Meeting Objectives, Current Program Structure and Organization, and Summary of Recent Reviews

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Fusion Materials Sciences Program Strategic Planning Meeting

August 26-30, 2002

Univ. California-Santa Barbara

Current Status of Fusion Materials Sciences Program

- **Excellence of science in program is very high**
  - **Recent favorable review by high-level scientific panel**
  - **Fusion materials program is being viewed as a model for NE Gen IV and NASA space reactor programs**
  - **We are working to increase the visibility of our science within the fusion (plasma physics) program**

- **Fusion materials R&D is increasingly recognized as a critical step in the achievement of fusion energy**
  - **OFES (N.A. Davies)**
  - **Office of Science (R. Orbach)**
  - **Presidential Science Advisor (J. Marburger)**

- **We must redouble our efforts to further improve the scientific quality of the fusion materials program**

Meeting Objectives

- **US fusion materials program: what is known; what is needed; how can we best obtain the necessary information**
- **Optimization of US/J planned experiments**
- **Assess research plan on key fundamental fusion materials issues**
  - **Primary damage and microstructural evolution in irradiated materials**
  - **Deformation (flow localization, thermal and irradiation creep)**
  - **Fracture mechanisms**
  - **Helium embrittlement**
  - **Alloy development/materials by design**
  - **Ceramic Composites (SiC/SiC)**
- **Assess balance of Fundamental and Applied R&D Portfolio**
  - **R&D for burning plasma experiment (next step option)**
  - **IFMIF programmatic support; also assess role of spallation sources**
  - **Diagnostic materials and other special purpose materials R&D**
  - **Discuss V alloy vs. ferritic alloy research allocation**

Structural Materials will Strongly Impact the Technological Viability, Safety, and Economics of Fusion Energy

- Key issues include thermal stress capacity, coolant compatibility, safety, waste disposal, radiation damage effects, and safe lifetime limits
- The 3 leading candidates are ferritic/ martensitic steel, V alloys, and SiC/SiC (based on safety, waste disposal, and performance considerations)
  - Commercial alloys (Ti alloys, Ni base superalloys, refractory alloys, etc.) have been shown to be unacceptable for fusion for various technical reasons

Summary of several recent fusion energy blanket concepts

Structural Material	**Coolant/Tritium Breeding Material**					
	Li/Li	He/PbLi	H_2O/PbLi	He/Li ceramic	H_2O/Li ceramic	FLiBe/FLiBe
Ferritic steel						
V alloy						
SiC/SiC						

Fusion Materials Science Mission Statement

- Advance the materials science base for the development of innovative materials and fabrication methods that will establish the technological viability of fusion energy and enable improved performance, enhanced safety, and reduced overall fusion system costs so as to permit fusion to reach its full potential
- Assess facility needs for this development, including opportunities for international collaboration
- Support materials research needs for existing and near-term devices

Features of Restructured Fusion Materials Science Program

- Science-based materials research
- Principal product is *basic knowledge, theory, and models* needed to resolve feasibility issues of fusion materials
- Primary role of experiments is to guide and validate theory and models
- Utilize, leverage, and expand on revolutionary advances in computational and experimental methods (e.g.,nanoscience) for fusion materials design
- While focusing on long-term viability and attractiveness issues of fusion materials, apply expertise in near-term to current issues of plasma research and IFE studies

Upcoming decisions on ITER and "fast track" option may impact fusion materials research portfolio

