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Review of the Fusion Materials Research Program

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This report presents the results and recommendations of the deliberations of the U.S. Department of Energy (DOE) Fusion Energy Sciences Advisory Committee Panel on the Review of the Fusion Materials Research Program carried out during 1998. Metrics evaluated included evidence of recognition, publications per worker, new people attracted to the work and significance of recent accomplishments.

KEY WORDS: Fusion materials; fusion neutron source.

EXECUTIVE SUMMARY

The Fusion Energy Science Advisory Committee was asked to conduct a review of Fusion Materials Research Program (the Structural Materials portion of the Fusion Program) by Dr. Martha Krebs, Director of Energy Research for the Department of Energy (DOE). This request was motivated by the fact that significant changes have been made in the overall direction of the Fusion Program from one primarily focused on the milestones necessary to the construction of successively larger machines to one where the necessary scientific basis for an attractive fusion energy system is better understood. It was in this context that the review of current scientific excellence and recommendations for future goals and balance within the Program was requested.

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Scientific Quality of Present Program

The scientific quality of the work was judged to have elements of very high scientific quality and all elements are being conducted in a competent manner. Metrics evaluated included evidence of recognition, publications per worker, new people attracted to the work, and significance of recent accomplishments.

The current Program funding supports ~15 FTEs and represents about 3% of the DOE's Office of Fusion Energy Sciences FY1998 budget. It is, therefore, obviously not adequate to undertake the qualification of any new materials system. The Program has used the resources to focus on materials performance questions, particularly those associated with radiation damage.

Situational Analysis

In looking ahead at recommended future goals and the balance required to achieve them, it is important to consider the assessment of the current situation for fusion energy to provide a context for the Panel's suggestions and comments. Key aspects of this situational analysis included:

- Fusion energy R&D is inherently a long-range endeavor aimed at the development of an attractive power systems concept by the middle of the next century. The results of focused materials research and development will be determinant to the realization of the potential of fusion energy as well as important to the design and construction of nearer term experimental facilities.
- The U.S. Fusion Energy Sciences Program has been restructured to focus on science and technology innovation, while pursuing energy production technology through international collaboration.
- The use of fusion power by the world's societies will ultimately be determined by its relative attractiveness to other energy alternatives. Although the exact weighting of decision factors is impossible to establish at this time, it is clear that capital cost, operating expense, plant availability, worker and public safety, and final decommissioning and waste disposal costs will all be considerations.
- It is prudent to assume that the funding resources for R&D materials will continue to be constrained (as will be the overall U.S. program) at about present levels. Some modest growth may be possible. In the long-term, significantly more resources will be required to develop the materials and technology for fusion energy.
- In the near-term the materials R&D efforts will emphasize issues related to deuterium/tritium fusion. At the same time, the program needs to account for various possible magnetic and inertial confinement approaches. In the long-term alternate fusion fuel cycles should also be considered.
- One should anticipate continued, significant enhancement in computing capability as it relates to modeling of materials performance.

Key Issues

The materials feasibility issues for fusion energy are motivated by the long-term view of the needs for attractive, commercial power systems. From a users' perceptive (e.g., electric generating companies) the major requirements are economic competitiveness, safety (e.g., no accidents which lead to public evacuation near the site), a closed tritium fuel cycle, ability to maintain the power core, reliable operation (very low number of unscheduled shut-downs per year), and no, or at least minimal, radioactive material greater than Class C waste storage. Achieving economic competitiveness implies more compact reactors, which usually means higher power densities, high temperatures for high thermal efficiencies, modest component fabrication costs, low failure rates, high reliability, low unscheduled outages, and acceptable lifetimes to minimize scheduled replacements. Unfortunately, a clear materials/design path has not yet emerged that can provide a balanced combination of these important attributes.

Perhaps the most important "key issue" for fusion materials development is the recognition that the fusion environment and needs for an attractive power system concept present a major challenge involving a wide variety of complex, interacting phenomena and conditions. This directly implies that materials R&D activities should be considered as part of an integrated program along with engineering science research, technology/component development, and advanced design and systems assessments.

Goals and Objectives

The recommendation of the Panel, based on the current situation, is that the Fusion Materials Program adopt as its goal:

> *To provide the materials science knowledge base that will enable the utilization of fusion energy. The near-term emphasis will be on feasibility issues for in-vessel components for deuterium/tritium systems.*

The Panel further recommends the following as the main supporting objectives of the program:

1. Based on an integrated effort including materials research, advanced technology and design studies, identify candidate material systems for meeting the needs of fusion energy.
    - More fully integrate the planning and conduct of the materials R&D activities with engineering science research, technology/component development, and advanced design and systems assessments. System roadmaps are useful tools for defining the feasibility questions, necessary skills, and required resources.
2. Provide the knowledge base on the effects of the fusion environment on materials performance.
    - For each of the three materials approaches currently under study (ferritic alloys, vanadium alloys, and silicon/carbide-based composites), focus on the property limitations and the system level questions that could prevent an attractive design from being developed.

- IFE concepts may require special emphasis on thick liquid walls (may also be applied to MFE) and optical materials. An assessment that will identify the key materials feasibility issues related to IFE systems is needed.

3. Identify the performance-limiting phenomena and apply the materials science principles to the development of improved properties and the expansion of performance windows.
   - The combined advances in material science understanding and computing capability extend the ability to develop meaningful physically based, semi-empirical models that can guide and help interpret experimental information. These should be applied to the key identified feasibility issues. Crosscutting concerns, such as the overall effects of a combined high generation rate of gas and atomic displacements, are particularly good candidates.
   - Exploratory approaches and materials should be identified and pursued if they offer greater potential to satisfy the combined requirements of performance, reliability, safety, and long-term waste disposal.
4. Develop performance data and provide materials input for fusion design studies.
   - It is recognized that most of the extensive generation of detailed, system specific engineering design data will not be needed until such a time as the overall program is prepared to commit to an attractive energy system. It must be recognized that the development of the required information will require years to accumulate.
5. Pursue fusion energy materials science and technology as a partner in the international effort.
   - It is very important to coordinate the U.S. effort with others based on the complexity of the materials challenge and the level of resources available in the United States.

Balance of the Program

The Panel considered the appropriate balance between current programmatic elements in the context of the suggested goal and objectives and the overall international effort on materials. The intermediate term and, ultimately, long-term program objectives, would be enhanced by greater emphasis on data analysis and modeling and pathways to introduce exploratory and innovative materials concepts. These exploratory efforts should consider the needs of innovative magnetic confinement concepts, as well as the needs of inertial fusion energy.

The fusion materials program should maintain a focus on key issues related to in-vessel structures in a D-T fueled reactor, with significant emphasis on irradiation experiments. Those issues that threaten the viability of a design concept should be addressed first. It is recommended that the fraction of research related to basic understanding of materials performance in the fusion environment be increased. This increase is motivated by increased capability and sophistication of computer modeling, the need to make the most effective use of expensive and difficult-to-obtain materials data, and the desire to form stronger connections with the greater scientific community. There is also a great opportunity to develop and apply modern computational tools to engineering design, analysis, and simulation of in-vessel components. Such studies would benefit the materials research program by sharpening the understanding of performance requirements and promoting the development of advanced design methods needed to assure structural integrity without undue conservatism.

