials must be tested in successive generations of devices to be fully qualified for service. Thus, both the test modules and the major components of ITER will provide opportunities for materials testing. The use of low/reduced activation materials, such as ferritic steel or titanium, in major tokamak experiments would provide an important base of fusion experience for DEMO.

The panel considered the relative timing of the 14-MeV neutron source and the first phase of ITER. It was the consensus of the committee that it would be optimum for neutron materials-lifetime testing in the 14-MeV source and blanket-functionality testing in ITER to proceed in parallel. This would permit optimal choices for materials and blanket concepts to be tested in ITER's higher-fluence second phase. The neutron testing requirements of ITER—beyond a simple specification of MWa/m^2—ought to be established early in the EDA. In particular the size and configuration of testing ports need to be established, including issues of access and services such as electricity and coolants, including liquid metals. A crucial issue that requires attention is the degree to which blanket modules constructed with ferromagnetic materials, such as reduced-activation ferritic steels, can be tested in ITER. If they cannot be tested in ITER, they would seem to be precluded from use in a subsequent DEMO.

Finding:

- *ITER is an important element in the U.S. neutron-interactive-materials and component development program. Together with a high-flux 14 MeV neutron source, ITER, as conceived with two phases achieving a total fluence of 1-3 MW-year/m^2 on large material and blanket test modules, should provide the necessary testing and component development information for DEMO. It must be recognized, however, that fusion materials development will continue in DEMO and beyond.*
- *It is important that the ITER Project address the scope of ITER's module-testing capability, taking into account such issues as ferromagnetic effects and compatibility of coolants.*

The TPX device has as one of its draft supporting objectives "to gain technical experience with remote-maintenance techniques and reduced-activation materials in the interior of a tokamak vacuum vessel." TPX is designed to take advantage of reduced-activation materials and shielding to permit hands-on access to the interior of the vacuum vessel during its early phases of operation, and to all areas exterior to the vessel during the full lifetime of the machine. The use of a titanium vacuum vessel also means that if high-activation internal components are removed by remote-handling techniques, within one year the full machine becomes accessible for hands-on maintenance and reconfiguration. Practical experience with this vacuum vessel will provide valuable information for fusion-system use of titanium. Aspects of this experience associated with the use of barriers to prevent hydrogen permeation may be transferable to vanadium as well.

TPX, with its steady-state mission and relatively high duty factor, is an important testbed for the plasma-interactive characteristics of other reduced-activation materials as well. For example, if gas-target divertor operation is successful in reducing the peak divertor heat loads in TPX such that low or reduced activation materials can be used, then the divertor will be replaced with a more attractive reduced-activation design. This would not only permit tests of reduced-activation plasma-facing materials in a realistic plasma environment, but also reduce the interior radiation environment of TPX, which is favorable for the flexibility required for other aspects of the TPX mission.

Finding:
TPX will provide an important high-duty-factor, high-heat-flux tokamak plasma environment for testing the plasma-interactive properties of advanced materials. The approach of testing new materials in non-critical applications in one generation of device for application in later generations is a necessary element of the fusion materials development strategy.

In general, the panel found that the strategy of introducing reduced-activation and low-activation materials for plasma and/or neutron testing in one generation of devices, for subsequent use in the next generation, is probably the wisest approach for moving fusion towards the use of optimal materials. ITER and TPX both represent good implementations of this strategy.

5.4. D-Li SOURCE OF 14-MEV NEUTRONS

5.4.1. Introduction

Workshops and working groups under the aegis of the International Energy Agency (IEA) have been exploring options for an International Fusion Materials Irradiation Facility (IFMIF). An accelerator-based D-Li source has come to be the focus of this effort.

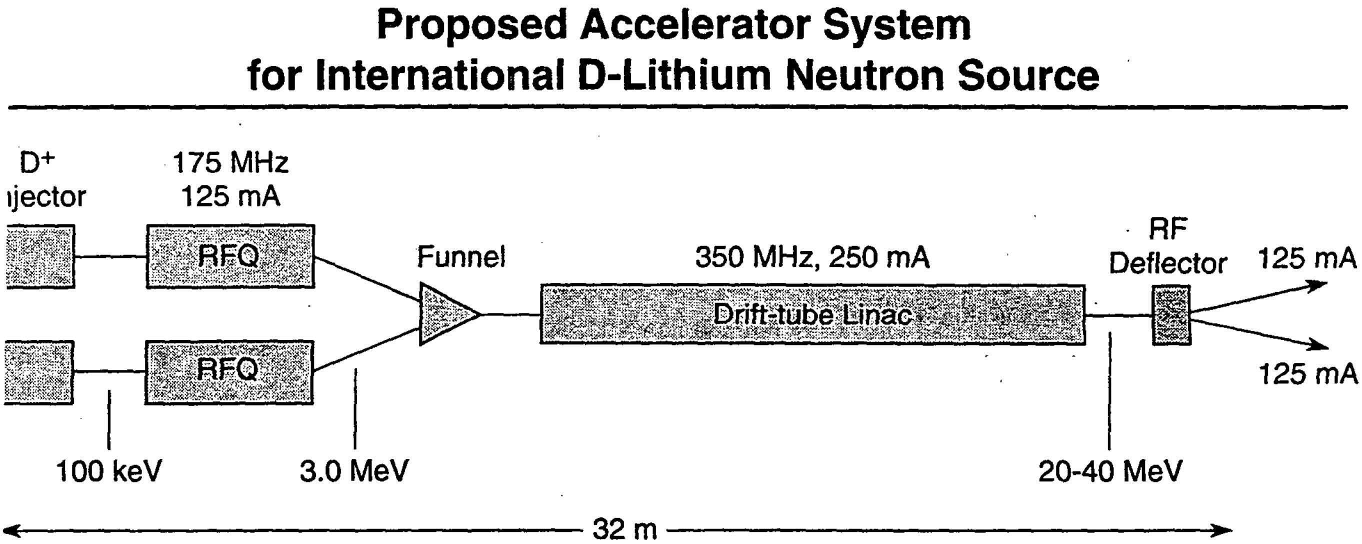
The DOE NIM Program is supporting, at the level of $700k in FY 1993, a design activity that builds on the D-Li Fusion Materials Irradiation Test (FMIT) facility program, which started in 1976 and was terminated in 1985. This design activity has contributors from LANL, ANL, and ORNL. Because of interest and support from other programs, considerable technical progress has been made on high-current accelerators since the FMIT program.

Although the neutron spectrum from a D-Li source does not exactly match that of a D-T fusion system, the high-energy component adequately simulates the displacement damage and helium transmutations to provide an effective fusion-materials test facility. It is clear that many of the material problems are not in the blanket or first wall region and do not see the same 14-MeV neutron spectrum. Thus, with proper placement of material in the D-Li source target region, the neutron source parameters may reasonably match the operating situation. It will be necessary to do detailed neutronics calculations around both the fusion energy source and the lithium target region to determine the best location for particular target material tests. This work will also need to involve accelerator physics experts in order to define the available deuteron source parameters.

Finding:
While the proposed accelerator technology for a D-Li neutron source is challenging (especially if superconducting rf cavities are chosen for the design), the beam current exceeds existing room-temperature cw systems by only a factor of two, and appears feasible. The design of the lithium target system will be difficult.

5.4.2. Accelerator Design Issues

Linear Accelerator Parameters. The concept and parameters of the proposed system are given in Figure 5-2. The accelerator could produce a 35-MeV deuteron beam with a total current of 500 mA. To achieve this current, two parallel accelerator modules each use two 125 mA ion sources and RFQ's followed by a funnel. The final beam on target would thus come from 2 separate beam lines. This concept allows for a phased approach: starting with a single ion source, RFQ, drift tube linac and beam transport line, and then adding a second ion source, RFQ and funnel to double the available current from, say, 125 mA to 250 mA. Finally, the whole system could be duplicated to give a 500-mA deuteron current capability. There is a high probability that these parameters are achievable with the proposed design frequencies and accelerating gradient, though it does represent a factor-of-two increase in current over existing cw engineered and operating systems.



Parameter	RFQ	DTL
Length (m)	5.4	16.3
Accelerating field, EoT (MV/m)		2.0 to 2.45
Aperture radius (mm)	6.0	9.0
Structure power (MW)	0.3 × 2	3.0
Beam power (MW)	0.4 × 2	8.0
Total rf efficiency	1.4	11.0
RF efficiency	0.57	0.73
Output emittance (norm., rms)		
Transverse (π mm-mrad)	0.27	0.34
Longitudinal (π mm-mrad)	0.46	0.52
RMS beam size (mm)	1.5	1.4

Figure 5-2. *Concept and parameters of the accelerator system for the proposed D-Li source of fusion-like neutrons.*

General Comments on the Proposed Design. Overall, the accelerator problems involve engineering or cost factors rather than fundamental physics problems and are, in principle, subject to solution. The physics of each of the structures (radio-frequency quadrupole or RFQ and drift-tube linac or DTL) is by this time well understood. An ECH driven cusp field or rf driven ion source satisfy requirements and are also reasonably well developed. Funneling of beams with an rf deflector has been demonstrated. The fact remains, however, that this accelerator is an extrapolation from existing machines, and will require some extension of existing technology in its development. While the design of a 20- to 40-MeV linac is fairly straightforward, accelerating 250 mA is difficult even for a pulsed machine. Adding cw operation makes this a challenging project.

Issues of damage or activation of components by the beam must be carefully addressed. The elimination of beam loss at frequency transition points is particularly difficult. Thus it is desirable that the design have only one frequency jump. At a low energy (8 MeV), another concern could be the possibility of longitudinal emittance growth caused by the rf-driven beam funnel.

One must also look at losses in the accelerator or transport line during turn-on or fast turn-off of the beam. A sudden partial power outage could cause sufficient low-energy (<40 MeV) beam loss to melt beampipes. There are also problems at the DTL klystrons when the beam suddenly disappears, since 75% of the rf power goes into beam loading. Accordingly, computations of the transport of a low-energy beam through the rest of the accelerator would have to be made. Detecting and controlling beam halo is also a very difficult problem; while the designers are aware of this, one cannot model the losses on the computer with the required accuracy of a few parts in 10^8 per meter.

The proponents of the D-Li approach have made estimates of beam loss that are acceptable for cw operation, based on Los Alamos Meson Physics Facility (LAMPF) experience. However, these estimates are not fully convincing due to the large extrapolation from LAMPF (800 MeV protons, 15 mA peak current, 1 mA average current) to this design. The beam-loss problem is compounded if a cryogenic DTL structure is used. New types of non-intercepting beam diagnostic equipment will be required for beam monitoring and control. Control systems will require very fast responses and tight tolerances.

Achieving and maintaining a uniform current density on the target is also important. There may be target-distortion problems, local increase in gas generation, or melting if the beam becomes focused or stationary due to loss of control by beam-shaping elements upstream of the target. One must do a careful investigation of single-component failures in the linac and transport line to eliminate failure mechanisms that could damage the target. The minimum time required to shut off the beam during a fault condition must be less than a few microseconds.

The proposal calls for a 70% plant availability. It is difficult to estimate the reliability that can be expected from the accelerator since it is a significant extrapolation from existing machines, but this is a key issue. Activation of components could in some cases require a remote handling capability, which increases costs and slows down maintenance, or require a cooldown time, which would also seriously compromise beam availability.

Demonstrated Accelerator Capabilities. A cw ion source developed and tested at Chalk River Laboratories has operated at 100 mA proton and 50-mA deuteron-beam currents and with an acceptable emittance at 60 keV output energy. The system has not been run for long enough to give good lifetime information, but the ECR source is believe to have long life potential.

The above source for protons has been used to inject into a CW RFQ operating at a frequency of 267 MHz and giving an output energy of 1.25 MeV. A maximum output proton current of 55 mA was achieved with a maximum transmission of 70% through the RFQ. This may be due to less-than-ideal matching between the source and the RFQ. The GTA at Los Alamos, which is a pulsed machine, achieved similar transmission percentages at somewhat lower H^- beam currents.

Funneling has been proposed as a method of using two injectors with a single drift-tube accelerator, mainly to allow for higher beam current capability without stretching the ion source and RFQ to their design limits. It also allows more-efficient filling of the higher frequency drift tube linear accelerator radio-frequency "buckets." A single beam funnel experiment has been carried out at Los Alamos using their Accelerator Test Stand at proton beam currents of up to 40 mA. Essentially 100% beam transmission with minimal longitudinal and transverse emittance growth was achieved. The only remaining question is that of beam interaction if a two-beam funnel is used.

There is relatively little experience with drift-tube linear accelerator sections operating in a cw mode. However, multi-drift-tube rf cavities operating in a cw mode are common in storage rings and have shown good reliability under heavy beam loading conditions. In general, these cavities can be protected against beam losses or synchrotron radiation—phenomena that could affect their performance. An rf trip tends to cause beam loss in other parts of the storage ring. This is not necessarily the case for a linear accelerator, where transient conditions can give rise to unexpected beam losses in the cavities themselves. This could be particularly bothersome in the case of a cryogenic accelerating structure, where beam heating could cause part of the superconducting structure to go "normal-conducting." The transition to normal conductance would give rise to a large mismatch in the feedline and could result in damage to the vacuum window. There could also be heating of, and possibly damage to, the accelerator structure due to increased power deposition there.

Beam Transport to Target. The beam transport system employs standard beam transport elements that have been well tested in existing accelerator facilities. The accelerator codes are well tested and have been verified against experiment. Practical problems, such as guarding against beam striking unprotected surfaces if a machine trip occurs, are the major concerns to be addressed.

5.4.3. Lithium Target and Test Assembly

Requirements. The key features of the lithium target and test assembly were defined in the context of original Fusion Materials Irradiation Test (FMIT) facility. The lithium target must satisfy two basic functions: providing the lithium nuclei to serve as the target for the deuteron beam and removing the energy deposited by the beam. It must also be capable of operating in the accelerator vacuum environment. The approach used to satisfy these functions is a relatively simple flowing jet of liquid lithium that moves rapidly through the beam, intercepting the beam and convectively removing the beam energy. A combination of high-velocity flow and geometry keeps the liquid lithium from boiling, even in the vacuum conditions of the beam. The associated lithium loop facility provides for adequate flow in the jet, lithium purification, and sufficient heat removal.

The test assembly must effectively use the neutron flux generated by the D-Li reaction. The neutron flux, spectrum, and flux gradient are fundamental parameters that must meet the materials test requirements. A high flux (equivalent to ~20 dpa/year) volume of about 1 liter has been specified by the materials community. In addition, a flux gradient of <10% per cm is desired. Temperature control of better than ±15° C with test temperatures from about room temperature to >800° C is required. The test assembly must be readily replaceable to provide high machine efficiency. The associated coolant loop system must provide for adequate heat removal and system compatibility.

Target/Test Assembly Design. The proposed target design is similar to that of the original FMIT. Recent design efforts have resulted in a proposed expanded beam approach with a higher beam current to provide increased test volume. A beam size of 50 to 100 cm^2 (7 × 7 or 10 × 10 cm) is proposed, as compared to the 3 cm^2 (1 × 3 cm) beam size of the original FMIT. This concept provides more-uniform flux profiles, optional test volume, and simpler beam and target systems. For designs with a specially curved back plate to assure jet stability, the lifetime of the back plate is substantially increased with the larger target area. An alternate concept with a free jet and no back plate has also been considered.

