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# FINESSE

## A Study of Issues, Experiments and Facilities for Fusion Nuclear Technology Research & Development

Interim Report

Volume II

**October 1984**

Center for Plasma Physics and Fusion Engineering
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# CHAPTER 3

# FUSION NUCLEAR ISSUES

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# 3. FUSION NUCLEAR ISSUES

## 3.1 Introduction

### 3.1.1 Purpose

Many uncertainties exist in the actual operation of present day fusion reactor conceptual designs. The expected consequences of these uncertainties vary greatly in magnitude: on one extreme the uncertainties are so large that the feasibility of the reactor design is at stake, and on the other extreme the uncertainties may simply require moderate redesign, reduce performance, or increase cost.

This chapter contains a comprehensive list of engineering issues for fusion reactor nuclear components. The list explicitly defines the uncertainties associated with the engineering operation of a fusion reactor and addresses the potential consequences resulting from each issue. It is hoped that this list will be useful to engineering researchers, reactor designers, experimentalists, and program planners in identifying the areas of greatest concern.

Generic examples of blankets were needed to focus the effort to identify the majority of the requirements on a fusion test facility. The number of blanket options was limited to liquid metal (Li and LiPb) and solid breeder ($Li_2O$ and ternary ceramics) concepts. Other concepts (e.g., molten salt) are not likely to substantially change the test requirements for a fusion facility. However, they do need to be considered in determining near-term experimental programs.

There is an intentional bias towards testing issues--those issues likely to require nuclear testing before a commercial reactor could confidently be built. However, it is not limited to testing alone; the entries in the list are described as "issues/technical areas" to allow broader categories. The issues serve to identify the testing needs which are listed in the following chapter. Also, the quantification of test requirements depends heavily on the issues. The most critical issues are used to define the required test conditions.

The precise definition of an issue is difficult. One reason for this is the interrelated nature of the technical disciplines and the phenomena involved. For example, in the liquid metal blanket, thermal stresses may be a primary cause of structural failures. The thermal stresses are a function of temperature distributions, which depend on velocity profiles and MHD eddy current paths, which in turn are strongly dependent on geometry and magnetic field. Structural failures are also affected by materials properties changes due to irradiation, corrosion, etc.

It is arbitrary to some extent how to break out pieces of the overall blanket behavior and call them separate issues. For example, the only real issue for the blanket is the demonstration of adequately meeting its functional requirements of tritium breeding and energy conversion at economical and safe conditions, e.g. thermal conversion efficiency, reliability, etc. To help alleviate this problem and still retain technical specificity in the issues, an attempt is made to illuminate the logical pathway to the ultimate consequences or failure modes. These relate to the basic blanket functions of structural integrity, tritium breeding, heat transport, materials compatibility, etc.

Another reason why long term, integrated testing issues are difficult to define is that near term experiments and analysis may result in the resolution of issues or the elimination of certain blanket designs. The uncertainties we define today may no longer be uncertain five or ten years from now. Special effort has been made to emphasize those issues thought to be generic or long-lasting.

### 3.1.2 Organization

The list is arranged according to the reactor components affected by the nuclear environment. The blanket/first wall tends to be the dominant nuclear component and is represented by approximately half of the issues. Plasma interactive components, including the first wall, limiters, divertors, vacuum systems, and auxiliary heating systems account for another 25%. The remainder of the issues involve nuclear aspects of the shield, magnets, instrumentation and control, tritium processing system, and balance of plant.

Table 3.1-1 shows the structure of the issues list, including subheadings within the blanket and plasma interactive components. A concise table of issues appears in Section 3.2, together with table entries for potential impact, design specificity, level of concern, and relevant environmental conditions. Section 3.3 draws out the most critical issues which serve as a focal point for the remainder of the FINESSE study. In Section 3.4, each issue from Section 3.2 is explained in detail, giving the rationale behind the table entries. The numbering of the table in Section 3.2 exactly corresponds to the numbering of the write-ups in Section 3.4. Finally in Section 3.5, there are lists of safety and subsytem interaction issues. These lists are primarily for cross reference purposes. They provide a convenient way to find issues which are incorporated in many places throughout the main list.

### 3.1.3 Explanation of Entries and Abbreviations

The potential impact for each issue helps to determine the level of concern, or importance, of the issue. Seven possible impacts have been defined and are listed in Table 3.1-2. These are divided into two classes of issues: feasibility issues and attractiveness issues. In general, a feasibility issue is more serious because it could rule out a component concept on scientific grounds without considering the cost, complexity, or safety implications relative to alternate energy sources. The most serious issues are those which can close the device operating window, or design window, thereby eliminating the design.

The attractiveness issues may still be very serious--possibly making a reactor design impractical on the basis of cost or safety. Any feasibility issue which is generic to a class of designs is considered to possess a critical level of concern. Other issues are regarded as high, medium, or low levels of concern depending on a qualitative judgement on their overall severity.

The relevant environmental conditions include the neutron field and other parameters, such as surface heat flux, stresses, geometry, etc. An attempt is made to clarify the need for neutrons by defining the most important effects that neutrons contribute to that issue. The three main categories are: bulk heating, materials damage, and specific reactions. These are abbreviated in the tables as H, D, and R, respectively. Table 3.1-3 lists these with specific examples. Table 3..1-4 lists the abbreviations for the very large number of environmental parameters. Also listed are miscellaneous abbreviations used throughout.

Table 3.1-1 Reactor Components Affected by the Nuclear Environment

1. Blanket
   A. Structure
   B. Coolant
   C. Breeder, Multiplier, and Purge
   D. Coolant - Structure Interaction
   E. Breeder - Structure Interaction
   F. General Blanket

2. Plasma Interactive Components
   A. First Wall and General HHFC Concerns
   B. Limiter/Divertor
   C. Vacuum Systems
   D. RF Components (Auxiliary Heating)

3. Shield

4. Tritium Processing System

5. Magnets

6. Instrumentation and Control

Table 3.1-2 Definition of Potential Impact Table Entries

| | | |
|---|---|---|
| Feasibility Issues: | DW | May Close the Design Window |
| | US | May Result in Unacceptable Safety Risk |
| | UL | May Result in Unacceptable Reliability, Availability or Lifetime |
| Attractiveness Issues: | RP | Reduced System Performance |
| | RL | Reduced Component Lifetime |
| | IC | Increased System Cost |
| | RS | Less Desirable Safety or Environmental Implications |

Table 3.1-3 Neutron Effects

| | |
|---|---|
| H | Bulk Heating |
| D | Materials Damage<br>- Displacements<br>- Helium Production<br>- Segregation<br>- Transmutations |
| R | Specific Reactions<br>- Tritium Breeding<br>- Helium Production<br>- Structure Activation<br>- Sputtering<br>- Radiolytic Decomposition<br>- Transmutations |

Table 3.1-4 Key to Parameters

| | | | |
|---|---|---|---|
| F | Fluence | PMI | Plasma-Materials Interactions |
| $\phi$ | Flux | G | Geometry |
| S | Spectrum | Q | Power Density |
| T | Temperature | t | Time |
| $\sigma$ | Stress State | q | Surface Heat Flux |
| C | Chemical Environment | P | Pressure |
| I | Impurities | $P_t$ | Tritium Pressure |
| H | Tritium | v | Velocity |
| A | Dimensions (Area) | N | Cyclic Operation |
| B | Magnetic Field Strength | s | Surface Condition |
| B,b | Transient Magnetic Field | $\gamma$ | Gamma Radiation |

Other Abbreviations

| | |
|---|---|
| TC | Ternary Ceramic |
| SB | Solid Breeder |
| LB | Liquid Breeder |
| LM | Liquid Metal |
| DS | Draw Salt |

## 3.2 Summary Tables

Table 3.2-1 contains the list of fusion nuclear issues as described in Section 3.1. The total number of issues is 120, with approximately half in the blanket, 25% in plasma interactive components, and the remaining 25% in the shield, tritium processing systems, magnet, and instrumentation and control. Twenty-one of the issues are listed as critical: 15 in the blanket and 6 in PIC.

Table 3.2-1 Fusion Nuclear Testing Issues

| Issue/Technical Area | Potential Impact | Design Specificity | Level of Concern | Operating Environment: Neutron | Operating Environment: Parameters |
|---|---|---|---|---|---|
| I. BLANKET/FIRST WALL ISSUES | | | | | |
| A. STRUCTURE | | | | | |
| 1. Changes in Properties and Behavior of Materials | US,UL | generic | critical | D,R | $\phi$,S,F,T,$\sigma$,H,N |
| a. Prediction of Radiation Damage Indicators | US,UL | generic | high | D | S |
| 2. Deformation and/or Breach of Components | | | | | |
| a. Effect of First Wall Heat Flux and Cycling on Fatigue or Crack Growth Related Failure | DW,RS,UL | tokamak | critical | H,D | Q,T,t,G,$\sigma$,N |
| b. Magnetic Field Interactions within the Structure | | | | | |
| 1) Magnetic Forces due to Disruptions and Magnetic Transients | DW | tokamak | high | — | B,$\dot{B}$,G,$\sigma$,T,v,C |
| 2) Magnetically Induced Stresses in Ferritic Steels | RL,IC | ferritic steels | low | R,D | B,$\dot{B}$,S,F,$\phi$, T,G,N |
| c. Failures at Welds and Discontinuities | RS,UL | generic | high | R,D | A,$\phi$,S,F,T,$\sigma$,N |
| d. Failures due to Hot Spots | RS,UL,DW | generic | high | H,D,R | B,G,T,$\phi$, S,F,v,q |
| e. Interaction of Primary and Secondary Stresses and Deformation | UL,IC | generic | high | H,D,R | S,F,$\phi$,q, T,$\sigma$,G |
| f. Failure due to Shutdown Residual Stress Effects | UL,IC | generic | high | D,R | S,F,$\phi$,q,T,$\sigma$,G |
| g. Effect of Swelling, Creep, and Thermal Gradients on Stress Concentrations | UL,IC | generic | medium | D,R | S,F,q,T,$\sigma$,G |
| 1) Response of Grooved Surface Concepts | RP,IC,UL | design | medium | H,D | t,q,T,$\sigma$,S,F |
| h. Interaction between Surface Effects and First Wall Failures | UL,RL | generic | medium | D | PMI,q,t,T, I,$\sigma$,B,F |
| i. Self-Welding of Similar and Dissimilar Metals | UL | generic | low | H,D,R | $\phi$,S,F,T,$\sigma$,G |
| 3. Tritium Permeation through the Structure | | | | | |
| a. Effectiveness of Tritium Permeation Barriers | US | generic | critical | D | T,I,C,$\gamma$,$P_t$, S,F,$\sigma$ |
| b. Effect of Radiation on Tritium Permeation | RC,RS | generic | medium | D | T,$\phi$,S,$P_t$,F,$\gamma$ |
| 4. Structural Activation Product Inventory | RC,RS | generic | low | R | S,F,I |

Table 3.2-1 Fusion Nuclear Testing Issues (contd.)

| Issue/Technical Area | Potential Impact | Design Specificity | Level of Concern | Operating Environment: Neutron | Operating Environment: Parameters |
|---|---|---|---|---|---|
| **B. COOLANT** | | | | | |
| 1. MHD Pressure Drop and Pressure Stresses | DW,RP | self-cooled LM | tokamak:C mirror:H | H,D | G,B,v,T |
| 2. MHD and Geometric Effects on Flow Distributions | RP | generic | LM: C SB: H | — | G,v,B |
| 3. Coolant Flow Stability | UL,RL | $H_2O$ and He | high | H | G,v,$\phi$,q,T,p,$\sigma$ |
| 4. Stability/Kinetics of Tritium Oxidation in the Coolant | IC,RS | generic | He:H Li-He:M salt:M | — — — | C,G,T,v,p, $p_t$,$\gamma$ |
| 5. Helium Bubble Formation Leading to Hot Spots | UL,RL | LM | low | R | G,v,$\phi$ |
| **C. BREEDER AND PURGE** | | | | | |
| 1. Tritium Recovery and Inventory in Solid Breeder Materials | | | | | |
| a. Intragranular Tritium Diffusivity and Solubility | US,UL,IC | SB | critical | R,D | T,F,I,S,$\phi$,C,p |
| b. Tritium Surface Migration and Desorption | RP,RS | SB | high | H,R,D | T,I,G,F |
| c. Porosity, Purge Flow Distribution, and Transport | RP,RS | SB | high | H,R,D | p,T,G,F,t |
| 2. Liquid Breeder Tritium Extraction | US,RP | LB | Li:M LiPb:H | R,(D) | C,I,T,p,v,F,$\phi$ |

Table 3.2-1 Fusion Nuclear Testing Issues (contd.)

| Issue/Technical Area | Potential Impact | Design Specificity | Level of Concern | Operating Environment: Neutron | Operating Environment: Parameters |
|---|---|---|---|---|---|
| C. BREEDER AND PURGE (contd.) | | | | | |
| 3. Temperature Limits and Variability in Solid Breeder Materials | | | | | |
| a. Temperature Limits | DW | SB | critical | H,R,D | T,F,I,S,$\phi$,p |
| b. Thermal Conductivity Changes under Irradiation | DW,RL | SB | high | H,(R,D) | $\phi$,T,G,I,p,F,t |
| c. Effect of Cracking | UL,RL | SB | high | H,(R,D) | G,T,$\sigma$,N,$\phi$,F |
| d. Effect of LiOT Mass Transfer | DW | $Li_2O$ | high | H,R | |
| 4. Tritium Release Form from Solid Breeder | IC,RS | SB | high | R | $\gamma$,T,I,G,F,C |
| D. COOLANT-STRUCTURE INTERACTIONS | | | | | |
| 1. Mechanical and Materials Interactions | | | | | |
| a. Mass Transport Rates and Consequences due to Corrosion and Sputtering | DW,US, UL,RS | generic | critical | H,D,R | G,T,v,B,I,F |
| b. Mechanical Wear and Fatigue from Flow-Induced Vibrations | RP | generic | medium | — | T,G,v,$\sigma$ |
| c. Failure of Coolant Wall due to Stress Corrosion Cracking | US,UL | $H_2O$ | low | R,D | S,F,t,T,$\sigma$,C |
| d. Failure of Coolant Wall due to Liquid Metal Embrittlement | UL,RL | LM | low | R,D | " |
| 2. Thermal Interactions | | | | | |
| a. MHD Effects on First Wall Cooling and Hot Spots | DW,UL | LM | critical | H,D | G,$\dot{B}$,v,T,q,$\phi$ |
| b. Response to Cooling System Transients | IC,RS | generic | LM and DS:C $H_2O$ and He:L | H | B,$\dot{B}$,$\phi$,t,q,G, T,v,$\sigma$,p,F |
| c. Flow Sensitivity to Dimensional Changes | RL,RS | $H_2O$ and He | medium | H,D | G,q,$\phi$,T,v,p,$\sigma$ |

Table 3.2-1 Fusion Nuclear Testing Issues (contd.)

| Issue/Technical Area | Potential Impact | Design Specificity | Level of Concern | Operating Environment: Neutron | Operating Environment: Parameters |
|---|---|---|---|---|---|
| E. SOLID BREEDER/MULTIPLIER-STRUCTURE INTERACTIONS | | | | | |
| 1. Solid Breeder Mechanical and Materials Interactions | | | | | |
| a. Clad Corrosion from Breeder Burnup Products | DW,RP,RL | SB | $Li_2O$:C TC:M | H,R | S,F,$\phi$,G,C |
| b. Strain Accommodation by Creep and Plastic Flow | UL,RS | SB | $Li_2O$:C TC:M | H,R,D | T,$\sigma$,t,S,F,G |
| c. Swelling Driving Force | DW,UL,RS | $Li_2O$ | $Li_2O$:C TC:L | H,R,D | F,$\phi$,S,G,T |
| d. Stress Concentrations at Cracks and Discontinuities | UL,RS | SB | high | H,R,D | G,T,N,$\phi$, S,F,$\sigma$ |
| e. Thermal Expansion Driving Force | DW,UL,RS | SB | medium | H(D,R) | T,G,N,$\phi$,S,(F) |
| 2. Neutron Multiplier Mechanical Interactions | | | | | |
| a. Swelling Driving Force in Beryllium | UL,RL | Beryllium | high | H,R,D | $\phi$,S,F,t,T,G |
| b. Strain Accommodation by Creep in Beryllium | RP,RL | Beryllium | medium | H,R,D | S,F,t,T,$\sigma$,G |
| c. Mechanical Integrity of Unclad Beryllium | RP,RL | unclad Be | low | H,R,D | G,$\phi$,S,F,t,T,$\sigma$ |
| 3. Thermal Interactions | | | | | |
| a. Breeder/Structure Interface Heat Transfer (Gap Conductance) | DW,US,UL | SB | critical | D | G,$\phi$,$\sigma$,T,C,p,v |

Table 3.2-1 Fusion Nuclear Testing Issues (contd.)

| Issue/Technical Area | Potential Impact | Design Specificity | Level of Concern | Operating Environment: Neutron | Operating Environment: Parameters |
|---|---|---|---|---|---|
| F. GENERAL BLANKET | | | | | |
| 1. DT Fuel Self-Sufficiency | DW | generic | critical | | |
| a. Uncertainties in Achievable Breeding Ratio | DW | generic | critical | R | $\phi$,F,S,G |
| 1) Lithium Burnout Effects | RP,RL | SB/mult | medium | H,R | S,F,$\phi$,T,G,C |
| b. Uncertainties in Required Breeding Ratio | DW | generic | critical | — | all |
| 2. Tritium Permeation | | | | | |
| a. Permeation from Breeder to Blanket Coolant | US,UL | generic | SB,LiPb:H Li:M | R,D | T,p,I,F,N |
| b. Permeation Characteristics at Low Pressure | RP | generic | high | — | p,$p_t$,C,I, T,v,s |
| 3. Chemical Reactions | US | generic | high | R | C,G,T |
| a. Chemical Reactivity of Lithium | US,RS | LM | high | — | C,G,T |
| 4. Tritium Inventory Behavior during Transients | RS | generic | SB:H, Li:M LiPb:L | D,R | T,C,G,v,$\sigma$ |
| 5. Uncertainties in Failure Modes and Frequencies | UL,RS | generic | high | D | all |
| 6. Nuclear Heating Rate Predictions | RP | generic | high | R,H | $\phi$,S,F |
| 7. Blanket Response to Near Blanket Failures | US,UL | generic | medium | — | T,G,$\sigma$,v,p,C |
| 8. Assembly and Fabrication of Blankets | UL,IC | generic | medium | — | G |
| 9. Recycling of Irradiated Lithium and Beryllium | DW,IC | Be,Li | low | R | $\phi$,S,T |
| 10. Prediction and Control of Normal Effluents Associated with Fluid Radioactivity | RP,IC,RS | generic | low | — | |

Table 3.2-1 Fusion Nuclear Testing Issues (contd.)

| Issue/Technical Area | Potential Impact | Design Specificity | Level of Concern | Operating Environment: Neutron | Operating Environment: Parameters |
|---|---|---|---|---|---|
| II. PLASMA INTERACTIVE COMPONENTS | | | | | |
| A. GENERAL CONCERNS | | | | | |
| 1. Materials Data Base Development | RL,UL | generic | high | D | F,T,G,q,σ |
| 2. HHFC Surface Damage Mechanisms | | | | | |
| a. Physical Sputtering and Redeposition | DW,UL,RL | generic | critical | — | PMI,B,G |
| b. Arcing and Related Erosion | UL,RL | generic | high | — | PMI,B,G |
| c. Chemical Erosion | UL,RL | generic | medium | — | PMI,T,I |
| d. Surface Damage due to Helium Implantation (Blistering) | RL | generic | medium | — | PMI,F,T,σ |
| e. Disruption-Induced Surface Melting and Erosion | UL,RL | generic | medium | — | PMI,B,$\dot{B}$,q, I,T,C |
| 3. HHFC Thermomechanical Response | | | | | |
| a. HHFC Structural Integrity | UL,RL | generic | high | D | PMI,q,G,T, σ,B,$\dot{B}$ |
| b. Thermal Hydraulic Techniques | UL,RL | generic | high | — | PMI,q,G,T,v |
| c. Leading Edge Design | UL,RL | generic | high | H,D | PMI,B,G,F,q |
| d. Heat Sink Bond Fabrication and Failure | UL | generic | high | D | PMI,T,F,σ |
| e. First Wall Hot Spots due to Plasma Spatial Distribution | DW | generic | LM:H $H_2O$:M | H,D | PMI,q,T,σ,F |
| f. Disruption Electromagnetic Loading | DW,US | generic | tokamak:H mirror:L | D | PMI,$\dot{B}$,q,σ,F |
| 4. Plasma Edge Conditions and Exhaust | | | | | |
| a. Plasma Edge Temperature and Density Control | DW | tokamak | critical | — | PMI,G,I |
| b. Helium and Impurity Exhaust | DW | tokamak | high | D | PMI,B,G,T |
| c. Plasma Exhaust Stream Pressure and Composition | RP,RL | generic | medium | — | PMI,p,I |
| d. Surface Conditioning Effectiveness | UL,RL | generic | medium | — | PMI,G,I,T |
| 5. Safety | | | | | |
| a. Tritium Permeation and Inventory | DW,US | generic | critical | D | PMI,F,T,σ,q |
| b. Tritium Inventory Behavior during Maintenance | IC | generic | high | D | φ,S,F,T,PMI |
| c. Eroded Activation Product Behavior in the Vacuum Chamber | IC,RS | generic | medium | R | S,F,φ,G,q |

Table 3.2-1 Fusion Nuclear Testing Issues (contd.)