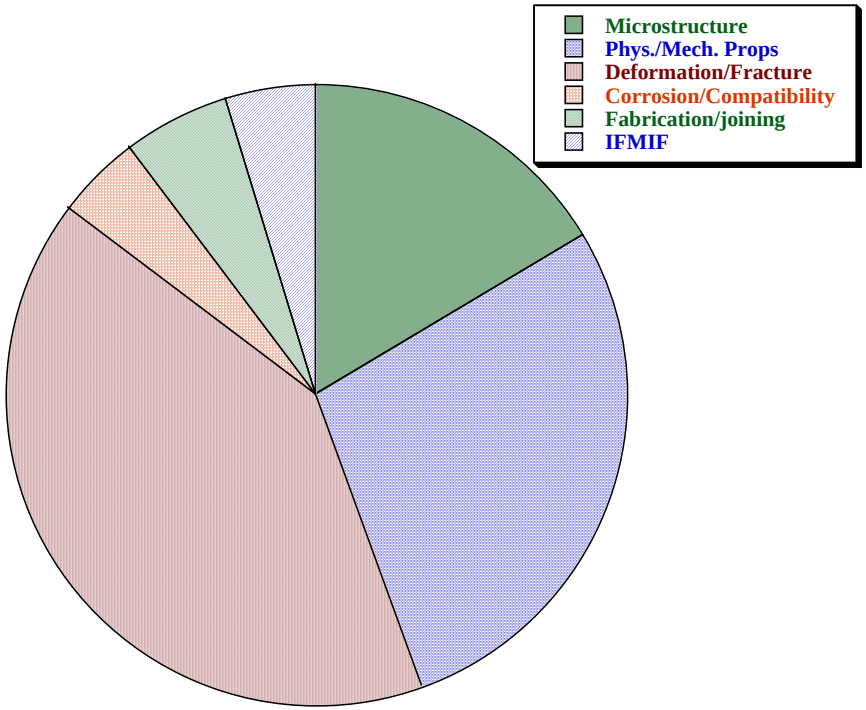
Key Cross-cutting phenomena for Fusion Structural Materials

Mech. props

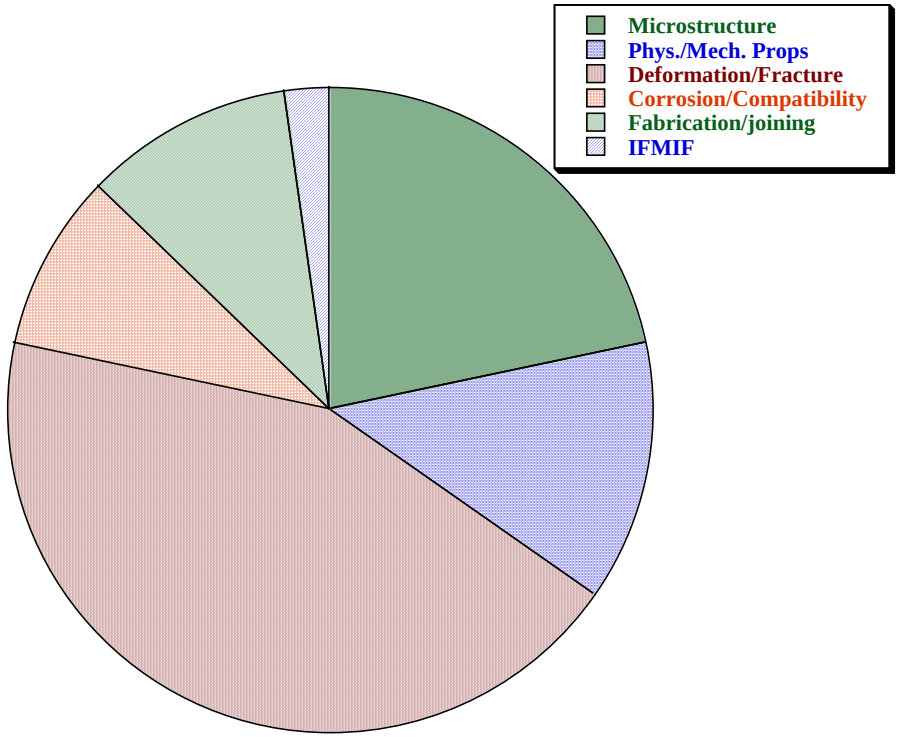
F/MS	V	Cu	SiC	Phenomena, Issues, Comments
***	***	***	-	hardening and nonhardening embrittlement including underlying microstructural causes and the effects of helium on fast fracture
**	**	**	-	flow localization, consequences and underlying microstructural causes
***	***	*	*	helium effects on high temperature deformation and fracture, and development of improved multiphase alloys for helium control
**	**	**	**	thermal and irradiation creep
**	**	**	**	fatigue
**	***	*	*	hydrogen and interstitial impurity effects on deformation and fracture
*	***	-	**	coatings, multilayers, functionally graded materials
**	**	**	***	swelling and general microstructural stability
**	***	**	***	welding, joining and processing issues
		*	***	physical properties, e.g. thermal conductivity
			***	permeability of gases
**	**	**	**	erosion, chemical compatibility, bulk corrosion, cracking, product transport

- Much of the R&D on current RAFMs, V alloys, etc. can guide the development of future advanced alloy systems