> *Finding:*
> *The volume of high neutron fluence for a D-Li source is small but appears sufficient to support materials development when used in conjunction with fission reactors. This approach appears to be the most direct route to attaining the needed materials testing capability. Additional plasma physics and significant fusion technology development would be required to implement a 14-MeV neutron source based on a mirror plasma target. This source could provide a larger volume of high neutron flux in a single facility than would a 250-mA D-Li source. The neutron spectrum would not be exactly that found at a fusion system's first wall, but it would not include the high-energy (>14 MeV) neutrons of a D-Li source.*

Key Issues. Most aspects of the lithium target and test assembly design have been demonstrated or analyzed in detail. There do not appear to be any feasibility issues associated with this concept; however, areas in which further analysis or demonstration is required include:

- Demonstrating the stability of the larger lithium targets;
- Defining the lifetime and performance limits of the target system, including the back plate;
- Demonstrating acceptable purity control of the lithium system; and
- Demonstrating satisfactory beam-on-target performance.

The first three issues can be resolved relatively easily. The requirement for a beam-on-target demonstration would require a much larger effort. This test was not conducted for the original FMIT. The possibility of combining a beam-on-target test jointly with the accelerator performance test may provide an economically effective development approach.

5.5. BEAM-PLASMA NEUTRON SOURCE

5.5.1. Introduction

Compared to the D-Li source, there has been relatively little effort directed towards beam-plasma sources. The Panel heard presentations on several mirror-based plasma target sources. Among these were the Beam-Plasma Neutron Source (BPNS), based on an extrapolation of the 2XIIB experiment; a gas dynamic trap being studied in Russia; and a concept for toroidally linked mirrors. As the BPNS has had the most significant concept study or development of these three items, we limit our remarks to it.

The principal advantages of a mirror-based neutron source are a 14-MeV primary spectrum similar to that of real fusion devices, along with the prospect of an irradiation volume 3× that of an accelerator-based system at high fluxes (up to 7× at lower fluxes); see Figure 5-3. Subsidiary advantages are that construction of the BPNS produces an investment in the development and demonstration of technologies essential to fusion itself, such as production of dc neutral beams; large-throughput pumping and tritium handling; and dealing with activation, contamination, and maintenance issues of fusion components and systems. These advantages compared to the accelerator-based D-Li system are, however, offset by a limited database on the physics and technology.

5.5.2. BPNS Design Issues

The basic BPNS system is shown in Figure 5-4. Neutrons are generated in a two-component plasma generated when intense neutral deuterium beams are injected into a dense tritium plasma column. The energy confinement of the deuterons is determined by drag losses on the plasma electrons; the resulting heating maintains the column. Energy loss along the magnetic field is limited by the thermal resistivity of the column; the energy is spread over a large area at the ends of the column by spreading the magnetic flux tube and the cooling of the plasma in the gas in the end regions.

The initial design study was based on the trapping of 60 MW of deuterons (150 keV, 400 A); later, unpublished studies have indicated that a system based on neutral beams generated from positive ions achieves maximum efficiency at 120 keV, the energy used in the beams on TFTR. In BPNS, this injection is predicted to result in 1 MW of neutrons at 14 MeV, corresponding to 5 W/m^2 in a volume of 1 liter. The source could be operated at reduced power at the cost of lower efficiency; e.g., operation at 1/4 power would generate a flux of about 1/6 the above due to a lower electron temperature in the plasma column.

5.5.3. BPNS Physics Status

The physics of the BPNS is extrapolated from 2XIIB. There are, however, significant differences between the 2XIIB plasma and the plasma for the BPNS. The line density, n•l, of the proposed plasma is an order of magnitude or so higher than in 2XIIB, and the neutral beams are more energetic (120 vs. 20 keV). The result is that shine-through and charge-exchange losses are estimated to be reduced dramatically. The background stream plasma is planned to provide >3/4 of the plasma density; 2XIIB was operated with the stream plasma density as high as the hot ion density, although typical operation at high electron temperatures involved stream plasma densities in the few-percent range.

Radial and volume energy loss fractions in BPNS must be much lower than 2XIIB for this concept to succeed. In 2XIIB, there was significant power in line radiation from oxygen impurities (up to 10 W/cm^3). Extrapolation to BPNS, assuming that the beams are the dominant impurity sources, indicates radiation of 15 W/cm^3, small enough not to be a problem in power balance or wall heating. Similarly, estimates of heating from charge exchange on beam neutrals do not indicate a problem. However, a key question is the ability to screen the plasma from neutrals and impurities generated in the end regions, both of which cause volume power losses from the core plasma. Since Q ~ 2% in BPNS, even a 2% ratio of the core-volume rates to the end-loss rates would make the heat flux on the samples being tested equal to the neutron power flux. This effective doubling of the power being deposited on the samples would require aggressive active cooling, which might itself significantly attenuate the neutron flux to the material samples.

The plasma outside the central mirror is very much different in BPNS than in 2XIIB, and the electron energy balance is correspondingly very different. The plan is to transport the plasma along the magnetic field lines outside the mirror plasma in a long, narrow column, and then spread them dramatically and dump the loss energy into a gas target with pressure ~ 1 atmosphere. Spitzer thermal resistivity along the field lines should support the relatively high T_e in the core plasma, despite the higher streaming plasma density/beam ion density ratio in BPNS compared to 2XIIB. Note also that the scenario is rather similar to the gas-target divertor concept being developed for tokamaks. Unfortunately, the physics of such a gas target is not thoroughly understood.

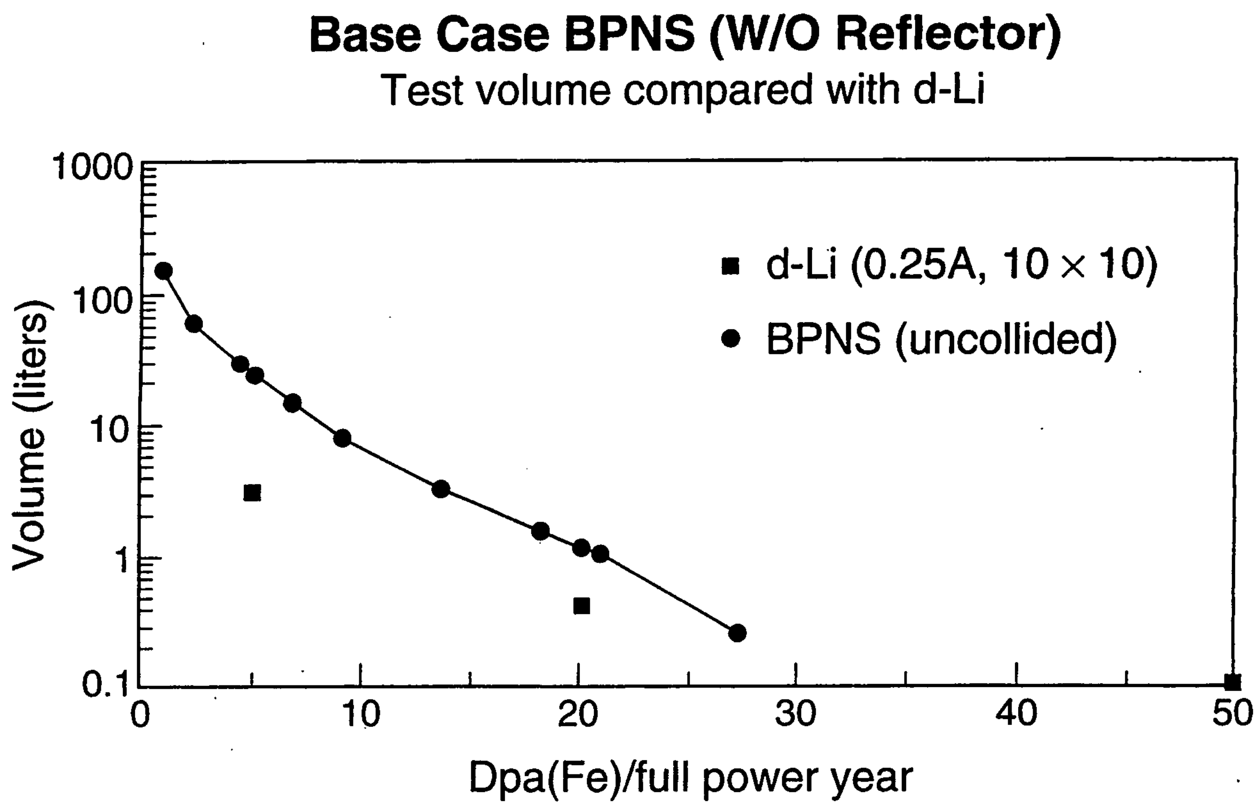


Figure 5-3. Performance comparison of the D-Li and BPNS systems.

Materials testing neutron source; LLNL design utilizes a linear, two component plasma

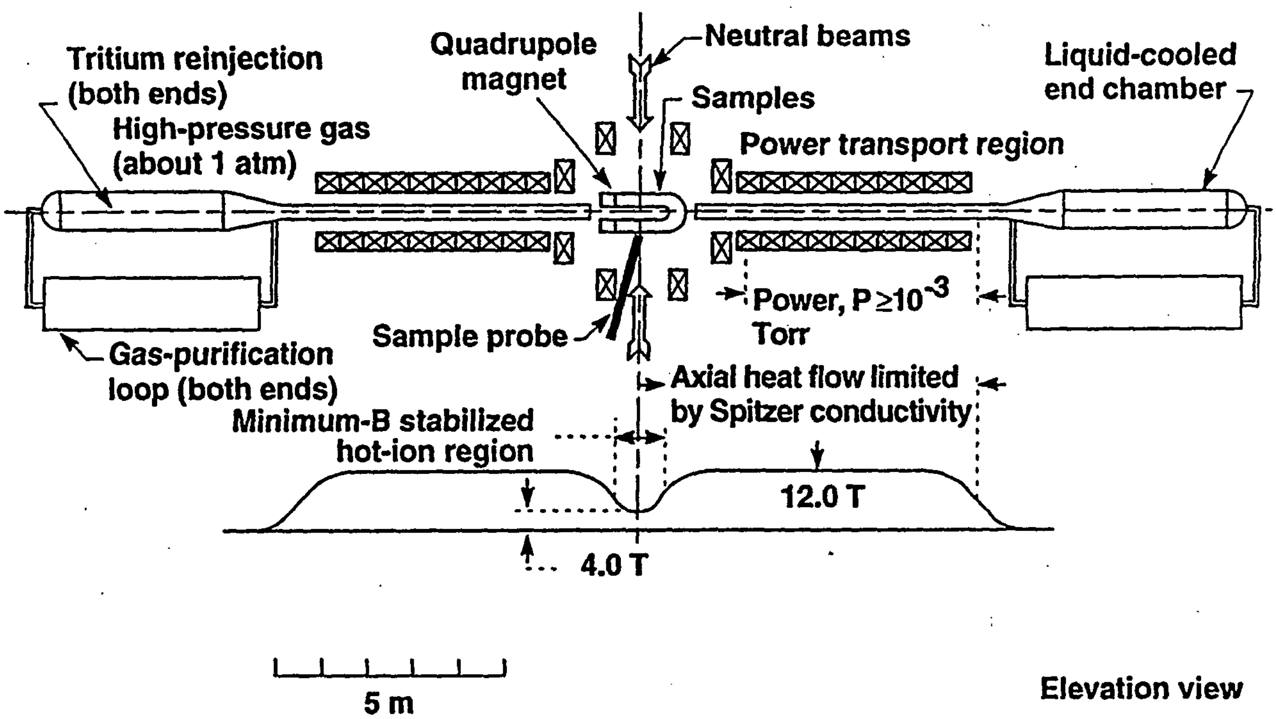


Figure 5-4. The concept of the BPNS.

5.5.4. BPNS Demonstrated Capabilities and Technology Growth

Neutral beams. The neutral beams are based on the 5-s, 120-keV beams used on TFTR, for which long-pulse operation is being developed for TPX. However, the BPNS depends upon truly DC 120 keV neutral beams. The beams planned for TPX will run at duty cycles of only a few percent and thus do not represent the full issues of steady-state cryopumping and gas recycling, electrode erosion, availability, and maintenance that must be faced by the BPNS system. The power requirements for the neutral beams in a BPNS are quite high; this may affect the operating cost.

Tritium. The proposed system for handling and recycling the tritium is based on the TSTA at LANL, which has reliably processed 1000 G of tritium per day (with a 120-G inventory). However, the issues of tritium inventory management, recycling, and separation are formidable. The deuterium neutral beams will inject about 1 kg of deuterium into the core plasma per day. If the stream-gas fueling of the (positively biased) core plasma is much less efficient than the beam fueling, as seems reasonable, and the T target density is to be 3–5× the D-beam ion density, it seems that a very large T throughput will be required. A large surface area will be available to absorb tritium, possibly resulting in a significant tritium inventory issue. It is possible that an operating BPNS will require management of, and recovery of tritium from several separate hydrogen streams.

Quadrupole magnet. The present design of BPNS uses a quadrupole magnet constructed of copper. An issue concerns neutron irradiation of this magnet. Although the present design was used to estimate a lifetime > 5 years due to increased copper resistivity and insulator damage from irradiation, the problem may be more severe than previously thought. In that case, the present design concept would have to be modified to remove the magnets from the high neutron flux zone to allow shielding adequate to assure a 5–10 year magnet lifetime. In general, the panel was concerned that the BPNS itself would be as much the subject of neutron irradiation tests as the material samples.

Technology extrapolations. The technology extrapolations assumed (or developments required) are large for this concept. Parallel technology development programs may be necessary and may be a prior condition for assurance of success.

Maintenance and activation. The supporting facilities required to maintain the BPNS and the activation and/or contamination issues that impede maintenance and affect cost, availability, and reliability have not been detailed. No subsystem lifetimes or life cycles were presented to the panel, nor were operational cycles for the overall device postulated.

Findings:

- *Additional plasma physics and significant fusion technology development would be required to implement a 14-MeV neutron source based on a mirror plasma target. This source could provide both a larger volume of high neutron flux in a single facility than would a 250-mA D-Li source. The neutron spectrum would not be exactly that found at a fusion system's first wall, but it would not include the high-energy (>14 MeV) neutrons of a D-Li source.*

- *The trade-off of cost vs. testing volume for either a D-plasma or a D-Li source has not been made.*

6. INERTIAL FUSION ENERGY ISSUES

6.1. INTRODUCTION

The neutron and charged-particle environment of IFE materials can be quite different from that of MFE materials. A major difference is that IFE fusion-system cavities may have enough low-density gas (≤ 1 torr) to absorb the charged particles' energy and a substantial fraction of the soft x-rays. Second, many IFE cavities are designed to operate with either thin coatings of liquid metals on the first-wall surfaces or thick (~0.1–1 meter) regions of flowing liquid metal or solid granules between the target and the first wall. In either of these cases, any charged particles or photons that make it across the cavity will be absorbed in the liquid metal. Some of it then evaporates while the remaining liquid conducts the heat to the first wall over a time scale longer than the deposition time (10 ns to 1 μs) of the incident radiation.

If the layer of liquid or flowing solid particles between the target and the first wall is thicker than a neutron mean free path (5–10 cm), the neutron spectrum will be considerably softened. A thick layer of material could also absorb neutrons, further reducing the damage rate in the solid structural material. The end result of softening the neutron spectrum and/or absorbing neutrons will be to reduce both the transmutation and displacement rate by comparison to an MFE system with the same power output.