| Issue/Technical Area | Potential Impact | Design Specificity | Level of Concern | Operating Environment | |
|---|---|---|---|---|---|
| | | | | Neutron | Parameters |
| B. LIMITER/DIVERTOR SPECIFIC ISSUES | | | | | |
| 1. Maintenance and Replacement | UL | tokamak | high | D | G,(PMI,F) |
| 2. Choice of Limiter vs. Divertor | DW,UL,IC | tokamak | high | — | PMI,G |
| 3. Alignment | DW,RL | tokamak | medium | D | PMI,G,q,B,$\dot{B}$ |
| C. VACUUM SYSTEMS | | | | | |
| 1. Compound Cryopump Helium Pumping and Regeneration Lifetime | RP,RS | generic | medium | H,D | p,T,I,G,$\sigma$,t,F |
| 2. Vacuum Chamber Outgassing and Leak Rates | RP,RS | generic | medium | — | G,$\sigma$,T,p |
| 3. Large-Diameter Vacuum Valve Reliability | UL | generic | low | D | t,I,G,F |
| 4. Vacuum Pump Operation under Thermal/Pressure Transients | IC,RS | generic | low | — | p,q,T,t |
| D. RF COMPONENTS (Auxiliary Heating Systems) | | | | | |
| 1. RF Launcher Performance Requirements | UL,RL | generic | critical | R,D,H | $\phi$,S,F,$\dot{T}$,B, q,G,$\phi$,$\dot{B}$, |
| 2. Window and Feedthrough Performance | UL,RP | generic | critical | R,D,H | $\phi$,S,F,G,T |
| 3. RF Transmission System Performance Requirements | RP,RL | generic | medium | R,D,H | $\phi$,S,F,G,T |

Table 3.2-1 Fusion Nuclear Testing Issues (contd.)

| Issue/Technical Area | Potential Impact | Design Specificity | Level of Concern | Operating Environment: Neutron | Operating Environment: Parameters |
|---|---|---|---|---|---|
| III. SHIELD | | | | | |
| 1. Shield Effectiveness | | | | | |
| a. Protection of Sensitive Components | RL | generic | high | D | $\phi$,F,S,G |
| b. Biological Dose During Operation and Maintenance | RS | generic | high | R | $\phi$,F,S,G |
| c. Analytical Techniques and Data Base | RL,IC,RS | generic | high | R | $\phi$,F,S,G |
| 2. Shield Compatibility with Blanket including Assembly and Disassembly | RS,IC | generic | high | H,R,D | $\phi$,S,F,G,T,B |
| 3. Time Constant of Magnetic Field Penetration for Plasma Control | RP | tokamak | medium | — | $\dot{B}$,$\phi$,G |
| 4. Shield Compatibility with the Vacuum Boundary and One Turn Resistance | RP | design | low | D | $\phi$,S,F,G |
| IV. TRITIUM PROCESSING SYSTEM | | | | | |
| 1. Impurity Removal in the Fuel Cleanup Process | UL,RP,IC | generic | high | R | v,G,C,I,T$\phi$,F |
| 2. Tritium Monitoring and Accountability | UL,RS | generic | high | H,R,D | v,G,I,C,t,$\phi$,F |
| 3. Tritium Losses in Solid Waste | RP,IC,RS | generic | high | — | I,C,PMI,F,t |
| 4. Tritium Extraction from Water Coolant | US | $H_2O$ | high | — | v,C,I,G,T |
| 5. Tritium Processing System Integration | RP | generic | high | — | v,G,t,I |
| 6. Atmospheric Cleanup Process | RP,IC,RS | generic | medium | — | C,G,t |
| 7. Breeder Tritium Extraction Stream Characteristics | RP,IC | generic | low | R,D | v,G,C,I,$\phi$,F |

Table 3.2-1 Fusion Nuclear Testing Issues (contd.)

| Issue/Technical Area | Potential Impact | Design Specificity | Level of Concern | Operating Environment: Neutron | Operating Environment: Parameters |
|---|---|---|---|---|---|
| V. MAGNETS | | | | | |
| 1. Structural Overloading and Quenching due to Plasma Disruptions | UL,IC | tokamak | high | — | $B,\dot{B},\sigma,T,G$ |
| 2. Internal Cooling Requirements and Cryostability | IC | generic | high | H,R | $B,\phi,S,T$ |
| 3. Maximum Levels of Radiation Damage and Recovery Process for Magnet Components | | | | | |
| a. Critical Current Reduction | RP | generic | high | R,D | $\phi,F,S,T$ |
| b. Electrical Resistivity of the Stabilizer | RL | generic | high | R,D | $\phi,F,S,T$ |
| c. Insulator Structural Degradation | RL | generic | high | R,D | $\phi,F,S,T,\sigma$ |
| d. Annealing of Radiation Damage | UL | generic | high | — | T |
| e. Consequences of Magnet Failures | | | | | |
| VI. INSTRUMENTATION AND CONTROL | | | | | |
| 1. Definition of Transducer Lifetimes and Hardening Requirements | UL | generic | high | D,R,H | T,S,F,t,q |
| 2. Breakdown of Insulation Resistance | UL,RP | generic | high | R | T,S,F |
| 3. Decalibration of Transducer through Transmutation | RL | generic | medium | D,R | T,S,F |
| 4. Ceramic Insulator/Substrate Seal Integrity | RL | generic | medium | D | T,S,F |
| 5. R.F. Transmission Losses in Horns, Antennae, Wave Guides, and Windows | RP | generic | medium | R,D,H | $S,F,\phi T,q$ |
| 6. Optical Window, Lens, and Prism Darkening and Distortion | RL | generic | medium | D,R,H | $S,F,T,\phi$ |
| 7. Shielding of Instrument Penetrations | IC,RS | generic | low | D,R | $S,F,\phi$ |
| 8. Radiation Effects on Electrical Components beyond the First Wall and Shield | RL,IC | generic | low | D,R | S,F |
| 9. Cable Noise from R.F., Magnetic Fields, Charges Particles, etc. | RP | generic | low | R | $B,\phi,S,PMI$ |

## 3.3 Critical Nuclear Technology Issues

The issues table in Section 3.2 contains a large number of specific technical issues ranging in complexity and importance. Each of these issues impacts key aspects of feasibility, safety, and/or economic potential of fusion reactors. Resolving these issues requires new knowledge through experiments, models, and theory.

Table 3.3-1 summarizes the most critical issues in a format that is easy to follow. The sub-entries in this table are taken mostly from the main issues table and represent those issues with the largest uncertainties leading to the greatest potential impact.

### 3.3.1 DT Fuel Cycle Self-Sufficiency

Fuel self-sufficiency is a necessary goal for fusion as one of a very limited number of options for a long-term, renewable energy source. Attaining fuel self-sufficiency in DT fusion reactors cannot be assured prior to resolving present uncertainties in both the required and the achievable tritium breeding ratios.

The required tritium breeding ratio, TBR, is uncertain due to lack of data and models to reliably predict the tritium behavior throughout the fuel cycle. One example of such uncertainties is the magnitude of the achievable tritium fractional burnup in the plasma. A low fractional burnup results in large tritium inventories in the plasma fueling and processing systems and results in high TBR. The burnup fraction depends on the characteristics of the plasma and the impurity control and exhaust system, which presently are not well known. Another example is the magnitude of tritium inventory in the blanket, particularly for solid breeders where there is a lack of adequate data, for example on tritium release and retention under irradiation. All of these effects result in uncertainties in determining the required excess in the tritium breeding ratio above unity.

The achievable tritium breeding ratio is also uncertain. For many concepts, the estimated values for the achievable TBR does not have enough margin to cover present uncertainties in both the achievable and required TBR's. Some of the uncertainties in the tritium production rate are due to alternatives in specifying reactor design choices, such as the type of impurity control and plasma heating system, and the details of material constituents, geometry, and other characteristics of the blanket and other components. Other uncertainties exist in our predictive capabilities due to limitations in both neutronics computational methods and available nuclear data.

### 3.3.2 Thermomechanical Performance of Blanket Components under Normal and Off-Normal Operation

The environment of a fusion reactor blanket is very demanding on materials and structures. This includes a combination of high temperatures, particle and heat fluxes, neutron irradiation, and high magnetic fields. These result in thermal and mechanical loads in all components under normal and off-normal conditions that must be kept within acceptable engineering limits. In addition, these components must survive changes in these loads and in material properties for adequate life under the radiation environment. At present, there are large uncertainties in estimating thermomechanical loads and in predicting the resulting response of components.

Liquid metal blankets appear to have greater uncertainties than solid breeder blankets in this area. The most serious arise from MHD effects, which couple the fluid, thermal, and structural responses in a way that is very sensitive to geometry and which depend on magnetic and neutron fields. Many of the phenomena occuring in liquid metal blankets are new and virtually unexplored.

For all blankets, large uncertainties exist due to the interaction of large primary and secondary stresses with irradiation effects. The first walls of some blankets are designed to operate with significant plastic deformations. Time dependent responses to thermal and irradiation creep are not well known, particularly for short pulse devices. In addition to the responses, the sources of loading are also uncertain. Specific examples include plasma disruptions (which may or may not be present) and hot spots due to coolant flow paths, plasma variations, and nonuniformities due to in-vessel components and penetrations.

### 3.3.3 Materials Compatibility

All combinations of materials present compatibility problems of some degree, such as corrosion, chemical reactions, and degradation of materials properties. The selection of materials and determination of operating limits for selected combinations require new data and understanding of the interactions among candidate materials in the presence of the fusion environment.

One area of uncertainty is the effects of coolant, breeder, and purge on the structural material and its failure modes. Stress corrosion cracking in water cooled systems and embrittlement in liquid metal systems are two examples which may limit the lifetime and reliability of the blanket.

Materials compatibility plays an important role in the selection of the blanket operating conditions, and in some cases it represents a critical feasibility limit. Materials compatibility problems are generally accounted for through imposing temperature limits; for example, to limit the corrosion rate and reduce the radioactive mass transfer and structure thinning to acceptable limits. At present, available data on corrosion of liquid lithium and lithium leads result in low temperature limits for steels. These limits rule out liquid metals with austenitic steels and provide only a narrow design window with ferritic steels. There is a serious concern that corrosion by liquid metals may be substantially enhanced in the presence of magnetic fields. Therefore, reliable data on corrosion of structural materials by liquid metals in the fusion environment is a critical requirement to establishing the feasibility of liquid metal blankets. Similarly, adequate data is needed on the compatibility of breeder with structure and tritium recovery fluid with breeder and structure for solid breeder blankets.

One of the most visible implications of materials selection is the safety risk and consequences. Some of the most serious risks associated with the blanket include: lithium chemical reactions with air and water, structural material oxidation and volatility at high temperature (especially for vanadium), and activation, mobilization and transport of radioactive isotopes. Many of the experimental needs in this area are for basic measurements to aid in materials selection; however, after materials have been chosen, the need remains to investigate the safety related aspects of the design.

### 3.3.4 Identification and Characterization of Failure Modes and Rates

Knowledge of failure modes and rates is necessary in the research and development of engineering components because of their critical impact on the economic potential and safety. There is virtually no data on failure modes and rates of the nuclear components in the fusion environment. Prudent selection of feasible and attractive designs is extremely difficult without such data. For example, pressurized water coolant/solid breeder blankets presently offer substantial savings in the capital cost of a tokamak reactor, but the primary issue with such blankets is whether the failure rates and modes can result in acceptable operational economics and safety. Analysis has identified some possible failure modes; for example, crack growth under cycling, cracking at weld and discontinuities. Experiments are required to examine these potential failure modes. However, the most important information from experiments is expected to be the identification of unforseen failure modes in the unique fusion environment. These unknowns place severe requirements on the test conditions, because it is not clear which environmental conditions are the most important.

### 3.3.5 Tritium Inventory and Recovery in the Solid Breeder under Actual Operating Conditions

Tritium inventory and recovery in the solid breeder is important for two reasons. First, as mentioned above, the feasibility of solid breeder blankets depends on whether or not they can breed enough tritium to satisfy DT fuel self-sufficiency conditions. The required breeding ratio increases with the breeder tritium inventory. Secondly, this tritium inventory may be a large safety risk, depending on its magnitude and mobility.

Uncertainties are very large; in some cases there are orders of magnitude of uncertainty associated with some of the tritium transport processes. These relate to both fundamental tritium transport mechanisms and to the actual behavior in the fusion environment, such as consequences of structural and breeder mechanical interactions. Within the solid breeder material, transport depends on intragranular diffusion, surface kinetics, and porosity. These processes are very sensitive to the fabricated microstructure and operating conditions, particularly the radiation environment.

The breeder temperature profile is particularly crucial because a relatively narrow window of operation is predicted, based on unreasonably high inventory at low temperature and sintering and materials properties changes at high temperature. Reliable data to accurately define these temperature limits does not exist. Some interactive effects which can have a large impact on the temperature window include breeder/cladding gap size changes, swelling and creep interactions with the structure, radiation effects on thermal conductivity, cracking, and LiOT corrosion effects.

### 3.3.6 Tritium Permeation and Inventory in the Structure

Tritium permeation is primarily a safety concern, but the attempt to control it can have a large impact on design and operation. The problem is thought to be most critical for in-vessel components where tritium passes from the plasma chamber into the coolant streams. The magnitude of permeation depends on the plasma edge conditions, on trapping in the structure (which may depend strongly on irradiation), and on the effectiveness of techniques for controlling permeation such as coatings. In the bulk of the blanket, permeation can be significantly altered by the form of the tritium -- either $g_a$s or oxide -- and by the presence of protium ($H_1$). The form of tritium as it is released from the breeder is uncertain, as well as its chemistry and kinetics as it circulates through the coolant and purge loops.

### 3.3.7 In-Vessel Component Thermomechanical Response and Lifetime

In-vessel components have special problems with thermomechanical performance in addition to those in the bulk blanket. In-vessel components include the first wall, limiters and divertors, RF antennas, beam dumps, and others. These special problems stem from the very high heat and particle fluxes that these components are exposed to under normal operating conditions, and from the potentially high thermal loads and electromagnetic forces under off-normal conditions, e.g., plasma disruptions. Erosion and redeposition is one of the largest uncertainties. This issue has far-reaching implications on lifetime, failure modes, and design choices. The structural integrity of in-vessel components is uncertain due to the high thermal stresses and presence of local hot spots (for example at the limiter leading edge). Bonds may be necessary if the surfaces are protected by coatings or composite structures. The structural response of these bonds is a particular concern.

### 3.3.8 Radiation Shielding

Shielding must protect both personnel and sensitive reactor components.

Components with the most stringent protection requirements include superconducting magnets, some elements of plasma heating and exhaust systems (for example, RF windows or cryopanels), and instrumentation and control. Any component which must contain ceramics or any other material with a high sensitivity to radiation will also cause concern. In some cases, for example, the inboard region of a tokamak, the thickness and materials of the shield have substantial impact on the economics of the reactor.

Sophisticated neutronics techniques exist for the prediction of the radiation field and associated nuclear responses. But uncertainties in accuracy remain due to modeling complexities, nuclear data uncertainties, limitations of calculational methods in void regions and deep radiation penetration problems, and time dependent behavior of materials and structures. For example, it is likely that components will deform during operation, which may lead to unpredictable streaming paths. Improvements in methods, data, and experimental verification of predictive capabilities are needed.

Establishing accurate radiation protection requirements is necessary, particularly for components whose shielding is either physically difficult or results in substantial economic penalty. This requires quantitative knowledge of the effect of radiation on components.

### 3.3.9 Accuracy and Survivability of Instrumentation and Control

Failure of instrumentation and control may have a very serious impact on the safety and operation of the reactor. The vulnerability of these components depends to a large extent on radiation shielding as described above. However, because of the added effects of all of the environmental condition present in a fusion reactor (e.g., magnetic field), this category is considered as a separate issue. Instrumentation and control components often contain materials which are sensitive to radiation, electromagnetic effects, and corrosion. It is necessary in a number of key cases to develop new measurement techniques because presently available instruments will not function properly in high fields, with bulk heating, or in corrosive environments. In addition, innovative techniques for measurements related to new phenomena in the fusion environment are needed in order to obtain meaningful information from experiments.

Table 3.3-1. Critical Fusion Nuclear Technology Issues

1. DT Fuel Cycle Self-Sufficiency:

   - Achievable Tritium Breeding
     e.g., Effects of Blanket Material Choices and Internal Details
     Extent of Plasma Coverage (Choice of RF vs. Neutral Beams, Limiter vs. Divertor)
     Uncertainties in Neutronics Methods and Data
   - Required Tritium Breeding
     e.g., Dependence on Plasma Recycling (Limiter vs. Divertor, Pumping Efficiency)
     Tritium Inventory in the Blanket, Plasma Exhaust, Storage, etc.
     Tritium Extraction and Processing System Inventories and Efficiencies

2. Thermomechanical Performance of Blanket Components under Normal and Off-Normal Operation:

   - Liquid Metal MHD Effects: Relationship of Fluid Flow, Heat Transfer, and Structural Response in the Presence of Magnetic Fields, Bulk Heating, Surface Heating, and Full Geometric Complexity
   - Interaction of Primary and Secondary Stresses and Deformation
   - Effect of Swelling and Creep on Stress Concentrations
   - Consequences of Plasma Disruptions
   - Sources and Consequences of Hot Spots

3. Materials Compatibility:

   - Effect on Design Limits
     e.g., Liquid Metal Corrosion Temperature Limits
     LiOT and Lithium Burnup Effects
   - Influence on Failure Modes
     e.g., Liquid Metal Embrittlement and Stress Corrosion Cracking
   - Impact on Safety and Reliability
     e.g., Transport of Radioactive Isotopes
     Oxidation/Volatility of Vanadium
     Lithium Chemical Reactivity
     Blocking of Coolant or Purge Streams

4. Identification and Characterization of Failure Modes and Rates:

   - Crack Growth and Brittle Fracture with Irradiation
   - Vulnerability at Welds and Discontinuities
   - Discovery of Unforseen Failure Modes

Table 3.3-1 (cont.)

5. <u>Tritium Inventory and Recovery in the Solid Breeder under Actual Operating Conditions:</u>

- Radiation Effects on Tritium Diffusivity and Solubility
- Variability in Temperature due to Radiation Effects and Mechanical Interactions (Gap Conductance, Cracking, Swelling, Creep, etc.)

6. <u>Tritium Permeation and Inventory in the Structure</u>

- Magnitude in In-Vessel Components Under Actual Operating Conditions (Including Effects of Plasma Side Conditions, Radiation, etc.)
- Form of Tritium ($T_2$,$T_2O$) Released from Solid Breeder
- Effectiveness of Control Methods Such as Permeation Barriers

7. <u>In-Vessel Component Thermomechanical Response and Lifetime</u>

- Erosion and Redeposition Mechanisms and Rates under Various Plasm Edge Conditions
- Heat Removal Techniques
- Structural Integrity of Components and Bonds
- Leading Edge Design of Limiters

8. <u>Radiation Shielding</u>

- Accuracy of Prediction
- Data on Radiation Protection Requirements

9. <u>Accuracy and Survivability of Instrumentation and Control</u>

- Accuracy and Decalibration in the Fusion Environment
- Lifetime Limits due to Radiation Effects

## 3.4 Issues Descriptions

This section contains the detailed descriptions of the issues listed in the main issues table in Section 3.2.

# I. BLANKET

## I.A STRUCTURE

### Issue I.A.1 Changes in Properties and Behavior of Materials

Description: The interaction of neutrons with structural materials results in changes to the material, including: 1) displacement of lattice atoms from their original sites, 2) nuclear transmutation of original elements, and 3) helium and hydrogen production. The effects of these neutron produced changes on the many properties of materials are a function of many variables such as temperature, environment, material grain size, etc. The properties and behavior currently believed to be most important to fusion reactor designers are those that relate to the structural integrity and mechanical stability of the materials.

Properties such as tensile strength, ductility, density, fracture toughness, creep, and crack initiation and growth need to be accurately known in order to design a safe reactor structure. Neutron irradiation will change these properties; therefore, the property changes need to be measured as a function of neutron dose under the appropriate operating conditions.

Potential Impact: (US,UL) The potential impacts of not knowing the way in which material properties vary with neutron irradiation are: 1) system failure with serious safety implications, and 2) failure resulting in serious implications on machine operation and availability, including reliability and maintainability. For example, an increase in the ductile to brittle transition temperature of ferritic steels, with increasing neutron dose, could result in brittle fracture of the first wall during lower temperature maintenance periods.

Design Specificity: (generic) The need for structural material property data is generic to all neutron producing reactor concepts.

Overall Level of Concern: (critical) Because virtually all material properties change considerably with increasing neutron irradiation and because the impact of not knowing the value of the property change is serious relative to the operation and safety of any neutron producing facility, it is critical that the issue of material properties and behavior in a neutron environment be measured.

Operating Environment/Neutrons: (D,R) The interaction of neutrons with materials changes the physical and chemical microstructure of the parent material. Furthermore, nuclear transmutation products introduce new elements into the material lattice that may significantly affect the material behavior and properties. Helium, for example, will be produced in significant quantities in fusion neutron spectra and is believed to strongly effect the nucleation and distribution of neutron induced voids.

Operating Environment/Parameters: The properties and behavior of structural materials are sensitive to virtually all of the environmental parameters. The range of temperatures, stresses, flux and fluences, etc., expected to exist in the reactor concept being designed must be present in the testing program.

## Issue I.A.1.a Prediction of Radiation Damage Indicators

Description: Radiation damage indicators are used in developing predictive correlations between radiation effects on materials and the characteristics of the neutron field (flux, spectrum, and fluence). The important indicators are: 1) atomic displacements, 2) gas (primarily hydrogen and helium), and 3) transmutation of nuclides. Calculations of these indicators presently suffer from uncertainties due to inadequate modeling and deficiencies in basic nuclear data

Potential Impact: (US,UL) Large uncertainties in radiation will make it difficult to calibrate theoretical models for predicting radiation effects and will result in large risks in extrapolating the limited experimental irradiation data to other conditions (e.g., different neutron spectrum, higher fluence, different temperature, etc.)

Design Specificity: generic

Level of Concern: (high) This issue is particularly important for structural materials and ceramic breeders.