Fusion Materials Sciences R&D Portfolio



FY98 funding



FY01 funding

- Continued emphasis on mechanical properties

Fusion Materials Science Program

	Theory-Experiment Coordinating Group*				
	Microstructural Stability	Physical & Mechanical Properties	Fracture & Deformation Mechanisms	Corrosion and Compatibility Phenomena	Fabrication and Joining Science
Materials for Attractive Fusion Energy					
• **Structural Alloys*** - Vanadium Alloys - F/M and ODS Steels - High T Refractory Alloys - Exploratory Alloys					
• **Ceramic Composites*** - SiC/SiC, other CFCs					
• **Coatings**					
• **Breeder/multiplier Materials**					
• **Neutron Source Facilities**					
Materials for Near-Term Fusion Experiments					
• **PFMs (Refractory Alloys, etc.)**					
• **Copper Alloys**					
• **Ceramic Insulators**					
• **Optical Materials**					

*asterisk denotes Fusion Materials Task Group

Interactions within International Fusion Materials Community

Science issue	Activity	US	Japan	EU	Russia	China
Deformation & fracture	V alloys	IEA working gp.			IEA working gp.	
		DOE/Monbusho				
Deformation & fracture, Nanoscience (ODS)	Ferritic steel	IEA working group				
		DOE/JAERI				
Deformation mechanisms, enhanced thermal cond.	SiC/SiC	IEA working group				
		DOE/Monbusho				
		DOE/JAERI				
Cross-cutting theory & modeling phenomena	Theory & modeling	IEA working group				
Electric, dielectric props.	Ceramic insulators	IEA working group				
		DOE/Monbusho				
Accelerator physics, liquid jet thermohydraulics, He gas cooling technology	Neutron source (IFMIF)	IEA working group				

Fusion Materials Sciences Community Governance

MASCO (MAterials Science COordinators)
S.J. Zinkle (ORNL), chair
N.M. Ghoniem (UCLA)
R.H. Jones (PNNL)
R.J. Kurtz (PNNL)
R. Mattas (ANL)
G.R. Odette (UCSB)
R.E. Stoller (ORNL)
B. Wirth (LLNL)

	Theory/Expt coordinating committee Zinkle*, Kurtz, Odette (steering committee) Ghoniem, Stoller, Wirth
Structural alloys Odette (chair) Hoelzer, Kurtz, others (choose from subject experts on an as-needed basis)	
Ceramic composites Jones (chair) Snead, Lucas, others (choose from subject experts on an as-needed basis)	
Crosscutting Theory & Modeling N.M. Ghoniem (chair)	

*Fusion Materials Sciences program leader

Fusion Materials Sciences Research Task Groups

Topical Team	Team Leader	Proposed Team Members
Experimental Microstructure	Zinkle	Edwards, Gelles, Ghoniem, Hoelzer, Odette, Wirth
Experimental Fracture and Fatigue	Odette	Gelles, Ghoniem, Grossbeck, Klueh, Kurtz, Lucas, Sokolov, Wirth, Yamamoto, Zinkle
Experimental Deformation and Constitutive Law	Lucas	Edwards, Hoelzer, Odette, Wirth, Yamamoto, Zinkle
Deformation and Fracture Modeling	Ghoniem	He, Kurtz, Odette, Osetsky, Wirth, Zinkle
Microstructural, Multiscale-Multiphenomena Modeling	Stoller	Heinisch, Kurtz, Odette, Osetsky, Srolovitz, Wirth, Yamamoto, Zolb, Zinkle
High Temperature Deformation and Fracture	Kurtz	Ghoniem, Grossbeck, Hoelzer, Lucas, Odette, Zinkle,
Processing, Fabrication and Joining	Klueh	Gelles, Grossbeck, Hoelzer, Odette, Zinkle
Coatings and Compatibility	Pint	Jones, Mattas, Natesan, Odette
Materials Design Interface	Ghoniem	Majumdar, Mattas, Odette, Yamamoto, Zinkle
Ceramic Composites	Jones	Lucas, Snead, White, Youngblood
Advanced & Innovative Materials	Hoelzer	Gelles, Klueh, Kurtz, Ghoniem, Odette, Snead, Was, Zinkle
Irradiation Experiments	Zinkle	Kurtz, Ghoniem, Odette, Stoller, Wirth

Task group charter, meeting frequency, membership, etc. still needs to be discussed

The Materials Science Program Provides the Underlying Materials Science Knowledge Base within the VLT