One area that will also be different in IFE systems is the rate at which the neutrons damage the first solid structural members. In a MFE steel first wall, a 1 MW/m^2 neutron wall loading induces damage at the rate of ~3 x 10^{-7} dpa/s and produces an appm He/dpa ratio of ~20. (See the figures in Section 1.) In an IFE system, the same average neutron wall loading will result in instantaneous dpa rates of ~10 dpa/s (not corrected for pulse effects) and time-averaged values of ~3 × 10^{-7} dpa/s. If the same neutron wall loading was incident on a 50 cm thick flowing liquid "wall," the time-averaged damage in the steel behind the wall would be reduced to 10^{-8} dpa/s and the He/dpa ratio would be reduced to 2. The instantaneous damage rate would be reduced to ~1 dpa/s.

However, IFE also presents unique materials problems not found in MFE—in the final focusing elements and final optics, for example. For short-wavelength laser IFE systems, the final focusing mirrors will have to have dielectric coatings, which are quite sensitive to degradation by neutrons. Such final-focusing elements may have to be placed as far back as 40 meters or more from the target, the distance being entirely determined by the neutron damage to the special coating. In heavy-ion IFE systems, the superconducting final magnets will have to be protected. In light-ion IFE systems, the diode accelerators—especially the electrical insulators—will have to be protected from neutrons.

6.2. EXTENT OF THE DOE PROGRAM IN IFE MATERIALS

At present there is no visible IFE materials program. Some activities in tritium breeding materials (i.e., Li_2O) would be applicable, as well as what little effort there is on superconducting magnet materials. However, the study of radiation effects on structural materials is being conducted with a fission-spectrum, steady-state neutron source at either an instantaneous rate too low by a factor of 10^7 or at a time-averaged rate a factor of 10 to 100 too high; in either case, the He/dpa ratio is not correct. (These comments hold true for the MFE materials program as well.) There appears to be no program to test the coatings for optics, nor does there seem to be any program to measure the effect of extremely high damage rates (~0.1 to 1 dpa/s) on a 1–10 Hz rep rate basis.

> *Finding:*
> *Materials research within OFE is completely dominated by the needs of the magnetic fusion program. Little if any thought and no funding have been given to unique materials needs for inertial fusion.*

6.3. LEVEL OF ADDITIONAL EFFORT NEEDED

A program to study radiation effects upon final optics should begin. This is a critical problem for both near- and long-term IFE systems because it determines final optic lifetime and/or the size of the building needed to hold all the final mirrors. The initial program can be conducted in a fission reactor. Eventually, a 14 MeV (and degraded spectrum) source will be needed. This could be the same as the one used for the MFE work, but some auxiliary experiments may have to be conducted with a pulsed source to understand the rate effects.

Additional work on insulators for light-ion IFE and superconducting magnets for heavy-ion IFE is also required. Again, early use would be made of fission reactors, but final confirmation would have to be made with the "correct" 14-MeV spectrum and time structure.

The choice of IFE structural materials will probably be the same as for MFE, with perhaps more emphasis on woven C-C or SiC-SiC composites to contain the liquid metals in the target chamber. Here the research should concentrate on the time structure of damage, both experimentally and theoretically.

> *Finding:*
> *IFE benefits from some of the MFE materials work. However IFE also has some unique requirements, e.g., pulsed neutron effects on the final focusing element or the ion-beam delivery systems, and pulsed neutron effects in general.*

7. EVALUATION CRITERIA FOR LOW/REDUCED ACTIVATION MATERIALS

The definition and criteria for low/reduced activation materials require updating; the near-surface burial criterion no longer appears either necessarily required or sufficient.

The 1982 DOE Panel on Low Activation Materials for Fusion Applications (the "Conn Panel") provided the valuable benefit of focusing effort on low/reduced activation materials. However, their report has resulted in overemphasis on waste disposal issues, especially on meeting U.S. criteria for near-surface burial, as adapted from 10 CFR 61. It is increasingly recognized that this sole criterion is not adequate to define low/reduced activation materials for four reasons.

1. 10 CFR 61 is not based on fusion waste forms and isotopes and is thus not adequate for fusion. (Fetter et al. have adapted 10 CFR 61 for fusion, but this has no regulatory force, and the issue of waste form—activation of solid components—remained unaddressed.)
2. Future near-surface burial may well involve criteria more stringent than 10 CFR 61 is today.
3. There are several other safety and environmental criteria requiring attention: short-term accident dose potential, decay heat, ability to recycle/re-use materials, and biological hazards of other waste forms. (Piet et al. have proposed a framework for integrating these various objectives.)
4. 10 CFR 61 is only a U.S. criterion. As fusion becomes more international, the objectives for materials development should become more international and less subject to (possibly changing) national regulatory criteria.

The U.S. program for low/reduced activation materials for fusion has been distorted by U.S.-specific regulatory policy that was set for fission power and radioactive medical waste. The radioactive waste associated with those activities is largely either very high level (such as spent fuel rods) or rather low level (such as contaminated clothing). Future decommissioning of fission power plants, and perhaps ITER, might lead to an intermediate waste category and associated disposal technology. This is, in fact, the international tendency. Much of this waste cannot be confidently disposed of near the surface, but does not require isolation for as long, or with as high a level of assurance, as spent fuel, which requires deep geological disposal.

Thus, one may anticipate moving the fusion goals from the narrow objective of near-surface burial to a broader agenda of principally avoiding high-level waste. The means to this end include recycling and re-use as practical, near-surface burial, and maybe intermediate level disposal. However, an intermediate level category will not be a panacea; long-lived isotopes are still likely to be restricted to very low concentrations.

> *Finding:*
> *The definition and criteria for low/reduced activation materials require updating. In addition to waste management, there are several other safety and environmental criteria requiring attention: short-term accident dose potential, decay heat, ability to recycle/re-use materials, and biological hazard of other waste forms.*

As the definition for low/reduced activation materials changes, the priorities and appropriate compositions for specific material classes may change. Some previously dropped candidates like titanium alloys may deserve another look.

A committee chaired by Professor William Stacey of the Georgia Institute of Technology has been chartered by OFE to develop evaluation criteria for low/reduced activation materials. This committee has not yet completed its work, hence this Panel was not able to review their recommendations.

> *Finding:*
> *The upcoming Stacey committee will re-integrate what is known about low/reduced activation criteria. As the definition for low/reduced activation materials changes, the priorities and appropriate compositions for specific material classes should change.*

APPENDIX A: THE FEAC CHARGE LETTER TO PANEL 6

Department of Energy
Washington, DC 20585

SEP 01 1992

Professor Robert W. Conn
University of California, Los Angeles
6291 Boelter Hall
405 Hilgard Avenue
Los Angeles, California 90024

Dear Bob,

I would like the Fusion Energy Advisory Committee (FEAC) to evaluate the Neutron Interactive Materials Program of the Office of Fusion Energy (OFE). Materials are required that will satisfy the service requirements of components in both inertial and magnetic fusion reactors -- including the performance, safety, economic, environmental, and recycle/waste management requirements. It is acknowledged that this will require a sustained effort over many years. Given budget constraints, is our program optimized to achieve these goals for DEMO, as well as to support the near-term ITER program?

The goal of the OFE fusion materials program is to develop the materials for all components of fusion reactors. Parallel activities focus on (a) meeting functional requirements, for the near-term applications in ITER, and (b) developing materials optimized for both functional requirements and environmentally attractive features needed for longer range applications. The FEAC evaluation should include the work on materials for structural components and on ceramics for insulators and other components in the high neutron flux reactor regions.

Your evaluation of the materials program should include consideration of balance. Is the balance appropriate between:

a. near-term (ITER) and longer range applications;
b. the several candidate materials for longer range structural applications;
c. structural materials and ceramic insulators; and
d. domestic and collaborative international programs?

The program relies heavily on the use of fission reactors for irradiation experiments that partially simulate the fusion environment. The need for a "fusion neutron source" is also widely recognized. Would you please comment on the following: adequacy of planning to maintain and use available facilities; development of new facilities (especially a fusion neutron source); and additional supporting facilities needed to conduct the complete program.

A major focus of the long-range materials program is the development of reduced activation materials (sometimes called low activation materials). Would you please review the evaluation criteria for materials activation used to direct this program. These criteria include considerations of environmental effects, safety, recycle potential, and waste management, in addition to performance requirements.

I would like to have the FEAC evaluation and recommendations on the Fusion Materials Program by February 1993. This will be important for decisions both on the inertial and magnetic fusion energy programs.

Sincerely,

William Happer

William Happer
Director
Office of Energy Research

APPENDIX B. FEAC PANEL 6 MEMBERS

Klaus Berkner (Chair)
Lawrence Berkeley Laboratory

Richard Siemon (Vice Chair)
Los Alamos National Lab.

Ken Batchelor
Brookhaven National Laboratory

Everett Bloom
Oak Ridge National Laboratory

Jay Davis
Lawrence Livermore National Laboratory

John Davis
McDonnell Douglas Aerospace

Steve Dean
Fusion Power Associates

John Garnier
Du Pont Lanxide Composite Inc.

Rob Goldston
Princeton University

Greg Haas
Department of Energy

Russ Jones
Battelle/Pacific Northwest Laboratory

Gerry Kulcinski
Univ. of Wisconsin

Steven J. Piet
Idaho National Engineering Laboratory

Paul Reardon
Superconductor Super Collider Laboratory

Shahram Sharafat
University of California, Los Angeles

Dale Smith
Argonne National Lab.

John Stringer
Electric Power Research Institute

Ken Wilson
Sandia National Laboratory

Clement Wong
General Atomics

Appendix C. FEAC Panel 6 Agenda/Discussions

Meeting #1: San Francisco, CA

December 2, 1992

Event	Speaker
Opening Remarks	Klaus Berkner
Overview of the OFE Materials Development Program	Bill Wiffen
Materials Requirements for the Near Term ITER	Dale Smith
Materials Requirements for Tokamak Reactors	Rich Mattas
Materials Requirements for IFE Reactors	Wayne Meier
Materials - Safety & Environmental Issues	Steve Piet
Panel Discussion	All

December 3, 1992

Event	Speaker
Neutron Source Requirements for Materials Development	Don Doran
The International Program	Bill Wiffen
Planning for Future Committee Meetings and Report Assignments	Committee
Planning Discussions Continued	Committee

Meeting #2: Dallas, TX

January 13, 1993

Event	Speaker
The Major Programs	
ITER Materials Program	Arthur Rowcliffe
Ferritic/Martensitic Steels	Everett Bloom
Vanadium Alloys	Dale Smith
Si C/Si C composites	Russ Jones
Insulating Ceramics	Gene Farnum
Panel Discussions	All

January 14, 1993

Event	Speaker
14 MeV Neutron Sources	
D - Li Target	Smith/Jameson
Plasma Target	Hooper/Molvik/Coensgen

Materials Program for Plasma Facing Components .... Ken Wilson
Ti Alloys for Fusion - Why were they dropped? .... John Davis
Users' Perspective on Materials Needs
    ITER Diagnostics .... Ken Young, PPPL
    Materials Needs for the Next Generation Fusion Device . . .
        A Designer's Perspective .... Tom Shannon, ORNL
    The Role of Reduced Activation Materials in TPX .... Ulrickson or Goldston
Committee Discussion .... All

January 15, 1993

Event	Speaker
Experience in Developing Materials for Specific Programs	
Development of Cladding and Duct Materials for the Liquid Metal Fast Breeder Reactor	Jim Laidler, ANL
Development of Titanium Alloys and Gas Turbine Materials	Jim Williams, GE
Materials Development for the National Aerospace Plane and Other Advanced Aircraft	John Dimmock, McDonnell Douglas
User's Perspective on Materials Needs (continued)	
Neutron Interactive Issues for Magnets	Dick Reed, MIT/Boulder NIST
Blanket Materials	Glen Wollenberg, PNL
Panel Discussions, Writing Assignments	All

Meeting #3: St. Louis, MO

February 11, 1993

SiC/SiC Composites Produced by the Chemical Vapor
    Infiltration Process.. Al Fresco, Du Pont
Panel Deliberations and Report Writing .... All

February 12, 1993

Panel Deliberations and Report Writing .... All

Appendix II

Minutes of FEAC Meeting of March 4-5, 1993.

MINUTES

Meeting of Fusion Energy Advisory Committee
Germantown Auditorium
U.S. Department of Energy
Germantown, MD 20874

March 4 and 5, 1993

Present:
Dr. Robert W. Conn, Chairman, UCLA
Dr. David E. Baldwin, LLNL
Dr. Klaus H. Berkner, LBL
Dr. Ronald C. Davidson, PPPL
Dr. Stephen O. Dean, Fusion Power Associates
Dr. John P. Holdren, UCB
Dr. Robert L. McCrory, Jr., University of Rochester
Dr. Norman F. Ness, University of Delaware
Dr. David O. Overskei, General Atomics
Dr. Ronald R. Parker, MIT
Dr. Barrett H. Ripin, NRL
Dr. Marshall N. Rosenbluth, UCSD
Dr. John Sheffield, ORNL
Dr. Richard E. Siemon, LANL
Dr. Harold Weitzner, NYU

Thursday, March 4, 1993

Welcome and Opening Remarks

Dr. Conn called the meeting to order and welcomed the committee members to the U.S. Department of Energy Auditorium at Germantown. He reviewed the agenda for the meeting and indicated where changes might be necessary to accommodate schedule variations.

Program Update from DOE

Dr. N. Anne Davies, *Office of Fusion Energy*, reviewed the status of the program on behalf of the Office of Fusion Energy. Her first viewgraph contained two statements, one taken from President Clinton's vision of change for America, and the other from the DOE News. They are reproduced below:

A VISION OF CHANGE FOR AMERICA, February 17, 1993

Fusion offers the promise of abundant energy from readily available fuels with low environmental impact. The centerpiece of the research effort in magnetic fusion energy is a collaboration among the United States, the European Community, Japan, and Russia to build an International Thermonuclear Experimental Reactor (ITER). Design and construction of ITER will be a multibillion dollar effort that would take two decades to complete. The United States must maintain a vital domestic research program to support our efforts on ITER. Yet, the U.S. has not commissioned a major new machine for fusion research since the early 1970's. This investment would fund moderate growth in the U.S. fusion energy program above inflation to allow construction of a new facility, the Tokamak Physics Experiment (TPX). Estimated additional spending between 1994 and 1997 is $210 million in outlays; ($90 million in 1997).

DOE NEWS, February 17, 1993

"$20 million in 1994 and $372 million in 1994-98 to initiate construction of the Tokamak Physics Experiment. This is the 'next step' in advanced fusion research and continues U.S. leadership in basic energy research."

Dr. Davies pointed out that the apparent differences in the numbers contained in the two news releases could cause confusion. The differences arose for two reasons: (a) the first statement talked in terms of budget outlay while the second talked in terms of budget authority, and (b) the first statement covered a four year period while the second covered a five year period.

Dr. Davies stated that the fusion budget for FY94 was due in Congress by April 5, 1993. It still had not been finalized and was presently going back and forth between OFE and OMB. She reviewed the FY93 budget:

President's Proposal	$ 359.7 million
Appropriation	$ 339.7
General Reduction	$(8.5)
FY92 Carry-over	$ 8.6
Total Available	$ 339.8 million

The D-T program in TFTR was funded at $80.8M in FY93, and the schedule for the campaign was now quite tight. The start up of TPX had been delayed to provide more funding for TFTR. ITER funding was continuing as planned and ILSE funding was level at the 1992 value. Dr. Davies drew attention to the fact that $1 million had been set aside in FY93 for new small initiatives in response to FEAC's suggestion that a program to foster new concepts and ideas be introduced. The program was underway and a number of proposals had been received and were under evaluation.