Operating Environment/Neutrons: (D) Neutrons with representative fusion spectrum are required.

## Issue I.A.2 Deformation and/or Breach of Component

Distortion and failure of components may result from both primary and secondary stresses. Primary stresses are those stresses which result from mechanical loadings such as coolant pressure, vacuum loading, and electromagnetic loads. Secondary stresses are those stresses which result from thermal gradients, swelling, and thermal and irradiation creep.

The interaction of these phenomena together with the cyclic nature of a fusion reactor results in complex time, temperature, and neutron fluence dependent stress histories in first wall/blanket components. Large stresses, distortions, or failure may result. Swelling is the most likely source of excessive deformation of components. Excessive deformation can lead to failure of the component or can cause problems for removal of the component. In addition, large deformations may lead to local neutron streaming and maintenance problems.

## Issue I.A.2.a Effect of First Wall Heat Flux and Cycling on Fatigue or Crack Growth Related Failure

Description: First wall/blanket structures are subjected to high temperatures, thermal gradients, coolant pressures, dead weight loads, corrosive environments, and severe radiation. They will encounter cyclic stress conditions which will cause cumulative damage in structural components, which will limit life. In high temperature designs, other effects of cycling must be considered, including shakedown, ratcheting, and fatigue In addition, creep and yielding must be considered in a complete blanket structural analysis.

Wall loading will have a large effect on the critical failure mode of a first wall/blanket. Based on stress histories and associated fracture mechanics analysis, lifetime at low wall loadings is controlled by stresses during the plasma burn. At higher wall loadings, lifetime is controlled by residual stresses present during the non-burn period. The primary failure mode is likely to be flaw growth leading to coolant leakage.

Potential Impact: (DW,RS,UL) As wall loading is increased, thermal stresses will increase, and therefore lifetime will decrease. An excessively short lifetime will present a serious implication on the design window. Changes in wall loading and cycling have the potential for affecting system operation and availability.

Design Specificity: (generic/tokamaks) This issue is generic to all tokamak first wall/blanket concepts. For mirrors, wall loadings are lower and operation is steady state, so this issue does not apply.

Overall Level of Concern: (critical) The level of concern for changes in wall loading and cycling is critical. Changes in wall loading and cycling should not result in immediate failure. However, it will decrease life of the component. If life is greatly decreased, the design window could be seriously impacted.

Operating Environment/Neutrons: (H,D) Neutrons are required as a potential source of heating and for materials damage since crack growth depends on the materials properties.

Operating Environment/Parameters: For testing to resolve the effects that changes in wall loading and cycling have on stresses and life, the expected surface heat flux (up to 100 $w/cm^2$) and operating temperature, operating time, number of cycles, stress level, and component geometry are required.

## Issue I.A.2.b Magnetic Field Interaction within the Structure

### Issue I.A.2.b.1 Magnetic Forces due to Plasma Disruptions and Magnetic Transients (see also PIC issue II.A.3.e)

Description: Metallic structures in time-varying magnetic fields will experience induced electric currents and complex interactive magnetic forces. As a consequence of component geometry, these body forces can lead to complex states of stress -- large in magnitude and difficult to predict theoretically. Plasma disruptions are an extreme example of a magnetic field transient. They are inherent in present tokamak operations and are also assumed to occur in mirror reactor operation. Enhanced radiation, particle flux, and the rapidly changing magnetic field associated with a plasma disruption translate into heating of the first wall and fairly high stresses in the first wall structure on a time scale significantly less than one second. Irradiation embrittlement and change in the DBTT (ductile-to-brittle transition temperature) reduce the ability of the first wall structure to withstand disruptions. This may cause premature failure after a limited number of such disruptions. The combination of raised temperature, complex induced stresses, and altered material properties in a complex geometry leads to a high degree of uncertainty.

Potential Impact: (DW) The detailed interaction between the plasma and the structure during a plasma disruption is not known at this time. It is anticipated that the present risk to the fusion device is substantial.

Design Specificity: (tokamaks) The interaction of the plasma and first wall structure is generic to all reactor concepts, but the effects of the interaction may be less severe for mirror designs.

Overall Level of Concern: (high) Very little is known about the severity of plasma disruptions on the scale anticipated for commercial fusion devices. A limited number of such disruptions could lead to failure of the component. Therefore, the overall level of concern for this subissue is high.

Operating Environment/Neutrons: (--) While neutron spectrum and fluence may affect failure modes and component lifetime, they are not required to assess the interaction between the plasma and the first wall.

Operating Environment/Parameters: Magnetic field, rapidly changing magnetic field, temperature (for failure modes), first wall geometry, and stress

Issue I.A.2.b.2 Magnetically Induced Stresses in Ferritic Steels

Description: In ferromagnetic alloys such as HT-9, there exist large magnetically induced primary stresses in the structural components. Calculating and predicting failure is very complex and testing of act-alike modules is essential.

Potential Impact: (RL,IC) Design to accomodate magnetostatic forces will increase the cost and complexity of the design, and when added to the other loads already present in the structure may result in reduced lifetime.

Design Specificity: (ferritic steels) This issue is generic to designs employing ferritic steels.

Overall Level of Concern: (low) This issue has a low level of concern because analysis shows that the magnetic forces will saturate at a level that can be handled.

Operating Environment/Neutrons: (R,D) Neutrons are needed in testing, both for specific reactions and displacement damage. The effect of neutrons on materials properties will alter the responses of the material to magnetic loading, including deformation and failure modes. Spectrum, fluence, and flux are important test parameters.

Operating Environment/Parameters: The complexity of electromagnetic loading in full components makes an act-alike shape or full scale module necessary to attain proper simulation of electromagnetic loads. The entire operating temperature range should be explored in testing.

Issue I.a.2.c.: Failures at Welds and Discontinuities

Description: A variety of effects may lead to failure of a first wall/blanket component at a weld. In general, welds are located at discontinuities which are sources of stress concentrations. In addition to high stresses at a weld, the weld region may react differently than the parent material in an irradiation environment. Differential swelling between the weld and parent material can lead to a build-up of internal stresses. Localized helium and gas build up in the weld region can cause the weld to respond differently than the parent material.

Potential Impact: (RS,UL) Failure of welds can pose a safety implication and force reactor shutdown. If a weld fails, it has the potential for causing tritium containing coolant to spill out.

Design Specificity: generic

Overall Level of Concern: (high) Failure of a weld has a high level of concern because it will affect operation. Welds are the most likely location for a first wall/blanket component to fail.

Operating Environment/Neutrons: (R,D) Neutrons are required, for testing, to produce material damage. Neutrons are also required to determine the effects of differential swelling between the weld and the parent material.

Operating Environment/Parameters: Testing parameters required to resolve this issue are flux, neutron spectrum, neutron fluence (250 dpa), temperature (400-600°C), and atmosphere (environment the weld will be in to determine if stress corrosion cracking will be a problem).

Issue I.A.2.d.: Failures due to Hot Spots

Description: Local hot spots in the first wall/blanket module can lead to failure. At the location of hot spots, there will be high thermal gradients which will produce high thermal stresses. Because of the cyclic nature of a fusion reactor, these high thermal stresses can cause failure by fatigue or crack growth. The rate of crack propagation is strongly temperature dependent and is therefore much enhanced at these hot spots.

Hot spots can result from stagnation points in the coolant flow channels, from improper location of coolant channels, from the solid breeder separating from the blanket coolant, and from local cracking in the solid breeder.

Potential Impact: (RS,UL,DW) Local failure at a hot spot has the potential for limiting the design window for the first wall/blanket. If hot spots occur, lifetime will be decreased. To eliminate these hot spots, the first wall/blanket will have to be redesigned. In addition, system failure will affect system operation and availability.

Design Specificity: generic

Overall Level of Concern: (high) Hot spots leading to failure have a high level of concern due to their safety implications.

Operating Environment/Neutrons: (H,D,R) Neutron heating may be required to obtain the hot spots prototypical of a specific blanket concept. Neutrons will be required as a source of specific reactions (e.g., He production) and material damage. Neutron effects contribute to the materials properties, and therefore are an important environmental condition for reproducing failure modes.

Operating Environment/Parameters: To assess the effects of hot spots on failure, the geometry of the first wall/blanket is required along with the expected operating temperature (400-600°C). Neutron spectrum, flux and neutron fluence will be required. In addition, heat flux, coolant velocity, and magnetic fields (in liquid metal blankets) will also be important.

Issue I.A.2.e.: Interaction of Primary Stresses, Secondary Stresses and Deformation

Description: Primary stresses are those stresses which result from mechanical loadings, such as coolant pressure, vacuum loading and electromagnetic loads. Secondary stresses are defined as stresses which relieve themselves as deformation takes place. Thermal stresses and swelling are examples of secondary stresses.

Secondary stresses in the plastic regime may occur in tokamak first walls. Deformation can result from both primary and secondary loadings. In the design of a first wall/blanket for a fusion reactor, a tradeoff is made between stresses and deformation. If deformation is a problem, additional constraint can be added. However, as additional constraint is added, stresses increase and life will decrease. In a fusion environment swelling is the most probable source of excessive deformation.

Swelling can cause stresses in the component by three different means. First, flux or temperature gradients cause differences in the swelling rate for different parts of the structure (differential swelling), resulting in increases in stresses (similar to thermal gradients producing thermal stresses). Second, overall constraint of the component restricts the ability of swelling stresses to be relieved by expansion. If swelling stresses are high, buckling or crippling of the component can ocur. Third, stresses can be imposed on the component by differential swelling rates between different materials.

Irradiation creep will help to relieve swelling stresses. However, at shutdown, these stresses will reverse and could cause cracking. On a cyclic machine this stress reversal at shutdown will result in a shorter life.

Potential Impact: (UL,IC) Interaction between primary stresses, secondary stresses, and deformation must be understood before first walls can be designed for maximum life. Low first wall lifetime is a major contributor to system costs.

Design Specificity: generic

Overall Level of Concern: (high) The level of concern is high because of the potential safety hazard. The effects of irradiation on the behavior of a first wall/blanket module is unknown and needs to be resolved by testing.

Operating Environment/Neutrons: (H,D,R) testing to resolve this issue, neutrons are required as a source of heating, to produce specific reactions and to produce material damage.

Operating Environment/Parameters: Testing parameters required to resolve this issue are flux, neutron spectrum, neutron fluence (100 dpa), surface heat flux (100 $w/cm^2$), geometry (needed to model constraint of first wall/blanket), temperature (400-600°C), and stress (design allowable stress level for material being tested).

Issue I.A.2.f.: Failure Due to Shutdown Residual Stress Effects

Description: During a plasma burn, the first wall will be subjected to compressive thermal stresses. These stresses may not cause structural damage or failure. However, stresses will relax during the plasma burn by thermal and irradiation creep causing residual tensile stresses to remain during the nonburn portion of the cycle. These cyclic tensile stresses will contribute to flaw growth, leading to possible failure of the structure or to coolant leakage. The residual tensile stresses will also increase the risk of brittle failure during downtime, caused by stresses exceeding the ultimate strength of the material or by stress intensities exceeding the fracture toughness in the region of a crack.

Potential Impact: (UL,IC) Failures due to shutdown residual stresses will affect operation and increase system cost.

Design Specificity: generic

Overall Level of Concern: (high) The initial stresses at the start of reactor operation are usually relieved in part by creep mechanisms. This creep relaxation is responsible for the residual stresses upon shutdown and are, therefore, directly related to the initial stresses. Later in the reactor's life, swelling will affect the residual stresses. The phenomena of creep and swelling are fairly well understood; the largest uncertainties involve the accuracy of predicting the initial stresses in a complex geometry.

Operating Environment/Neutrons: (D,R) For testing to resolve this issue, neutrons are required to produce specific reactions and to produce material damage.

Operating Environment/Parameters: Testing parameters required to resolve this issue are flux, neutron spectrum, neutron fluence (100 dpa), surface heat flux (100 $w/cm^2$), temperature (400-600°C), and stress (design allowable stress level for material being tested).

## Issue I.A.2.g: Effect of Swelling, Creep and Thermal Gradients on Stress Concentrations

Description: The most likely location for a failure in the first wall/blanket to occur is at a stress concentration. Stress concentrations will occur at abrupt changes in the cross section, at discontinuities in the structure, and at any cracks that may be present in the structure. The amount of the increased localized stress at a point (stress concentration) is dependent on the state of stress, stress gradient, temperature, and rate of straining. Swelling of the first wall/blanket will increase stresses at discontinuities by changing the state of stress and stress gradients. Stresses resulting from swelling will be highly dependent on thermal gradients and on the amount of constraint on the structure at the stress concentration. Irradiation creep will relieve stresses at the discontinutiy. However, at shutdown, these stresses will reverse and could cause cracking. Thermal gradients will produce thermal stresses at the stress concentration. In addition to thermal stresses, thermal gradients will produce differential swelling stresses.

Potential Impact: (UL,IC) Swelling creep, and thermal gradients will affect stress intensities at a discontinutiy. These higher stresses can result in failure at the stress concentration which can seriously affect operation availability, and lifetime of a fusion reactor. System cost will also be impacted.

Design Specificity: generic

Overall Level of Concern: (medium) The response of stress concentrations on the first wall/blanket in a neutron environment has a medium priority. It is anticipated that the structural material will not swell until neutron exposures are greater than 5 MW-y/m$^2$.

Operating EnvironmentNeutrons: (H,D,R) For testing to resolve this issue, neutrons are required as a source of heating, to produce specific reactions and to produce material damage.

Operating Environment/Parameters: Testing parameters required to resolve this issue are neutron spectrum, neutron fluence (100 dpa), surface heat flux (100 w/cm$^2$), geometry (needed to model constraint of first wall/blanket), temperature (400-600°C), and stress (design allowable stress level for material being tested).

Issue I.A.2.g.1: Response of Grooved Surface Concepts

Description: Because of the likelihood of high erosion rates on the first wall of a fusion reactor, the first wall thickness will need to be increased to achieve an adequate life. As first wall thickness is increased, thermal stresses will increase, resulting in a shorter life. One possible solution for decreasing thermal stresses in a thick first wall is to groove the surface. However, addition of grooves will lead to stress concentrations at the groove bottom. Grooving will allow the material above the grooves to operate at a temperature higher than the structural temperature limitation. Therefore, a detailed design study must be conducted to achieve the optimum design configuration.

Potential Impact: (RP,IC,UL) If grooving the first wall does not reduce thermal stresses and increase life, system performance will be degraded. In addition, the first wall will have to be replaced more frequently, therefore, increasing system cost and affecting operation.

Design Specificity: (design) This issue is relevant for tokamak type reactors that have a grooved first wall to relieve thermal stresses.

Overall Level of Concern: (medium) The level of concern is medium because of its impact on first wall lifetime.

Operating Environment/Neutrons: (H,D) Radiation damage, especially embrittlement, may be of concern. The temperature profile in first walls $>$ 0.5 cm thick is significantly affected by neutron heating.

Operating Environment/Parameters: Testing parameters required to resolve this issue are operating time, surface heat flux (100 $w/cm^2$), operating temperature (400-600°C), stress level in the first wall, neutron fluence, and neutron spectrum.

Issue I.A.2.h.: Interaction Between Surface Effects and First Wall Failures

Description: The first wall surface is subjected to damage from charged particles, neutrons, neutral atoms, and electromagnetic radiation. These cause sputtering of atoms from the free surface, blistering by implantation, and transmutations. Erosion of the first wall will cause increased primary stresses which can lead to rupture.

Potential Impact: (UL,RL) Surface effects can affect operation and availability of a fusion reactor. If damage to the first wall is excessive, it will require replacement of the first wall/blanket module more frequently. This will reduce component lifetime and increase system cost.

Design Specificity: (generic) Surface effects are generic to all first wall/blanket concepts and reactor types.

Level of Concern: (medium) The level of concern for surface effects is medium. The plasma/first wall interaction effects need to be resolved to improve life of the component. Surface interactions should not cause immediate failure of the first wall.

Operating Environment/Neutrons: (D) Neutrons are only required to produce potential material damage.

Operating Environment/Parameters: Testing parameters required to resolve this issue are plasma interactions, surface heat flux (up to 100 $w/cm^2$), operating time, temperature (400-600°C), plasma impurities (may affect erosion rates), stress level in the first wall, magnetic field, and neutron fluence.

Issue I.A.2.i: Self Welding of Similar and Dissimilar Metals

Description: If components come in contact because of excessive deformation, these components could weld together. If self welding occurs, removal of components for maintenance will be difficult, if not impossible. If dissimilar metals come in contact they could also weld together by corrosion.

Potential Impact: (UL) Self welding of similar and dissimilar metals can affect operation and availability of a fusion reactor. If two parts are welded together, removal from the reactor will be difficult, affecting scheduled downtime.

Design Specificity: generic

Overall Level of Concern: (low) Self welding of similar and dissimilar metals is a low concern. If excessive swelling forces components to touch and become welded together, reactor availability will be adversely affected. This will, in addition, result in increased system costs.

Operating Environment/Neutrons: (H,D,R) Neutrons are required to resolve this issue as a source of heating, by producing specific reactions, and to produce material damage. Neutrons may affect the response of a given material.

Operating Environment Parameters: Testing parameters required to resolve this issue are flux, neutron spectrum, neutron fluence, operating temperature, stress level, and geometry of components.

Issue I.A.3 Tritium Permeation through the Structure

Issue I.A.3.a Effectiveness of Tritium Permeation Barriers

Description: In order to reduce tritium permeation, barriers of various types may be provided at critical locations. For example, surface coatings may be provided in the 1st wall, limiter/divertor plates, coolant tubes, blanket cell, vacuum chamber and steam generators. The effectiveness of these barriers is uncertain.

Potential Impact: (US) In the event the tritium permeation barriers do not work as expected, tritium permeation into primary/secondary coolant or the tritium leakage to reactor room increases. These may cause serious safety implications or necessitate additional tritium processing systems for the coolant or the room air.

Design Specificity: (generic) All blanket designs have some form of barriers, but the importance of this issue depends on the design

Level of Concern: (critical) Since this issue is generic to all blankets and can result in unacceptable safety consequences, the level of concern is critical.

Operating Environment/Neutrons: (D) Radiation damage affects the effectiveness of the barriers.

Operating Environment/Parameters: In addition to the parameters which influence tritium permeation, the structural integrity of the composite material (including barriers) with irradiation must be tested.

Issue I.A.3.b Effect of Radiation on Tritium Permeation

Description: Radiation is known to affect tritium movement and trapping in non-metals such as solid breeding materials or oxide coatings on metal structures. In addition, neutrons may affect permeation and trapping in metal structures. Some experiments indicate $\gamma$-ray irradiation may enhance tritium permeation in metals.

Potential Impact: (IC,RS) If radiation increases the trapping of tritium, the tritium inventory may become too large and lead to economic penalty. On the other hand, radiation enhancement of the tritium permeation to the coolant or to the reactor room air will cause a safety concern.

Design Specificity: generic

Level of Concern: (medium) Since both excessive enhancement and excessive reduction of tritium permeation leads to problems, the level of concern for this issue is medium. This effect should be accurately known.

Operating Environment/Neutrons: (D) Damage by neutrons is very important.

Operating Environment/Parameters: Besides the parameters influencing permeation, stress may affect crack growth, which may in turn affect tritium release.

Issue I.A.4 Structural Activation Product Inventory

Description: DEMO will have a significant fluence of 14 MeV neutrons which cause the structures near the plasma to become activated. It will be necessary to know the isotope inventory that will be produced. Reasons include maintenance exposure, release in corrosion and sputtering, release during accidents, and waste management/decommissioning.

Experiments are needed to verify neutron calculations of blanket materials. The key uncertainties are the production cross sections of some very long-lived isotopes and the actual impurity levels in engineered materials and corresponding activities.

Potential Impact: (IC,RS) Incorrect prediction of very long-lived isotopes could lead to incorrect assessment of waste management and decommissioning needs and costs. Incorrect prediction of activation products resulting from impurities could lead to incorrect assessment of several maintenance/safety issues and corresponding costs.

Design Specificity: generic

Level of Concern: (low) The level of concern is low because the uncertainties associated with near-term materials (DEMO) are fairly low.

Operating Environment/Neutrons: (R) Neutrons with the correct energy and sufficient fluence are needed to measure cross sections for long-lived isotope production. Neutrons with sufficient fluence are needed for activation analysis of engineered materials to determine actual impurity levels and corresponding produced isotopes.

Operating Environment/Parameters: Spectrum, fluence and impurities.

## I.B COOLANT

### Issue I.B.1 MHD Pressure Drop and Pressure Stresses:

Description: The MHD pressure drop in self-cooled liquid metal blankets can be so large that the pressure at the inlet to the blanket could result in primary stresses exceeding the strength of the structural materials. Reducing the fluid velocity would reduce the pressure drop, but this occurs at the expense of higher temperatures in the blanket. The MHD pressure drop is therefore seen to be closely tied to both the thermal hydraulic and structural behavior of the blanket.

The main source of uncertainty in the value of the total MHD pressure drop comes from geometric complexities. This includes end effects, nonuniformities along the flow path, channel bends, and others. Temperature related effects may be important due to the temperature dependence of properties and the existance of thermoelectric MHD effects. Time dependent changes in electrical properties due to corrosion and irradiation materials damage may also play a role.

Potential Impact: (DW,RP) Liquid metal blankets are often designed to operate at the highest flow rate possible in order to maintain acceptable temperatures at the first wall. Since any of the uncertainties could easily exceed the low margin in some designs, this issue could have a serious impact on the design window. Even if the design window does not close, an unexpectedly high pressure drop would directly result in reduced blanket performance due to limits on the first wall temperature.

Design Specificity: (self-cooled liquid metal) MHD pressure drops are serious only in self-cooled liquid metal designs. Tokamaks are particularly susceptable, especially the inboard blanket, due to their high magnetic fields and high surface heat flux.