Introduction of new ideas and people to the fusion materials program should be encouraged. Modest increases in funding and yearly opportunities for competitive, peer-reviewed proposals are possible mechanisms to support such renewal. Innovative approaches to promoting sustained and mutually beneficial collaborations between laboratories, universities, and industry should be developed. Standards of quality, performance, and progress toward program goals should also be more fully developed and used to prioritize the investments made by the Office of Fusion Energy Sciences.

Specialized Facilities for Materials Research and Development

As part of the overall charge, the Panel was asked to review the program efforts aimed at a fusion neutron source test facility including U.S. involvement in the international fusion material irradiation facility (IFMIF). The Panel also considered the general topic of specialized facilities for materials research and development.

In the absence of a test facility with a prototypical fusion environment, fission reactors will remain the primary test facilities for fusion material irradiation. The value of fission reactor irradiation can be enhanced considerably by: (1) continued emphasis on innovative techniques to better simulate helium, hydrogen and other transmutation rates; and (2) more emphasis on modeling to better understand and extrapolate radiation damage results to those expected in fusion spectra.

The panel did not make a technical assessment of the merits of an accelerator-based neutron test facility.

Because of the current fusion budget situation, there are considerable uncertainties in the decision to construct IFMIF. Given such uncertainties, it does not seem prudent to assume that an IFMIF-type facility will be available over the next decade. If funding for a materials test facility becomes available, the panel believes that a review of the relative merits of different materials and blanket test facilities concepts should be made at that time. Both plasma-based volumetric sources and accelerator systems should be considered.

Resource Allocation Perspective

The current Fusion Materials Program is funded at about an annual budget of $6 million. The activities that are covered by these resources are currently focused on advanced ferritic alloys (~25%), vanadium alloys (~50%), and SiC composites (~25%) but with smaller efforts on modeling, neutron source studies, and insulating ceramics. These funding levels must be considered in the context of the world-wide effort that is shown in Appendix 1. For the total international effort, roughly 45% is on ferritic alloys, 14% on silicon carbide composites and 22% on vanadium alloys. The Panel felt that the U.S. effort should continue to remain involved with the ferritic alloys program while exploring the potential for vanadium alloys and silicon carbide composites. The Panel believes that some enhancement is needed in modeling and materials to support exploratory concepts for both MFE and IFE that are emerging in the restructured Technology Program. It is recommended that a modest increase be made in the Fusion Materials Budget of $1 million to $2 million dollars per year to support these new initiatives.

Additional modeling and knowledge-base development support should be sought from outside the fusion materials program (such as combined efforts with the BES materials program, the ER strategic simulation initiative, and the Stockpile Stewardship materials modeling effort.

At the modest level of the current base program, there are few resources available beyond what are needed to address the identified materials system feasibility issues. However, if a flat materials budget is necessary, then the Panel recommends that the SiC program be reduced and, if necessary, a smaller reduction of the vanadium program to allow the recommended initiatives in modeling and exploratory approaches. This recommendation on funding priorities is based on the following rationale:

- There are serious issues related to the ability to fabricate large complex components out of an inherently brittle material like SiC composites for use in the fusion environment even if the irradiation performance problems are solved.
- The vanadium program is the largest U.S. program and would therefore be the least impacted by the modest funding reduction.
- The level of funding for advanced ferritics is the minimum necessary to leverage the larger programs in the EU and Japan.

Background

The Fusion Energy Science Advisory Committee was asked to conduct a review of the Fusion Materials Research Program (the Structural Materials portion of the Fusion Program) by Dr. Martha Krebs, Director of Energy Research for the Department of Energy. This request was motivated by the fact that significant changes had been made in the overall direction of the Fusion Program, from one primarily focused on the milestones necessary to the construction of successively larger machines to one where the necessary scientific basis for an attractive fusion energy system is better understood.

It was in this context that the review of current scientific excellence and recommendations for future goals and balance within the Program was requested. The last Review of the Fusion Materials Program (although broader in charter than this Review) occurred in 1993. The scientific excellence of the current Program was considered in the context of the conclusions reached by that review. Key results from 1993 included: (1) that low/reduced activation materials offer the potential to improve the safety and environmental performance of fusion energy; (2) that preparation for building a Demonstration Reactor requires that both ITER and a 14 MeV neutron source proceed on a similar schedule; (3) that fission-reactor testing is a crucial element of any viable strategy; (4) that ultimately the needed materials qualification effort will require an investment of several hundred million dollars; and (5) that an evolutionary rather than revolutionary introduction of new materials is suggested.

In general, the current review found that the materials work sponsored by the Office of Fusion Energy Sciences (OFES) was responsive to these major conclusions. The Program is almost exclusively focused on the development and preliminary qualification of low activation materials. About 60% of the budget is directed toward understanding their response to neutron irradiation.

The make-up of the Committee comprised a mixture of materials scientists familiar with the requirement of advanced nuclear systems as well as physicists and nuclear engineers knowledgeable of the needs of both magnetic and inertial fusion systems.

Background information was provided through the OFES (Dr. F. W. Wiffen) and at a Panel meeting held in Pittsburgh on March 2–3, 1998, where many principal contributors provided expert opinion on both the current status and the future needs for the Program.

A second meeting of the Review Panel was held in San Diego on April 16–17, 1998, to formulate a position on the key Panel findings.

Scientific Quality of Present Program

The Panel developed four metrics to assess the scientific quality of the current program:

1. publications and peer recognition;
2. an evaluation of recent technical achievements;
3. interest by other segments of technology as evidenced by technology transfer; and
4. the ability to attract young professions to work on the program and university interactions.

Based on these metrics, the Panel concluded that the present program was judged to have elements of very high scientific quality and all elements of the program are being conducted in a competent manner.

Highlights from this review included:

1. Publications and Peer Recognition:
   - 300 papers published between 1995 and 1998.
   - Publications prolific; rate has been 4.5/full-time equivalent/year.
   - 50% of publications in *Journal of Nuclear Materials*.
   - Four members of the community have been named Fellow of the American Society of Metals, two of the American Nuclear Society.
2. Recent Technical Achievements—Six were noted to be particularly significant. These were:
   - The superior resistance to radiation-induced shifts in the Ductile-Brittle Transition Temperature (DBTT) and the superior swelling resistance of the low activation 9Cr-2WVTa ferritic/martensitic steel is a major finding that has very important implications for performance of devices in radiation environments. This alloy is the basis for Japanese development efforts on the F82-H steel.
   - The success of molecular dynamic (MD) simulations in describing cascades in iron and in demonstrating that the primary radiation damage event is similar for fission neutrons and 14 MeV neutrons allows both further modeling and simulation and fission reactor-based experiments to proceed with greater confidence.
   - The development of physically-based micromechanical models for failure in the ferritic/martensitic steels and the progress in developing methodologies to relate small specimen property measurements to full-size components greatly increases the confidence in the results of tests on irradiated specimens and in radiation environments where the physical facilities limit the size of specimens. These results should find widespread applications because almost all mechanical property testing is conducted on samples that are small relative to the size of structural components.
   - The controversy surrounding the claim of permanent electrical degradation of ceramic insulators exposed to radiation that generates point defects was resolved by a series of cleverly-designed and carefully-conducted experiments in collaboration with Japan.
   - The SiC/SiC composite program element has established a strong interaction with U.S. industry and other DOE programs. It has made effective use of the SBIR program.
   - Significant progress has been made in developing the technology base for vanadium alloys. A commercial heat of 1200 kg of the alloy V-4Cr-4Ti has been successfully produced, with impurity control, and has been formed into a variety of product forms (plate, sheet, rods). Advances in both Gas Tungsten Arc (GTA) and electron beam welds have produced weldments with acceptable unirradiated DBTT.
3. Transfer of Technology

Although technology transfer is not a main thrust of this program, the extent to which its findings are adopted by the commercial section is an indicator of the quality of work. The panel identified at least four areas in which significant interaction has occurred. The steel industry has adopted many of the developments associated with the ferritic/martensitic steels and there now exists a good industrial base for these materials. Second, the procedure for MD calculations have been adopted by segments of the semiconductor industry to predict and model the irradiation effects associated with ion implantation during fabrication of device. The third example is the use of fracture mechanic tools to allow the extension of results from small test specimens to the prediction of the performance of large components. Finally, it was noted that the interaction with industry on the SiC composites has been extensive.