Dr. Davies provided the committee with an update concerning the International Fusion Materials Test Facilities Study. This was being conducted under the auspices of the IEA. Dr. Bill Wiffen, OFE, was the chairman of the committee that was undertaking the study. It was intended to involve the Russian Federation as a full technical partner. Currently consensus was being developed for decisions concerned with proceeding with the conceptual design of an accelerator-based materials irradiation facility and on studies that could lead to the conceptual design of a plasma-based source for high-volume irradiation needs. It was hoped to complete the work by October 1993.

Dr. Berkner asked if an accelerator-based source had already been selected for this work. Dr. Davies answered affirmatively. Dr. Conn commented on the President's statement concerning fusion, saying that it sounded a very positive note for the program. Dr. Davies agreed that the statement was extremely positive and added that fusion was receiving strong support from the Administration. Dr. Ripin asked if it was intended to set aside $1 million each year for new initiatives. Dr. Davies responded that that would depend upon a number of factors including how well the sponsored work progresses, upon the budget situation, and upon the quality of the proposals received.

Status of the ITER Program

- **Overall Activities**

Dr. Thomas R. James, *Office of Fusion Energy*, presented the status of ITER activities in general. He showed the organization chart and explained how the organization was intended to function. Two major meetings had already been held. The first, involving the Technical Advisory Committee, had resulted in support for the Director's proposals for magnet test facilities, magnet manufacturing feasibility studies, and long-lead procurement of superconducting magnet strand materials. The second, involving the Management Advisory Committee, had disapproved the Director's proposal for 50% credit for test facilities, had recommended urgent approval of magnet test facilities and magnet manufacturing feasibility studies, and had recommended initiation of procurement for superconducting magnetic strand materials.

Dr. James indicated that the ITER Council had requested that the Technical Advisory Committee conduct an assessment of the preliminary ITER design, and that the Management Advisory Committee review the work program, the Joint Central Team staffing situation, and the tasks for and allocations between the Joint Central Team and the various Home Teams.

Dr. James reported that a good start had been made with the recruitment of U.S. personnel to the Joint Central Team. Out of a target total of fourteen U.S. scientists suggested for Protocol 1 in San Diego, six were already on site and two others had accepted a position or were in transit. He pointed out that Dr. Rosenbluth, of FEAC, had joined the team and was already spending 50% of his time at the EDA headquarters. Recruitment for the team at Naka was also proceeding well while recruitment for Garching had proceeded more slowly but was now gathering momentum.

Referring to the selection of a site for construction of ITER, Dr. James stated that the FY93 Energy and Water Development Committee Report had directed the DOE to provide "a plan for selection of a U.S. candidate site for future construction of ITER". The ITER Director had requested proposals from the parties by December 1994 but since the U.S. had not yet started the site-selection process, it was unlikely that a U.S. candidate site would have been selected by then and this would delay the final decision on the site. This, in turn, would delay the start of site-specific design activities and the onset of on-site R&D.

Dr. James reviewed the issues that ITER was facing. First, despite strong U.S. support, the formation of the Joint Central Team was proceeding more slowly than anticipated. The financial problems being experienced by the Russian Federation were impacting their participation and hindering their sending of personnel to the Joint Central Teams and to meetings, although the Russians were now taking steps to correct the situation. He stated that it was becoming clear that the parties would all prefer to undertake the majority of the R&D via the "home teams" rather than the JCT. Each party was interested in involving their industries in the project and making them more knowledgeable, thus to increase their competitiveness for the construction phase of ITER.

Dr. James referred to the National Energy Policy Act which called for a fusion energy program "that by the year 2010 will result in a technology demonstration which verifies the practicability of commercial electric power production." He pointed out that if this goal is to be achieved, then the base program funding needs to be increased.

Finally, Dr. James reviewed the current U.S. priorities regarding ITER. These were:

- Support for the formation of the Joint Central Team
- The provision of help to the JCT by the U.S. Home Team on design issues and R&D planning
- Preparing, responding to, and negotiating task agreements
- Bringing U.S. industry teams into the program

Dr. Parker commented that the U.S. Home Team was making by far the best effort of any of the parties' home teams and should be commended for their efforts.

- **Home Team Activities**

Dr. Charles C. Baker, *Oak Ridge National Laboratory*, summarized key ITER-related activities with respect to the U.S. Home Team. He stated that the U.S. Home Team had been reorganized and that U.S. industry was now a part of the team. He emphasized that the U.S. Home Team was providing design support to the Director and the Joint Central Team and that the development of specific Task Agreements with the Director was underway. Input from the U.S. fusion community was continuing to be made via the ITER Steering Committee - U.S. (ISCUS) and the Industry Council.

Dr. Baker made the point that the budget for ITER activities in FY1994 was going to be tight. He indicated that ten national laboratories and ten universities were currently participating in U.S. work on ITER. Responses to five RFP's that had been issued in technology R&D areas had led to the selection of five industrial consortia that would join the U.S. Home Team activities and undertake work in these technology areas. The five consortia had comprised nine companies. Dr. Baker provided the following details:

Magnets: Contracting Institution - MIT
Industry Team - General Dynamics, Westinghouse Electric

Blankets: Contracting Institution - ANL
Industry Team - McDonnell Douglas, Westinghouse Electric, U. Wisconsin, U. Illinois

Plasma Facing Components:
Contracting Institution - SNL-A, UCLA
Industry Team - McDonnell Douglas, Westinghouse Electric, GA, Rockwell, Ebasco, U. Illinois

Remote Handling:
Contracting Institution - ORNL
Industry Team - Rockwell, GA, CIMCORP

Vacuum Vessel:
Contracting Institution - ORNL
Industry Team - Pitt-Des Moines, Grumman

An RFP relating to the sixth area of industrial participation, Design/Integration, had recently been issued by LLNL. Responses were due by March 5.

Dr. Baker provided details of recent changes in the U.S. Home Team organization. He then compared the current major design parameters for ITER with those that had emerged from the CDA phase, and indicated where and how the U.S. Home Team was supporting the initial design efforts of the Joint Central Team. Finally, he reviewed the Task Agreement Process that was being employed to share the R&D work between the parties. Dr. Weitzner asked if the tasks were to be reasonably equitably shared between the parties. He pointed out that if this were not to be the case, certain projects might be omitted from the U.S. ITER base program and this could adversely affect the U.S. program overall. Dr. Baker responded that there was no guarantee that the credits for any item of work would be exactly what the U.S. would like them to be.

Dr. Overskei reminded Dr. Baker that he had shown that ten national laboratories, ten universities and nine companies were now participating in the ITER program. He asked for details of the split in ITER funding between them. Dr. Baker replied that this year, approximately 15% of the funding would go to industry. The target for next year, and for each subsequent year, was 30%. Dr. Overskei commented that this was not representative of the situation in Japan. Dr. Baker agreed that this was true. He added that he anticipated that the situation in the European Community would be similar to that in the U.S.

Dr. Dean addressed Dr. Parker and asked if the same level of activity was going on in Europe as in the U.S. Dr. Parker replied that the JCT at Garching had only just begun to interact with the European Home Team. In the U.S., the Home Team had taken the initiative and the program had started quickly. In Europe, the JCT had been required to take the initiative and, since the team was still being formed, the start had been slower. Dr. Parker added that, so far, the Japanese presence was missing at Garching. He then asked Dr. James if the necessary funding was available in the U.S. for the JCT. Dr. James responded that the highest U.S. priority was helping the JCT. He confirmed that there was adequate funding to reach the required level of support in FY94.

TFTR

- **Status and Plans**

Dr. John Willis, *Office of Fusion Energy*, provided a description of recent history for TFTR and recounted a number of problems that had been identified while readying the tokamak for use with tritium. In particular, over-zealous implementation of DOE requirements for nuclear systems, lack of experience with requirements on nuclear systems, and problems with the gyrotron scattering diagnostic and the tritium pellet injector had resulted in cost pressures. The need for tighter cost controls, detailed schedules and enhanced management for the whole TFTR program was recognized, and it was generally agreed that nuclear safety requirements needed revision to be appropriate to the low hazard levels of TFTR, rather than to those of conventional nuclear reactors, while still being consistent with safe operation.

Revised plans to prepare TFTR for D-T were drawn up towards the end of 1992 and were reviewed by DOE in December. The review panel endorsed the revised plans and concluded that the cost estimates were credible and that the schedule was feasible, provided that the Secretary of Energy was prepared to accept the revised ES&H plans.

Secretary Watkins had since approved the revised start-up plan for D-T in TFTR, and PPPL had strengthened the project management team. The run-time on PBX had been reduced to generate additional contingency funding and the gyrotron scattering system, the tritium pellet injector, and other elements of the scope of work had been eliminated to maintain budget and schedule. Some safety-related hardware changes had been reconsidered and deleted from the plans. Dr. Willis concluded that the schedule for the oversight reviews was still very tight but, despite the remaining concerns, the TFTR program was still on schedule to begin D-T experiments in September 1993.

Dr. Overskei asked if compensation had been made to the program for the over-zealous approach that had been taken towards the use of tritium. Dr. Davies responded that the Secretary of Energy had signed off on the modified ES&H plans.

- **D-T: The Path to Fusion**

Dr. Dale Meade, *Princeton Plasma Physics Laboratory*, presented the research plan for the D-T project at Princeton Plasma Physics Laboratory. The intention was to conduct the program in two phases. The first phase would involve about 100 shots in D-T and would take place during the last quarter of calendar year 1993. The aims were to produce a maximum of 5 MW of fusion power, to measure tritium transport and to evaluate diagnostic performance with 14 MeV neutrons. The second phase, due to start in February 1994, would involve approximately 1000 shots in D-T. The aims were to maximize fusion power (~10 MW) and alpha-driven effects, to investigate confinement and heating in D-T plasmas, to evaluate alpha diagnostics, to investigate alpha heating of electrons, to study energetic alpha transport, to document alpha collective instabilities, to study alpha ash accumulation and to evaluate RF heated D-T plasmas.

Dr. Meade emphasized that a lot of shots would be carried out to avoid the dangers that could arise from doing too few. He displayed data that had been generated by JET which showed that ntT had decreased in JET by a factor of two with only 10% of tritium in the mixture. He questioned what would happen with 50% of tritium and pointed out that JET had not conducted a large enough number of shots to make predictions possible. He stated that TFTR would carry out enough shots to generate the required data.

Dr. Meade reviewed the results of the last deuterium run on TFTR prior to the start of the D-T program. Dr. Overskei asked if the experiments had shown signs of ICRF heating. Dr. Meade responded that they had seen efficient ICRF heating, and ICRF would be used to increase alpha particle beta during the D-T experiments. Dr. Meade presented graphs showing the present deuterium results and projections to deuterium-tritium, and performance figures for advanced tokamak regimes that had been developed for TFTR. Dr. Meade presented figures indicating the radioactivity levels that would be experienced at various locations surrounding the tokamak following a worst-case accident. He made the point that the Princeton community had accepted the numbers. At the nearest residence, the level was a low 2mR. Dr. Holdren requested the number of grams of tritium that had been assumed in arriving at the numbers. Dr. Meade replied that he had based the calculations upon the use of 2.5 grams of tritium.

Dr. Meade informed the committee that the process of obtaining DOE tritium-handling approvals was torturous, unreasonable and very costly. He related the history of the process and pointed out that approval via the Nuclear Regulatory Commission process would have been an order of magnitude less costly. Dr. McCrory asked if Dr. Meade could place a figure on the cost of the approval process. Dr. Meade responded by displaying a viewgraph that showed that the Tiger Teams and new DOE regulations had added $40 million in costs and that as a result several program elements had to be canceled.

Dr. Meade stated that TFTR would be decommissioned and decontaminated starting within two years after D-T shutdown. A decontamination period involving deuterium operation would be needed to reduce the in-vessel tritium inventory. He pointed out that JET had been able to remove 97% of the tritium that had been injected into the vessel. Dr. Berkner asked if a plan had been prepared for the disposal of radioactive materials upon completion of the project. Dr. Meade replied that a plan had been prepared and that all radioactive material would be sent to Hanford to be buried as low-level waste.

Tokamak Physics Experiment (TPX)

- **Project Status**

Dr. John Willis reviewed the progress that had been made with the project since the last meeting of FEAC in September 1992. In November 1992, Deputy Secretary Stuntz had approved KD-0 (mission need) and conditionally approved KD-1a (new start - design only). This had authorized the development of a conceptual design report and allowed DOE to request funds for preliminary design in FY94 provided that TPX can be accommodated in ER's out-year budgets.

Dr. Willis stated that the baseline performance had been upgraded from 3.35T/1.7MA to 4T/2MA as recommended by the TPX National Council. The management structure for the project had been established in December 1992 and a Program Advisory Committee had been selected to advise on planning the experimental program and setting initial operating requirements, and to help coordinate physics R&D efforts within the fusion community. Dr. Willis reported that Dr. Keith Thomassen had been placed in charge of the program, Dr. John Schmidt in charge of the project, and Dr. Stewart Prager as Chairman of the National Council.

Dr. Willis stated that an estimate of the Total Project Cost (TPC) had been developed in February 1993 and amounted to approximately $500 million in 1992 dollars. He emphasized that the exact final cost would depend both upon the funding profile and upon a number of as yet unresolved accounting issues. The estimate had assumed completion of the project in 1999, in line with the original FEAC recommendation. However, the out-year budget levels of the Investment Package (based on estimates made towards the end of 1992) would force the project to be stretched out to 2000 or 2001, which was again consistent with the recommendations of FEAC for the various budget scenarios that they had reviewed in their formulation of program strategy.

Dr. Willis reported that the conceptual design review for TPX was scheduled for the end of March at Princeton. The review panel comprised technical experts from the U.S., Europe, Japan and the Russian Federation. It would be chaired by Dr. James Callen of the University of Wisconsin. The panel had been asked to evaluate the soundness of the TPX physics and engineering design, given the mission objectives and performance parameters of the device, and to determine whether the project's cost estimates and schedules appeared credible.

A general discussion took place concerning the validity of the cost estimates, and whether it would be better to separate the design and cost estimate reviews. Dr. Siemon asked if any independent assessment of the magnet development program and of magnet costs was contemplated. Dr. Parker asked if it was possible that the experts on magnets who were working on ITER could help. Dr. Willis responded that he had experienced great difficulty in persuading ITER personnel to take an interest in this matter: They were engrossed in their own program.

- **The TPX Program**

Dr. Keith Thomassen, *Princeton Plasma Physics Laboratory*, presented an overview of the TPX program. He provided a chart of the TPX organization and indicated where TPX would fit within the current world fusion program. He stated that the mission of TPX was to significantly extend the normal operating range and duration of conventional tokamaks by continuous control of critical plasma parameters, thus to allow the development of attractive, compact, steady-state fusion reactors. Dr. Thomassen outlined the specific objectives of the program. He reviewed the initial TPX machine parameters and pointed out that these were the values that had been used in determining the total project cost (TPC). He compared these parameters with the maximum values that could be achieved for the tokamak but stressed that the achievement of enhanced performance was not included in the TPC. Dr. Thomassen discussed the operating scenarios that were planned for the machine and pointed out that it was intended to use only hydrogen during its first two years of operation. Dr. Thomassen concluded with a detailed review of the divertor system.