Level of Concern: (tokamaks:critical, mirrors:high) Because of large uncertainties and the fact that a large MHD pressure drop could close liquid metal design windows for tokamaks, this is a critical testing issue. For mirrors the level of concern is high.

Operating Environment/Neutrons: (H,D) Since temperatures affect the MHD pressure drop, neutron heating may be needed. Other sources of heating would probably substitute, because temperature effects are not the dominant uncertainties. Materials properties changes due to neutron irradiation have not been estimated, but could be significant - particularly if the electrical properties at the fluid/structure interface were altered.

Operating Environment/Parameters: As stated above, exact geometry is critical. Other important test conditions are magnetic field strength and geometry, velocity, and temperature. Certain dimensionless parameters must be considered in order to maintain the proper flow regime, for example:

$H = aB\sqrt{\sigma/\mu}$ the Hartmann number

$Re = \frac{\rho v d}{\mu}$ the Reynolds number

$N = H^2/Re$ the interaction parameter

$\phi = \frac{\sigma_w t}{\sigma_f a}$ the wall conductance ratio

Issue I.B.2 MHD and Geometric Effects on Flow Distributions

Description: In all blanket designs there are multiple parallel coolant paths. If the flow is not shared equally between the channels, then the ratio of peak to average temperature in the blanket is usually increased. For the solid breeder blankets, flow distribution problems generally arise due to the large number of parallel channels and the small channel dimensions. In this case, geometric nonuniformity is a source of nonuniform flow. For the liquid metal blankets there are generally fewer channels; magnetic field effects and global eddy currents tend to dominate flow distributions.

Potential Impact: (RP) Poor flow distributions generally translate into higher hot channel factors, which reduces the overall performance of the blanket. In an extreme case, where redesign is impossible, flow distribution problems in the liquid metal blanket could limit the design window.

Design Specificity: generic

Level of Concern: (LM:critical, SB:high) Temperature limits in all blanket types -- but particularly for self-cooled liquid metal blankets — are an important concern for materials compatibility, temperature related radiation damage, and failure modes. Flow distribution problems directly results in higher peak temperatures, which therfore makes it a critical level of concern.

Operating Environment/Neutrons: (--) Neutrons are not needed for begining of life flow distribution problems. The related problem of solid breeder flow sensitivity to dimensional changes requires neutrons.

Operating Environment/Parameters: Geometry is critical. Velocity is important, and for the liquid metal blankets magnetic field is essential.

## Issue I.B.3 Coolant Flow Stability

Description: The reference solid breeder blanket concepts are cooled by either $H_2O$ or He, both of which are subject to flow instabilities at the conditions employed. For helium, the flow is restricted to many small parallel passages at high velocity; such situations are often prone to flow-induced vibration, depending on specific design details. For water, many parallel tubes are employed; in addition to the problem of flow-induced vibration in such systems, there is the potential for flow oscillations between channels, particularly if any two-phase coolant exists (such as in a hotter-than-average channel). Either type of instability can lead to premature structural failure by fatigue, caused either by the mechanical stress or fretting due to vibration, or by cyclic thermal stresses. In addition, coolant flow oscillations will affect any temperature-dependent phenomena, for example hot spots.

Potential Impact: (UL,RL) As discussed above, this issue can lead to systemmatic premature failure of components in or near the cooling system, resulting in decreased availability and increased maintenance cost. This can also lead to reduced system performance if coolant conditions are adjusted in an attempt to reduce the severity of the instability.

Design Specificity: ($H_2O$ and He) This issue is generic primarily to $H_2O$ and He coolants, due to the conditions under which they are ususally employed: helium is operated at high velocity, and water is usually operated near its boiling point. Other coolants operate much farther from their boiling points, at lower velocity, and (in the case of liquid metals) with significant damping due to MHD effects.

Level of Concern: (high) The consequences of this issue are quite severe: excessive downtime, high maintenance cost, and/or degraded system performance. Furthermore, experience in similar areas indicates that some flow instability is to be expected in early design, hence the consequences are likely to occur unless this issue is addressed. The level of concern is therefore high.

Operating Environment/Neutrons: (H) Neutrons may be required in some tests for the purpose of heating. This is less likely for flow vibration concerns and more likely for instabilities in which the neutronic effect of the coolant (usually water) has an important influence.

Operating Environment/Parameters: Tests to address this issue must simulate: local heating rates, surface heat loads, geometry, temperature, velocity, mechanical stress, and coolant pressure.

Issue I.B.4 Stability/Kinetics of Tritium Oxidation in the Coolant

Description: The kinetics of reactions altering the chemical form of tritium released from the breeders during the residence in the purge gas or coolant in the blanket must be known. The conversion of tritiated water into the elemental form will result in increased tritium permeation into the steam generator or the containment.

Potential Impact: (IC,RS) If the tritium permeation into the steam generator or the containment becomes excessive, safety measures such as tritium permeation barriers, coolant processing or emergency gas clean-up system must be provided adding an enconomic penalty.

Design Specificity: (generic) The problem is most severe in blanket systems using helium as the purge gas or coolant and to draw salt.

Level of Concern: The level of concern depends on the choice of breeder/-coolant; high for helium and medium for Li-He and salt.

Operating Environment/Neutrons: (--) Neutrons are not required.

Operating Environment/Parameters: Temperature, chemical composition, velocity of the purge gas or the coolant are important, as is gamma radiation.

Issue I.B.5 Helium Bubble Formation Leading to Hot Spots

Description: The liquid metal breeders will produce both tritium and helium when exposed to a neutron flux. The dissolved concentration of these gases is expected to be very small at anticipated conditions. Although tritium will be continually removed from the liquid metal, several separation methods - such as diffusion through a hydrogen window - will not separate the helium. Several mechanisms exist for concentrating helium into bubbles, including stagnated coolant regions or blocked channels. These gas pockets may create local hot spots in the structure due to reduced surface heat transfer.

Potential Impact: (UL,RL) Serious hot spot formation could reduce the lifetime of the blanket or result in a high temperature related failure mode.

Design Specificity: (liquid metal) This issue is generic to liquid metal blankets.

Level of Concern: (low) Helium bubbles may be important, but they are not generally considered as a factor in blanket design. The overall level of concern is low.

Operating Environment/Neutrons: (R) Neutrons generate the helium in the liquid metal coolant. It may be possible to study helium bubble formation by externally supplying helium to the blanket.

Operating Environment/Parameters: Geometry and flow conditions are the most important parameters. If neutrons are used to generate the helium, then neutron flux is also necessary.

## I.C BREEDER AND PURGE

### Issue I.C.1 Tritium Recovery and Inventory in Solid Breeder Materials

### Issue I.C.1.a Intragranular Tritium Diffusivity and Solubility

Description: The first step in tritium recovery from solid breeders is extraction from the solid phase where it is generated. This step consists of a steady-state or equilibrium tritium concentration, and a dynamic component due to the finite time for excess tritium to diffuse out of the solid.

The equilibrium concentration includes tritium dissolved, chemically bound and physically trapped in the solid. There is substantial uncertainty in the thermochemistry of these systems. Recent results have put the Li-O-T system into better perspective, and the solubility, energies and phases are reasonably well understood. Ternary compounds, including $LiAlO_2$, have a much more complex chemistry. It is presently believed that the appropriate phases and reasonable dissolved tritium inventories can be attained if the tritiated vapor pressure is kept below about 100 Pa.

Purge stream chemistry and radiation complicate the picture. If $H_2$ is present in the purge, the dissolved tritium is virtually eliminated, while if $O_2$ is added, it is enhanced. Radiation transmutes lithium into tritium and leaves excess oxygen ($Li_2O$) or metal oxides (ternary ceramics). With sufficient burnup or high local tritium production rates, the local chemistry may be sharply changed or pushed from equilibrium. Physical trapping in radiation-induced bubbles, vacancies or dislocations is also possible, but not yet predictable. The relative contributions to trapping from displacement damage (primarily from neutron scattering, not necessarily tritium production recoil), helium production, or neutron-flux induced detrapping (of some importance in helium trapping in metals) need to be determined.

The diffusion of tritium may occur through several mechanisms, depending on local conditions such as temperature and vacancy concentration. The data base is limited, and recent results have revised estimates of tritium diffusivity in $Li_2O$ and $LiAlO_2$ by orders of magnitude. Current best estimates imply that diffusion will be very fast in $Li_2O$ but very slow in $LiAlO_2$ under reactor temperatures and grain sizes. In the presence of radiation, the concerns are changes in the migration mechanism (through increased bubbles, helium density, dislocations and vacancies), and changes in the grain size or diffusion distance. Grain growth is expected to be small in $LiAlO_2$, but large in $Li_2O$. Concerns over grain growth rates at high temperatures and diffusion rates at low temperatures have contributed to assumed operating limits for the solid breeder temperature.

Potential Impact: (US,UL,IC) An increased inventory is a major safety concern because of enhanced permeation during operation and hazard during accidents. It is an economic penalty because of the larger initial tritium supply before the device becomes self-sufficient. If burnup is a limit, more frequent blanket replacement may be required.

Design Specificity: (generic/solid breeders) The concerns hold for all solid breeder compounds.

Level of Concern: (critical) The present lack of data (particularly under irradiation), semiempirical nature of the analysis, and expected dominance of these processes in controlling tritium recovery from solid breeders, makes this a critical issue.

Operating Environment/Neutrons: (H,R,D) Neutrons are the heating source that establishes the temperature profile. Both solubility and diffusion are exponentially dependent on temperature. Neutrons produce tritium from lithium, giving both the source term and the transmutation effect. Neutrons produce displacement damage which affects tritium diffusion and physical trapping. Helium produced by neutrons may have some influence. Spectrum effects may be important in the dpa/T rate.

Operating Environment/Parameters: (T,F,C,p,I,S,$\phi$) The temperature is the single most important parameter. Since it will vary by up to 600 K across the breeder, strong variations in inventories, recovery rates and mechanisms can be expected. Fluence, flux and spectrum provide the source terms for tritium, chemistry changes, and micro- or macro-structure changes. Impurities in the solid phase may interfere with the classic tritium diffusivity and solubility. Typical operating parameters are 800-1200 K, 0.1-100 μm grain sizes, 0-20 MW-yr/$m_2$ fluence, 1 wppm tritium concentrations.

Issue I.C.1.b Tritium Surface Migration and Desorption

Description: After diffusing to the surface of the grains, tritium must eventually desorb and enter the gas phase in order to be carried away in the purge stream. There may also be some motion along the surface itself, particularly along grain boundaries where there is little or no open porosity. This grain boundary movement is believed to be fast compared to the diffusion time, over comparable distances. However, surface kinetics related to recombination, desorption and absorption may be a rate-limiting step. The overall solubility is ideally related to the tritiated vapor pressure over the surface, but surface impurities may help or hinder the process. For example, the addition of $H_2$ reduced inventories in the TRIO experiments, while the addition of $O_2$ increased it.

Potential Impact: (RP,RS) Surface effects may affect the tritium soluble inventory, or the rate of desorption of diffused tritium. This could increase (or decrease) the anticipated inventory and recovery time. On the basis of present data, it is believed that the addition of $H_2$ will reduce tritium inventories to quite small levels in $LiAlO_2$ and possibly $Li_2O$.

Design Specificity: (generic/solid breeders) The surface migration and desorption step is common to all solid breeder designs, and the data uncertainties exist for all candidate compounds.

Level of Concern: (high) Present data implies that surface processes are not limiting $Li_2O$ and $LiAlO_2$, and furthermore, the addition of $H_2$ may reduce the overall blanket inventories. However, this is a key step that has not been understood in detail, particularly under irradiation, nor possibly with realistic impurity levels.

Operating Environment/Neutrons: (H,R,D) Neutrons are primarily important as a source of heating, which determines the temperature profiles and thus the kinetics. To the extent that surface chemistry and movement are important, then neutron-induced transmutation (affecting surface chemistry), damage (changing structure of surface), or helium production (changing surface structure or porosity with accumulating helium bubbles) may be important.

Operating Environment/Parameters: (T,I,G,F) Temperature is the most important parameter since the processes are thermally-activated. Impurities will complicate the reactions and make the results difficult to predict quantitatively, although qualitatively only the addition of hydrogen is likely to decrease inventory. Significant surface migration may be necessary if there is little open porosity. Both the ease of movement and the need for it, as well as area available for surface reactions, are dependent on geometry (grain size, particle size, porosity) and on fluence (restructuring, LiOT transport, He bubbles). Typical conditions are 800-1200 K, 0.1-100 μm grains, 0-15% porosity, up to 1 mm sized solid particles, and 0-20 $MW\text{-}yr/m^2$ fluence, tritium partial pressure (1-100 Pa), and tritium production rates (10 x $10^{20}$ $atom/cm^3$ $Li_2O$).

## Issue I.C.1.c Solid Breeder Porosity, Purge Flow Distribution, and Tritium Transport

Description: Once in the open porosity, the tritiated vapor species are expected to permeate through the breeder, reach the purge stream and be convectively swept away. The permeation will involve regions where molecular flow will dominate, and regions where binary collisional diffusion will dominate.

Analysis of tritium transport at beginning-of-life may be possible, but when large temperature gradients, cracking, restructuring, grain growth, creep, sintering and LiOT transport occur, then the complexity is expected to preclude realistic analytical treatment. These phenomena could also divert or interrupt the narrow purge channels and cause preferential purge flow. Thus, variations, in purge effectiveness and tritiated vapor pressure, both across the blanket and with time/fluence are possible. The communication between breeder regions at different conditions (temperature, burnup) through the purge flow may also be important. Interaction of purge gas with structural components may be important in establishing the thermodynamic environment.

Potential Impact: (RP,RS) Changes in purge flow distribution and porosity will likely lead to increases in tritium inventory, reduced tritium recovery and increased hazard from tritium inventory.

Design Specificity: (generic/solid breeders) Purge flow is common to all solid breeders. $Li_2O$ design expected to be affected by creep closure of purge channels and porosity.

Level of Concern: ($Li_2O$:high, ternary compounds:medium) Several interactive effects between hot and cold regions of blanket, or between different breeder plates or modules, may arise. Substantial changes in tritiated vapor pressure distribution, and thus soluble inventory, are possible.

Operating Environment/Neutrons: (H,R,D) Neutrons are first a source of heating. This provides both absolute temperatures (for thermally-activated processes) and temperature gradients (for cracking, restructuring and mass transport). Neutrons are a source of tritium internally in the solid breeder, which must then find its way out of the purge streams. Neutrons also enhance sintering and weaken the material structurally.

Operating Environment/Parameters: (P,T,G,F,t) Gas phase transport depends on pressure for collisional diffusion, temperature for diffusion and restructuring, and geometry for the overall permeability. Fluence partially determines restructuring, although some is thermally-driven. Temperature limits have been estimated to reduce the amount of restructuring, but have not been tested. Operating time is important for thermally-activated restructuring, as well as cracking associated with burn/dwell cycling. Typical parameters are 0.1-0.6 MPa helium purge, 1-200 Pa tritiated vapor, 800-1200 K, 1-5 mm spacing between 1-5 mm diameter purge channels, 15% solid breeder porosity, 0-20 MW-yr/$m^2$.

## Issue I.C.2 Liquid Breeder Tritium Extraction

Description: Tritium bred in the blanket must be recovered under steady-state conditions at acceptable levels of tritium concentration and tritium overpressure to minimize inventory and permeation. The scientific feasibility of achieving acceptable levels of less than ~1 wppm in liquid lithium has been demonstrated, but not on an engineering scale. No scientific feasibility tests on $Li_{17}Pb_{83}$ have been performed, and there is some uncertainty about how to effectively maintain the low levels needed to control permeation. The basic tritium diffusivity in liquid metals influences extraction efficiency. Uncertainties are a factor of ten in lithium and an unknown amount in LiPb.

Another concern is the effects of the extraction process on the liquid breeder loop. Extractor compounds may enhance loop corrosion and impose thermal or pumping power penalties in self-cooled systems.

Potential Impact: (US,RP) Poor tritium extraction will lead to high tritium partial pressure and high inventory in the liquid breeder, and substantially enhance permeation. Some extraction methods require processing large throughputs of liquid breeder, with possible effects on the primary heat transport system (thermal and pumping power), especially with $Li_{17}Pb_{83}$.

Design Specificity: (generic/liquid breeder) Tritium extraction is a concern for all liquid breeders.

Level of Concern: (Li:medium, LiPb:critical) On the basis of present data, tritium extraction from lithium needs a large-scale engineering demonstration but should be feasible. Methods for $Li_{17}Pb_{83}$ are somewhat speculative at this present point.

Operating Environment/Neutrons: (R,D) For external tritium extraction, neutrons are possibly important as a source of impurities, sputtering, neutron damage and are the source of tritium.

Operating Environment/Parameters: (C,I,T,p,v,F, $\phi$) The primary variables are the tritium concentration and impurity levels in the breeder. The temperature and pressure may also be significant if the extractor has to operate at breeder conditions. Available throughputs may be limiting.

Issue I.C.3 Temperature Limits and Variability in Solid Breeder Materials

Issue I.C.3.a Temperature Limits

Description: The upper and lower temperature limits define the design window within which a solid breeder blanket wll be operated to achieve its primary functions (i.e., tritium production and recovery, heat generation and removal, etc.) while providing adequate blanket lifetime. Temperature limits are a reflection of all the temperature limiting issues, for example LiOT transport, tritium recovery and mechanical interaction issues.

Potential Impact: (DW) It is important that temperature limits for solid breeder materials be met in viable blanket designs. Presently, wide temperature limits are not predicted. Considering the low thermal conductivity of solid breeder materials and the high heat generation rates near the first wall, it is necessary to optimize blanket cooling components, i.e., coolant ($H_2O$ or helium) and structure. By increasing the fraction of coolant components within the blanket, it is necessary to reduce the fraction of solid breeder, which sometimes reduces the overall tritium breeding ratio. Changes in heat transfer characteristics will result in increased temperature gradients within the blanket.

Design Specificity: (generic/solid breeders) The issue is generic to solid breeder blankets, although different temperature limiting issues generally apply to different solid breeder materials and the same solid breeder materials with different micro-structures.

Overall Concern: (critical) There is a critical level of concern for temperature limits because they reflect design limiting issues such as tritium recovery, mechanical interaction and LiOT transport.

Operating Environment/Neutrons: (H,R,D) Neutrons are the heating source that generates temperature gradients within the solid breeder material. Temperature gradients within the solid breeder must be bounded by the temperature limits which dictate either more closely spaced coolant channels or lower heat generation rates.

Operating Environment/Parameters: Temperature and temperature gradients are important in temperature limits. Specific solid breeder materials are thought to have specific temperature limits. Neutron fluence effects influence temperature limits through the operating issues that limits the temperatures.

Issue I.C.3.b Thermal Conductivity Changes Under Irradiation

Description: The thermal conductivity of solid breeder materials is a physical or system (as in the case of $K_{eff}$ for sphere-pac blankets) property that determines, along with other factors, the range of breeder operating temperatures. Changes in solid breeder thermal conductivity dictate changes in blanket operating temperatures.

Potential Impact: (DW,RL) Changes in thermal conductivity of solid breeder materials are expected to result in higher solid breeder operating temperatures which could decrease tritium recovery and increase LiOT transport and mechanical interaction, hence decreasing lifetime and performance.

Design Specificity: (generic/solid breeders) This issue is generic to most solid breeder designs. Solid breeder thermal conductivities and sphere-pac effective thermal conductivities need to be determined with and without irradiation effects.

Level of Concern: (high) The overall concern of this issue is high because of the seriousness of its potential impacts on termperature variability, physical integrity, tritium, inventory and recovery, and lifetime.

Operating Environment/Neutrons: (H,R,D) Neutron damage and defect production in the solid breeder materials is expected to interrupt the phonon conductance process within the lattice and degrade K and $K_{eff}$.

Operating Environment/Parameters: ($\phi$,T,G,I,P,F,t) Neutron wall loading $\Phi>1$ MW/m$^2$, and temperature ($\gamma LiAlO_2$ $350<T<1200°C$, $Li_2O$ $350<T<1000°C$) are expected to be the dominant factors affecting thermal conductivity damages. Changes in thermal conductivity are expected to begin at low fluence levels (1 $MW-yr/m^2$) and may continue or may saturate up to goal fluence (20 $MW-yr/m^2$). Thermal conductivity, especially in sphere-pac, can be influenced substantially by gas pressure.

Issue I.C.3.c Effect of Cracking of Solid Breeder

Description: Macro and microcracking of solid breeder materials can be caused by thermal and swelling gradients strains, stresses generated from mechanical interaction and grain boundary separation.

Potential Impact: (UL,RL) Solid breeder cracking can impact lifetime and thermal/mechanical performance of the blanket. Cracking affects blanket thermal performance by contributing cracks, especially when normal to heat flow direction, which reduce heat transfer. Changes due to cracking are unpredictable becasue brittle fracture and cracked fragment relocation processes are stochastic in nature.

Design Specificity: (generic/solid breeders) This issue is generic to most solid breeder blanket concepts, but sphere-pac designs are a notable exception.

Overall Concern: (high) The overall concern for this issue is high because of its potential impact on blanket thermal/mechanical performance and lifetime. This is particularly the case for sintered solid breeder materials.

Operating Environment/Neutrons: (H,R,D) Neutron heating provides the driving force for thermal stres cracking and helium production generates swelling-induced cracking.

Operating Environment/Parameters: (G,T,$\sigma$,N,$\phi$,F) Neutron wall load (1 to 5 $MW/m^2$), and geometry dictate the temperature (350 to 1000°C - $Li_2O$; 350 to 1200°C - $LiAlO_2$) and stresses caused by temperature gradients (200 to 700°C). Swelling induced cracking requires higher fluence levels (2 to 2 $MW-yr/m^2$).