4. Attraction of young professionals and university interactions

Another indicator of quality is the ability to attract highly qualified, recent graduates to the program activities. The recent additions to the research staff have doctorates from respected universities and have outstanding records in their graduate studies. They have blended with the staff who have extensive experience in irradiation testing and alloy development to form strong teams.

University interactions include the support of doctorate research at University of California–Santa Barbara, RPI, University of Tennessee–Knoxville, Northwestern University, and Auburn University. In many cases, investigators at one of the laboratories have acted as co-advisors for the graduate study. This activity provides input and guidance for the next generation of materials scientists/engineers.

Situational Analysis

In looking ahead at recommended future goals and the balance required to achieve them, it is important to consider the Panel's assessment of the current situation for fusion energy to provide a context for our suggestions and comments. Key aspects of this situational analysis included:

- Fusion energy R&D is inherently a long-range endeavor aimed at the development of an attractive power systems concept by 2050. The results of focused materials research and development will be determinant to the realization of the potential of fusion energy, as well as important to the design and construction of nearer term physics experiments.
- Work to date has illustrated the challenges presented to a first wall and blanket system by a 14 MeV neutron spectrum. System solutions, such as thick liquid walls that reduce the neutron damage to the structural components, might expand the performance of IFE or MFE systems. Thin liquid walls are also of interest, even though they would not reduce the radiation damage significantly because they would sharply lower the thermal and fatigue loading due to the incident heat flux.
- The use of fusion power by the World's societies will ultimately be determined by its relative attractiveness to other energy alternatives. Although the exact weighting of decision factors is impossible to establish at this time, it is clear that capital cost, operating expense, plant availability, worker and public safety, and final decommissioning will all be considerations.
- The U.S. Fusion Energy Sciences Program has been restructured to focus on science and technology innovation, while pursuing energy production technology through international collaboration.
- It is prudent to assume that the funding resources for materials R&D will continue to be constrained (as will be the overall U.S. program) at about current levels. Some modest growth may be possible. In the long-term, significantly more resources will be required to develop the materials and technology for fusion energy.
- In the near-term, the materials R&D efforts will emphasize issues related to DT fusion. At the same time, the program needs to account for various possible magnetic and inertial confinement approaches. In the long-term, alternate fusion fuel cycles should also be considered.
- One should anticipate continued, significant enhancement in computing capability as it relates to modeling of materials performance.

Key Issues

The materials feasibility issues for fusion energy are motivated by the long-term view of the needs for attractive, commercial power systems. From a users' perceptive (e.g., electric generating companies) the major requirements are economic competitiveness, safety (e.g., no accidents which lead to public evacuation near the site), a closed tritium fuel cycle, ability to maintain the power core, reliable operation (very low number of unscheduled shut-downs per year), and no, or at least minimal, radioactive material greater than Class C waste storage. Achieving economic competitiveness implies more compact reactors, which usually means higher power densities, high temperatures for high thermal efficiencies, modest component fabrication costs, low failure rates, high reliability, low unscheduled outages, and acceptable lifetimes to minimize scheduled replacements.

Unfortunately, a clear materials/design path has not yet emerged that will allow D-T–based fusion to become an attractive energy source with a balanced combination of the system attributes just described. In recent years, the Fusion Materials Program has focused on ferritic steels, vanadium alloys, and silicon carbide composites.

It is generally believed that ferritic steels represent the lowest risk in building a demonstration plant and the first commercial reactors. It has a fabrication base, a good unirradiated database, and can be provided by a number of companies worldwide. For magnetic fusion, the risk is its ferro magnetic characteristic, and if that limits plasma control, then it cannot be used, although this is obviously not a limitation for inertial systems. A second issue is the ductile to brittle transition temperature (DBTT). Because the DBTT temperature after irradiation is on the order of 100°C, the design would have to ensure that the structural temperature is always above 100°C. Another major issue is a temperature limitation of about 550°C (creep limit) that may reduce the reactor efficiency relative to other alternatives.

Vanadium alloys represent a longer range option than ferritic alloys because there is currently no fabrication experience equivalent to ferritic steel. Currently, there is only one supplier in the United States and one in the Russian Federation. It would take a major investment to develop a commercial infrastructure of an equivalent level to the investment the government made in the titanium industry for application to aircraft. Before vanadium alloys can be deployed, it may be necessary to find applications other than fusion, unless fusion can invest $100 million (see vanadium assessment report done by DOE) to develop the necessary commercial infrastructure. Until this infrastructure is built, it is difficult to estimate the eventual materials costs, although it is reasonable to assume they will be several times that of the ferritic alloys. The fusion designer might consider putting it on noncritical fusion components to develop confidence in the material. The main issue with vanadium is that it may be compatible with only a single coolant material (lithium) and, therefore, lacks flexibility in design. The magnetohydrodynamic issues associated with using a liquid metal coolant will require the development of a workable insulator coating.

Silicon carbide composites are truly exploratory materials at this time. It is expected that they will be the most expensive of the three materials to fabricate based on current experience in the aircraft industry, where composites have been difficult to economically include despite 10 years of effort due to design and fabrication issues. The inherent low energy absorbing capability of the structure represents a key design hurdle. Other major challenges are the reliable transfer of mechanical loads to a primary structure and the inherent permeability of the material system. If this latter issue prevents helium from being used as the coolant, it is not clear what other alternatives exist.

Therefore, perhaps the most important "key issue" for fusion materials development is the recognition that the fusion environment and needs for an attractive power system concept present a major challenge involving a wide variety of complex, interacting phenomena and conditions. This implies directly that materials R&D activities should be considered as part of an integrated program along with engineering science research, technology/component development and advanced design and systems assessments. Thus, it is important to think in terms of material systems that meet several operational requirements, such as acceptable impacts on plasma performance, heat extraction at high temperatures, structural integrity under normal and off-normal condition, tritium breeding, radiation shielding, and adequate reliability, maintainability and repairability, to achieve acceptable availabilities. The choice of materials to meet such requirements must result in a compatible combination of coolant, structure, and other materials as required (e.g., lithium-containing and neutron multiplication materials for tritium breeding, electric insulators, tritium barriers, etc.).

The Panel finds that the development of materials for attractive fusion power systems is a major challenge involving a wide variety of requirements, complex phenomena, and conditions. It is necessary to continue to consider material systems in an integrated fashion.