Technology Program Element	Types of Materials Addressed	Key Materials Issues
¥ **Materials Science**	¥ **Structures** ¥ **Coatings** ¥ **Insulating ceramics** ¥ **Optical materials**	¥**deformation,fracture mechanisms** ¥ **thermodynamic, kinetic stability** ¥ **electric, dielectric degradation** ¥ **F center formation, stability**
¥ Plasma Technology	¥ Plasma facing/high heat flux components ¥ Magnet components ¥ ICH/ECH launcher/ antennas	¥ plasma interactions, heat transport ¥ critical current, insulator perform. ¥ low-loss coatings and feedthroughs
¥ Fusion Technology	¥ Fuels (tritium) ¥ Breeder systems	¥ tritium permeation ¥ thermal, neutronics, hydrodynamics
¥ IFE	¥ Chamber wall ¥ Final optics	¥ durability, tritium retention ¥ surface crazing, bulk defects
¥ Safety	¥ Structure, coolant, breeder	¥ volatization, decay heat
¥ Advanced Design	¥ Overall integration	¥ compatibility, performance limits

Fusion Materials Science is the Vital Link Between the Fusion Energy Sciences and Materials Science Communities

- Researchers in the Fusion Materials Science program are housed in materials science departments at their institutions (provides access to the broader materials science community) and are actively involved in numerous non-fusion cutting-edge materials science endeavors (provides targeted leveraging)
  - We have very good interactions with the materials science community

- What is the appropriate balance between our interactions with materials science community and our interactions with the fusion science community?
  - Historically limited interactions of fusion materials program with fusion technology and plasma physics communities

Summary of planned US irradiation experiments

- Predominantly US/Japan collaborative irradiation capsules
  - Smaller efforts using informal EU collaborations and HFIR rabbit capsules
- DOE/JAERI Phase IV fusion materials collaboration
  - Focus is on deformation and fracture behavior of ferritic steels (and other alloys), including He effects
  - Three HFIR target capsules (~25 cm3 volume each; 10, 40dpa, 300/400/500˚C
  - Two HFIR RB* capsules: with, without Eu shielding (~200 cm3 volume each), 6dpa, 300/400˚C
  - Typical irradiation matrix: tensiles, fracture, DFMBs
- DOE/MEXT Jupiter-II "ALiVE" capsule
  - Focus is on deformation and fracture behavior of V alloys, incl. irrad. creep
  - Eu-shielded HFIR RB* capsule, 450/600/700˚C
  - Follow-on capsule proposed for ~2004 (details to be decided)
- DOE/MEXT Jupiter-II HFIR PT-rabbit and RB* capsules
  - Focus is on radiation effects in 3rd-generation SiC composites (and other materials at 600-1400˚C, dpa
  - Tensile, fracture toughness, thermal conductivity

Key findings from 2001 peer review

- **Overall scientific quality of research is high**
- **Seven general findings were identified, and an action plan was formulated to address these issues**
  - **Education and training**
  - **Program scope, mission, priorities and balance**
  - **Interaction with other (fusion) programs**
  - **Chemistry and corrosion R&D program**
  - **Coordination of theory and modeling program**
  - **Helium effects research program**
  - **V alloy R&D (fabrication) and MHD insulator program**
  - **External visibility (interaction with fusion community)**

Key findings from 2001 peer review

Review Panel Generalized Findings & Recommendations	Community Comments and Actions
With regard to **education and training,** in light of program restructuring away from fusion energy development and toward science-based research, reassess funding allocations between labs and universities and the effectiveness of university programs for meeting future scientist and other human resource needs of fusion materials research.	The fusion materials sciences program has made a concerted effort to increase the level of participation by university professors and students in the past two years (University funding for fusion materials tripled from 1998 to 2001). We will continue to seek opportunities to attract the highest quality materials scientists, and monitor the university/lab funding ratio (benchmarked against similar ratios in the fusion program).
With regard to **program scope, mission, priorities, balance,** assess whether or not it is possible and advisable to increase the rate of progress toward solving critically important fusion structural material issues by focusing on a smaller set of materials systems, perhaps eliminating research for a period of time on the lowest priority system.	One of the pillars of the reorganized fusion materials science program is an emphasis on cross-cutting materials science phenomena. In the current research program, a limited number of model alloys encompassing a range of compositions are highly valuable in order to assess intrinsic physical phenomena. The topic of research portfolio balance will be discussed in detail by the fusion materials community during a materials program team meeting scheduled for late August, 2002.
With regard to interaction with other programs, identify ways to improve connections with and support for next step burning plasma experiment studies.	The FIRE design team has recently established regular informal communications with the fusion materials science program in order to obtain expert advice on a wide range of materials issues. This activity will also be aided by the newly established materials engineer activities in the materials science program.