Issue I.C.3.d Effect of LiOT Mass Transfer

Description: The phenomenon of LiOT gaseous transport in the blanket proceeds by vaporization of LiOT at a high temperature location and disassociation into solid $Li_2O$ and gaseous $H_2O$ at a colder location. Vapor pressure measurements above $Li_2O$ indicate a partial pressure of LiOT at temperatures of 800°C and above. Uncertainty now exists on the magnitude of mass transport at temperatures between 700 to 1000°C.

Potential Impact: (DW) Potential impacts of this issue is plugging of purge flow paths or porosity so as to reduce tritium recovery and decrease blanket lifetimes.

Design Specificity: ($Li_2O$) The issue is generic to all solid breeder designs using $Li_2O$. Mass transfer of LiOT from solid breeders other than $Li_2O$ has not been experimentally observed.

Level of Concern: ($Li_2O$:High) Overall concern for this issue is high for $Li_2O$ blankets because of the seriousness of its potential impact on tritium recovery and blanket lifetimes.

Operating Environment/Neutrons: (H,R) Neutrons provide the tritium which forms the LiOT gas molecules for a steady state transfer of material within the blanket. Neutrons also produce the temperature gradient necessary to have transfer.

Operating Environment/Parameters: (T,$\phi$,F,t,G,C,P) Temperature gradients which extend from 700 or 1000°C down to less than 700°C are required to observe LiOT transport. The specific geometry, especially purge flow, and tritium partial pressure (1 to 200 Pa) are important in determining LiOT mass transfer. The tritium production rate and overall tritium production (19 x $10^{20}$ atom/$cm^3$) are also important in determining the magnitude of transfer.

Issue I.C.4 Tritium Release Form from Solid Breeder

Description: Since blankets operate at high temperature, tritium produced in the breeder could potentially permeate into the blanket coolant and then through the steam generator. The permeation loss is strongly determined by the chemical form. If the tritium can be produced in or converted to the tritiated water form, permeation losses can probably be reduced to acceptable levels. Recent tests indicate that tritium may be largely produced in the elemental form.

Potential Impact: (IC,RS) Tritium permeation into the coolant is a substantial safety penalty since further tritium transfer outside of the primary coolant is difficult to prevent. One way to reduce the tritium transfer is to provide coolant processing system for removing tritium, which then adds an economic penalty.

Design Specificity: (generic/solid breeders) The fractions of tritium release forms differ for each solid breeder.

Level of Concern: (high) The rate of tritium permeation into the blanket coolant must be compared with that of permeation through the 1st wall and limiter/divertor. The level of concern becomes higher when the permeation into the blanket coolant is dominant and the cost of the coolant processing system is prohibitively high.

Operating Environment/Neutrons: (R) Neutrons react with solid breeders to produce tritium.

Operating Environment/Parameters: Temperature and chemical composition of purge gas, especially hydrogen and oxygen content influences the tritium release form. Radiolytic decomposition of the tritiated water and solid breeder geometry such as pellet versus sphere pack may also be important.

## I.D COOLANT/STRUCTURE INTERACTIONS

### Issue I.D.1 Mechanical and Materials Interactions

### Issue I.D.1.a Mass Transport Rates and Consequences due to Corrosion and Sputtering

Description: Corrosion, neutron sputtering, and other mechanisms are expected to result in mass transport of foreign matter in both the coolant and helium purge systems. This foreign matter becomes activated and can redeposit in other areas, which influences the type of maintainance which can be performed. Other consequences of excessive mass transport include the loss of integrity of structural materials due to wall thinning, and the plugging of the system due to localized deposition.

In solid breeder blankets, corrosion particles may interact with the field and preferentially accumulate in particular regions of the blanket. In liquid metal blankets, MHD velocity profiles are expected to have a dominant effect on the entire process of corrosion and redeposition. The magnetic field causes a reduction in the mass transfer boundary layers thickness, which results in enhanced deposition or recession, particularly near flow perturbations (e.g. entrances and bends). In addition, local hot spots due to MHD flows will enhance the local rate of wall thinning.

One of the largest sources of uncertainty is in the interaction of materials inside the blanket with materials in the remainder of the heat transport system. The most serious of these is impurity transport from refractory to non-refractory alloys, a situation which would exist if vanadium will be used as a structural material.

Potential Impact: (DW,US,UL,RS) Corrosion rates set upper limits on coolant temperatures and therefore mass transport is a design limit issue. In addition, the possibility exists for system failures with safety and availability implications, and for reduced performance and lifetime. There are also safety implications due to the transport of radioactive elements.

Design Specificity: (generic) Every design has some degree of mass transport, but the severity is very design dependent. The issue is a primary factor in choosing desireable materials combinations for blankets.

Level of Concern: (critical) Because of the potential impact and the extent to which mass transport determines blanket design and the choice of blankets, this is a critical testing issue.

Operating Environment/Neutrons: (H,D,R) To the extent that bulk heating affects temperature profiles, corrosion rates will depend on solubilities, diffusion coefficients, and other temperature dependent effects. Direct sputtering of materials requires neutrons, and the possibility of corrosion rate dependence on irradiation requires neutrons for materials damage. Because hydrogen isotopes may substantially change the corrosion mechanism, tritium may be needed.

Operating Environment/Parameters: Geometry, temperature, and velocity are important for basic corrosion effects. The magnetic field may be important for both types of blankets, but especially for liquid cooled ones. Impurities can substantially alter the corrosion process as well as materials damage due to neutron fluence.

## Issue I.D.1.b. Mechanical Wear and Fatigue from Flow Induced Vibrations

Description: Fluid flow around or through a structure can excite oscillations in the structure. These vibrations depend primarily on the fluid velocity, flow path, and density, and on the natural vibration frequencies of the structure. The major issues that can arise from these vibrations are wear or fretting and fatigue failure of the structure.

Wear is of particular concern in blankets such as the BCSS helium cooled lithium oxide blanket. The coolant velocity is high (33 m/s), and the breeder is in the form of wire-wrapped clad slabs. Coolant channels are kept open between slabs by means of the wire wrap, such that motion of one slab with respect to an adjacent slab will result in rubbing of the wires against the cladding. This potential problem occurs any time adjacent structures are in contact with, but not bonded to, one another.

Fatigue failure due to vibrations can occur in any structure with flowing fluids. Addressing this issue will require detailed dynamic structural analysis and possibly full scale flow testing.

Potential Impact: (RP) Mechanical wear and fatigue from flow induced vibrations will affect system performance and cost.

Design Specificity: (generic) This issue is generic to all first wall/-blanket modules and reactor types that have flowing fluids.

Overall Level of Concern: (medium) Mechanical wear and fatigue from flow induced vibrations has a medium level of concern. Fatigue and fretting due to flow-induced vibrations are common problems that have been dealt with in industry in many different situations.

Operating Environment/Neutrons: (--) Neutrons have no effect.

Operating Environment/Parameters: Testing parameters required to resolve this issue are geometry of the first wall/blanket module, expected operating temperature, stress level, and coolant velocity.

## Issue I.D.1.c Failure of Coolant Wall Due to Stress Corrosion Cracking

Description: Stress corrosion cracking refers to an environmentally enhanced failure mode. An important aspect of this phenomenon is the synergism between applied stress and the corrosive substance. In the absence of stress, the host material is resistant to the corrosive element. In the absence of a corrosive environment, the response of the material to the applied stress state alone would be quite benign. But in the presence of both stress and corrosive elements, crack propogation is significantly increased, ductility is sharply reduced, and catastropic failure is possible.

The pressurized hot water stress corrosion of austenitic stainless steel has been observed for many years in the nuclear reactor industry. It therefore deserves attention in the analysis of fusion reactor designs. It is important, in general, because it is difficult to design for this mode of failure. Stress corrosion is very sensititve to even slight differences in microstructure and chemistry consequent to variation in heats of material (or difference just present in welds). Thus, local compositional and microstructural evolution caused by exposure to the fusion environment can cause similar unpredictability. Even the process of irradiation hardening below 500°C can enhance this mode of failure by strengthening the matrix relative to the crack plane, which is likely to be a grain boundary in PCA.

Potential Impact: (US,UL) The potential impact of such unexpected failure on the coolant wall in this design is system failure, with serious implications on safety, operation, and availability. The introduction of tritium into the coolant and hence, the environment, is a likely outcome of such failure and very undesirable. The loss of coolant and possible volatile interaction between coolant and hot breeder makes this a very serious issue.

Design Specificity: ($H_2O$) This issue is generic to water cooled systems, but its likelihood and severity are quite design specific.

Overall Level of Concern: (low) Due to the aforementioned specificity and the fact that the PCA material is well understood in similar environments, this issue has a low level of concern.

Operating Environment/Neutrons: (R,D) In testing, neutrons are needed to produce displacement damage necessary to enhance creep, solute redistribution, and irradiation hardening and softening. Neutrons are also needed for specific reactions to study the effects on this phenomenon of helium bubbles, dissolved hydrogen, and other species produced via high energy neutron reactions. Hence, spectrum and fluence are important parameters.

Operating Environment/Parameters: Stress corrosion cracking in this alloy is of concern over the entire temperature range of interest at stresses from 5-50 MPa.

Issue I.D.1.d Failure of Coolant Wall Due to Liquid Metal Embrittlement

Description: When a material is susceptible to embrittlement by liquid metals, it can experience crack propagation at rates on the order of meters per second, even at very low stresses. This embrittlement can, at times, be so severe that exposed materials have spontaneously fractured along grain boundaries, crumbling into fine particles under zero applied stress. Liquid metal embrittlement is temperature and strain rate sensitive. It is, therefore, important that it be studied under the right conditions. It exhibits a "ductility trough" as a function of temperature: one sees sharp decreases in the ductility of the host metal above some threshold temperature, but ductility is recovered at some higher temperature. This recovery temperature increases with increasing strain rate. Finally, this phenomenon is sensititive to the presence of impurities, both in the host and in the liquid metal.

Even though embrittlement of HT-9 and the vanadium alloy by Li or LiPb has not been observed, testing has not been extensive on this subject. Also, because of the possibility of catastrophic failure, it is difficult to design for this phenomenon and, therefore, it is an important issue to address. Local chemistry variations such as exist in heat-to-heat variation, in welds, and produced by neutron irradiation might induce this phenomenon unexpectedly.

Potential Impact: (UL,RL) Failure of coolant channel walls by liquid metal enhanced cracking can, depending on location, inject vaporized Li or LiPb into the plasma with consequent effects on its quality. Leaks of liquid metal into other regions of the reactor would cause immediate shutdown and cleanup. The impact of such occurrences would be system failure, with serious implication on operation and availability or, at the very least, reduced component lifetime.

Design Specificity: (liquid metal) This issue is generic to all liquid metal designs.

Overall Level of Concern: (low) Even though generic to all liquid metal designs, the likelihood and severity of consequences of failure by liquid metal embrittlement are sufficiently small that it is classified as a low level of concern.

Operating Environment/Neutrons: (R,D) For reasons similar to those stated in the discussion of stress corrosion failure, neutrons are needed in testing both for specific reactions and for displacement damage. Hence, spectrum and flux are important experimental parameters.

Operating Environment/Parameters: The entire temperature range of operating interest should be studied, as well as stresses from 5-350 MPa.

### Issue I.D.2 Thermal Interactions

### Issue I.D.2.a MHD Effects on First Wall Cooling and Hot Spots

Description: The thermal efficiency of the blanket power conversion system depends primarily on the average temperature of the coolant at the blanket exit. Blanket failure modes, however, depend upon local temperatures either within the structure or at the coolant/structure interface. The peak temperature within the blanket is often a primary design limit due to corrosion, thermal stresses, or materials properties under irradiation. In liquid metal blankets, further restrictions are imposed by minimum fluid temperatures to avoid freezing and maximum flow rates due to the MHD pressure drop.

Magnetic field effects are the largest source of uncertainty for the liquid metal blankets. MHD velocity profiles are known to exhibit a high degree of sensitivity to geometric and magnetic field perturbations - even more so than for the pressure drop. Very thin boundary layers, shear layers, and flow stagnation points are possible, leading to local or even widespread areas of altered heat transfer. Examples of this behavior occur at channel entrance/exit points and at bends. In addition to bulk velocity profile changes, the presence of a strong magnetic field is known to suppress turbulence, which also hinders good heat transfer.

Potential Impact: (DW,UL) The issue of first wall cooling and hot spots is related to the MHD pressure drop and also has a direct impact on the design window. Performance is degraded with large peak-to-average temperatures because the thermal cycle efficiency requires high average temperatures.

Severe miscalculation of temperature peaking could result in reduced lifetime or catastrophic failure.

Design Specificity: (liquid metal) The issue of hot spots is generic, but the severity of the problem and associated uncertainties are very design dependent. The highest level of concern exists for liquid metal blankets in which MHD effects are active.

Level of Concern: (critical) Because this issue limits the design window for liquid metal blankets and could result in system failures with serious safety implications, the level of concern is critical.

Operating Environment/Neutrons: (H,D) Since volumetric heating alters the temperature distribution within the coolant and structure, neutron bulk heating or its equivalent is required. Since thermophysical properties change under irradiation, neutron materials damage is also required.

Operating Environment/Parameters: Because of the importance of MHD effects, geometry and magnetic field are both critical parameters. Surface heating, bulk heating, and temperatures are also needed to study the thermal hydraulic behavior and its consequences.

Issue I.D.2.b Response to Cooling System Transients

Description: Any cooling system in could experience several types of cooling transients. These include loss of cooling, flow blockage, loss of coolant flow, and loss of site power. Reactors, including DEMO, will have to be designed to survive such transients, hence adequate ability to predict system response to such transients is needed.

Potential Impact: (IC,RS) Inaccurate prediction could lead to either over-design with associated costs or under-design with potential for serious fault condition.

Design Specificity: generic

Level of Concern: (LM and DS:critical, $H_2O$ and He:low) Understanding and modeling of liquid metal and molten salt coolant transients are at an early stage. The former has the key uncertainty of the influence of steady or changing magnetic fields on liquid metal flow. This MHD concern is also relevant for salts, for which little or no cooling transient modeling has been performed. Because these various uncertainties are so high, it is important that they be resolved. Helium and water coolants are far better understood so that the level of concern is low. The key unknowns for these latter two fluids are more associated with the particular fusion blanket geometry than with uncertainties concerning the fluids themselves.

Operating Environment/Neutrons: (H) Neutrons may be needed for heating profiles so that an adequate neutron flux is desired.

Operating Environment/Parameters: For the liquid metal and salt cases, both steady and changing magnetic fields are required. All fluids require transient tests with appropriate time duration, heat fluxes, geometry, temperature, flow velocities, pressures, and stresses.

## Issue I.D.2.c Flow Sensitivity to Dimensional Changes

Description: First wall/blanket designs featuring helium or water coolant typically employ many small parallel coolant channels. These channels are sufficiently small that a number of common mechanisms such as thermal expansion, swelling, fracturing, and manufacturing tolerances, can effect large-percentage ( 10%) changes in passage dimensions. Such changes will result in altered coolant flow distribution and hence in the module temperature distribution. In some cases a thermally unstable situation could result in which case passages might become completely blocked. This can affect tritium recovery, structural failure modes, etc.

Potential Impact: (RL,RS) The main adverse effect of this issue will be an increased random failure rate due to local overheating of first wall/blanket components, resulting in reduced component lifetime.

Design Specificity: ($H_2O$ and He) This issue is generic to $H_2O$ and He-cooled blanket concepts. Passages for other coolants are much larger compared with the expected sizes of dimensional changes.

Level of Concern: (medium) Although potential impact of this issue is severe, it is rather unlikely that widespread failure will occur. Its level of concern is medium.

Operating Environment/Neutrons: (H,D) Neutrons are required for both heating and damage in order to develop realistic dimensional changes.

Operating Environment/Parameters Tests to address this issue will require similation of: local heating rates, surface heat loads, geometry, temperature, velocity, mechanical stress, and coolant pressure.

## I.E SOLID BREEDER/MULTIPLIER-STRUCTURE INTERACTIONS

### Issue I.E.1 Solid Breeder Mechanical and Materials Interactions

The mechanical interactions between the solid breeder material, the neutron multiplier, and the metal structure can lead to either degradation of the component performance or seriously limit the useful lifetime or safe operation of a particular blanket module. These mechanical interactions are driven by the differences in the thermal expansion, creep, and swelling behaviors of the solid breeder material, neutron multiplier, and/or metal used for the structure. The expected restructuring of the solid breeder material also impacts this mechanical interaction.

### Issue I.E.1.a Clad Corrosion from Breeder Burnup Products

Description: As a result of the conversion of lithium into tritium, the chemistry of the solid breeder will change. In $Li_2O$, LiOT may form at particular ranges of temperature and $T_2O$ partial pressures. In ternary ceramics such as $LiAlO_2$ and $Li_8ZrO_6$, the elimination of lithium causes nonstoichiometry, i.e. compositional changes away from stoichiometry (Li/Al=1, Li/Zr=8, ...). The resulting change in the chemical environment of the solid breeder may impact the compatibility between the structure and the breeder.

Potential Impact ($Li_2O$:DW, ternary compounds:RP,RL) LiOT is known to be highly corrosive, and its formation, transport and contact with structure is to be avoided. This leads directly to constraints on operating temperatures. Changes in stoichiometry in ternary ceramics leads to the formation of new phases (e.g. $LiAl_5O_8$ from $LiAlO_2$). Material property changes such as melting points, and compatibility between the structure and the breeder may limit the lifetime or performance of the blanket.

Design Specificity: (generic/solid breeders) $Li_2O$ blankets are subject to the formation of LiOT. Ternary ceramic blankets will need a neutron multiplier and are thus more susceptable to lithium burnup because the lower energy neutrons emitted from the multiplier are readily captured by lithium.

Level of Concern: ($LiO_2$:critical, ternary compounds:medium) Overall concern is critical for $LiO_2$ blankets because of its potential impact on the design of the blanket. Compatibility of irradiated ternary ceramics is untested, although there is not any particular known corrosive compound.

Operating Environment/Neutrons: (H,R) Neutrons dictate the burnout of lithium and the production of tritium. They also control the heat generation, and thus temperatures at the breeder/structure interface.

Operating Environment/Parameters: (S,F,$\phi$,G,C) In addition to the neutronic parameters, including spectrum, the geometry of the multiplier, breeder, and structure, and any other contributors to the local chemistry (e.g. $H_2$ added to purge) may be significant.

Issue I.E.1.b Strain Accomodation by Creep and Plastic Flow

Description: Mismatch mechanical interaction strains may be accommodated in a variety of ways. Accommodation may be accomplished in the solid breeder material itself, by larger gaps or voids at beginning-of-life or by more compliant structural components. The fact that $Li_2O$ can be hot pressed at low temperatures (600°C) and stresses belies the potential of internal accommodation.

Potential Impact: (UL,RS) The potential impact of strain accommodation is that lifetime limits associated with mechanical interaction structural failure will be extended. However, accommodation by hot pressing of the porous solid breeder material will eliminate porosity and reduce purge flow channels, thus impairing tritium recovery and the production of an adequate fuel supply. Gaps and voids tend to reduce the overall breeding ratio of a blanket.

Design Specificity: (genereic/solid breeders) Mismatch strain accommodation is generic to all solid breeder blankets but specific in character and extent to each design with dilational creep of $Li_2O$ as an example.

Level of Concern: ($Li_2O$:critical; ternary compounds:medium) The overall level of concern for strain accommodation factors is critical since the viability of the $Li_2O$ design in particular is dependent upon it.

Operating Environment/Neutrons: (H,R,D) Neutrons provide the heating which generate the thermal environment in the blanket. In addition, creep in solid breeders may be a function of helium buildup and damage.

Operating Environment/Parameters: (T,$\sigma$,t,S,F,G) In the case of accommodation by dilational creep of $Li_2O$, temperatures (350 to 1000°C) and scaled geometric configurations are important factors. In the case of thermal expansion mismatch strains, thermal cycling at low fluences (0.2 MW-yr/$m^2$) will be initially important with temperature variability effects and swelling contributing at higher fluences (2 to 20 MW-yr/$m^2$).

## Issue I.E.1.c Swelling Driving Force for Mechanical Interaction

Description: Unrestrained swelling in $Li_2O$ has been experimentally measured to be approximately four percent diametral at an equivalent burnup of 10 MW-yr/$m^2$. Both breeder-in-tube designs and breeder-out-of-tube designs cannot achieve even reduced lifetime goals without direct contact between solid breeder materials and structural materials.

Potential Impact: (DW,UL,RS) Structural component failures which compromise tritium purge gas boundaries or even plasma chamber boundaries can result from swelling induced strains. Plasma operation and fuel supply would in turn be affected. Deformation of structural components can degrade thermal hydraulic performance. All these phenomena contribute to a reduced blanket life.

Design Specifity: (generic/$Li_2O$) Designs based on $Li_2O$ are particularly sensitive to swelling, while designs with $Li_4SiO_4$ and perhaps $Li_8ZrO_6$ may be less affected. Designs based on $LiAlO_2$ appear immune with present information.

Level of Concern: ($Li_2O$:critical, ternary compounds:low) For $Li_2O$ blankets the level of concern is critical since it directly limits its application of unrestrainable.

Operating Environment/Neutrons: (H,R,D) Neutrons provide the helium which is responsible for swelling in $Li_2O$. Heating from neutrons generates the temperatures in the blanket which influence swelling. Damage to the lattice is thought to affect swelling.

Operating Environment/Parameters: (F,$\phi$,S,G,T) Neutron fluence (5 to 20 MW-yr/$m^2$) is of interest in swelling along with a neutron capture cross section of (.3 to 50 barns). Low fluence testing (0 to 2 MW-yr/$m^2$) is of little value. The geometric configuration directly impacts the magnitude of strains. Temperature (350 to 1000°C - $Li_2O$; 350 to 1200°C - $LiAlO_2$) appears to directly influence swelling.