Based on this finding, the Panel recommends that materials R&D activities in the U.S. Fusion Energy Sciences Program should be developed and managed as part of an integrated effort involving materials research, advanced technology and component development, and advanced design activities. The approach to this integrated effort should include the development of "roadmaps" to guide program implementation and should account for the inherent different time scales for research and design activities. We note that "advanced design" includes a variety of studies including detailed engineering efforts (e.g., ITER), conceptual reactor studies (e.g., ARIES), component evaluations (e.g., APEX), and benchmark calculations.

For almost all fusion energy concepts, including both magnetic and inertial fusion, there are systems-level issues that require the combined efforts of materials and engineering science research and component development. The key issues are:

- Identify materials and design concepts with higher power density capability.
- Identify materials and design concepts that can achieve high temperatures resulting in high thermal efficiencies.
- Identify materials and design concepts with sufficiently low failure rates, which when combined with operation and maintenance concepts for suf-

ficiently fast change out times, resulting in an acceptably high availability.

- Identify materials and design concepts that provide for tritium self-sufficiency for deuterium/tritium concepts.
- Identify materials and design concepts that do not require public evacuation under hypothetical accidents.
- Identify materials and design concepts that minimize radioactive waste storage and disposal (e.g., meet Class C requirements and consider recycling).
- For the various materials and design concepts identified above, realistically estimate the effects of the high neutron fluxes and other factors in the operating environment on important system attributes that may degrade continuously with time, like operational limits availability, reliability, as well as ultimate component lifetimes. Other factors in the operating environment like chemical compatibility and optical properties are expected to be important to particular concepts.
- For the various materials and design concepts identified above, define criteria for establishing materials performance limits and identify those material key issues and properties of highest importance.

Many fusion power plant concepts have been studied. The authors of such studies have chosen different balances among the issues identified above. The materials research program should increase the level of understanding of materials limiting phenomena to the point that fusion energy program leaders have the information necessary to make decisions among the various options at appropriate times in the future. This understanding should come from a balanced combination of theory, computer simulation, and materials data.

Proposed magnetic fusion energy (MFE) and inertial fusion energy (IFE) power plant designs sometimes employ in-vessel components and reaction chambers that have some similar issues. Thus, the materials R&D program should study the range of data applicable to both MFE and IFE cases (e.g., increasing the range of He/dpa ratios). However, some very different materials issues exist that will be important to any determination of their feasibility. The materials research program should expand its focus to include the following:

- Working with the design community as concepts are developed, the program should assess what type of materials R&D program is required to support concepts containing thin and/or thick liquid first walls to protect structures from very high neutron wall loadings.
- The program should expand its list of materials receiving attention to include those of interest in IFE reaction chambers and innovative magnetic confinement concepts and include consideration of materials compatibility issues. Examples include copper and other alloys that may be required for high-heat flux components and/or copper magnets.
- The program should resolve what differences, if any, in material damage may exist because of the pulsed versus steady-state operation of MFE concepts as well as the extreme pulsed nature of the IFE neutron flux and how best to obtain data necessary to resolve any uncertainties.
- There are a variety of special purpose material needs related to diagnostics and optical equipment for MFE and IFE. For example, the performance of the optical interface between the driver and the reaction chamber in laser-driven power plants is critical and will strongly affect inertial fusion energy feasibility decisions in the next decade. The materials research program should model and measure how optical properties of candidate materials degrade in the pulsed IFE neutron environment and if and how to mitigate this degradation (e.g., high-temperature self-annealing).

Goals and Objectives

The recommendation of the Committee, based on the current situation and the key issues, is that the Fusion Materials Program adopt as its goal:

> *To provide the materials science knowledge base that will enable the utilization of fusion energy. The near-term emphasis will be on feasibility issues for in-vessel components for deuterium/tritium systems.*

The Panel further recommends the following as the main supporting objectives of the program:

1. Based on an integrated effort including materials research, advanced technology and design studies, identify candidate material systems for meeting the needs of fusion energy.
   - More fully integrate the planning and conduct of the materials R&D activities with engineering science research, technology/component development and advanced design and systems assessments. System roadmaps are useful tools for defining the feasibility questions, necessary skills, and required resources.

2. Provide the knowledge base on the effects of the fusion environment on materials performance.
   - For each of the three materials approaches currently under study (ferritic alloys, vanadium alloys and silicon carbide based composites), focus on the property limitations and the system level questions that could prevent an attractive design from being developed.
   - IFE concepts may require special emphasis on thick liquid walls (may also be applied to MFE) and optical materials. An assessment that will identify the key materials feasibility issues related to IFE systems is needed.
3. Identify the performance-limiting phenomena and apply the materials science principles to the development of improved properties and the expansion of performance windows.
   - The combined advances in material science understanding and computing capability extend the ability to develop meaningful physically based, semi-empirical models that can guide and help interpret experimental information. These should be applied to the key identified feasibility issues. Crosscutting concerns, such as the overall effects of a combined high generation rate of gas and atomic displacements, are particularly good candidates.
   - Exploratory approaches and materials should be identified and pursued if they offer greater potential to satisfy the combined requirements of performance, reliability, safety, and long-term waste disposal.
4. Develop performance data and provide materials input for fusion design studies.
   - It is recognized that most of the extensive generation of detailed, system specific engineering design data will not be needed until such a time as the overall program is prepared to commit to an attractive energy system. It must be recognized that the development of the required information will require years to accumulate.
5. Pursue fusion energy materials science and technology as a partner in the international effort.
   - It is very important to coordinate the U.S. effort with others based on the complexity of the materials challenge and the level of resources available in the United States.

Balance of the Program

Based on the information on the U.S. and International Fusion Materials Programs that is included as Appendix 1, the Committee considered the appropriate balance between current programmatic elements in the context of the suggested goal and objectives and reached the following conclusions.

1. The fusion materials program would benefit from an increase in the fraction of research related to the modeling of materials behavior.
   - The fusion materials program should maintain a focus on key issues related to in-vessel structures in a D-T fueled reactor, with significant emphasis on irradiation experiments. However, the fraction of research related to basic understanding of materials performance in the fusion environment should be increased. This increase is motivated by increased capability and sophistication of computer modeling, the need to make the most effective use of expensive and difficult-to-obtain materials data, and the desire to form stronger connections with the greater scientific community. This basic research should develop mechanistic, microstructurally based models of irradiation effects on material properties. Such semi-empirical models can be used to evaluate, correlate, and extrapolate engineering data; and to provide insight on pathways to improved materials. The modeling approaches should include direct simulation methods, like those based on molecular dynamics and Monte Carlo techniques, which are rapidly developing to link macro- and meso-size scales with rigorous treatments of key phenomena that occur at the atomic scale.
2. In recognition of the new direction in the fusion energy sciences program, additional emphasis should be placed on developing the knowledge base for fusion materials.
   - The fusion materials research program should emphasize: (a) innovative experiments to address key common and long-term issues; (b) assessment of information to provide the best estimates of stress-temperature-displacements per atoms (dpa)-corrosion limits that can be systematically refined and improved with continuing research; (c) increasingly reliable property predictions; and (d) mechanism-based approaches to improved materials. In the near and intermediate term, development of this knowledge base will primarily rely on intermediate dose fission reactor irradiation experiments coupled with an expanded basic

research and modeling effort. This effort should be coupled with the recommended increased efforts to develop micro-mechanical predictive models.