Key findings from 2001 peer review (cont'd)

Review Panel Generalized Findings & Recommendations	Community Comments and Actions
With regard to activities in **chemistry and corrosion,** assess the appropriateness of the current level of effort on oxidation/ corrosion studies and review experimental techniques in these studies to determine if improvements should be made.	A discussion of the corrosion research priorities will be held during the fusion materials program team meeting scheduled for late August, 2002.
With regard to activities in theory and modeling, assess the appropriateness of the current level of effort on theory/ modeling and identify ways that theory/modeling activities can work more effectively among each other and with experimental programs.	A theory&modeling/experimental researcher workshop has been organized (May 2002, UCLA) as a first step to enhance the collaborative interactions within the modeling program and between experimental and modeling activities. This topic will be discussed in more detail during the Aug. 2002 fusion materials team meeting.
With regard to helium effects assess the appropriateness of the current level of effort on helium effects and the effectiveness of the approaches being used to evaluate helium effects.	Helium effects are a major focus of the majority of the multi-year proposals funded in the 2001 theory and modeling initiative, and are also the primary focus of the DOE/JAERI collaborative HFIR irradiation program that will begin in the summer of 2002. It is clearly recognized as a very important factor in the development of viable fusion materials.

Key findings from 2001 peer review (cont'd)

Review Panel Generalized Findings & Recommendations	Community Comments and Actions
With regard to activities in vanadium alloys and insulator coatings, assess the appropriateness of the current level of effort on vanadium alloy insulator coating research and review experimental techniques to determine if improvements can be made and if the rate of progress can be increased.	A set of quantitative technical metrics have been developed to aid in the assessment of the performance of the various candidate MHD insulators. A community-led rigorous assessment of the scientific feasibility and technical maturity of the leading candidate MHD insulator coatings will be performed in the summer of 2002. Significant advances in the understanding of the physical metallurgy of the V alloy system have been attained by fusion materials scientists in the past 6 years (when the last US V alloy heat was fabricated), and this improved understanding is being used in a current effort to fabricate high-quality V alloy tubing for an upcoming US/Japan JUPITER-II collaborative irradiation experiment.
With regard to external visibility, present results of fusion materials research to broader audiences, such as at ANS-sponsored meetings	Although researchers on the fusion materials program have been recognized numerous times with national materials science awards, the program has relatively weak connections with the fusion technology and plasma physics communities. In order to enhance the connections with the rest of the fusion program (while maintaining our important strong ties to the broad materials science community), the fusion materials program will work within the VLT and actively participate in few selected fusion technology meetings. A materials/plasma facing components workshop and an advanced ferritic steel materials/chamber technology workshop were held in April, 2002, and a series of fusion materials seminars at plasma physics institutions are being planned, beginning with a PPPL colloquium. Fusion materials scientists will be the lead organizers of the ANS Topical on Fusion Energy to be held in Washington DC in November, 2002.

Overview of Fission, Spallation, and d-Li Neutron Sources for Fusion Materials R&D

Neutron Source	Advantages	Disadvantages
Fission Reactors	Well-characterized spectra Allows medium-high damage regimes to be investigated in bulk specimens Operating funds provided by multiple users (non-fusion)	Low He/dpa ratio
Spallation	Allows high-He irradiation conditions to be explored Operating costs may be largely provided by non-fusion agencies	Not designed for materials irradiations (physics/ neutron scattering facility)* He/dpa,H/dpa ratio too high Pulsed irradiation; requires detailed analysis
D-Li	Correct He/dpa ratio, etc. Dedicated materials irradiation facility	Operating funds completely provided by fusion

***feasibility of limited-volume "rabbit" irradiation facility in SNS is being explored**

Strategy for Deployment Schedule of Fusion Materials intense neutron irradiation facility (IFMIF)

- Acquisition of the fundamental constitutive properties of irradiated materials is essential for the analysis of the performance of irradiated components
- Development of materials will likely require several iterations of materials irradiation & alloy modification (requiring >15-20 years to develop and qualify materials)
- IFMIF should be deployed in advance of a plasma technology test bed (strong interactions between users of each facility are essential)
  - Cf. Snowmass 2002 report and Wednesday Aug. 28 discussion