## Issue I.E.1.d Stress Concentrations at Cracks and Discontinuities

Description: Both thermal expansion and swelling mismatch strains imply that expansion of the solid breeder deforms the surrounding structural components. This deformation of the structural components in the blanket need not be homogeneous and, hence, can lead to failure strains earlier than would be expected from homogeneous strains. Configurational stress concentration factors may possibly be dealt with by design changes, but operational factors such as solid breeder cracking will not be as controllable.

Potential Impact: (UL,RS) Stress concentration factors accentuate the potential impacts of thermal expansion and swelling induced mechanical interaction, hence further reducing lifetime.

Design Specifity: (generic/solid breeders) Stress concentrations are expected to not only be dependent on the selection of solid breeder materials but also on the exact configuration of both the solid breeder and structural components.

Level of Concern: (high) Because stress concentration effects are so design dependent and not an intrinsic feature of a material, a level of concern of high was selected. But in the final assessment of design viability, strain concentration effects may play a critical role on a specific design.

Operating Environment/Neutrons: (H,R,D) Neutrons have essentially no effect on the stress concentration effect itself but without heating and swelling, it may be impossible to evaluate.

Operating Environment/Parameters: (G,T,N,$\phi$,S,F,$\sigma$) The geometry associated with a specific design is expected to control stress concentration. Cracking in the solid breeder material can cause stress concentration associated with thermal cycling, temperature gradients ($\Delta T$ = 200 to 700°C) and swelling.

## Issue I.E.1.e: Thermal Expansion Driving Force

Description: Thermal expansion in solid breeder materials will exceed that of the surrounding structural materials leading potentially to mechanical interaction. Mismatch strains during one plasma start-up are bounded by the relative thermal expansion values but could exceed yield. Although the gross thermal expansion can be calculated, the effects of cracking, setting, and porosity are not clear.

Potential Impact: (DW,UL,RS) Structural component failures which compromise tritium purge gas boundaries or even plasma chamber boundaries can result from these strains. Plasma operation and fuel supply would in turn be affected. Deformation of structural components can degrade thermal hydraulic performance.

Design Specifity: (generic/solid breeders) Thermal expansion mechanical interaction is generic to all solid breeder blanket designs, but designs with no gap, i.e., sphere pak, are particularly sensitive.

Overall Concern: (medium) The level of concern for thermal expansion interaction is judged medium at present, but may prove to be limiting for specific blanket designs.

Operating Environment/Neutrons: (H,D,R) Neutrons provide the internal heating which generates the temperature gradients causing thermal expansion. Helium production and damage are only important in that they affect the temperature variability.

Operating Environment/Parameters: (T,G,N,$\phi$,S,F) Two operating parameters determine the temperature distributions within the blanket: heat generation and geometry (size). Since thermal cycling can reconfigure strains, it is of importance. The neutron wall loading (1 to 5 $MW/m^2$) and spectrum determine in part the heat generation distribution throughout the solid breeder.

## Issue I.E.2 Neutron Multiplier Mechanical Interactions

### Issue I.E.2.a Swelling Driving Force in Beryllium

Description: Beryllium as a neutron multiplier is required in many solid breeder blankets to increase the tritium breeding ratio by virtue of its high n,2n cross section. Helium production in beryllium [$^9Be(n,2n)2^4$ He] is expected to cause swelling of over 10% in the bulk material at high temperature and moderate fluences (5 $MW\text{-}yr/m^2$). Theoretically, when the volume of swelling reaches 30%, the interconnected helium bubbles will form along grain boundaries causing the metal to become friable.

Potential Impact: (UL,RL) Swelling of beryllium can induce mechanical interaction strains in neighboring components causing structural failure and necessitating blanket replacement.

Design Specificity: (beryllium) Swelling in beryllium, is of concern for all blankets with beryllium multipliers.

Level of Concern: (high) The viability of many solid breeder designs is based upon the use of beryllium so it is of high concern to those designs in which swelling does not preclude the use of beryllium.

Operating Environment/Neutrons: (H,R,D) Neutrons produce the damage and helium responsible for swelling in beryllium. In addition, neutrons are the source of heat which establishes the temperature profiles within the neutron multiplier section.

Operating Environment/Parameters: Neutron fluence (0 to 20 $MW-yr/m^2$) and temperature (400 to 600°C) are the two most important parameters which influence swelling in beryllium. Neutron energy spectrum is important in establishing helium production and dpa rates.

Issue I.E.2.b Strain Accommodation by Creep in Beryllium

Description: Mechanical interaction strain and internal stresses from helium induced swelling are expected to increase with time in beryllium as swelling continues. Radiation induced creep can relieve these stresses and strains by plastic flow. Low temperature radiation creep results exist, from which estimates can be made at blanket operating temperatures.

Potential Impact: (RP,RL) The impact of strain accommodation in beryllium is to lengthen the lifetime before swelling induced blanket failure occurs.

Design Specificity: (beryllium) These concerns hold for all beryllium neutron multipliers.

Level of Concern: (medium) In the case of radiation induced creep, not developing a data base does not increase a failure situation and therefore is classified as medium. It is, though, an important issue which affects cost, lifetime and performance.

Operating Environment/Parameters: Neutron wall loading (1 to 5 $MW-yr/m^2$) and spectrum (E>2Mev) temperature (400°C to 600°C) and geometric configuration provide the environment for creep over the time the blanket is to operate. Prestress in the beryllium provides an initial driving force for creep.

Issue I.E.2.c Mechanical Integrity of Unclad Beryllium

Description: As swelling takes place, internal stresses are generated in beryllium. Theoretically, when volume swelling reaches 30%, interconnected helium bubbles along the grain boundary will cause beryllium to be friable. Some blanket designs require unclad beryllium to maintain its own integrity for positioning of other components.

Potential Impact: (RP,RL) Fracturing of unclad beryllium could cause beryllium migration through the coolant or purge system. Fracturing of beryllium encapsulated within structural alloys would change cooling characteristics with possible overheating leading to additional swelling. Cracking of beryllium into large or granular pieces can allow rearrangement within the blanket resulting in accentuated mechanical interaction with structural components.

Design Specificity: (generic to unclad beryllium)

Level of Concern: (low)

Operating Environment/Neutrons: (H,R,D) Neutrons produce the heating, nuclear reactions and damage in beryllium which lead to loss of mechanical integrity.

Operating Environment/Parameters: A nmeutron fluence representing the life of the multiplier (5 to 20 MW-yr/$m^2$) is important to the mechanical integrity issue. Since damage and transmutation increase at high neutron energy, neutron energy spectrum (E>2Mev) is important to damage rates. Temperatures (400°C to 600°C) and temperature gradients are important in the swelling process.

Issue I.E.3 Thermal Interactions

Issue I.E.3.a Breeder/Structure Interface Heat Transfer (Gap Conductance)

Description: The solid breeder/structure interface is a key area in determining the solid breeder operating temperature operating range in all solid breeder blanket concepts. Since the design of these concepts is severely restricted by the acceptable temperature windows for solid breeder materials, it is imperative that the thermal properties of the breeder/structure interface be predictable. Current understanding and analytical tools are more than sufficient to predict these properties _if_ the gap geometry and conditions are known. Unfortunately, due to uncertainties in manufacturing tolerances, purge gas pressure and composition, and gap geometry changes, significant uncertainty in the gap thermal properties exists. The largest contributors to this uncertainty are changes in the gap geometry due to differential thermal expansion, breeder rearrangement (cracking, ratcheting, etc.) and time-dependent material changes such as swelling, creep, mass transport, etc.

Note that the issue is not the magnitude of the interface heat transfer coefficient, but rather its long term unpredictability. It is not acceptable to design a blanket on a worst case (or best case) basis, since any deviations from the assumption will result in actual breeder temperatures above or below allowable values. Thus, this issue forces prudent blanket designers to employ operatonal temperature windows even smaller than those dictated from tritium/-materials considerations in order to allow a design margin for interface heat transfer unpredictability.

Potential Impact: (DW,US,UL) As discussed above, this issue directly impacts the blanket design by further restricting the useful solid breeder tempeature window. Failure to address this issue can result in unacceptably low tritium recovery and concomitant high inventory.

Design Specificity: (solid breeder) This issue is generic to all present solid breeder blanket concepts, due to the narrow temperature window and the need for a separate coolant stream. Large changes in the temperature window or radical design changes (such as using the solid breeder as the coolant) could possibly eliminate this issue.

Level of Concern: (critical) This issue represents a feasibility (go/no go) issue for a large class of blankets and will also represent a serious operational concern. The consequences of not addressing this issue can thus be quite severe.

Operating Environment/Neutrons: (D) Neutrons will be required in at least some tests addressing this issue to develop the material damage which will produce changes in the interface geometry. Neutrons may also be useful (though not required) in developing desired temperature profiles in tests.

Operating Environment/Parameters: The following environmental aspects will be required in tests addressing this issue: local power density (0.1-10 $w/cm^3$), chemical environment (purge composition), geometry, temperature profiles, purge flow velocity, mechanical stress/restraint, and purge pressure. A low neutron fluence ( $<$ 1 $MW\text{-}yr/m^2$) is adequate to evaluate beginning-of-life gap conductance, but goal fluence levels (20 $MW\text{-}yr/m^2$) are required to verify lifetime capabilities.

## I.F GENERAL BLANKET CONCERNS

Issue I.F.1 DT Fuel Self-Sufficiency

a) magnitude of required tritium breeding ratio

b) magnitude of achievable tritium breeding ratio

Description: Attaining fuel self sufficiency in fusion devices operated on the DT cycle requires that the achievable tritium breeding ratio ($T_a$) is equal to or greater than the required breeding ratio ($T_r$). The latter ($T_r$) is a function of the desired doubling time and many plasma and reactor parameters such as the tritium fractional burnup, tritium inventories in the blanket, tritium processing system, other reactor components and storage. There are substantial uncertainties associated with these parameters, and hence with $T_r$. Estimating the achievable breeding ratio presently suffers from uncertainties associated with system definition and from uncertainties in prediction for a given system. The system definition uncertainties relate to: 1) technology choices (e.g., limiter or divertor, neutral beams vs. rf) that impact parasitic neutron absorption and the fractional volume of the blanket denoted for non-breeding purposes and 2) the degree of details presently available for blanket and reactor design. The prediction uncertainties are those associated with the neutronics geometrical mnodeling, basic nuclear data, data processing and calculational methods.

Potential Impact: (DW) Failure to attain fuel self sufficiency is not permissible since fusion is being developed as a renewable energy source and since there is no other practical and economical means of supplying tritium to fusion reactors. Therefore, all choices of design concepts materials, and performance characteristics for the plasma, blanket and other reactor components must ensure satisfying the absolute requirement of attaining self sufficiency. Therefore, experimental data and analytical modeling are necessary to reduce the uncertainties associated with $T_r$ and $T_a$. Failure to do so will make it practically impossible to reduce options and make prudent selection for design concepts and performance parameter ranges for many of the reactor components (e.g., plasma, impurity control and exhaust, auxiliary heating, first wall blanket, etc.).

Design Specificity: (generic) Generic for all types of reactors operated on the DT fuel cycle.

Level of Concern: (critical) DT fuel self sufficiency is considered an absolute requirement for fusion reactors.

Operating Environment/Neutrons: (R) Fusion neutron spectrum is necessary for verifying the neutronics performance. A 14 MeV point neutron source with sufficient intensity is considered an indispensable means of verification of neutronics methods and data. However, direct verification in a fusion device is necessary. In a fusion device, it is found that the tritium production profiles in an individual blanket module (not surrounded by other blanket modules) are greatly different from the corresponding values in a full coverage blanket. Depending on the magnitude of both the required and achievable tritium breeding margins, firm confirmation of attaining fuel self sufficiency conditions may not be possible prior to a full scale demonstration plant.

Operating Environment/Parameters: Accurate prediction of the required breeding ratio requires experimental data from the operation of a complete fuel cycle system, which is a fusion device with nearly all its components, particularly plasma, plasma exhaust system, blanket, tritium processing systems. The most important parameters are tritium fractional burnup in the plasma, tritium extraction and separation efficiencies and tritium inventories throughout the system.

## Issue I.F.1.c Lithium Burnout Effects on TBR

Description: During the lifetime of a solid breeder blanket, it is possible to burn out a significant fraction of the lithium isotopes in localized regions of the blanket, especially near neutron multipliers. The extent of burnout is dependent on lifetime goals and blanket neutronics. Neutronically, the loss of lithium results in a lower local neutron capture rate which in turn causes lower tritium and heat generation rates in that region.

Potential Impact: (RP,RL) Blanket calculations have demonstrated that the burnup of lithium in localized regions does not impact the overall tritium breeding ratio. Instead, tritium breeding shifts from regions of high burnup to regions where lithium remains. This shift does represent a design limitation in that blanket configurations must accommodate large variations in heat generation rates in order to maintain solid breeder temperatures. There may also be reduced tritium breeding, since in general the neutrons will have to penetrate further into the blanket to find lithium.

Design Specificity: (neutron multiplier) Blankets with a neutron multiplier are more subject to lithium burnout effects because the lower energy neutrons emitted from the neutron multiplier into the solid breeder posses a high capture cross section which leads to high burnup near the multiplier.

Level of Concern: (medium) The level of concern for burnout effects is medium. Nonstoichiometry effects have not been observed experimentally as of yet. In addition, changes in heat and tritium generation rates through the life of the blanket have not been fully analyzed, but may be calculable.

Operating Environment/Neutrons: (R) Neutrons dictate the burnout of lithium from the solid breeder.

Operating Environment/Parameters: (S,F,$\phi$,t,G,C) In addition to the neutronic parameters, especially spectrum, the geometry of the neutron multiplier and solid breeder are important in determining burnout effects. Lithium ceramics with low lithium atom densities, like $LiAlO_2$, are typically more sensitive to burnout effects at end of life (20 $MW\text{-}yr/m^2$).

## Issue I.F.2 Tritium Permeation

### Issue I.F.2.a Permeation from Breeder to Blanket Coolant

Description: Tritium permeation from the breeding material into the coolant may be a problem at heat transfer surfaces where large areas of relatively thin walls separate breeder and coolant. In the absence of cracks, tritium will diffuse through structural components at a rate determined by surface kinetics, tritium vapor pressure and permeability. Corrosion/chemistry at both interfaces of structural components may either inhibit or enhance permeability (through adsorption, decomposition, recombination and desorption processes). Alternately, engineered barriers added to reduce permeation may be degraded by local chemistry or cracking. Cracking of the barriers alone, or through the entire clad, will strongly affect permeation. Uncertainties include surface kinetics (barrier effectiveness, aging), hydrogen diffusivities, the overall tritium vapor pressure and species.

Potential Impact: (US,UL) Tritium permeation into the coolant is a substantial safety penalty since it may be difficult to prevent further tritium transfer outside of the primary coolant. Alternately, a major tritium permeation problem would require replacing the faulty blanket modules. Alternatively, very high coolant flow rates or high tritium extraction efficiency is required in the coolant.

Design Specificity: (generic) Permeation is a major safety concern for all breeder designs due to the relative ease of hydrogen permeation, realistic tritium vapor pressures, and by the thin breeder/coolant interfaces needed for thermal efficiency.

Level of Concern: (solid breeder:medium,Li/V:medium,LiPb:critical) It is a high concern for solid breeders, a medium concern for separately-coded Lithium with certain structural materials (especially V), but a critical concern for separately-cooled LiPb due to the low solubility of tritium which may force a high tritium vapor pressure, depending on the tritium extraction system.

Operating Environment/Neutrons: (R,D) Neutron damage in the clad material and barriers may change the diffusion characteristics. Neutrons are the source of tritium, and influence the local tritium concentration.

Operating Environment/Parameters: (T,p,I,F,N) Clad temperature and tritiated vapor pressure are the key variables. There is some concern that different permeation processes may be important at the pressures expected under reactor conditions, lower than have typically been used to measure permeation constants. Furthermore, neutron damage, and realistic coolant, purge and breeder impurities/corrosion products will affect the surfaces. Burn/dwell cycling may intiate or propagate cracks. Typical parameters are 700-800 K, 1-200 Pa tritiated vapor pressure, 0-20 $MW\text{-}yr/m^2$.

Issue I.F.2.b Permeation Characteristics at Low Pressures

Description: Tritium loss by permeation through structures such as heat exchangers and steam generators is an environmental concern. Since tritium pressures are expected to be low at these structures, estimating permeation from measurements at higher pressures is inaccurate.

Potential Impact: Tritium loss through the heat transfer system is difficult to control and could be a significant public acceptance issue.

Design Specificity: (generic)

Level of Concern: (high) Could impact design and materials selection.

Operating Environment/Neutrons: (--) Neutrons are not required.

Operating Environment/Parameters: Factors likely to affect permeation at low pressures are the chemistry of heat transfer materials, impurities, gamma radiation, and thermal conditions.

Issue I.F.3 Chemical Reactions

Description: The generic area of chemical reactions involves many subissues. Potential consequences include activation product volatilization (an accident release mechanism), structural oxidation (a structural failure mechanism), and energy release (sources of energy to drive accidents). Conditions which potentially lead to these conclusions include accidental contact of reactive materials and high temperatures.

Potential Impact: (US) (a) For structural metals with high oxidizing potential, e.g., vanadium alloy, accidental oxidation could be catastrophic -- a serious safety failure. (b) For less oxidizing metals, e.g., steels, accidental oxidation could lead to the release of radioactivity and severe degradation of properties, potentially prohibiting re-use or causing failure. (c) For chemically active liquid metals, e.g., Li and 17Li-83Pb, accidental contact with some oxidants could cause activation product volatility and substantial energy release. A recent 17Li83Pb/steam test produced 870°C temperatures before the test had to be terminated. (d) For less chemically active fluids, oxidation and/or volatility from high temperatures could lead to radioactivity release. (e) For solid breeders and beryllium multiplier, accidental oxidation could lead to property degradation or radioactivity/chemical toxicity mobilization. High temperatures could lead to material volatility.

Design Specificity: (generic)

Level of Concern: (high) The overall level of concern will vary with the details of the reactor. For example, a tokamak with a water-filled limiter would result in a substantially higher level of concern than a mirror with few water-filled components. For the sub-cases listed above, the level of concern is as follows: (a) V-alloy--scoping tests show rapid oxidation leading to vanadium volatility and liquid oxide formation for certain conditions. The viability of any design with such a metal requires further understanding of the problem and adequate control. (b) Steels--property degradation and oxide volatility is significant in oxidizing scoping tests. Although not absolutely critical, further knowledge is needed to know the extent of the problem and perhaps ways to control/minimize it. (c) Adequate knowledge to understand and control Li/air, Li/water, and 17Li-83Pb/water reactions is critical for those reactor concepts. (d) Adequate knowledge is needed for other fluids, before DEMO. Some, e.g., draw salt, appear quite volatile even without oxidation. (e) Information is also needed for the solid breeder and beryllium multiplier, although the level of concern is lower than for items a through d above.

It is emphasized that as new materials are considered, scoping tests are critical to at least determine the possible level of concern. Materials not mentioned for blanket use but mentioned for other uses, e.g., the limiter, include tantalum and copper. No scoping tests have been performed on these materials. Tantalum should be somewhat similar to vanadium and copper similar to steels, although only tests can determine this.

Operating Environment/Neutrons: (R) Neutrons are only needed to induce relevant isotopes in solid materials. For example, Sc46, Sc47, Sc48 are important radioisotopes that would be produced in V-15Cr-5Ti; however, scandium is not initially present in the alloy. Hence, only tests with irradiated samples can accurately indicate scandium behavior. Neutrons are not needed for tests with fluids since small amounts of relevant atoms could be directly added to the fluid. For neutron tests, sufficient fluence at appropriate neutron energies are needed to produce sufficient quantities of relevant elements. Exact duplication of all isotopes in relative amounts similar to that produced in a fusion spectrum is not needed.

Operating Environment/Parameters: For all sub-cases, several test variables need to be examined: time, impurities in test sample, temperature, flow velocity of oxidants, pressure of oxidants, geometrical mode of contact, and the chemical oxidizing environment itself.

## Issue I.F.3.a Chemical Reactivity of Lithium

Description: Pure lithium reacts chemically with air (oxygen, nitrogen, and water vapor) and also water and concrete. The water reaction can be particularly violent. Hydrogen is released in this reaction, which leads to a further hazard for hydrogen combustion in air. Because of the large amount of water in concrete, this energy source for chemical reactions is the largest single potential energy source in the entire fusion system. This makes it mandatory in designs with lithium to provide protective measures in the event of coolant loss.

LiPb eutectics also exhibit some reactivity, but at a much reduced level. Some LiPb-cooled designs even incorporate water coolant for the first wall or high heat flux components.

One of the key reasons why lithium-cooled systems find disfavor is this issue. Experience working with a large lithium-cooled system may be a valuable source of information to determine reliability and operational hazards.

Potential Impact: (US,RS) If lithium can be demonstrated to be capable of application to a system as large and complex as a fusion reactor, then this would have a major impact on the choice of blanket materials. Conversely, if the problems appear insurmountable, then lithium would be ruled out on the ground of safety.

Design Specificity: (liquid metals) Lithium reactivity is generic to all liquid metal cooled designs, but especially a problem for pure lithium coolant/breeders.

Level of Concern: (high) This is a very serious issue, but only applies to a limited set of blanket designs.

Operating Environment/Neutrons: (--) Neutrons are not required to study the severity of lithium chemical reactions. On the other hand, radiation damage will affect failure modes and rates, which contributes to the overall level of concern for systems employing lithium. This is considered to be a failure modes issue.

Operating Environment/Parameters: Temperature is a vital parameter, as well as the presence of non-blanket components (heat exchangers, etc)

## Issue I.F.4 Tritium Inventory Behaviour During Transients

Description: Off normal events such as thermal transients are expected for fusion reactor blankets. Since solid breeders may contain large inventories of tritium, the vulnerability of this tritium to release is an important safety issue.

Potential Impact: (RS) Release of large amount of tritium will have serious safety implications.