3. An increase in involvement with integrated component modeling would be beneficial to the fusion materials program.
   - There is a great opportunity to develop and apply modern computational tools to engineering design, analysis and simulation of in-vessel components. Such studies would benefit the materials research program by sharpening the understanding of performance requirements and promoting the development of advanced design methods needed to assure structural integrity without undue conservatism. These studies will also lead to major improvements in the engineering science underlying advanced in-vessel designs. Although the fusion materials program should not take the lead in these studies, it should increase its participation in these activities.
4. An increased emphasis should be placed on resolving the key feasibility issues raised by each materials systems in conjunction with other parts of the Fusion Program. Examples for each of the three materials systems which are currently under some level of development include:
   - Ferritic steels
     — The suitability of the application of ferromagnetic materials for in-vessel components in magnetic confinement devices (in collaboration with researchers outside the materials program and with some emphasis on Tokamaks). This should include an analysis of the perturbations of the device's magnetic fields and issues of dynamic control of the plasma.
     — The effect of irradiation, including the influence of helium, on fracture toughness, ductility and constitutive properties to better determine performance constraints over the temperature range of interest.
     — Alloy development and design concepts resulting in higher, maximum operating temperatures in a fusion irradiation environment.
   - Vanadium alloys
     — The viability of electric insulators for candidate liquid metal/vanadium systems and the suitability of coolants other than liquid lithium and possible designs to accommodate the chemical reactivity of lithium (in collaboration with researchers outside the materials program).
     — The effect of irradiation, including the influence of helium, on fracture toughness, ductility, and constitutive properties to better determine performance constraints over the temperature range of interest.
     — High temperature limitations, with particular emphasis on the role of helium in creep and creep rupture and alloy development strategies to expand these limits.
   - SiC/SiC composites
     — Structural joining methods and identification of properties and methods for designing thermal-mechanically loaded, inherently brittle structures.
     — Irradiation effects on thermal conductivity, the stability of fibers and fiber coatings, including the effects of transmutations.
     — Coatings and claddings to provide adequate hermiticity for helium coolants.
5. Opportunities for new and innovative approaches to fusion materials research should be expanded.
   - The motivation for new approaches is illustrated by Table 1, which shows the results of initial calculations done for the APEX study. The allowable neutron loads are sensitive functions of the assumed fraction of the charged particle energy that reaches the first wall, the thickness of the wall, the coolant temperature and the results from detailed analysis of the specific design. While, therefore, the absolute estimates of allowable neutron wall loadings would be expected to change in other studies, the general trends would be expected to be

Table 1. Peak Wall Load Limits for "Dry" First Wall*

Material (Interface Temperature)	Allowable Peak Neutron Wall Loading (MW/m^2)
Ferritic Steel (500°C)	1.5
V-Cr-Ti (600°C)	3.2
SiC-SiC (700°C)	2.5
Oxide-Dispersion Strengthened Ferritic (ODS) (600°C)	2.6
Nb1Zr (700°C)	6.6
Tungsten (800°C)	8.8
TZM (800°C)	13
T111 (800°C)	11.6

* Information taken from "Exploring Novel High Power Density Concepts for Attractive Fusion Reactors," APEX Studies, M. Abdou, *et al.*

maintained. The preliminary APEX calculations shown in Table 1 indicate the possible limitations for any of the current candidate materials in allowable neutron wall loading relative to the level of 7 MW/m^2, which is viewed as an attractive design target. Future inclusion of materials which had previously been eliminated based on long term activation level consideraons alone may open up the system design window. These exploratory efforts should consider the needs of innovative magnetic confinement concepts as well as the needs of inertial fusion energy.

- Therefore, the introduction of new ideas and people to the fusion materials program should be encouraged. Modest increases in funding and a yearly opportunity for competitive, peer reviewed proposals are possible mechanisms to support such renewal. Innovative approaches to promoting sustained and mutually beneficial collaborations between laboratories, universities, and industry should be developed.

6. Peer review should be expanded along with the use of well-defined measures of quality and progress towards program goals.
   - Standards of quality, performance, and progress toward program goals should be more fully developed and utilized at both universities and national laboratories. These metrics should be used to facilitate an ordering of programmatic priorities toward the more promising new developments in material systems. Periodic expert peer reviews in the context of these metrics should be supported. The review panels should include leading materials scientists from outside the program.

Specialized Facilities for Materials Research and Development

As part of the overall charge, the panel was asked to review the program efforts aimed at a fusion neutron source test facility including U.S. involvement in the IFMIF. The Panel also considered the general topic of specialized neutron irradiation facilities for materials research and development.

The fusion environment in which the materials of the in-vessel system have to function is complex and arguably more challenging than faced by any other potential power generation concept.

The time dependent change in mechanical properties and dimensional stability of candidate structural materials that result from the high rate of creation of both point defects and gas atoms increase the difficulty of designing a structure that can reliably sustain the primary and secondary loads imposed by high heat fluxes, coolant circulation and magnetic forces. In addition, there are complex thermal/chemical/mechanical/electrical/magnetic interactions that must be accommodated while the system converts the nuclear energy to a usable form of heat and breeds the tritium required by the fuel cycle.

In a realistic R&D program, particularly for fusion where no appropriate facilities now exist, tests proceed from simple measurements to more complex prototypes in order to reduce cost and facilitate understanding of basic effects and phenomena. Generally, tests can be classified as basic single effect, multiple effect/multiple interactions, and integrated tests.

The structural material program has focused on: (1) basic property measurements on non-neutron test stands, and (2) exploring radiation effects on structural materials. The only available irradiation facilities are fission reactors. These have been used extensively by the U.S. materials program as well as by the rest of the world (including numerous international collaborations).

Although fission reactors generally have relatively large volume and high neutron flux, the neutron spectra are much softer than those encountered at the first wall in "dry-wall" design concepts. In order to better simulate fusion neutron damage relevant parameters such as the helium-to-dpa ratio, special techniques such as helium charging and boron and nickel doping were used. The program should investigate a range of helium/dpa levels between 0.1 and 15 to encompass the various design possibilities.

In the absence of a test facility with a prototypical fusion environment, fission reactors will remain the primary test facilities for fusion material irradiation. The value of fission reactor irradiation can be enhanced considerably by (1) continued emphasis on innovative techniques to better stimulate helium, hydrogen and other transmutation rates, and (2) more emphasis on modeling to better understand and extrapolate radiation damage results to those expected in fusion spectra.

An additional possibility considered was a spallation neutron source such as that planned to be built at Oak Ridge (Appendix 2). Unfortunately, it has been concluded by other Review Panels (Reference 8 of Appendix 2) that the pulse nature of the beam, the uncertain He/dpa ratio resulting from the high energy tail of the neutron spectrum, and the low rate of dpa generation rate minimizes the usefulness of spallation sources to fusion materials research.

It should be noted that current designs for in-vessel components can be classified into: (a) "evolutionary" and (b) "revolutionary" concepts. The "evolutionary" concepts have a "dry" solid first wall. They are based on (1) self-cooled liquid metal breeder or (2) ceramic solid breeders cooled by helium (or water). These "evolutionary" concepts are relatively better understood because they have been the focus of the international R&D program for over 20 years. In these concepts, the "dry" solid first wall is exposed to an intense neutron flux that includes a large high energy (14 MeV) neutron component. The helium-to-dpa ratio is typically in the range of about 4 to 15 for vanadium alloys and ferritic steels, depending on breeder, coolant, and design. Helium production in silicon carbide is typically an order of magnitude higher than in steels. Deeper into the blanket, this ratio drops rather rapidly because neutron-induced helium production reactions have a typically high energy threshold. Thus, fission reactor simulation becomes increasingly more relevant in the deeper regions behind the first wall.