Dr. Parker asked if the Japanese had any plans to interact with TPX. Dr. Willis responded that nothing specific had been agreed since TPX does not yet exist.

Dr. John Schmidt, *Princeton Plasma Physics Laboratory*, presented the history of the TPX project and provided summaries of the schedule to date and of the schedule that was planned for the future. Dr. Weitzner asked if there would be a role for industry in the management of the project after the device had been switched on. Dr. Schmidt replied that it was not yet clear what industry's role would be after design and construction were complete, but that continuing participation was not ruled out.

Dr. Schmidt presented a comparison of chronological cost estimates which led to a general discussion of the reasons for increases and decreases in certain items. Referring to the latest estimate of $497 million, Dr. Conn asked what total contingency amount had been included in the cost. Dr. Schmidt replied that the contingency allowance was approximately $80 million. Dr. Siemon pointed out that the magnets represented one in the list of items for which the cost had increased significantly. He asked if Dr. Schmidt could give the committee an assurance that the contingency in the magnet area was large enough. Dr. Schmidt responded that he was not expecting any "surprises" in the magnet area that would cause the contingency to be exceeded.

- **Views of the National TPX Council**

Dr. Stewart Prager, *University of Wisconsin*, described the functions of the Council and provided a membership list. The functions were to provide oversight, to participate in decisions on programmatic aspects including mission, technical scope , cost and schedule, to advise on project management and execution, and to ensure national participation in the project. The Council had held three meetings: Following each meeting, the findings were communicated by letter to Dr. Davidson.

Dr. Prager reported that the Council was pleased with the project management and had strong confidence in the capability, enthusiasm, and cohesion of the team. The Council felt that the project staff had done an outstanding job in evolving the design within cost boundaries. The costs that they had reviewed had always been quoted in 1992 dollars. Dr. Prager commented that the Council felt that the latest cost estimate, although higher than previous estimates, still fell within a range that would be acceptable since there was much less potential for escalation than for previous figures.

Dr. Prager stated that a plan was evolving to ensure a substantial rôle for industry and that the Council believed the approach would be beneficial both to the project and to the readiness of U.S. industry for fusion. The Council considered that the mission must be disseminated persuasively to the fusion community and to policy makers but appreciated that the multi-faceted aspect of the mission would complicate its dissemination. Dr. Dean stated that he was a member of the TPX Council and that he did not agree that PPPL had provided a substantial role for industry in the project.

Dr. Prager presented the Council's comments on the mission which were that TPX was seeking to improve qualitatively the tokamak reactor by discovering new regimes which would lead to lower field, or higher power density, or smaller reactors. He emphasized that this was distinct from ITER goals, although TPX results could influence ITER operation. Dr. Weitzner commented that the mission and goals could be made clearer. Dr. Parker agreed that the statement needed to be sharpened up, particularly with respect to power density.

Dr. Prager stated that the goals for TPX could be viewed in several ways. He indicated that a tepid goal would be to prove that nothing bad would happen in steady-state operation. A more exciting goal would be to discover new operating regimes. The greatest excitement might come from the discovery of new physics.

Dr. Overskei asked if the Council had looked at upgradability with respect to project cost. Dr. Prager replied that the magnetic field would not be upgradable, but the power supplies would be. Dr. Overskei asked if the Council felt that the machine performance should be degraded. Dr. Prager responded that the consensus was that it should not. Dr. Overskei asked if the Council had established what the upper limit of cost should be to maintain the present parameters. Dr. Prager replied that it had not. He added that the Council had felt comfortable with the original estimate of $440 million and that they still felt comfortable at the new higher number of $497 million since there was now far less room for error. Dr. Prager cautioned that the Council would not be comfortable if the estimate rose above the latest figure.

Dr. Overskei asked who, if anyone, was advertising the Council's satisfaction with the program. Dr. Prager responded that the Council had not discussed an advocacy campaign. He added that he thought this would be better left to PPPL. Dr. Conn made the point that once a person or committee becomes an advocate, that person or committee can no longer have a purely objective rôle.

Dr. McCrory commented that the mission statement was less than persuasive. Based upon it, he questioned how TPX could possibly influence ITER operation. Dr. Baldwin interjected that Dr. Thomassen's statement had defined the mission more clearly and that Dr. Prager's statement was just a simplification of it. Dr. Prager stated that he would expect TPX to influence ITER, and added that he would also expect the device to be operational in time to influence ITER.

Review of Charge for Panel 6

Dr. Conn reviewed the Charge to FEAC that had led to the work of Panel 6. In particular:

> "I would like the Fusion Energy Advisory Committee (FEAC) to evaluate the Neutron Interactive Materials Program of the Office of Fusion Energy (OFE). Materials are required that will satisfy the service requirements of components in both inertial and magnetic fusion reactors — including the performance, safety, economic, environmental, and recycle/waste management requirements.... Given budget constraints, is our program optimized to achieve these goals for DEMO, as well as to support the near-term ITER program?"
>
> "Is the balance appropriate between:
>
> a. near-term (ITER) and longer range applications;
> b. the several candidate materials for longer range structural applications;
> c. structural materials and ceramic insulators; and
> d. domestic and collaborative international programs?"

Report of Panel 6 on Materials

Dr. Klaus Berkner presented the findings of Panel 6. He started by providing the membership of the panel, which had comprised nineteen persons. Dr. Berkner then indicated the persons who had made presentations to the panel and what their specific topics had been. He outlined the lessons to be learned from other materials development programs. Typically, 15% of a program is devoted to materials development which, given the current fusion budget, implies that $50 million per year should be spent within OFE, before consideration of the added complexity arising from the effects of neutron damage. Dr. Berkner stated that the use of new materials is driven both by application need and by technology development. Close interaction and frequent iterations between materials developers and system designers is standard practice. The introduction of new materials is evolutionary not revolutionary, with early introduction into real use helping to provide an experience base.

Dr. Berkner stated that the materials needs for fusion are many but that none of them were "show stoppers" although some may require design-around programs that would be costly or cumbersome. He reported that there was no structural material (of either high or low activation variety) that had been demonstrated to meet fusion requirements at DEMO fluences (~5MW-yr/m^2). Dr. Berkner said that plasma-facing components were being challenged to meet mechanical and thermal performance requirements but that neutron effects were not yet receiving much attention. Superconducting magnets, even though in a relatively low fluence region, need insulators that can withstand moderate fluences. Such material, even for ITER, has not yet been identified. He stated that ceramic insulators don't insulate under high fluxes and that optical components turn opaque after moderate fluences.

Dr. Berkner stated that there were compelling arguments for the development of low activation materials (LAM's), one being that the fusion community would not be able to "sell" fusion to the environmental community without having a credible LAM program in place. From current safety and environmental perspectives, material selection would be the single largest factor in fusion success. Dr. Berkner emphasized that LAM's represented the only way to exploit the fundamental fusion advantage since the "ash" from the reaction would have no long-lived isotopes. There would be no conventional nuclear waste although, eventually, there would be a large volume of radioactive material to be disposed of, i.e. the machine itself.

Dr. Berkner reviewed the criteria that formed the framework within which low/reduced activation materials were being developed. He stated that the U.S. program for low/reduced activation materials was being driven by U.S.-specific regulatory policy that was set for fission power and radioactive medical waste (10CFR61), rather than by one which had been developed for fusion. The long range NIM program had focused on environmental requirements to meet near-surface burial as defined by 10CFR61 for radioactive waste. Dr. Berkner said that safety issues arising from the generation of high level short-lived radiation must also be considered. He informed the committee that the DOE had formed the "Stacey Panel" to review the low/reduced activation criteria for fusion, but the panel had not yet met and so Panel 6 had not reviewed this issue.

Dr. Berkner presented to FEAC copies of a report that described the activities of Panel 6.

Dr. Richard E. Siemon presented a summary of the U.S. Neutron Interactive Materials Program. The major tables that he reviewed were taken from the Panel 6 report. With reference to structural materials, Dr. Siemon pointed out that ferritic/martensitic steels possessed excellent prospects for survival at high fluence and provided better engineering performance than austenitic steels. A strong industrial data base was available for these materials, and potential means for developing reduced activation alloys have been identified. The need was to eliminate molybdenum and niobium from the alloys through substitution of vanadium, titanium and tantalum, and then to qualify the resulting low/reduced activation alloy. Dr. Siemon pointed out that careful heat treatment during welding would be required, but stressed that the main question to be answered was whether or not a tokamak can be built from a magnetic steel. No tokamak has ever been constructed using such material.

Dr. Siemon stated that titanium alloys exhibited a promising, although relatively undeveloped, irradiation data base and were available from a mature fabrication industry. The constituent elements of titanium alloys, with the exception of aluminum which is essential, are all low/reduced activation materials. Dr. Siemon pointed out that the problem with these alloys is one of hydrogen solubility, although the feasibility of barrier coatings could be explored. Dr. Siemon reported that the moderate irradiation data base for vanadium alloys showed that these materials might be suitable for fusion but that they suffered from limited industrial experience. There are few commercial suppliers of such alloys. Fabrication, chemical compatibility and fracture toughness issues needed to be resolved.

Dr. Siemon discussed SiC/SiC composites, which represent a new class of materials that is being developed via an emerging technology. The composites exhibit excellent high-temperature properties and possess the highest known potential as low/reduced activation candidates. He pointed out that the irradiation data base was sparse, and stressed that mechanical properties, as they might relate to the material as a whole, were difficult to define because of variations in fiber type, architecture, volume fraction, interface type and thickness, and matrix production method. Dr. Siemon said that austenitic steel was probably the best off-the-shelf material for the construction of ITER, if it were decided that the device would be water cooled. Type 316 stainless steel could be used at temperatures of up to 400-450^{o}C and up to fluences not to exceed 1-3MW-yr/m^2. He pointed out that the material would have little relevance for DEMO because of its poor thermal physical properties at high temperature.

Dr. Siemon reviewed the special needs of plasma-facing components (PFC's). He pointed out that the environment in which these materials had to function, involving exposure to high heat flux and first-wall radiation doses, made them the most highly stressed materials in the reactor. Typically, duplex structures were considered which combined a plasma-facing material of low atomic number backed by an actively cooled substrate of high thermal conductivity. Dr. Siemon said that duplex structures intended for use in ITER needed to be irradiated before being subjected to high heat flux, but the test facilities were not available. He indicated that a 14-MeV source would be especially desirable for testing low-Z divertor materials because of their generally large (n, alpha) cross-sections, and added that knowledge of radiation effects upon PFC's was minimal. Dr. Siemon stated that for magnet materials, relatively low fluence can be damaging at 4^{o}K. In current ITER designs, welds and insulation were considered the items of greatest uncertainty.

Dr. Siemon presented a summary of the thoughts of Panel 6 regarding a 14-MeV neutron source and other test facilities. He stated that testing in fission reactors was vital to fusion materials development. The loss of the Fast Flux Test Facility (FFTF) was a major setback. It had possessed a relatively hard neutron spectrum and a sample volume of 5 litres. The High Flux Irradiation Facility (HFIR) at ORNL was now the primary fusion testing facility and the remaining life of the pressure vessel gave cause for concern. Dr. Siemon outlined the programmatic rôle of a 14-MeV neutron source. He stated that ITER was expected to provide integrated testing of large components to moderate levels of fluence (1 - 10 dpa), while TPX would permit testing of materials that would address high-heat-flux issues at low fluence. What the program needed was a 14-MeV source that would provide higher flux than ITER, and that could be used for testing large numbers of small specimens at a time. This would support an iterative campaign of fusion-relevant irradiations needed as the first step towards qualifying improved materials for DEMO. Dr. Siemon stressed that, in order to prepare for DEMO, given the long lead time involved in materials development, the 14-MeV source should be in operation before ITER.

Dr. Siemon described what a typical 14-MeV source could look like. In answer to a question, he stated that the volume of the test chamber would be approximately a litre. This led to the question of whether or not an expensive 14-MeV neutron source with a volume of a litre or less would be of sufficient benefit to the program to justify its cost. Dr. Everett Bloom, *Oak Ridge National Laboratory*, responded from the audience that many useful tests could be made on small specimens of material that could be tested in a relatively small volume. It was not necessary to test full size components to generate the data that was needed for materials development.

Friday, March 5, 1993

Outlook for the Future

Dr. Robert L. Hirsch presented a paper to FEAC entitled "Changing Directions in Fusion Research Needs". The full text is reproduced below:

CHANGING DIRECTIONS IN FUSION RESEARCH NEEDS

"It is my view that DOE should accelerate some of the changes in program direction that have been initiated recently. I feel strongly that the world needs fusion power. It's potential is enormous. However, it's development challenges are incredibly complex, as this audience well knows. To optimally develop any technology, early, tight coupling to the marketplace is needed. That was a major lesson of the 1980's in virtually all areas of technology development. In electric power generation, the client today is the electric utilities, who know the marketplace better than anyone else.

Utilities haven't been seriously involved in fusion for a very long time, if ever. Utilities know the realities of building and operating real power generators in the real world better than any other entity. They or people with their kind of practical, pragmatic orientation will ultimately evaluate fusion's viability.

Don't confuse "utilities" with "industry". Industry is often motivated by near-term contracts, and, even if contractors or potential contractors know better, they are unlikely to criticize for fear of losing contracts or contract opportunities. Anne Davies has already asked for utility advisors to assist her, and she will have access to the Fusion Working Group that we are organizing under EPRI.

The utilities have learned and are learning many harsh realities today, particularly in nuclear. Nuclear power in the U.S. is not growing; it is in fact having to deal with significant negative pressures. Today's nuclear problems include the following:

- High O&M costs;
- Need for expensive capital investments;
- Very high levels of detailed regulation;
- No accepted means for radwaste disposal;
- Very high decommissioning costs;
- Lower cost alternative electric generation options.

The lessons and realities of nuclear power as viewed by many of the utilities that own them are different than many of you may realize. While I fully expect a number of nuclear's problems will be solved before the advent of fusion, the concerns about complexity, management of radioactivity, high levels of regulation and costs will continue in my view. There should not be the slightest doubt that they will be problems for fusion also. Public acceptance will be a big problem for fusion that shouldn't be forgotten either.

Consider the characteristics of DT tokamak and laser-fusion reactors as currently envisioned. They will be extremely complex, highly radioactive, likely to be highly regulated, and costly. Even if DT tokamak or laser fusion reactors had the same capital costs as a fission reactor (an enormous challenge), fusion reactors would lose out to advanced fission reactors, which are a reliable, known quantity.

As you know, EPRI has recently reestablished a small fusion program. Let's consider some of what has come out of that effort thus far. A fusion panel study has provided some excellent guidance, softly delivered so as to minimize trouble. Some of the very few fusion-knowledgeable utility people that I have spoken with indicate that none of them believes that tokamak or laser fusion reactors, as currently envisioned, would be acceptable to the electric utilities.

Let me turn to materials. As you well know, there are some enormous materials problems related to DT fusion. Accordingly, you have empaneled a materials study recently. The facts seem to be:

- There are no qualified materials today for DT fusion reactors.

- If you select stainless steel, you will have to effectively rebuild your fusion reactor every 5-10 years and dispose of many times the amount of radioactivity that would come from a fission reactor of the same power level.

- If you want to develop a low activity material, it will be very costly and very time consuming, and you are likely to still have to rebuild the reactor every 5-10 years, that is unless some of these liquid or powder walls prove viable.