Design Specificity: (generic)

Level of Concern: (solid breeders:high, lithium:medium, LiPb:low) Large tritium releases to the environment must not take place. The level of concern is high for solid breeders and lower for liquid metals corresponding to their lower anticipated tritium inventory inventory.

Operating Environment/Neutrons: (D,R) Neutron damage to structural materials and neutron damage and tritium production rate distribution in solid breeders influence the tritium release.

Operating Environment/Parameters: For thermal transients, the tritium release is expected to be strongly affected by the temperature dependence of solubility and diffusion constants. Surface release mechanisms may also be significant. Stresses may result in cracking and hence increased tritium release.

## Issue I.F.5 Uncertainty in Failure Modes and Frequencies

Description: Most of the issues are concerned with consequence, ignoring the frequency part of risk. Abnormally high failure frequencies or new failure modes could result in severe problems for DEMO. All available reactor-relevant testing should be screened for evidence of high failure frequencies or new failure modes. In some cases, specific dedicated test series may be required to gain adequate operating time.

Potential Impact: (UL,RS) Abnormally high failure frequencies or new failure modes could lead to low machine availability, increased maintenance problems, and/or safety failures.

Design Specificity: generic

Level of Concern: (high) High risk components incorporating new technology must be tested to determine failure possibilities to use in DEMO; hence, the level of concern is high.

Operating Environment/Neutrons: (D) Neutrons are needed for damage studies.

Operating Environment/Parameters: Each high-risk component should be tested in prototypical conditions.

## Issue I.F.6: Nuclear Heating Rate Prediction

Description: One of the primary functions of the blanket during reactor operation is to convert the kinetic energy of the incident neutrons into sensible heat through neutrons and emitted gamma-ray interactions with the blanket constituents. The uncertainty associated with local and integrated heat generation is attributed to geometrical definition, modeling, calculational methods and nuclear data.

After reactor shutdown, heat is generated through the radioactive decay of radionuclides generated during operation. The uncertainty associated with decay heat prediction is attributed to uncertainties in basic data, such as the decay branching ratio, spectrum and energy of emitted particles and the decay half-life. An additional source of uncertainty in the decay heat prediction is due to the assumption inherent in the codes and methods used in the evaluation.

Potential Impact: (RP) Poor prediction of heat generation during operation has implications on the design limit (thermal hydraulics and tritium recovery characteristics) and the performance of the blanket. A target accuracy of ~15% in spatial distribution and of <10% in the global value seems satisfactory for heat generation prediction. Improvements in prediction can be achieved by periodically updating the codes used to generate the kerma factors (response function for generating nuclear heating) to include new types of nuclear data as they become available and to improve the accuracy in calculation.

The required accuracy in afterheat prediction is generally lower and a target accuracy of ~25% is adequate. Currently, however, the data used for activation and afterheat evaluation is poor, and many neutron cross sections for radionuclides generated in fusion blankets have not yet been evaluated and, therefore, are simply ignored in the calculation.

Design Specificity: generic

Level of Concern: (high) The level of concern regarding a large uncertainty in heat generation prediction is high since many parameters related to the blanket performance are temperature dependent. Examples of these parameters include the tritium release characteristics which have a specific temperature window. The level of concern with decay heat prediction is medium since afterheat is ~ 1-3% of the total heat generated during reactor operation and the problem of afterheat removal is not as critical as the case in fission reactors.

Operating Environment/Neutrons: (R,H) Neutrons interacting with the blanket materials through elastic, inelastic, and charged-particles emission reactions are the main contributor to heat deposition. However, particularly in a stainless steel type structure, the contribution from gamma-ray heating is dominant. Except for irradiation purposes, neutrons are not required for decay heat testing.

Operating Environment/Parameters: Heat deposition in the blanket during operation is a strong function of neutrons and gamma ray fluxes, spectra, and fluences. Decay heat after shutdown is a strong function of the previous history of operation (flux, energy, fluence and spectrum).

## Issue I.F.7 Blanket Response to Near-Blanket Component Failure

Description: Components near the blanket may fail, subjecting the blanket to abnormal conditions, possibly causing them to fail. Both the conditions and blanket response are uncertain. In general, interactions among components are poorly understood.

Potential Impact: (US,UL) Abnormal conditions could cause failure for blankets with reactive metals, Li, 17Li-83Pb, and or V. For the case of a tokamak with a water-cooled limiter, a metal/water interaction would appear to have serious safety implications. Any blanket could be harmed by such interactions from surrounding components. Tokamaks are more of a concern because of (a) the closer proximity of a limiter to the blanket in a tokamak versus halo scrapers and other components in a mirror, (b) the higher heat load on a limiter, (c) the fact that a coolant leakage could trigger a disruption in a tokamak that would further subject the blanket and limiter to a high thermal flux and transient magnetic influences.

Design Specificity: (generic)

Level of Concern: (medium) For tokamaks with reactive metals and water-cooled limiters, the issue is of high concern and must be resolved. For others, the level of concern drops somewhat but is still medium.

Operating Environment/Neutrons: (--) None.

Operating Environment/Parameters: Tests must include prototypical temperatures, geometries, stresses, coolant velocities, coolant pressures, transient pressures, and chemical environment.

## Issue I.F.8 Assembly and Fabrication of Blankets

Description: Some of the current blanket designs are geometrically complex and contain a large number of parts to be assembled, including welding, machining and fitting. Tolerances in many cases are small, for example in the solid breeder breeder/cladding gap. The weldability of major structural alloys (particularly vanadium, but also HT-9 to some degree) is uncertain. Composite elements such as coated first walls or insulating plates may be difficult to bond. Since no one has yet attempted to construct one of these full components, there is uncertainty regarding the actual difficulties involved.

In addition, the fabrication of the solid breeder is uncertain. The basic material must be produced with high purity and assembled into the final form with the desired microstructure (e.g. grain size, porosity) on an assembly line basis. $Li_2O$ is relatively easy to form, but some precautions are necessary since it is hygroscopic and since LiOH is corrosive. $LiAlO_2$ requires more effort to form, and in particular there is no good technique at present for producing the desired sphere-pac breeder.

Potential Impact: (IC,UL) If fabrication and assembly of the blanket is more difficult than currently expected, the cost would clearly be higher and the reliability of the blanket might be reduced.

Design Specificity: generic

Level of Concern: (medium) Problems with building blankets are not considered to be a feasibility issue. However, known problems such as weldability of vanadium or formation of sphere-pac $LiAlO_2$, as well as the general complexity of present designs, give this a medium level of concern.

Operating Environment/Neutrons: (--) Neutrons are not required.

Operating Environment/Parameters: Geometry is the only critical parameter.

Issue I.F.9 Recycling of Irradiated Lithium and Beryllium

Description: Sufficient beryllium resources exist to consider beryllium as a neutron multiplier for first and second generation fusion reactor service (~1800 to 3000 G We-y, respectively), but beyond the second generation close attention to beryllium recycling losses will be required. Since beryllium will be activated in the fusion environment (primarily due to impurities), a remote fabrication technology will be required.

Potential Impact: (DW,IC) Without the development of recycling, beryllium neutron multiplier should only be considered for use in the first generation of fusion reactors.

Design Specificity: (beryllium) These concerns hold for all blankets with beryllium neutron multipliers.

Level of Concern: (medium) Presently available recycling technology is both expensive and results in large losses of material. Since the extended use of beryllium is dependent upon adequate recycling a medium level of concern is appropriate.

Operating Environment/Neutrons: (R) Neutrons provide the activation of the beryllium and the heat and transmutations that generate the internal helium which must be removed during recycling.

Operating Environment/Parameters: A total neutron fluence (5 to 20 MW-yr/$m^2$) neutron energy spectrum and operating temperatures (400°C to 600°C) are the principal controlling parameters.

## Issue I.F.10 Prediction and Control of Normal Effluents Associated with Fluid Radioactivity

Description: Several fluids will be radioactive: blanket coolant, blanket breeder or breeder purge stream, shield coolant, and limiter-type component coolant. The source of the radioactivity can be activation of the fluid itself, activation of impurities in the fluid, sputter products from the walls, and corrosion products from the walls. This radioactivity could reach the environment via direct leakage to a steam generator, leakage/spillage into the reactor building, or waste streams from fluid processing systems. Leakage or spillage into the reactor building also causes increased radiation fields there, complicating maintenance and increasing occupational exposure.

Potential Impact: (RP,IC,RS) Over-estimating effluents could lead to siting restrictions and/or excessive control costs. Under-estimating effluents could lead to having to restrict operation to reduce effluents to the levels planned for or adding expensive remedial control systems. For the higher activity fluids, 17Li-83Pb and draw salt, the impact could be so severe that reactor operation would have to be substantially reduced or halted.

Design Specificity: generic

Level of Concern: Because the radioactivity is very high (hence high potential impact), and the uncertainty is high, the level of concern is high for either 17Li-83Pb or draw salt fluids. Other liquid metals and salts are better understood and warrant only a medium level of concern. The effluents for water and helium streams are fairly well understood, but some information is still needed; the associated level of concern is low.

Operating Environment/Neutrons: (--) Neutrons are not needed for direct effluent tests. Sputtering and corrosion tests are generally needed first; some of those require neutrons.

Operating Environment/Parameters: Operating experience is needed with prototypical fluid systems to determine the potential for leaks and radioactivity levels in waste streams.

# II. PLASMA INTERACTIVE COMPONENTS

## A. General Concerns

### Issue II.A.1 HHFC Materials Properties

Description: A major issue associated with all plasma-side materials is the lack of a comprehensive bulk property database. The high heat flux components in some cases have special materials and special materials problems. For example, copper alloys are the leading candidates for heat sink materials in the near term. More information is needed in the areas of elevated temperature tensile properties and fatigue/crack growth behavior before a reference alloy can be selected.

High heat flux components will be subjected to moderate to high neutron fluences. The critical issue with a radiation environment is whether the high heat flux components are sufficiently resistant to radiation damage to operate for the desired lifetime. The materials used for high heat flux components are considered to be new to the study of radiation damage effects, so there is very little data available. Radiation affects thermophysical properties, mechanical properties, and the dimensional stability of materials.

The use of refractory metals for high heat flux applications appears desirable for some operating conditions. The major issue associated with these metals is the lack of an adequate baseline and fabrication data base. The needs include the acquisition of data on all relevant bulk properties in both the unirradiated and irradiated conditions.

Potential Impact: (RL,UL) Inadequate material selection would impair the component lifetime and could have serious implications on the plant operation and availability.

Design Specificity: (generic) This issue, in the sense of promoting materials development on a broad basis, is generic to high heat flux components. The emphasis towards special material groups or properties may change, though, depending on the particular component requirements.

Overall Level of Concern: (high) The issue has a high priority since numerous parameters and properties are involved and long lead times in irradiation testing, lifetime testing and process developments are required.

Operating Environment/Neutrons: (D) The long term issues described above require irradiation tests of small probes in a fast neutron flux up to medium to high fluences to investigate irradiation damage.

Operating Environment/Parameters: (F,T,G,q,$\sigma$) In the near term, a neutron fluence of 20 dpa is appropriate. For long-term development, fluences up to 50 dpa may be required. The temperature range is < 1000°C for plasma-side materials and 400° to 750°C for heat sink materials. Bulk property data may be investigated at small probes; fabrication techniques, however, have to be proven with probes of prototypic size and shape (i.e. 1 x 1 $m^2$, 3D curvature). Typical heat fluxes range between 3 and 5 $MW/m^2$, possibly up to 10 $MW/m^2$.

## Issue II.A.2 HHFC Surface Damage Mechanisms

### Issue II.A.2.a Physical Sputtering and Redeposition

Description: The erosion of plasma side materials by energetic particle bombardment has been identified in all design studies for future fusion devices as one of the most stringent life-limiting factors for high heat flux components. The sputtering yield (i.e., the number of atoms released from the wall per incident particle) is highly dependent on the particle species, the particle energy, the material, and the incidence angle. In the presence of a magnetic and/or electric field, the sputtered particles are generally reionized and redeposited at the wall only a short distance from their origin. Thus, the net erosion can be small compared to the amount of atoms relocated, yet the penalties imposed on the design are signigicant. This leaves large uncertainties in lifetime predictions.

The consequences of sputtering depend on the material. For instance, in SiC and BeO, preferential sputtering may result in changes in surface composition and properties. In high-Z materials, self-sputtering may exceed unity, causing very rapid erosion. For all materials, some of the sputtered atoms may reach the plasma as impurities, linking physics and engineering issues.

Sputtering yield as a function of particle energy has been extensively measured for most candidate plasma-side materials for the most relevant particle species and energy ranges. In connection with theoretical models, sputtering rates can be predicted within an uncertainty of about a factor of two for laboratory conditions. Larger uncertainties exist at shallow angles for special materials like compounds, for redeposited material and for self sputtering. In a fusion device another source of uncertainties evolves from poorly defined boundary conditions. These include particle energy and its spectral and spatial distribution, particle flux and its spatial distribution, transport length of sputtered atoms depending on their charge state, the magnetic field relative to the surface, and electric potential. This leads, in summary, to large uncertainties in local sputtering predictions for future devices and the requirement to better understand and model this issue.

Potential Impact: (DW,UL,RL) The sputtering redeposition problem complicates the design (thick walls, special materials, special fabrication processes, bonding techniques, etc.) and thus makes it less reliable with respect to thermo-mechanical performance. This could imply serious availability problems. The sputtering erosion can reduce the component lifetime significantly, leading to high system down times and high maintenance cost.

Design Specificity: (generic) Sputtering is generic to high heat flux components, although most important to limiters and divertors. Here the largest uncertainties in sputtering/redeposition predictions exist. Also, portions of the first wall with high charge-exchange particle flux can be severely affected.

Overall Level of Concern: (critical) Life limitations and impurity introduction into the plasma make the completion of the data base, model development for sputter/redeposition processes and measurements in real devices a most important issue.

Operating Environment/Neutron: (--) No significant effect of neutrons is anticipated.

Operating Environment/Parameters: (PMI,B,G) Energetic particle bombardment is required, primarily with light ions and electrons in the energy range typical for plasma edge conditions, i.e., 10 to 1000 eV. For beam dump application, energies up to 200 keV are of interest. Besides light ions, typical impurity ions like oxygen, and wall species of candidate plasma-side materials shall be included. A magnetic field up to about 10 Tesla is necessary with variable angles between field lines and surface normal. The geometry should be varied between easy-to-model shapes (e.g., planar probes) and realistic limiter leading edge contours.

Issue II.A.2.b Arcing and Related Erosion

Description: Metal surfaces exposed to plasmas with densities of $n_e \approx 10^{11} cm^{-2}$ and electron temperatures of $T_e \approx 10$ eV can be subject to extensive surface erosion with a pattern similar to that of vacuum arcs. The arcs causing this erosion appear to be driven by the space charge potential between the plasma and the wall and require only one electrode.

Arcing processes impact wall conditioning and impurity control. A single arc can release $10^{16}$ to $10^{18}$ impurity atoms, enough to cause a major disruption if the impurities consist of high-Z material. Therefore, it is crucial to control arcing. In present day machines, wall conditioning by discharge cleaning as well as by regular plasma operation seems to be very efficient in eliminating potential arcing sites. However, it is not clear now whether future devices with higher plasma densities and temperatures can be conditioned similarly. It is conceivable that for high enough plasma densities and temperatures arcing might occur continuously. In this case, arcing would become an erosion concern.

Potential Impact: (UL,RL) Arcing is a concern of impurity introduction and an initiator for plasma disruptions. This would severely impact plant operation and possibly reduce the lifetime of plasma interactive components, especially of the first wall. At high plasma density and temperature, erosion damage of the high heat flux components is conceivable.

Design Specificity: (generic) Arcing is mainly a concern of limiters and divertors, but, in principle, it must be considered in all components exposed to plasma (ions and electrons) exceeding the density and temperature mentioned above, e.g., plasma collecting components in the end cells of a tandem mirror.

Overall Level of Concern: (high) Future fusion devices will exceed the density threshold for arcing in the edge plasma by orders of magnitude, and it is not clear whether arcing can be suppressed sufficiently by surface conditioning. Therefore, arcing must be given a high priority.

Operating Environment/Neutrons: (--) It is not expected that neutron damage would have a significant effect on arcing, at least not at low to medium neutron fluences typical for high heat flux components.

Operating Environment/Parameters: (PMI, B, G) Typical edge electron densities and temperatures relevant for limiters and divertors may be as high as $n_e \sim 5 \times 10^{19}$ $cm^{-3}$ and $T_e \sim 10\text{-}1200$ eV, respectively. The magnetic field is in the order of 5-10 Tesla. Geometry seems to be important.

## Issue II.A.2.c Chemical Erosion

Description: Chemical erosion refers to a broad class of phenomena in which the erosion of a surface under irradiation is influenced by chemical changes induced in the near surface region by plasma material interaction. The outstanding example of chemical erosion is hydrogen bombardment of graphite, where methane is formed. Hydrogen effects on candidate carbides ($B_4C$, SiC and TiC) have also been assessed as well as the effects of oxygen on the erosion of refractory metals. In the case of tungsten, for instance, even a decrease in the erosion rate has been predicted, when tungsten surfaces are covered with a monolayer of oxygen.

The current level of understanding of chemical erosion is limited. In many cases, there is sufficient data to estimate the potential impact of particular chemical processes under well-defined conditions, but there is little fundamental understanding of the processes involved, e.g., surface chemistry, phase changes, formation of alloying, and segregation. Thus, it is not possible to extrapolate the existing data base on chemical erosion to the fusion environment.

Potential Impact: (UL,RL) The most important impact for future fusion devices is seen in the erosion rate and, thus, on the component lifetime, especially for higher wall temperatures. In the near term, impurity introduction into the plasma may be the dominating concern.

Design Specificity: (generic) Chemical erosion is generic to all high heat flux components, but it is most relevant to components designed for high wall temperatures and high duty factors. The material is a key feature in chemical erosion, where carbide coatings seem to be more susceptible than metal surfaces.

Overall Level of Concern: (medium) Chemical erosion is not expected to be the dominant contribution to the total erosion in designs where erosion is the life-limiting factor. However, the example of graphite shows that chemical effects can be prohibitive in material selection.

Operating Environment/Neutron: (--) No neutron damage effect on chemical erosion is known.

Operating Environment/Parameters: (PMI,T,I) Plasma parameters, especially impurity contents, such as oxygen, nitrogen, or atoms released from the first wall, are important. In the wall material the surface temperature in the upper region (up to 1000°C), conditioning, and bulk impurities seem to be the key parameters.

## Issue II.A.2.d Surface Damage Due to Helium Implantation (Blistering)

Description: High energy alpha particles bombarding a metal surface are implanted in the near surface region. Since helium is insoluble in any metal, it immediately precipitates at the end of its implant range forming small gas bubbles. The growing bubbles can eventually interconnect and, due to the internal pressure, lead to surface deformation or exfoliation of micron thick surface chips (blistering).

Significant surface damage due to repeated blistering has been observed experimentally in the temperature range of 0.3 to 0.5 of the melting temperature and for high helium concentrations (~0.3 He/metal atom). Also, the alpha particle energy must be sufficiently high (> 1 keV). These conditions can be obtained in first walls by unconfined 3.5 MeV alpha particles. Little is known about hydrogen-helium synergistic effects. On the other hand, if blistering proves to be an important erosion source for future devices, then steps can be taken to alleviate blistering damage, for example by surface roughening, cold working, bulk porosity, or small grains.

Potential Impact: (RL) Blistering is a surface damage that could lead to lifetime reduction of plasma interactive components.

Design Specificity: (generic) This issue is generic to high heat flux components exposed to helium bombardment, such as limiters and divertors and possibly direct convertors in mirror devices. Also, the first wall of tokamaks can be affected.

Overall Level of Concern: (medium) Since blistering can hardly be predicted for future fusion devices, further investigation is needed. However, there is evidence that blistering damage can be limited, making the issue a medium priority effort.

Operating Environment/Neutrons: (--) Neutron damage is probably not important in blistering phenomena, although the trapping site pattern for helium agglomeration may change at high fluences accumulated, for instance, at non-replaceable first wall regions.

Operating Environment/Parameters: (PMI,F,T,$\sigma$) Particle species and energies typical for plasma edge conditions apply for limiters, divertors, and first walls. For the latter, the fraction of the unconfined 3.5 MeV helium particles is of primary concern. For direct converters, the particle energy is in the order of several hundred keV. The surface temperature ($400^\circ$-$1000^\circ$C) is important with respect to helium mobility and material strength. The stress state, which is normally a compression stress at the surface, may influence the trapping site pattern.

Issue II.A.2.e: Disruption Induced Surface Melting and Erosion

Description: A plasma disruption will deposit a relatively large heat load on a portion of the first wall which will lead to localized erosion and melting of the first wall structure. The interaction of this melt layer and the large electromagnetic fields associated with the plasma disruption is not known. The mechanical strength of the first wall will probably be degraded in the region of the plasma disruption and cracks may be initiated in that region which could eventually lead to a breach in the first wall's integrity.

Potential Impact: (UL,RL) Erosion due to the plasma from both routine operations and disruptions may lead to premature failure of the first wall's integrity which would require replacement of the blanket module before operations could be continued. If the erosion rates are more benign, then these phenomena impact the component's lifetime.

Design Specificity: (generic) The interaction of the plasma and first wall structure is generic to all reactor concepts. The impacts of the interaction may be less severe for mirror designs.

Overall Level of Concern: (medium) It is anticipated that suitable design can minimize the impact of erosion due to both routine operations and plasma disruptions; however, these issues may be the life-limiting phenomena for a blanket module. Therefore, the overall level of concern for this issue is medium.

Operating Environment/Neutrons: (—) While neutron spectrum and fluence way impact the time when failure occurs in the component, they are not required to assess the interaction between the plasma and the first wall.