In a "revolutionary" or exploratory concept for magnetic and inertial fusion, liquid layers flow in front of the first wall. Such liquid layers will remove the surface heat flux and reduce thermal stresses in the first wall. If these liquid layers are thick, the neutron flux at the first wall changes in two ways: (a) reduction in magnitude and hence in the neutron irradiation dose for the first wall, and (b) softening the spectrum. A reduction in both the flux and the helium-to-dpa ratio of more than an order of magnitude is predicted in some recent, but yet unproved designs. Recent work on these "revolutionary" designs is motivated by the desire to increase the power density (high neutron wall loading) capability in fusion systems. But they also appear to reduce the radiation damage problem in the first wall to a more manageable level. Another important observation is that fission reactor irradiation becomes more relevant, and in some cases ideal, for simulation of the radiation environment in the structural materials of these "revolutionary" concepts.

The fusion program has long considered the need for specialized facilities for neutron irradiation of materials as well as other facilities for the R&D needs of fusion technology and material systems.

The Panel received a presentation on the results of the Conceptual Design Activity (CDA) of an accelerator-based neutron source, called IFMIF. The CDA was an international collaboration that involved Europe, Japan, the United States and Russia and it was concluded in December 1996. The IFMIF-CDA design would provide a testing volume in excess of 1.00 L over a wide range of neutron flux. About 0.5 L of test volume is at a neutron flux equivalent greater than 2 MW/m^2. This high flux region is for post-irradiation tests of miniaturized specimens of first wall and blanket structural materials. Additional test volume of more than 5 L will provide a neutron flux ranging from 2 MW/m^2 down to 0.1 MW/m^2. In addition, more than 100 L of volume are available at low flux below 0.1 MW/m^2. This volume at low flux conditions may be useful to test a variety of different materials including fully instrumented specimens under various loading conditions. The total estimated capital cost of IFMIF is about $800 million.

The Panel did not make a technical assessment of the merits of an accelerator-based neutron test facility, nor did it review the details of the CDA design. Because of the current fusion budget situation, there are considerable uncertainties in the decision to construct IFMIF. This budget situation is further complicated by the delay in the decision to construct the ITER.

Given such uncertainties, the Panel recommends that the Program continue to develop a knowledge-base on materials properties and system feasibility issues that does not assume that any nonreactor irradiation facilities are available over the next decade. If funding for a materials test facility becomes available, the Panel believes that a review of the relative merits of different materials and blanket test facility concepts should be made at that time considering the multitude of needs of the entire fusion technology program. Both plasma-based volumetric and accelerator systems should be considered.

At this time, the U.S. materials program funds the accelerator-based IFMIF activity at the low level of $300,000. The Committee recommends that continued support for this activity be considered in the context of international activities on the subject.

To support the recommended goal of establishing the feasibility of one or more in-vessel materials systems, it is noted that the appropriate gas/dpa ratios and levels can most easily be approximated in fission reactors for ferritic steels which commonly include small levels of nickel. The Committee, therefore, suggests that the Program consider as one possibility a strategy which emphasizes the development of ferritics for the design of the first D-T power-producing device, which in turn would be used to evaluate more revolutionary, ultimately more attractive materials. At that point in the maturation of fusion energy, a separate construction of a dedicated accelerator or plasma-based source to achieve high fluence irradiation of materials to support future commercial reactor designs would likely be warranted.

Resource Allocation Perspective

The current Fusion Materials Program is funded at about an annual budget of $6 million. The activities that are covered by these resources are currently focused on advanced ferritic alloys (~25%), vanadium alloys (~50%), and SIC composites (~25%) but with smaller efforts on modeling, neutron source studies and insulating ceramics. These funding levels must be considered in the context of the worldwide effort that is shown in Appendix 1. For the total international effort, roughly 45% is on ferritic alloys, 14% on silicon carbide composites, and 22% on vanadium alloys. The Panel felt that the U.S. effort should continue to remain involved with the ferritic alloys program while exploring the potential for vanadium alloys and silicon carbide composites. The Panel believes that some enhancement is needed in modeling and materials to support exploratory concepts for both MFE and IFE that are emerging in the restructured Technology Program. It is recommended that a modest increase be made in the Fusion Materials Budget of $1 million to $2 million per year to support these new initiatives.

Additional modeling and knowledge-base development support should be sought from outside the fusion materials program (such as combined efforts with the BES materials program, the ER strategic simulation initiative, and the Stockpile Stewardship materials modeling effort).

At the modest level of the current base program, there are few resources available beyond what are needed to address the identified materials system feasibility issues. However, if a flat materials budget is necessary, then the Panel recommends that the SiC program be reduced and, if necessary, a smaller reduction of the vanadium program to allow the recommended initiatives in modeling and exploratory approaches. this recommendation on funding priorities is based on the following rationale:

- There are serious issues related to the ability to fabricate large complex components out of an inherently brittle material like SiC composites for use in the fusion environment, even if the irradiation performance problems are solved.
- The vanadium program is the largest U.S. program and, therefore, would be the least impacted by the modest funding reduction.
- The level of funding for advanced ferritics is the minimum necessary to leverage the larger programs in the EU and Japan.

APPENDIX 1: REVIEW OF PROGRAMMATIC ELEMENTS OF THE U.S. FUSION MATERIALS PROGRAM

The Committee was presented with a review of the current technical status of the fusion materials program including a budget breakdown of the current programmatic elements, a comparison of the U.S. and foreign programs, and an overview of how the fusion program fits within the context of other U.S. materials R&D.

The U.S. fusion materials program currently is focused on three material systems: vanadium alloys, advanced ferritic alloys, and SiC composites. These materials were chosen based on a combination of performance potential, low activation (safety and environmental concerns), and technical feasibility as a material in a fusion power system. The degree to which each material system satisfies these criteria differs and current R&D is focused on solving radiation-related issues associated with each material system. Table 2 presents some of the pros and cons for each material along with the critical development issues for each material system.

Table 3 compares the budget of the U.S. and foreign materials programs and the distribution of that budget across the different alloys. The table indicates that the United States spends ~ 50% of their ~$6 million budget on vanadium alloys, and 25% on SiC composites and 25% on ferritic/martensitic steels. This is quite different than in the EU, where 90% of the effort is on ferritic/martensitic steels. In Japan about 40% is spent on ferritic/martensitic steels, with roughly equal amounts on SiC composites, vanadium alloys, and other materials. Russia spends about 40% of their budget on vanadium alloys and 45% on other materials. Very little is spent on ferritic/martensitic steels and SiC composites.

The United States augments its program by two bilateral agreements with Japan and Russia. Funds are received from Japan (~$2.8 million/year) to support collaborations using U.S. facilities. Funds go to Russian for access to their liquid metal fast spectrum fission reactor irradiation facilities. International steering committees coordinate the bilateral agreements and additional international coordination is probably the executive committee for the fusion materials agreement of the IEA.