And then there's ITER. If tokamak reactors, as currently envisioned, aren't acceptable, can ITER be possibly justified? If you build ITER, it will become the flagship of fusion and will likely eliminate the chance of serious funding for alternate concepts. If what ITER represents is seriously considered in public debate, there is a high probability that ITER will not be supported and the fusion program could collapse.

So what to do? I urge the DOE to accelerate changes that have already been started: Get serious utility oversight ASAP. Anne Davies has already asked for utility help, but this won't be easy to arrange. You recently restarted an alternate concept program. I urge you to scale up appropriate alternate concepts R&D as fast as you can. "Appropriate alternate concepts" refers to concepts that hold promise of working on the higher fusion fuel cycles and providing more attractive fusion power systems. Don't stop tokamak or laser-fusion research, but cut them back and reorient them in more acceptable directions. Get off of the DT fuel cycle to avoid frequent reactor reconstruction, large quantity radwaste disposal, and expensive materials development.

I've talked to many in the fusion community in recent years. While those people don't construct the need for change the same way that I have, their conclusions are often remarkably similar to what I have just outlined. I urge you to accelerate your changes and to reach out to the utilities for guidance and eventual partnership."

Dr. Overskei stated that there appeared to be no willingness on the part of the utilities to install the latest generation of improved fission reactors, and that in fact they were still using old-technology devices. He asked why they would want to support fusion. Dr. Hirsch responded that the utilities were regulated; they would make a profit no matter what they did. But, the economic environment was changing, cost pressures were building, and different energy technologies were competing for selection. He emphasized that the utilities would gravitate towards the lowest cost source of energy. Dr. Overskei said that Dr. Hirsch's answer had not addressed his question. He asked again why Dr. Hirsch felt that the utilities would be interested in supporting fusion. Dr. Hirsch replied that today the utilities were looking for new technology.

Dr. Holdren stated that he shared Dr. Hirsch's concerns regarding the tokamak. He pointed out that the current program was only viable at the current scale of operations. He added that it was necessary to ensure that the program was politically viable also. He stressed that it was the D-T fuel cycle, the tokamak reactor concept, and ITER that were maintaining the political viability of the program. Bearing the delicacy of the situation in mind, he asked Dr. Hirsch how he would go about changing the program. Dr. Hirsch responded that FEAC had already made a good start in changing the program through the introduction of the alternative concepts program. He urged the committee to continue in this manner and encouraged them to take the necessary risks. He added that if the fusion community was not prepared to take the risks involved in changing their program, then someone less well informed would do it for them.

Dr. Conn stated that it was not a question of accepting challenge. Rather, from 1981 through 1992, the fusion community had very painstakingly put together a national program and the logic behind the way in which this had been done was what was holding the program together. Dr. Hirsch agreed that it was easy for someone from the outside to look in and say they would have done things differently but admitted that he did not know what he would have done that was different. He stressed that the customer was "out of the loop" and that when utilities were approached on the subject of fusion they were not supportive.

Dr. Rosenbluth pointed out that the first practical demonstration of fusion power was still 30-50 years away. He asked why any commercial entity would wish to support a program that was that far away from exploitation. He added that although current materials were unsuitable for use in commercial fusion reactors, that was no reason to assume that better materials would not be available fifty years from now. He stated that no one knew what the design of a fusion reactor would be in fifty years time and that changing from a tokamak to some other unknown design was premature. Dr. Hirsch responded that even if the utilities were not prepared to provide financial support now, by not including them in the program, the fusion community was showing disrespect for them. He stated that the utilities really did care that the right things were being done in the short term as well as in the long term.

Dr. Conn stated that it was not a question of disrespect. The question was how best to approach them. He agreed that the fusion community might need to change the program, but that this should be done one step at a time. The problem was how to move in the right direction and change the program without taking a misstep.

Dr. Ness asked, given the framework of flat funding and the fact that a program to support new confinement initiatives was already in place, how could one make the changes that Dr. Hirsch was advocating. Dr. Hirsch responded that something would have to go. Dr. Ness asked if Dr. Hirsch endorsed TPX. Dr. Hirsch replied that he did not know enough about the project but added that one should not stop tokamak research completely.

Dr. Parker stated that the D-T fuel system was a good one. While it produced neutrons, which were undesirable, these could be absorbed by lithium to reproduce tritium. The radioactivity problem would then become a design issue. Dr. Hirsch said that he disagreed that D-T fuel should be used.

Dr. Overskei said that the program that Dr. Hirsch said needed changing had been endorsed by the fusion community's customer, and the customer was willing to pay for the program. He emphasized that fusion's customer was the U.S. Congress. He asked Dr. Hirsch if he was suggesting that the fusion community should tell Congress that the product that they were supporting was the wrong one but that another customer existed who wanted to develop fusion in a different direction. He asked Dr. Hirsch if he would be willing to pay for the program he was suggesting. Dr. Hirsch replied that he would not. He stated that the U.S. government was a "lousy picker of winners", and that the Congress was aware of it. He reiterated that the utilities were the real customers and that they represented the real world. He stated that the fusion community should get together with the utilities to form a partnership, take their input and lay out a new plan that the fusion community and customer could both agree upon. Dr. Hirsch said that such a program would evolve rather rapidly and would move in a new direction.

Dr. Conn explained how the fusion program had reached its present position, including its support of new initiatives, and added an explanation of the mission of TPX. Dr. Dean stated that while the $1 million that had been set aside for the new initiatives program was a good start, he agreed with Dr. Hirsch that more should be done to explore other directions. He stated that between 15 and 20% of the $350 million of annual funding for fusion should be devoted to alternative concepts. Dr. Hirsch emphasized that everyone wanted to do the correct thing, and that everyone wanted the program that was developed for fusion to be robust. In such circumstances, the fusion community should not be afraid to open up its program to persons on the outside and let them determine whether or not it was robust. If outside persons did not think it was, or if they thought that some other direction should be pursued, then perhaps the fusion community's program was not so robust after all.

Dr. Anne Davies pointed out that the U.S fusion program would not be all that easy to change. She emphasized that the U.S. program was no longer a stand-alone program. The U.S. was dependent upon international support. She stated that she had sent the report that Dr. Hirsch had prepared for her to her counterparts in the European Community, the Russian Federation and Japan. She asked Dr. Hirsch if EPRI had contact with counterparts in Europe and in Japan. Dr. Hirsch replied that EPRI had extensive international contact.

Public Comment

Mrs. Kathryne Thorpe, *General Atomics*, stated that it was her belief that if the fusion program were to abandon the D-T fuel cycle, the tokamak and ITER, Congress would abandon the fusion community. She added that it was obvious that Dr. Hirsch thought otherwise. She wanted to know why. Dr. Hirsch responded that either the fusion community must make changes to its program or changes would be imposed upon it.

Dr. Thomas James, *U.S. DOE*, stated that cogeneration plants were being constructed all over the USA, and not by the utilities. In view of this, he asked Dr. Hirsch if the utilities were indeed likely to be the final customer for fusion. Dr. Hirsch responded that it was anyone's guess what was going to happen.

Continuation of Report of Panel 6 on Materials and FEAC Deliberations

Dr. Berkner presented a series of recommendations that Panel 6 proposed FEAC should consider adopting. Dr. Conn suggested that the committee see all of the recommendations before commenting on any of them. The recommendations of the panel appear below:

OFE Organization

- A matrix task force for all materials development issues, with a single senior leader, should be established within OFE to coordinate the materials development effort.

Balance/Growth

- At present levels of funding the balance between the different structural materials in the base program is about correct, though additional funding for alternative low/reduced activation materials, e.g. SiC/SiC composites and vanadium alloys, (and possibly titanium alloys,) is warranted. If increments of funding are available for base-program structural materials, we recommend that the first priority should be to reassess the titanium alloy system and to strengthen the programs in vanadium alloys and SiC/SiC composites.

- The current funding level is not sufficient to assure the development of materials required for DEMO. If the overall program grows, the neutron irradiation materials program should be targeted for increases with the goal of doubling the effort.

ITER

- The ITER and TPX Projects should give serious consideration to the use of ferritic steel and/or titanium alloys in appropriate major components. (We understand that TPX already plans to use titanium alloy for its vacuum vessel). This would have the benefit of providing large-scale practical experience with DEMO-relevant materials.

- If more materials work is needed for ITER and if the U.S. is asked to provide more ITER materials work, it is extremely important that the long-term, base materials program be protected against diversion for non-DEMO-relevant materials development.

- In the areas of divertor structural materials, plasma facing components, and ceramics, the materials development programs are of great importance, but should be primarily driven by, and funded by, ITER - since the materials needs are tightly coupled to design decisions. The base materials program should focus on DEMO-relevant structural materials, with relatively smaller but still important effort on fundamental issues in ceramics.

14 MeV Neutron Source

- Preparation for building a DEMO requires that ITER and the 14 MeV neutron source proceed on similar time schedules. FEAC recommends that an international conceptual design effort for a 14 MeV neutron source be undertaken on a schedule which will permit international commitment to construction in parallel to the commitment to construct ITER.

- The time-schedule for fusion development dictates that an accelerator-based D-Li system must be the baseline approach for the 14 MeV neutron source.

- If the outlook for international construction of a 14 MeV neutron source is favorable, then funding the conceptual design of this facility should have the highest priority within the materials program.

- Funding for the 14 MeV neutron source must be incremental to the base program.

Referring to the recommendation on balance and growth, Dr. Sheffield stated that it did not present the time history of the program. He said that today's level of funding was not good enough: The austenitic steel program was currently winding down. He emphasized that some experiments took five years to complete. The proposed wording did not make these facts clear. Dr. Everett Bloom, from the audience, stated that from 1984 through 1994, a significant materials program had been, and would continue to be, in progress as a joint effort with the Japanese. He pointed out that this would soon end since only one experiment was due to continue beyond 1994.

Dr. Holdren suggested elevating the first sentence of the third bullet, concerning the current funding level, to a position of eminence. He stated that it should be less vague and more emphatic. He said that what the statement should say was that the current funding level was not even close to what was needed to assure development of the materials required for DEMO. He added that the statement should say what the current level of funding was. Dr. Holdren also disagreed with using the phrase: "If the overall program grows".

He stated that FEAC should say instead that if the U.S. wanted reasonable assurances concerning the timely development of materials for DEMO, then the program has to grow. FEAC should state by how much. Dr. Holdren stated that a similar situation existed for the 14 MeV source. He objected to the phrase: "If the outlook for international construction of a 14 MeV source is favorable". Instead, he suggested that FEAC should say that it was so important that there be such a source that the U.S. should be campaigning to ensure that the outlook was favorable. Dr. Holdren stated that in view of the substance of the report, a stronger, clearer, more quantitative statement was called for on these points, and it should be placed at the beginning of the recommendation.

Dr. Overskei said that he would prefer to decouple the materials program from the 14 MeV test facility. Dr. Conn suggested that a compromise might be to make the third bullet stronger and to place it first, and then to deal with the 14 MeV source separately. Dr. Overskei stated that there were two problems to be dealt with. The balance of the materials program within the whole fusion program was wrong, and the balance within the materials program itself was also wrong. Dr. Berkner indicated that the panel had not dealt with the balance of the program within the fusion program as a whole and that the recommendation had been carefully crafted to avoid the issue.

Dr. Rosenbluth stated that if the committee was going to move the third bullet into first place, then it should refer to more than just the Neutron Interactive Materials (NIM) Program. Dr. Baldwin concurred, stating that the committee should refer to a materials program aimed at the feasibility of the D-T cycle. Dr. Berkner responded that the charge had been to address the NIM program. He stated that the panel had, in fact, gone way beyond the charge that they had been given, but that to have looked at the entire program would have taken a great deal more time. Dr. Davidson asked if the panel had looked into the details of the international programs. Dr. Berkner responded that the panel had not. The panel had looked at the way in which they interacted with the U.S. program but had not looked into the details of each. Dr. Conn stressed that it would be important for FEAC to consider what others were doing, when the time came to craft its report.

Dr. Holdren stated that at the current level of funding, there was little assurance that the U.S. would have appropriate materials available as it moved towards DEMO. While he agreed with Dr. Overskei that the funding issue could be split away from that of the 14 MeV neutron source, he stated that the 14 MeV source should be dealt with second. He emphasized that the major recommendations should be placed at the beginning of the report. Dr. Weitzner agreed that FEAC should quantify both issues and that they should be closely coupled.

Dr. Rosenbluth stated that the committee was not coming to grips with the real question. He asked whether FEAC wanted to recommend a modestly increased program, say one that was a factor of two greater than at present, or a significantly larger materials effort, say at $100 million per year. Dr. Conn stated that FEAC should indicate what it thought was the minimum funding that was reasonable for the materials program, consistent with what was agreed at Crested Butte, and then explore how that funding might be achieved.

Dr. Conn stated that it appeared that the 14 MeV source should be the second item included in the report. He cautioned that the wording should make it very clear that the 14 MeV source is only one component within the program. Dr. Overskei emphasized that the program needed a 14 MeV source regardless of DEMO. It was needed simply for the testing of materials. The materials could be used for the construction of any fusion reactor. The testing source should not be coupled to any one device.

Dr. Weitzner said that the report should deal with the future of the entire program. It should be comprehensive and not deal with odd pieces. Dr. Conn pointed out that following this approach would take the committee a great deal of time. He suggested that FEAC should assume that the readers of its report knew a reasonable amount about the program and that as a result the committee need not deal with every issue in detail. Dr. Berkner questioned what constituted materials development, and where it stopped. He indicated that the entire program could be considered as materials development because basically everything that the program did involved materials. He pointed out that nuclear interactive materials and reduced/low activation materials issues kept arising during the panel's investigation as unique to the fusion program and that it seemed reasonable to concentrate on them.

Dr. Overskei said that while he did not disagree with the approach that the panel had taken, he still felt that the 14 MeV source should not be coupled to DEMO. Dr. Parker disagreed, stating that by coupling the source to DEMO, the committee would be setting the time frame for its construction. Dr. Overskei pointed out that there were other machines that would be constructed prior to DEMO that could benefit from the use of new materials. By tying the 14 MeV source to DEMO, the committee would delay the availability of the source and it would not be of value to earlier machines. Dr. Parker emphasized that something was needed to pace the materials program or it would not go ahead in a timely manner.

Dr. Baldwin pointed out that one pacing item would be the testing of materials in the latter stages of the ITER program. Dr. Conn agreed that the committee should indicate that the materials were needed in time to be tested in ITER and that they could then be used in the construction of DEMO. He stated that Dr. Baldwin's implied point was well taken, that materials development could not rely fully on test data but that components must be evaluated in their real working environment. Dr. Berkner pointed out that there was insufficient fluence in ITER to carry out detailed testing. Dr. Conn countered that it would not be necessary to test to end-of-life in ITER and that it would be sufficient simply to determine that the materials behaved in a satisfactory manner.

Dr. Overskei stated that it would even be desirable to have the 14 MeV source in time to treat new materials for use in TPX. Dr. Parker stated that a neutron source was not required to develop materials for use in TPX because TPX would not produce any neutrons. Dr. Dale Smith, from the audience, stated that some testing would indeed be desirable before ITER. He emphasized that one would not want to test large components in ITER unless one was reasonably sure that they would be suitable for DEMO. A lengthy discussion ensued regarding how to phase program timing with respect to ITER.