Table 4 presents the distribution of the current U.S. effort among the different materials technology development areas. Irradiation testing and evaluation makes up between 60% and 85% of the total expenditures for each of the three materials (V alloys, SiC composites, ferritic/martensitic steels). Significant effort is devoted to baseline property development and other critical materials

Table 2. Comparison of Candidate Fusion Material Systems

Vanadium Alloys	Pros	• Shows evidence of radiation resistance • Low activation of impurities are controlled • Offers temperatures of 650°C or higher
	Cons	• May only be limited to use with liquid metal coolant • Currently a small volume technology
	Technical Feasibility Issues	• Use with other coolants like He? • Viability of insulator coatings for Li/V system • Effect of irradiation including influence of He on fracture toughness, ductility, etc. • High temperature limits with emphasis on role of helium in creep and creep rupture
Advanced Ferritic Alloys	Pros	• Established technology • Reduced activation compositions match establish alloys behavior • Shows high fluence resistance to irradiation
	Cons	• Fracture toughness • Temperature may be limited to 550°C
	Technical Feasibility Issues	• Use of ferromagnetic materials for in-vessel components in magnetic fusion • The effect of irradiation, including the influence of helium, on fracture toughness, ductility, and constitutive properties • Allow development and design concepts resulting in higher maximum operating temperatures in a fusion irradiation environment.
SiC/SiC Composites	Pros	• Offer potential environmental and safety advantages • Offer temperature capability to 950°C
	Cons	• Unacceptable irradiation damage to first generation SiC fibers • May be viable only with He coolant
	Technical Feasibility Issues	• Structural joining methods • Methods for designing thermal-mechanically loaded, inherently brittle structures. • Irradiation effects on thermal conductivity, the stability of fibers and fiber coatings, including the effects of transmutations. • Coatings and claddings to provide adequate hermiticity for helium coolants.

technology areas if warranted by the material (e.g., welding vanadium alloys).

The linkages that the three major fusion materials development laboratories (ANL, ORNL, PNNL) have with other materials programs is shown in Table 5. A check mark indicates that there is sharing of staff and facilities between those programs and the OFES fusion materials program. Judging by the number of check marks in the table, there is a broad range of interaction at the working level between these programs. The committee

Table 3. Comparison of U.S. and Foreign Fusion Materials Programs

	Party				
	United States	European Union	Japan	Russia	TOTAL
Budget	~$6 M (+$0.5 M on Cu and SS for ITER)/15 FTEs	10 MECU/40? FTEs	61 FTEs	30? FTEs	
	Distribution by Alloy (%)/FTT				
Ferritic/Martensitic	23/3	90/36	38/23	10/3	45/65
SiC/SiC Composites	26/4	6/2	23/14	5/1	14/21
Vanadium Alloys	50/7	2/1	20/12	40/12	22/32
Other	1/1	2/1	19/12	45/14	19/28
					100/146

Table 4. Distribution of U.S. Efforts Among Different Materials Technology Development Areas

	Vanadium alloy	SiC Composites	F/M Steels
Fabrication and Baseline Properties	19	7	15
Welding/Joining	10	5	2
Corrosion, Compatibility	11	0	0
Test Methods Development	0	5	0
Irradiation Effects Testing and Evaluation	39	13	48
Irradiation Experiments and Facilities Operation	21	70	35
Total	100	100	100

feels that this list is impressive and that the leverage currently afforded by the linkages to these programs is quite high.

APPENDIX 2: OPTIONS FOR ACCELERATOR-BASED NEUTRON SOURCES FOR FUSION MATERIALS WORK[1]

Introduction

One of the major materials issues to be faced in developing attractive fusion power is the effect of the intense neutron fluxes associated with D-T fusion concepts. The first-wall neutron spectrum which contains a large 14 MeV component not only results in very high displacement rates (~20 dpa/yr at 2MW/m2) but also causes much higher transmutation rates than is experienced in fission reactors. The elements He and H are of particular concern, but other impurities can also be important. The influence of these transmutation products on property changes has been very well-established, the obvious example being the role of He in swelling behavior.

Although fission reactors are likely to provide the bulk of irradiation facilities for the foreseeable future, accelerator-based neutron sources have been proposed to provide the spectral response, high fluxes, and high fluences needed for the investigation of fusion materials. Such a source would be needed to validate and extrapolate the results from fission irradiations to fusion conditions, for materials development, and to provide design data for future high-fluence fusion devices (e.g., DEMO). Until suitable materials are developed in this way, the technology to design and build fusion-based facilities will not exist.

[1] Prepared by Dr. M. Saltmarsh of Oak Ridge National Lab.

Accelerator/Target Options

D-T sources are based on beams colliding with solid or gaseous targets, e.g., RTNS II. Such sources produce essentially mono-energetic 14 MeV neutrons, and because of target heating and lifetime issues, are generally limited to low fluxes (0.01–1 dpa/yr), fluences, and small volumes. A 1970s project (the intense Neutron Source) [1] would have allowed fluxes up to 10 dpa/yr but with a usable volume of only a few mm3.

Stripping sources based on the interaction of 30–40 MeV deuterons with low-Z targets [2]. Such systems provide neutron spectra which approximately match those of a fusion reactor as measured by transmutation rates (particularly He production) to dpa ratios. Credible designs exist which would provide fluxes > 20 dpa/yr using existing accelerator technology (beam-powers ~5–10 MW) [3]. Irradiation volumes at these fluxes would

Table 5. Linkages Between Fusion Materials Development Laboratories and Other U.S. Materials

Program	ANL	ORNL	PNNL
Other Fusion Work (e.g., blanket)	√		
DOE-BES (e.g., radiation effects, microscopy, alloy development, x-ray research)	√	√	√
DOE-Fossil Energy (e.g., SiC composite development)	√	√	√
DOE-EE (high temperature materials)		√	
NRC (irradiation effects)	√	√	√
DOE-Accelerator Production of Tritium	√	√	√
DOE-Naval Reactor	√		√
DOE-EM			√
DOE Joining Program	√		√
LWR programs (EPRI, Japan)	√		√

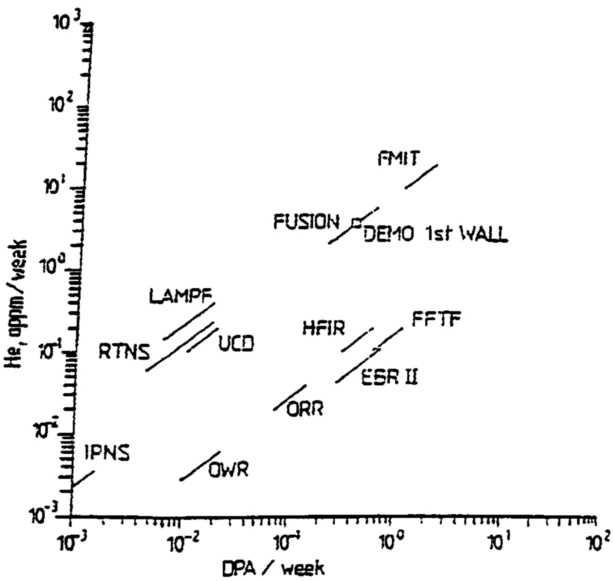

Fig. 1. Comparison of the weekly DPA and helium production rates in iron for various irradiation facilities. Original data from Greenwood *et al.*, ANL/FPP/TM-197.

be about 0.5 L, with more available at lower fluxes. Such designs do provide for steady-state operation, with intrinsic time structure periods in the range of a few nanoseconds or less, well below the range of concern for radiation damage effects [4]. There are two intrinsic issues with the D-Li sources: First, the existence of a high energy tail in the neutrons (En ~20–50 MeV) for which essentially no neutron cross-section data exist. This causes some uncertainty in calculated transmutation rates. Second is the relatively small volume available at high flux/fluence. Both of these issues have been judged to lead to acceptable levels of compromise [5].