Dr. Everett Bloom, from the audience, stressed that it was very necessary to provide an appropriate data base for each material. He stated that if new materials were to be developed in time for use in DEMO, then the 14 MeV source would have to be operational by the year 2000. Dr. Overskei added that, in addition, the materials program would have to be funded at a minimum of $20 million per year by 1998. Dr. Conn agreed that it would be important to include a phrase in the letter to Dr. Happer that indicated that the 14 MeV source should start operation by about the year 2000. This led to a lengthy discussion of the time scales that had been agreed on during the meeting at Crested Butte.

Dr. Berkner asked if FEAC saw the 14 MeV source as being part of the international program located in the U.S. Dr. Conn responded that the committee would deal with that point later. Dr. Overskei suggested that the first bullet in the recommendations relating to the 14 MeV source be modified to reflect that FEAC recommends that the U.S. initiate an international concept design effort . . etc. He also suggested that the last phrase in the bullet be deleted. There was general agreement to this.

Dr. Baldwin stated that the second bullet in this section was weakly phrased. There was general agreement to phrase it more strongly. Dr. Rosenbluth suggested that it might be wise to refer these recommendations to a particular budget scenario. Dr. Conn agreed and suggested that they should perhaps be tied to the reference budget scenario. He pointed out that the committee could then develop variations in their report as the budget scenarios changed.

Dr. Holdren said that the third bullet should be eliminated since it did not add anything to the overall argument. There was general agreement here also. A lengthy discussion followed concerning whether or not to retain the fourth bullet. It was agreed, finally, to remove the bullet because the current letter report would refer back to the scenarios and recommendations contained in the report developed at Crested Butte.

Dr. Conn said that he would like to return to the recommendations that had dealt with balance and growth and review the first bullet. Dr. Weitzner commented that he felt uncomfortable since this was too detailed and narrow a recommendation for FEAC. Dr. Berkner explained that the panel had agreed that the program should continue to emphasize the development of ferritic steels until it became clear that they were unsuitable either because of their magnetic properties or because of embrittlement in a fusion environment. Dr. Conn stated that since relatively little was being spent here at present, FEAC might like to review the advisability of emphasizing this particular development. He suggested that the committee might like to accept the advice of Dr. Hirsch and select the material that, collectively, they all thought would have the best future potential, rather than continuing to develop the material that was currently the most advanced.

Dr. Weitzner stated that while FEAC could suggest placing more emphasis on the development of low activation materials, it would not be wise to make choices now. He said that FEAC should not try to decide these issues. Dr. Sheffield agreed that FEAC should not try to micromanage the materials program. He stated that the fundamental problem that the program faced was lack of money. He suggested that FEAC should address that issue first. Dr. Sheffield said that FEAC should not take the report of a panel of experts and argue and amend their conclusions. He emphasized that their report should stand on its own merits. Dr. Conn agreed that the members of the panel had brought a lot of knowledge to their report.

Dr. Berkner explained that all of the materials that were being investigated in the development program would satisfy the low activation aspects. Since ferritic materials were further along in development and already possessed a large data base, it seemed logical to continue the development and to leave SiC/SiC composites for later years. Dr. Conn countered that enough was known about SiC/SiC material to enable one to gamble on it now. Dr. Dale Smith, from the audience, added that SiC/SiC material was not so temperature limiting as ferritic steels. Dr. Berkner said that, in reaching its recommendations, the panel had kept coming back to the fabrication knowledge base. This was extensive for ferritic steels whereas nothing existed for SiC/SiC.

Dr. Holdren presented a viewgraph of the hazard indices for the materials presently in the low activation materials program. He pointed out that while ferritic steels and vanadium alloys were better than austenitic steel, they were still not good enough. SiC/SiC was by far the best material. Dr. Holdren suggested that the fusion program needed to push in that direction. Dr. Conn agreed that that was the argument for SiC/SiC. A general discussion of radiation hazards followed.

Dr. Berkner reiterated the reasons that had led the panel to its specific priorities. The panel had agreed that the ferritic steels program should continue to receive the majority of the funding as was the case at present. Dr. Parker disagreed with this ranking. He stated that all potentially useful materials should have equal funding. He pointed out that there was no certainty that one could even make a tokamak using ferritic steel and questioned the wisdom of placing so much emphasis on the development of that material. Dr. Weitzner took the opposite view. He stated that ferritic steels were furthest along in the development cycle and the present indications were that they would be satisfactory. He suggested that their development should be pursued to a logical conclusion. Dr. Conn emphasized that ferritic steel would not be the material from which commercial fusion reactors would be constructed. He suggested that the fusion program should look at the most promising materials first rather than concentrating its effort on a material that ultimately would be rejected.

Dr. Ness asked why the fusion program was spending so much money on the computer center. Dr. Conn responded that that issue had been dealt with during the meeting at Crested Butte. He emphasized that FEAC had arrived at a set of priorities at the Crested Butte meeting that included the computer center funding, and that the present discussion was taking place within the reference budget scenario. Dr. Ness countered that computer centers currently had less beneficial value than previously because a single scientist working at a modern workstation could accomplish almost as much as a computer center that was a mere few years old. Dr. Conn agreed with Dr. Ness' assessment. Dr. Anne Davies explained for Dr. Ness the budgetary arrangement that had led to support for the computer center being included in the fusion program budget.

Dr. Conn stated that the FEAC statement should contain three thoughts: (a) that the fusion program was developing low activation materials; (b) that three major classes of materials were being studied, i.e. ferritic steels, vanadium alloys and SiC/SiC composites; and (c) that in the reference budget scenario FEAC agrees that the balance between the different structural materials in the base program is about correct, and that titanium alloys should be included if incremental funding becomes available. Dr. Overskei disagreed. He stated that there was no reason to put incremental funding into titanium. He emphasized that since SiC/SiC offered the best potential for success, all incremental funding should be allocated to accelerating this program. Dr. Holdren indicated that this course would be unwise because the program would be assuming greater risk in pursuing SiC/SiC alone, and pointed out that the material could not be developed in the needed time frame. Dr. Conn concurred that it came down to a question of risk management.

Dr. Berkner pointed out that the panel had not recommended directing incremental funding towards the development of titanium alloys. Rather, the panel had recommended reassessing the value of pursuing titanium, should incremental funding become available. Dr. Overskei asked what reason there could be for not pursuing the most promising material to its logical conclusion. He pointed out that at present the fusion program was equally ignorant in all areas. This led to a lengthy interaction between Dr. Overskei and Dr. Dale Smith, in the audience, concerning the potential value of titanium materials. Afterwards, Dr. Overskei commented that Dr. Smith had provided new information that was not in the panel's report. He questioned whether it was wise for FEAC to make a judgment based upon partial information. Dr. Berkner agreed that much of the information for titanium had not been included in the report, but stressed that there had been considerable disagreement within the panel also.

Dr. Berkner provided an explanation of the panel's recommendations concerning ITER. He stressed that while the panel had been aware that FEAC should not dictate to ITER, they had nevertheless felt strongly that if ITER were to follow the panel's recommendations, the materials program would be enhanced. The committee expressed general agreement with the sentiment alongside the first bullet.

With reference to the sentiment of the second bullet, Dr. Parker pointed out that it was not incumbent upon the U.S. to respond to new materials projects spawned by ITER. He stated that the paragraph needed rewriting. The committee agreed with this.

Referring to the third bullet, Dr. Parker indicated that plasma facing components should not be considered as part of just the ITER program. He emphasized that they should be looked upon as part of the neutron interactive materials program too. Dr.Berkner responded that such materials were currently being looked at solely as a part of ITER since the PFC program was ITER based. Dr. Parker stated that such materials should also have a small program outside of ITER. Dr. Conn stated that FEAC needed to modify the statement concerning the base materials program to make reference to this.

Dr. Rosenbluth raised the issue of adding cooling materials to the program. After general discussion, it was agreed that their inclusion would be most appropriate within the structural materials category, where coolants could result in stress corrosion.

A discussion between Drs. Conn and Overskei led to the suggestion that the European Community and Japan should be encouraged to work on near-term materials for ITER credit, since they both were very advanced in the development of these materials anyway, and that the U.S. program should concentrate on longer term issues. This met with general agreement from the committee.

Dr. Conn thanked the panel chair and the members of Panel 6 for the hard work that they had accomplished, and accepted their report, with thanks, on behalf of FEAC.

Responses to The Charge

Panel 6 had prepared a number of suggested responses to the Charge that FEAC was given concerning fusion materials. Although these were not discussed in any detail during the meeting, they were helpful in crafting the first draft version of the letter report. They are presented below:

Response to Charge: IFE vs. MFE

The special needs of the IFE program (optical components, final focus magnets, high intensity, short pulses) are not being addressed in OFE.

Response to Charge: Near-term (ITER) vs. Long-term

The ITER team is still evaluating various combinations of structural materials and coolants and, depending on the outcome, ITER may require an unexpected increase in materials R&D effort. Other areas where expanded efforts may be needed in the near term include divertor materials, ceramics and diagnostic components, and magnet materials. The structural materials funding for long-term applications is about twice as large as the funding for ITER materials. The Panel found this balance to be appropriate, but increases in ITER needs for non-DEMO-relevant materials development should not be allowed to cut into the base program. If the ITER design incorporated either ferritic/ martensitic steels or titanium alloys in high-fluence regions, then ITER development would also help identify good candidates for DEMO.

Response to Charge: Ferritic Steels vs. Vanadium Alloys vs. SiC/SiC Composites

Long-range materials work in fusion consists mainly of investigating these three candidate structural materials. (Titanium alloys may also be candidates, but there is currently no work being done on them). The size of the effort in these materials is roughly in the ratio of 4:2:1. Although the Panel found this balance appropriate, given current funding levels for the total program, these levels are insufficient to meet the aggressive needs and objectives of the long-term fusion program.

Response to Charge: Structural Materials vs. Ceramics and Diagnostic Components

The accumulated database for ceramics to date is very limited, and in comparison with structural metals, relatively little is known about their properties under irradiation. Although ceramics and diagnostic components make up a small percentage of the mass of a fusion core, their performance is likely to be critical for success of the system. In the last few years this situation has been recognized and funding for ceramic work has been increased through redirection of funding. The Panel found the increased effort and the change in emphasis appropriate. However, the current level of effort worldwide is probably not adequate to provide the non-structuralceramics data needed for ITER.

Response to Charge: Domestic vs. Collaborative International Programs

As in other elements of the fusion program, international collaborations play a key role in maximizing progress for the domestic dollars expended. The US materials program seems to be well integrated with the international effort. A major issue that is developing with regard to international collaboration involves the need for a 14-MeV neutron source, as described below.

Response to Charge: Neutron Irradiation Facilities

Testing in fission reactors is a vital component of fusion materials development, and the program relies on both mixed- and fast-neutron-spectrum fission reactors. There is concern about continued availability. One fast reactor (FFTF) is gone, and availability of the sole remaining one (EBR-II) is not assured.

The next generation of fusion facilities will provide opportunities for irradiation tests. ITER is a crucial element in the component development program, and TPX will provide an important high-duty-factor, high-heat-flux tokamak plasma environment for testing the plasma-interactive properties of advanced materials.

Preparation for building a DEMO requires that both ITER and a high-flux 14-MeV neutron source proceed on similar schedules. Two concepts have been proposed: a 35-MeV deuterium beam impinging on a liquid lithium target, and a 120-keV deuterium beam impinging on a mirror-plasma target.

While the proposed accelerator technology for a D-Li neutron source will be challenging (especially if superconducting rf cavities are chosen), the beam current exceeds existing room-temperature cw systems by only a factor of two, and appears feasible. The design of the lithium target system will be difficult, but much was accomplished in the earlier FMIT Project to demonstrate the concept. The volume of high neutron fluence for a D-Li source is small but appears sufficient to support materials development when used in conjunction with fusion systems. This approach appears to be the most direct route to attaining the needed materials testing capability.

Additional plasma physics and significant fusion technology development would be required to implement a 14-MeV neutron source based on a mirror plasma target . This source might be able to provide a larger volume of high neutron flux in a single facility than would a 250-mA D-Li source. The neutron spectrum would not be that found at a fusion system's first wall, but it would not include the high-energy (>14 MeV) neutrons of a D-Li source.

Report Preparation

Five paragraphs that were intended for incorporation in FEAC's letter of response to the charge were crafted during the latter stages of the meeting. These were reviewed by the committee and generally found to be satisfactory. The five paragraphs are given below:

- The current U.S. funding level for development of structural materials for fusion applications — about $10 million per year in the base and ITER programs combined — is inadequate to ensure availability of such materials on timescales consistent with operation of an attractive DEMO in 2025. A prudent structural materials effort would grow to about twice the current level by 1996-1997, and would continue to grow thereafter to provide for U.S. participation in international construction of a 14-MeV neutron source.

- The U.S. should seek an international commitment for design and construction of a high-fluence 14-MeV neutron source, with the aim of operation shortly after the year 2000. We consider the accelerator-based D-Li system to be the preferred approach for this function.

- Low/reduced activation structural materials must meet a variety of requirements to function in a reactor environment. Currently, the program supports efforts in three areas offering different mixes of benefit and risk; in order of decreasing support, these are ferritic steels, vanadium alloys, and SiC/SiC composites. Given the increments available in the assumed Reference Scenario, we recommend that priority be given to enhancing the vanadium-alloy and SiC-composite programs. Titanium alloys may also represent a promise that is not now under investigation and may warrant reassessment.

- The ITER and TPX Projects should give serious consideration to the use of low/reduced activation materials in appropriate major components. (We understand that TPX already plans to use titanium alloy for its vacuum vessel.) This would have the benefit of providing large-scale practical experience with low/reduced activation materials.

- It is important that the long-term, base materials program be protected against diversion for near-term non-DEMO-relevant materials development. The base materials program should focus on low/reduced activation structural materials, with relatively smaller but still important efforts on neutron irradiation issues in ceramics, coatings, and plasma facing components.

Terrence A. Davies
IPFR/UCLA
March 31, 1993

Appendix III

Minutes of FEAC Meeting of April 15, 1993.

MINUTES

Meeting of Fusion Energy Advisory Committee
Sheraton Reston Hotel
Reston, VA 22091

April 15 and 16, 1993

Present: Dr. Robert W. Conn, Chairman, UCLA
Dr. David E. Baldwin, LLNL
Dr. Klaus H. Berkner, LBL
Dr. Ronald C. Davidson, PPPL
Dr. Stephen O. Dean, Fusion Power Associates
Dr. John P. Holdren, UCB
Dr. Robert L. McCrory, Jr., University of Rochester
Dr. Norman F. Ness, University of Delaware
Dr. David O. Overskei, General Atomics
Dr. Barrett H. Ripin, NRL
Dr. John Sheffield, ORNL
Dr. Richard E. Siemon, LANL
Dr. Peter Staudhammer, TRW
Dr. Harold Weitzner, NYU

Thursday, April 15, 1993

Further Review of the Fusion Materials Development Program

Background

The topic that had been reviewed by FEAC at its meeting of March 4 and 5, 1993, was the development of materials needed for the fusion program. Before transmission of a letter-report to Dr. Happer, Dr. Ron Parker objected to one of the conclusions and it was therefore necessary for FEAC to review the matter again in public session.

In objecting to the conclusion concerned, Dr. Parker questioned the wisdom of the relative priorities that the various materials enjoyed within the current development program. The materials concerned were ferritic steels, vanadium alloys and SiC/SiC composites, with the development of ferritic steels receiving the major share of the available financial support. The conclusion at the March 4/5 meeting was to apply any incremental funding preferentially to the vanadium and the SiC/SiC programs. Dr. Parker did not support this position and preferred instead to reduce support for the ferritic steels program and to apply the resulting funding to the development of vanadium alloys. Dr. Parker contended that the ductile properties of ferritic steels made them unsuitable for fusion, and that neutron bombardment would result in the material becoming radioactive at a rate that was unacceptable. He expressed his concerns to Dr. Conn, and a series of communications took place between Dr. Conn and Dr. Parker in an endeavor to determine if a compromise could be reached in the wording that was acceptable to Dr. Parker while still embracing the sentiment that had been accepted by FEAC at the March meeting.

Following this exchange of correspondence and the wording of an alternative paragraph, Dr. Parker agreed that Dr. Conn could circulate, to all members of FEAC, the communications that had taken place between them together with both versions of the paragraph that was in dispute. Dr. Conn requested a "straw" vote of committee members to determine whether a strong preference existed for one paragraph or the other. No obvious choice emerged and it became necessary to debate the matter again in public session.

The Debate

Dr. Conn presented the result of the "straw" poll that had been taken:

Position on Paragraph	Number of Votes
Preferred the original version	6
Preferred the new version	3
Felt need for some modification	2
Expressed no preference	1
Failed to vote	5
Total	17

Dr. Conn then presented a viewgraph which contained a comparison of the two paragraphs:

ALTERNATIVE RECOMMENDATIONS ON THE BALANCE OF THE MATERIALS PROGRAM BETWEEN FERRITICS, VANADIUM, AND COMPOSITES

Alternative #1: The Original Version

Low/reduced activation structural materials must meet a variety of requirements to function in a reactor environment. Currently, the program supports efforts in three areas offering different mixes of benefit and risk; in order of decreasing support, these are ferritic steels, vanadium alloys, and SiC/SiC composites. Given the increments available in the assumed Reference Scenario, we recommend that priority be given to enhancing the vanadium-alloy and SiC-composite programs. Titanium alloys may also represent a promise that is not now under investigation and may warrant reassessment.

Alternative #2: The Proposed Amended Version

Low/reduced activation structural materials must meet a variety of requirements to function in a fusion reactor environment. Currently, the program supports efforts in three areas offering different mixes of benefit and risk; in order of decreasing support, these are ferritic steels, vanadium alloys, and SiC/SiC composites. Given the increments in funding available in the assumed Reference Budget Scenario, FEAC recommends that priority be given to enhancing the vanadium alloy and SiC/SiC composites programs, and that the ferritic steels program be reduced to a level not more than half that available to the two other materials. Studies by the ESECOM group commissioned by DOE/OFE several years ago showed that the two material groups, vanadium and SiC/SiC, were preferable for DT fusion reactors in terms of indices for safety and environmental characteristics. Titanium alloys may also represent a promising material that is not now under investigation and the DOE should consider whether a reassessment is warranted.

Dr. Conn also handed out to the committee copies of their responses to the "straw" poll, and the latest letter from Dr. Parker that had arrived just the day before the meeting started. He emphasized that this was the only paragraph that was in question and that there was still complete agreement on the others. He suggested that each member of FEAC should express his views in turn, but that Dr. Berkner should start, since he had been the Chairman of Panel 6, and that Dr. Siemon should follow Dr. Berkner since Dr. Siemon had been the co-chairman of the panel.

Dr. Berkner stated that the fusion materials program was so under-funded that it was unable to support any of the development efforts properly. In those circumstances, the panel had seen very little point in taking apart the present program and putting it back together with changed emphasis. Dr. Berkner reminded the committee that the panel had reviewed austenitic stainless steel, for which a great deal of knowledge concerning manufacturing and fabrication existed. The status of three other materials had also been investigated: ferritic steels, vanadium alloys and SiC/SiC composites. The panel discovered that the development of one other material, titanium, had been dropped due to lack of funding.

Dr. Berkner stated that a lot was already known about ferritic steels and that, at the very least, these materials would be suitable for shallow waste burial. Improvements to them were still being made and the panel had considered it wrong to de-emphasize this program when so much was known about such materials. Dr. Berkner pointed out that manufacturing and fabrication techniques had not yet been developed for vanadium: The material was also subject to hydrogen embrittlement.

Referring to SiC/SiC composites, Dr. Berkner said that only small pieces of such material had been made so far and that participants in the program were a long way away from being able to manufacture the material in significant size and quantity. Furthermore, no one knew how to weld such material and no one knew how to seal it hermetically.

Dr. Berkner emphasized that ferritic steels were further ahead than the other materials in their development, and since nothing had yet been discovered about the material to indicate that the work should be discontinued, the panel had felt it best that the development of ferritic steels should proceed in order to develop the data base. Dr. Berkner indicated that this was what the first (original) paragraph said. It did not tie DOE's hands, whereas the proposed amended (second) paragraph was overly prescriptive.

Dr. Weitzner stated that he preferred the original paragraph since he, also, felt that the amended one was too prescriptive. He said that he was prepared to support the second paragraph in preference to the first if FEAC agreed to remove the actual levels of support specified in it. Dr. Conn drew parentheses around the clauses to which Dr. Weitzner had objected and asked if Dr. Weitzner would support this paragraph if the words in parentheses were struck. Dr. Weitzner answered affirmatively.

The words that Dr. Weitzner proposed removing were:

> "Given the increments in funding available in the assumed Reference Budget Scenario, . . . and that the ferritic steels program be reduced to a level not more than half that available to the other two materials".

Subsequently, it was also agreed to remove the entire sentence:

> "Studies by the ESECOM group commissioned by DOE/OFE several years ago showed that the two material groups, vanadium and SiC/SiC, were preferable for DT fusion reactors in terms of indices for safety and environmental characteristics."

Dr. Sheffield said that he agreed with Dr. Berkner. He suggested that nothing should be changed until after the ITER Technical Advisory Committee's plan had been developed. At that time, FEAC could review the situation and determine what changes it might recommend. Dr. Sheffield added that, in the meantime, he preferred the original paragraph.

Dr. Overskei expressed concern over the existing ratios in the funding between the competing programs, and how they had been established. He indicated that the amended paragraph suffered from the same defect. In neither case was any justification provided for the ratios that were involved. He added that he would vote for the amended paragraph if all reference to levels of support was removed from it.

Dr. Siemon agreed that he had been unable to find adequate justification for the existing funding ratios. In general, he felt that more emphasis on materials with reduced-activation for the long-range development of fusion was needed. A gradual shift in funding from steels to vanadium would be sensible, especially since the EC and Japan already had strong efforts on steels and little or no effort on vanadium. Vanadium appears to offer the best combination of practicality and reduced activation. He would vote for the modified version of the amended paragraph.

Dr. Ness stated that since there was such a long lead time in the development of new materials, the fusion program should pursue the most promising materials now. He preferred the modified version of the amended paragraph. Dr. Baldwin also stated a preference for the modified amended paragraph.

Dr. Holdren stated that while he preferred the modified amended paragraph, he could also support the original one. He emphasized that what he found totally unacceptable was the statement that had been made at the previous FEAC meeting in March, that the "balance in the materials program was about right". He added that he would like to correct a statement made by Dr. Parker during the course of his communications with Dr. Conn that ferritic steels provide no advantages in terms of environmental safety. He emphasized that ferritic steels offer a large improvement over the austenitic variety but pointed out that the newer materials offered even greater advantages.

Dr. Ripin stated that he preferred the original version as articulated by Dr. Berkner, since Panel 6 had experts who looked into the technical issues. However, if Panel 6 agreed with the modified amended wording, then Dr. Ripin had no preference for it or the original. Dr. McCrory stated that FEAC was inclined to make judgments and comments that were beyond its expertise. He said that while it was perfectly correct for FEAC to point out that the program was underfunded, FEAC should not attempt to impose a technological solution upon the program. His preference was for the original paragraph. Dr. Davidson indicated that he also preferred the original paragraph.

Dr. Dean said that he preferred the original paragraph. The panel's report had shown that ferritic steels, vanadium alloys and SiC/SiC composites were all superior to austenitic steels. The amended paragraph tended to imply that vanadium and SiC were the only materials that offered improvement.

Dr. Staudhammer pointed out that all of the materials under consideration were in their infancy, and that very much work needed to be undertaken on their development. He stressed that FEAC should keep all the options open. His preference was for the modified amended paragraph.

Dr. Conn stated that he also favored the modified amended paragraph. While ferritic steels were better than the austenitic variety, the other two material systems were not just better but were significantly better. They offered a quantum improvement. He asked Dr. Holdren to display again the viewgraph that he had presented at the March meeting relating to the radioactive characteristics of the material systems concerned. Several members of FEAC requested that the viewgraph be recorded in the minutes of the meeting. The viewgraph is reproduced at the end of these minutes as Table 1. Dr. Dean stated that, in his view, the table did not indicate a "quantum improvement" of vanadium over ferritic steels, although one could argue that SiC offered a "quantum improvement".

Dr. Conn emphasized that the important criteria in the table were those described as "critical dose" and "chronic dose", since these were the dosages that would be relevant in the case of a reactor accident. Dr. Holdren pointed out that a structural material that would not work would bring no advantages at all. Dr. Conn suggested that the modified amended paragraph would permit DOE to choose whether to change the emphasis in the materials program, and when to change it, and would allow them to take into account variations in funding levels.

Dr. Conn asked for a show of hands to help determine whether FEAC should include the original paragraph, Alternative #1, or the amended paragraph, Alternative #2, as modified during the current discussion, in its letter-report to Dr. Happer. A vote was taken but it was clear that there was some confusion among members of the committeeconcerning the choice that was to be made. Dr. Conn clarified the situation and a second vote was taken. This vote was 13 - 1 in favor of including the modified amended paragraph, which read:

> Low/reduced activation structural materials must meet a variety of requirements to function in a fusion environment. Currently, the program supports efforts in three areas offering different mixes of benefit and risk; in order of decreasing support, these are ferritic steels, vanadium alloys, and SiC/SiC composites. FEAC recommends that priority be given to enhancing the vanadium alloy and SiC/SiC composites programs. Titanium alloys may also represent a promising material that is not now under investigation and the DOE should consider whether a reassessment is warranted.

Terrence A. Davies
IPFR/UCLA
April 21, 1993

Table 1

ACTIVATION HAZARDS VERSUS MATERIAL CHOICE

The following data are for first walls (only) of conceptual fusion-reactor designs developed in the ESECOM study[1], all with fusion powers around 3000 thermal megawatts and neutron wall loadings around 3 MW/m^2. Dose models have been updated since ESECOM and calculations performed for a stainless steel case (PCA - Primary Candidate Alloy, from Starfire study) derived from the ESECOM base case by substituting PCA for VCrTi alloy on a 1-to-1 basis (ESECOM contained no stainless steel cases)[2]. Inventory and dose calculations are for first-wall exposure of 20 $MWyr/m^2$. Confining attention to first walls eliminates effects of diverse materials in other reactor components in the ESECOM designs; inventories and doses for whole reactors would of course be higher. RAF = Reduced Activation Ferritic steel, VCrTi = vanadium-chromium-titanium alloy, SiC = silicon carbide (compositions are given below the table).

	PCA	RAF	VCrTi	SiC
Inventory at shutdown[A], gigacuries	1.8	1.2	0.5	0.8
Decay heat in first hour, gigajoules	22	16	8	3
Decay power density at 15 min.[B], W/cm^3	0.9	0.9	0.3	0.03
Maximum plausible critical dose[C], rem	380	190	90	0.9
Maximum plausible chronic dose[D], rem	14000	7000	300	0.4
Waste intruder hazard potential[E], rem*m^3/yr	300	0.6	0.8	0.02
Unshielded contact dose rate @ 7 d[B], rem/min	80000	30000	10000	0.7
Unshielded contact dose rate @ 30 yr[B], rem/hr	9000	60	0.6	0.3

A. A very poor index of anything, shown here to illustrate how badly it correlates with more meaningful indices of relative hazard.

B. Not shown in the transparency itself; added here to give a more complete picture.

C. Whole-body-equivalent critical dose (100% of dose experienced in first week after exposure + 50% of dose delivered in 8^{th}-30^{th} days after exposure) to an individual who remains on the plume centerline, 1 km from the release, for the duration of plume passage, under meteorological conditions that maximize this dose. Release fractions are 1.0, 0.3, 0.1 0.03, 0.01 for five categories of activation products classified from most volatile to most refractory. Threshold for no early fatalities is 200 rem. See Ref. [1].

D. Whole-body-equivalent chronic dose from ground contamination on plume centerline 10 km from release, to an individual who remains there for 50 years (includes inhalation of re-suspended material but not intake in food and water). Release fractions as in Note C. Threshold for no evacuation is 25 rem. See Ref. [1]

E. Volume-weighted maximum dose to an intruder into a shallow-burial repository between 100 and 1000 years after waste emplacement, per reactor-year of operation. See Ref. [1].

MATERIAL COMPOSITIONS ON WHICH THE FOREGOING DATA ARE BASED
(weight fractions)

PCA: 0.6488 Fe; 0.16 Ni; 0.14 Cr; 0.02 Mn, Mo; 0.005 Si; 0.003 Ti; 0.001 V; 0.0005 W; 0.0003 Al, Co, Nb; 0.0002 Cu, As; 0.0001 N, P, Ta; 0.00005 B, C, S, Zr, Sn; 0.00001 Sb, Ba, Tb, Ir, Pb, Bi; 0.000003 K; 0.000002 Cd; 0.000001 Ag.

RAF: 0.8516 Fe; 0.11 Cr; 0.025W; 0.0053 Mn; 0.003 V; 0.002 Si; 0.0015 C; 0.001 Ti; 0.00013 P; 0.00008 Al; 0.00007 O; 0.00006Ni; 0.00005 Co; 0.00004 S; 0.00003 Cu, Sn; 0.00001 B, N, Zr; 0.000005 Sb, Pb; 0.000004 Ta; 0.000003 K; 0.0000027 Mo; 0.000002 Ba, Tb, Ir, Bi; 0.000001 Nb, Cd; 0.0000009 Ag.

VCrTi: 0.798 V; 0.150 Cr; 0.050 Ti; 0.0003 Si; 0.0002 Al; 0.0001 N, O; 0.00005 C; 0.00004 Fe; 0.00003 P; 0.00001 S, Mo, Ta; 0.000004 Ni, Nb; 0.000002 Cu, As, W; 0.000001 Cl; 0.0000001 K.

SiC: 0.7005 Si; 0.2995 C; 0.000011 Fe; 0.0000003 Co.

REFERENCES

[1] John P. Holdren, David Berwald, Robert Budnitz, Jim Crocker, Jerry G. Delene, Ron Endicott, Mujid Kazimi, Robert Krakowski, Grant Logan, and Kenneth Schultz, "Exploring the Competitive Potential of Magnetic Fusion Energy: The Interaction of Economics with Safety and Environmental Characteristics", FUSION TECHNOLOGY, Vol. 13, No. 1, pp. 7-56, 1988. See also, by the same authors, "Report of the Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy", Report UCRL-53766, Lawrence Livermore National Laboratory, September 1989, 345 pp.

[2] S. K. Ho, T. K. Fowler, and J. P. Holdren, eds., "Code Development Incorporating Environmental, Safety, and Economic Aspects of Fusion Reactors (FY 89-91)", Berkeley, CA: Berkeley Fusion Engineering Project, University of California, November 1991, 167 pp.