Spallation sources which use high energy (~1 GeV) protons on a thick high-Z target. Spallation sources are the most efficient way to produce neutrons with an accelerator, in terms of neutrons/unit of beam energy. The target volume is intrinsically larger than in the D-Li case, leading to larger irradiation volumes, but smaller peak fluxes for the same beam power. The neutron spectra contain a high energy tail extending all the way to the incident beam energy which creates a substantial uncertainty in calculating most transmutation rates. As measured in terms of the He/dpa ratio, the spectrum is a closer match to fusion than to fission, as can be seen in Fig. 1 which compares a variety of sources including two spallation sources (LAMPF and IPNS) [6]. Taking LAMPF as indicative of modern spallation sources, the He/dpa ratio is seen to be high by a factor of two or so while the attainable fluences are too low by a factor ~50. Furthermore the intrinsic time structure of the beam (pulses every 8.3 ms) is likely to effect the radiation response in some materials, particularly at elevated temperatures. He/dpa ratios closer to the fusion value can be attained by moderating the neutrons, but this tends to lower the available fluxes [7].

An evaluation committee chaired by D. Doran concluded, “There is no sustained mission for LAMPF in the metals and alloy segment of the fusion materials program; the damage rates are too low, even with a significant upgrade, and there is a question of pulse effects at elevated irradiation temperatures. If damage rates were raised to 3 to 5 dpa/yr, useful mechanical property data might be obtained in the 40 to 360°C temperature range; however, a research program to evaluate effects of the higher energy tail would have to precede heavy program use” [8].

Similar considerations apply to use of the proposed ORNL Spallation Neutron Source (SNS), which would be a machine somewhat more powerful than LAMPF. It will be designed for an average beam power of 1 MW, compared with LAMPF’s nominal maximum power rating of 0.8 MW. The highest displacement rates due to neutrons would be on the stainless steel jacket surrounding the mercury target and are estimated to be in the range of 0.1–2.5 dpa/yr [9]. To serve the primary mission of neutron scattering, the beam time structure is planned to be microsecond pulses at 50 Hz, unsuited to studies of magnetic fusion structural materials.

Although spallation sources have been judged unsuitable for examining fusion specific issues in metals and alloys, there is a potential mission for basic studies of radiation effects, and for fusion-specific issues in some other materials, particularly where the pulsed nature of the beams can be put to advantage. These were examined and discussed in Doran [8].

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APPENDIX 3. LETTERS

January 14, 1998

Dr. John Sheffield, Chair
Fusion Energy Sciences Advisory Committee
Energy Technology Programs
Oak Ridge National Laboratory
Bethel Valley Road
Oak Ridge, TN 37831

Dear Dr. Sheffield:

This letter provides a charge to review a specific portion of the Office of Fusion Energy Sciences (OFES) program—our Materials Research Program. The OFES materials program was last reviewed by Panel 6 of FEAC, with FEAC reporting in April 1993 on the Neutron Interactive Materials Program. With the recent restructuring efforts conducted throughout most of the program, now including the interim FESAC report on ITER participation, the materials activities represent a principal program element remaining to be considered from this new point of view.

This review is focused on the Materials Research Program, (a separately defined budget line) which is comprised principally of the low activation structural materials research and our efforts aimed at the associated neutron source test facility. The applications of these low activation structural materials, e.g., blankets and first walls, should be considered to provide the context for this review.

Please address these topics:

1. goals for this element of our program,
2. scientific quality of the work,
3. balance in the various dimensions of the materials program, e.g., analysis, theory and modeling vs. empirical approaches for predicting performance; engineering component vs. material sample approach to testing; and single issue focus such as irradiation vs. systems approach with multiple environmental conditions such as corrosion and compatibility as well as irradiation,
4. mix of research performers,
5. balance of effort on candidate materials systems,
6. coordination, collaboration and balance among domestic and international participants, including our involvement in the international fusion materials irradiation facility activities, and
7. outreach activities.

The FESAC review should provide both an evaluation of the program strategy (including scope and priorities for future work) and a technical review/evaluation of the ongoing research in this program element.

We are organizing an overview presentation on the materials program for the January 22 FESAC meeting, as was noted at the last meeting. After this date, members of OFES and materials program researchers will be prepared to present to FESAC or a FESAC panel the details of the current program goals, approach, and content.

I would like to have the FESAC evaluations and recommendations on the fusion materials program by May 15, 1998. This advice will be important for planning and decisions on future work on materials in FY1999 and later years.

I appreciate the time and energy devoted by the members of FESAC and the FESAC panels to this continuing effort to evaluate, orient and improve the OFES program. I will look forward to hearing the Committee's recommendations on the fusion materials research activities.

Sincerely,

Martha A. Krebs
Director
Office of Energy Research
Department of Energy
Washington, DC 20585

May 28, 1998

Dr. Martha A. Krebs, Director
Office of Energy Research
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585

Dear Dr. Krebs:

The Fusion Energy Sciences Advisory Committee (FESAC) heard a presentation on the draft report from the Materials Program Review Panel, which has responded to your charge of January 14, 1998.

The draft report makes some very important recommendations about the fusion structural-materials program.

* There should be a greater emphasis on modelling of materials, using the growing capabilities in this area, to complement the experimental program in developing optimized materials. This area is a very good candidate for inclusion in the Strategic Simulation Initiatives.
* More emphasis should be given to understanding the complete systems into which the structural materials must fit to help in prioritizing the elements of the development program.

The FESAC agrees with these recommendations.

The FESAC has requested that the Review Panel consider certain modifications and add some clarifying sections to the draft report. The FESAC will review the final report in its July 30–31 meeting.

Sincerely,

John Sheffield, Chair
on behalf of the Fusion Energy
Science Advisory Committee

August 3, 1998

Dr. Martha A. Krebs
Director
Office of Energy Research
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585

Dear Dr. Krebs:

The FESAC met on July 30–31 and considered the charge in your letter of January 14, 1998, regarding the Materials Research Program. The FESAC accepted the report on the U.S. Fusion Program on Structural Materials, prepared by the subcommittee co-chaired by Dr. S. Harkness and Dr. C. Baker.

FESAC appreciates the very considerable work by the subcommittee, which has resulted in a helpful and articulate report. We particularly endorse the subcommittee's central recommendations that the materials program be strongly coupled with an overall systems approach, and broadened to allow increased modeling and innovative exploratory research on novel materials. The new initiatives outlined in the report represent significant scientific opportunities for the program, and should be supported if possible.

FESAC does believe that a continuing and broadening systematic exploration of a wide variety of materials in the context of both the magnetic and inertial fusion requirements is appropriate and consistent with the restructured fusion program's focus on science, innovation and long-term optimization of the fusion product. Such examination will require regular peer review to maintain balance among various candidate materials. The re-examination should take into account developments in other fields and seek opportunities to benefit from other, larger government and industrial materials programs. The fusion program will remain highly dependent on such leveraged activities as long as it lacks sufficient resources to fully qualify materials unique to fusion.

Sincerely,

John Sheffield, Chair
on behalf of the Fusion Energy
Science Advisory Committee