Operating Environment/Parameters: The following parameters are required: magnetic field, temperature (impacts failure mode), rapidly changing magnetic field, plasma, surface heat load, and impurities in the plasma

Issue II.A.3 HHFC Thermomechanical Response

Issue II.A.3.a: HHFC Structural Integrity

Description: The high heat flux components in a fusion device constitute a pressurized system within the vacuum boundary, designed to operate near the upper limits of practical thermal hydraulic performance. Large uncertainties exist in both the applied loads and the materials data base.

In order to remove the high surface heat fluxes anticipated in fusion devices (several $MW/m^2$), water cooled, high conductivity heat sink materials are required. Currently, copper alloys are the leading heat sink materials due to their superior thermal properties. However, the copper alloys with the highest thermal conductivities have the lowest yield stress values.

Failure of a HHFC is related to the combined effects of material properties, structural response, fabrication techniques, and geometric configuration. Areas of concern include bond integrity of protective layers, welds or brazing joints of the heat sink under thermal and pressure cycling, pipe joints at manifolds under external cyclic loads, stress corrosion in the coolant boundary, and crack growth in irradiated material and at geometrical discontinuities (e.g., grooves). Another potential failure source could be the forces, deflections and vibrations during plasma disruptions.

Potential Impact: (UL,RL) HHFC and, in particular, limiter and divertor coolant boundary failures have serious implications on the plant operation and availability. The detection of even a small leak can be troublesome. In case of both liquid metal and water cooling within the same device, leakages can become a safety issue. Since cyclic fatigue is anticipated to be a critical life-limiting factor, this issue can have serious implications on the component lifetime in general.

Design Specificity: (generic) This issue is generic to high heat flux components, but it is most important to limiters and divertors since a failure generic to the component would require high maintenance effort.

Overall Level of Concern: (high) This issue is judged to be of high importance for long-term fusion devices; however, it is very design specific and depends strongly on materials selection.

Operating Environment/Neutrons: (D) In an advanced stage, the issue would require a fast neutron environment to simulate the irradiation damage up to medium to high fluences. In an earlier stage however, many tests can be done without neutrons.

Operating Environment/Parameters: (PMI,q,G,T,$\sigma$,B,$\dot{B}$) Primary parameters to be investigated are the operating temperature in the range 400° to 800°C, depending on the heat sink material, and up to 1000°C for the plasma-side material; furthermore, the stress level (approaching the yield strength), and the geometric configuration leading to typical stress concentrations. The heat flux should be in the order of 5 to 10 $MW/m^2$. For investigating the structural response to magnetic field transients, a field of 5-10 T and a transient up to 1000 T/s is necessary.

## Issue II.A.3.b HHFC Thermal Hydraulic Techniques

Description: Three alternative thermal hydraulic heat removal techniques are presently considered for high heat flux components: (1) subcooled flow boiling (SFB) with water, (2) high velocity helium gas convection, and (3) liquid metal heat transfer in the presence of a magnetic field. The choice of technique will not only be based on thermal hydraulic capability but to a large extent on the impact on overall plant design. Therefore, in the near term, all three techniques have to be investigated in parallel, although possibly with different emphasis.

In general, the following aspects should be addressed (1) critical or maximum heat flux for thermal hydraulically optimized and technically feasible heat sink configurations, (2) temperature and flow distribution in large surface area components with large length-to-diameter ratio parallel coolant channels, (3) hot spot hot channel assessment in spacially and timely non-uniform heat fluxes, (4) operating transients including local temperature fluctuations due to stratification, e.g. in manifolds, (5) afterheat removal capability with natural convection flow, (6) channel wall erosion and corrosion as well as mass transfer and particle transport/deposition, (7) quality assurance and quality control procedures to prove leak tightness, (8) instrumentation and control. In the case of a liquid metal coolant, all the MHD issues apply.

Potential Impact: (UL,RL) The issue has serious implications on the plant operation and availability, since each of the sub-issues could lead to early component failure.

Design Specificity: (generic) This issue is generic to high heat flux components, but it is most important to limiters and divertors since a failure generic to the component would require high maintenance effort.

Overall Level of Concern: (critical) Predictability of the thermal hydraulics is most important for high heat flux components approaching the 10 $MW/m^2$ design limit, as is anticipated for limiters and divertors of long-term power plants. This is beyond present experience with large-scale, commercially utilized heat removal systems. (In liquid metal cooled fast breeder reactors, the heat flux at the fuel pin surface approaches 3 $MW/m^2$).

Operating Environment/Neutrons: (--) The neutron flux for limiters/divertors may contribute to the total heat flux on the order of 10 to 20%. This should be compensated for in the experiments by the surface heat flux, so that a neutron environment is not essential in near-term thermal hydraulic tests. Uncertainties implied by radiation effects (e.g., geometric changes, thermal conductivity changes) may be accounted for analytically.

Operating Environment/Parameters: (PMI,q,G,T,V) A surface heat flux of typically 5 to 10 $MW/m^2$ (for long-term application up to 20 $MW/m^2$), has to be provided for prototypic component dimensions, e.g., a surface size of approximately 1 x 1 $m^2$ to include manifold effects and large length-to-diameter ratios. The coolant temperature depends on the selected heat sink material and the coolant and may range from 200° to 800°C. The flow velocity and pressure are design dependent. They are anticipated to be on the order of 10 m/s and 1 MPa, respectively, for water or liquid metal. For gas cooling, they might be as high as 100 m/s and 5 MPa, respectively.

Issue II.A.3.c Leading Edge Design

Description: For reasons of maintenance and/or fabricability, large plasma-facing components have to be divided into a number of modules. Sometimes the modules even consist of several distinct elements. Components such as limiters, RF antennas, and plasma scrapers may also penetrate the plasma causing harsh plasma disturbances. In any case, the physical edges of the components, modules or elements constitute discontinuities with respect to the structural and thermal-hydraulic configuration, and to the particle and surface heat load. The result is increased erosion, degraded local cooling and complex mechanical behavior at the leading edges. Design provisions to alleviate the leading edge problems are, for instance, appropriate shaping (as in the case of the circumferential edge of a belt limiter), staggering of modules or elements (as in the case of divertor plate segments or beam dump elements), and protection with special materials. All measures result in additional design uncertainties requiring testing.

Potential Impact: (UL,RL) Improperly designed leading edges may result in excessive impurity introduction by sputtering, which would impair the plant performance, in hot spots, high local erosion and possibly in early component failure. In connection with redeposition and adequate gap sizes between limiter/divertor segments, maintenance questions are also involved.

Design Specificity: (generic) The leading edge problem is generic to high heat flux components at either component edges and/or at element edges. Appropriate countermeasures are very design specific.

Overall Level of Concern: (high) In the case of limiters and divertors, which seems to be the most important application, plasma control can be impaired and the component lifetime can be reduced. This gives the issue a high priority.

Operating Environment/Neutrons: (H,D) Neutrons can alter the volumetric heat in the structure and, thus, the temperature distribution. Neutron damage may lead to stress concentrations and strength degradations or to ablation of protective layers.

Operating Environment/Parameters: (PMI,B,G,F,q) Plasma parameters depend on the application. Particle energies range from 10-1200 eV for limiters and divertors, and up to several hundred keV for beam dumps and plasma scrapers. Most important are the parameters determining the particle and heat load at the leading edges, i.e., the magnetic field relative to the component, the macroscopic and the local geometry of the structure, and the particle energy and flux within the plasma stream. The ion flux at limiters and divertors can be as high as $10^{22}$ to $10^{23}$ $m^{-2}s^{-1}$. Neutron fluences up to about 50 dpa for future tokamak limiters/divertors are envisaged.

## Issue II.A.3.d Heat Sink Bond Fabrication and Failure

Description: A major need for high heat flux components is the development of fabrication and bonding techniques for structures composed of both plasma-side and heat sink materials. Specific bonding methods have not yet been developed, so that properies of the bonds are largely unknown. A secondary issue is the possible impact of bonding fabrication on the bulk properties of the heat sink. The temperature required for bonding may be in the range where the mechanical properties of copper alloys are seriously degraded.

Potential Impact: (UL) The impact of losing the bond integrity of HHFC coatings is to contaminate the plasma with impurities, degrading the plasma and possibly causing a quench. Once the coating (typically a low-Z material such as Be, TiC, etc.) is removed, the high-Z substrate material (copper, steel, etc.) will be exposed to the plasma.

Design Specificity: (generic) This issue is generic to all fusion concepts, but the low magnitude of surface heating in mirrors makes it less serious.

Overall Level of Concern: (high) The loss of bond integrity and resultant plasma contamination is of high concern because neutron resistant high heat flux coatings have not yet been developed, and the in-situ failure of bonds will likely be difficult to anticipate.

Operating Environment/Neutrons: (D) Neutron irradiation will have a potentially deleterious effect on the integrity of the bond between the low-Z coating and the substrate. Irradiation will result in differential volumetric swelling of the materials, gas generation, and changes in the material properties of the coating, bond region, and substrate, all of which will likely lead to premature loss of bond integrity.

Operating Environment/Parameters: The HHFC will be subjected to heat fluxes on the order of 5-10 $MW/m^2$ and neutron loadings of 1-5 $MW/m^2$ for fluences of 20-50 dpa. Plasma side materials will generally operate below 1000°C, and heat sink materials < 400°C for near-term machines and ETR's and < 750°C for future commercial machines. Plasma edge temperatures range from 20-100 eV for tokamaks and are approximately 10 eV for mirror machines.

## Issue II.A.3.e First Wall Hot Spots due to Plasma Spatial Distribution

Description: Spatial variations in heat and particle flux to the first wall will cause local "hot spots." Higher fluxes of charge-exchange neutrals are expected near limiter or divertor entrances, or near gas-puffing, neutral beam or pellet injector inlets. More energetic particles will strike the wall near heaters (NBI, RF). Axial changes in dimensions, particle confinement or burn parameters may cause enhanced losses to the first wall (e.g., magnetic field ripple). Plasma transport characteristics may also lead to local variations in edge conditions and thus first wall heating or erosion (e.g., localized "marfe" phenomenon observed on Alcator-C). Radiation and neutron flux variations are also possible due to device and plasma geometry. For example, the tokamak outboard wall is exposed to a larger plasma volume. Time variation in heating and erosion rates will occur, associated with startup/shutdown, power changes, and disruptions.

Potential Impact: (DW) The uncertainties in the magnitude and location of hot spots require that the first walls be conservatively designed. Sufficient design flexibility may not exist for some designs. Armor may need to be added in particularly troublesome locations. These uncertainties complicate the design and pose feasibility questions.

Design Specificity: (generic) All devices will experience local asymmetries due to geometry; placement of fueling, heating and exhaust equipment; and time variations due to startup/shutdown. Tokamaks are probably more sensitive due to the inherent asymmetry of the machine, the location of the limiter or divertor close to the first wall, and the harsher plasma/wall interaction. The first wall inside the mirror end cells will likely see strong spatial variations, but the heat and erosion flux may be reduced from the central cell, and there may be more engineering flexibility since there are no tritium breeding constraints.

Overall Level of Concern: (high) The exact magnitude of the hot spots are not well-known. However, first wall designs generally push enough engineering limits (particularly in tokamaks) that uncertainties in first wall conditions are important.

Operating Environment/Neutrons: (H,D) Neutrons are a source of heating and structural materials damage. Typically, the neutron heat load contributes 20% to the first wall temperature rise.

Operating Environment/Parameters: (PMI,q,T,$\sigma$,F) This is primarily a plasma interaction issue, and the flux, particle energy, and surface heat load are controlling. The amount of tolerance in the first wall design is a function of its temperature and operating stress state. Neutron fluence contributes to heating and radiation damage. Typical parameters are 0.1-1 MW/$m^2$ surface heat flux, usually mostly as radiation but with an appreciable component of 10-500 eV charge-exchange particles leading to 0.1-1 mm/yr net erosion rates. Local increases of a factor of ten in surface heating or particle flux are possible, and the particle energy may increase up to 100 keV or so near neutral beam injectors.

## Issue II.A.3.e Disruption Electromagnetic Loading

Description: The sudden loss of plasma is generally accompanied by the dumping of plasma kinetic energy on some exposed surface, and the dumping of stored magnetic energy within the interior vessel components. Depending on the time scale, area and volume for this dumping process, the resulting forces and temperatures may be substantial. At present, the tokamak "disruption" and the mirror "sudden loss of plasma" are not well understood in terms of characterizing their time and localization, as well as their frequency. It is anticipated that tokamak disruptions, presently fairly frequent, will be avoided in power reactors by some yet-to-be-determined method. Furthermore, mirror disruptions, already rare, are postulated as a once-in-lifetime design basis accident for safety purposes.

Potential Impact: (DW,US) Plasma disruptions are a potential driver for major failure of plasma-interactive components. This has both basic design and safety consequences.

Design Specificity: (generic) Tokamak disruptions are presently frequent and able to cause considerable damage. Mirror "disruptions" are presently rare, but may be of comparable severity and are considered at least as a design basis accident for safety purposes.

Overall Level of Concern: (tokamaks:high, mirrors:low) The frequency of occurrence in tokamaks is sufficient for this to be a high concern. For example, a disruption in JET in 1984 deformed the vacuum chamber by about 1 cm. It may be of comparable severity in mirrors (present estimates are somewhat lower than tokamaks) in terms of the magnetic forces generated, but will be much less frequent.

Operating Environment/Neutrons: (D) Neutrons cause radiation damage which structurally weakens the components that must absorb the disruption energy.

Operating Environment/Parameters; (PMI,$\dot{B}$,q,$\sigma$,F) The key variables are the amount of kinetic and magnetic energy dumped, the time scales for the dump, and the area/volume over which the dump occurs. The energy is expended as surface heat flux, or as magnetic field induced forces. Neutron fluence characterizes the extent of radiation damage. Estimated tokamak parameters are plasma kinetic energy dump on 10% of the first wall in a 20 ms time scale, generally on the inboard side, with magnetic forces roughly equivalent to a

0.6 MPa internal pressurization on the first wall/blanket. Up to 3 disruptions/year of moderate severity are assumed. In a mirror, the equivalent magnetic forces are similar, with a 0.03/year frequency.

## Issue II.A.4 Plasma Edge Conditions and Exhaust

### Issue II.A.4.a Plasma Edge Temperature and Density Control

Description: The plasma edge in a tokamak is at the same time a physical link and a thermal barrier between the hot core plasma and the relatively cold structure. Its operating conditions, characterized by the temperature and the density, are therefore important to the design of the plasma interactive components, especially to the first wall and the impurity removal and control system. For instance, the plasma edge conditions control the fraction of the alpha heat being radiated to the first wall and the fraction transported as kinetic energy by particles bombarding the limiter and divertor. This, in turn, determines the heat flux and the sputtering erosion at these components. Moreover, the particle transport in the plasma edge, which is related to the edge conditions, impacts particle removal and impurity control in the core plasma.

A related uncertainty is hydrogen recycling and its influence on the edge plasma. There are three main mechanisms for hydrogen recycling: (1) reflections; (2) photon, electron and ion desorption; and (3) hydrogen trapping, diffusion and molecular recombination. Theoretical models do exist; however, the governing coefficients are unknown for most candidate materials and surface conditions.

There is experimental evidence that the plasma edge operating regime can be influenced to a certain extent by the choice of fueling and heating methods, such as: radio frequency heating, resistive heating, neutral beam injection, gas puffing, pellet fueling. These methods along with mechanical shim devices could possibly provide means to control the plasma edge conditions from the control room according to required parameter settings (e.g., structural temperatures, tritium recycling, helium removal, partial power operation).

Potential Impact: (DW) The issue has serious implications on design limit and design window, in particular with respect to the heat flux in the first wall and related thermo-mechanical issues, to the erosion and heat flux of plasma interactive components, to the effectiveness of the impurity control system, and tritium recycling issues.

Design Specificity: (tokamak) The issue is generic to tokamak reactors. In tandem mirror reactors, the removed particles are collected at remote devices exterior to the magnetic confinement with little feedback to the core plasma.

Overall Level of Concern: (critical) The issue is critical since it is vital with respect to a stable plasma operation and is a prerequisite for establishing major device parameters and plasma interactive component operating conditions.

Operating Environment/Neutrons: (--) No effect.

Operating Environment/Parameters: (PMI,G,I) Tokamak plasmas with flexible and gradually approaching reactor plasma edge conditions and corresponding plasma material interactions (PMI) are necessary. Candidate edge temperature regimes are suggested to be either low ($T_s$ < 50 eV) or high ($T_s$ > 700 eV)[1] where $T_s$ is the pre-sheath temperature at the limiter or divertor plate. Geometry aspects and species (D, T, He, Impurities) variations are of primary concern.

## Issue II.A.4.b Helium and Impurity Exhaust

Description: The main purpose of the exhaust system of a fusion device is to remove the helium ash generated by the fusion of deuterium and tritium. It is necessary to maintain the helium concentration in the plasma at or below about 5%. This means that the exhaust gas stream has a high percentage of D and T, which is undesirable since the whole amount of exhaust gas has to be reprocessed before the separated D and T fractions can be refueled. The pumping capability for a given limiter or divertor pumping system is different for the individual species. It is related to the rate of generation of neutral particles and to their dynamic behavior in the edge region near the limiter or divertor, and is a matter of trade-off between physics and design considerations.

A second objective of the exhaust system is impurity removal. One class of effects which leads to impurity introduction from plasma-material interactions is surface damage, including physical sputtering, chemical erosion, arcing, and radiation-induced desorption. A second class of impurity introduction results from thermal wall effects, e.g., thermal desorption, segregation, evaporation, and sublimation. A third class is comprised of leaks through the vacuum boundary and through coolant confining walls in blankets, limiters/divertors, heating components, and shields. Finally, there will be a fourth class of impurities carried in process streams needed for plasma control, i.e., in the fuel injection, gas puffing, and neutral beams. Impurity control in the main plasma is related to the amount and location of impurity introduction, impurity transport in the edge plasma and in the main plasma, and removal capability of the impurity pumping system.

Potential Impact: (DW) The pumping capability fundamentally influences the plasma physics and, thus, the entire reactor performance, i.e., plasma control, first wall and limiter/divertor design windows,and fueling system. It also has an impact on the layout of the fuel reprocessing system including tritium storage and losses.

Design Specificity: (tokamaks) Optimized combined hydrogen and helium pumping by limiters or divertors is generic to long pulse or cw operating tokamaks. In tandem mirrors, ash removal is primarily achieved by selectively influencing the confinement behavior of the helium itself (drift pumping, radial transport behavior, charge-exchange pumping). As far as the impurity introductions are concerned, the issue is also of great importance to tandem mirrors.

Overall Level of Concern: (high) The potential impact outlined above gives the pumping issue a high priority for tokamak reactors. However it is not deemed to be critical in the sense of tokamak feasibility.

Operating Environment/Neutron: (D) No significant neutron effect is expected on the physical processes of helium pumping and and impurity introduction and exhaust. However, the leak tightness of major components is likely to be degraded by neutron damage.

Operating Environment/Parameters: (PMI,B,G,T) The plasma-materials interaction and the plasma-neutral gas interaction determine the neutral gas pressure in the neutralizer chamber and, thus, the pumping and recycling behavior. Besides the PMI, magnetic field (on the order of 5-10 T) and the macroscopic geometric transition edge plasma/neutralizer chamber/vacuum duct are important. Reference designs are proposed in the major design studies. The wall temperature influences the surface reactions. This is very design dependent and may typically be around $100^{\circ}$ to $300^{\circ}C$ for limiter designs and $400^{\circ}$ to $1000^{\circ}C$ for divertor chambers.

## Issue II.A.4.c Plasma Exhaust Stream Pressure and Composition

Description: The exhaust gas pressure and composition depend on the plasma edge conditions, the plasma exhaust system (divertor, limiter, halo scraper), and the vacuum system. In the more open exhaust systems such as pumped limiters, the exhaust gas pressure is very sensitive to the plasma edge. In more closed exhaust systems, such as an advanced bundle divertor, the divertor chamber gases are much more isolated from the plasma edge and the exhaust pressure is more predictable.

A second factor is the composition of the exhaust. This will likely not be a strong function of the exhaust pressure, but has a strong bearing on the design of the vacuum system which must be able to remove impurities as well as DT and helium. These impurities have to be separated prior to cryopumps in order not to foul up the cryocondensing or sorbing surfaces. Any cold traps, however, reduce the effective pump speed by a factor of 3-4. Condensible metals or dust are a different concern since they could reduce surface pumping efficiency, erode mechanical pump blades, or foul up seals and valves. These impurities will need to be removed periodically themselves, and the fuel cleanup system must be sized to handle them.

Potential Impact: (RP,RL) Impurities and pressure uncertainties lead to conservative designs with increased cost, or the risk of reduced performance.

Design Specificity: (generic) Vacuum and fuel cleanup systems are affected.

Level of Concern: (medium) Uncertainties in impurity composition and exhaust pressure translate to uncertainties in sizing the vacuum system and the fuel cleanup system. Although conservative design can add reasonable operating flexibility, the present uncertainties are sufficiently large to give this a medium level of concern.

Operating Environment/Neutrons: (--) No effect.

Operating Environment/Parameters: (P,I,PMI) The pressure of the exhaust gas and the impurity composition are uncertain. These are related to the overall machines design, exhaust system geometry and operation, and plasma-material interactions.

Issue II.A.4.d Surface Conditioning Effectiveness

Description: Surface conditioning refers to the sum of the physical and chemical processes that are applied to plasma interactive components prior to plasma operation. Conditioning is necessary to minimize impurity influx by thermal and particle-induced outgassing and other plasma-surface interactions. It also affects the hydrogen recycling behavior and the susceptibility of first wall surfaces to arcing.

Successful conditioning methods have been employed at first walls in present generation fusion devices. These involve pretreatments (i.e., material selection, physical and chemical cleaning, vacuum baking), and in-situ conditioning by some form of hydrogen discharge cleaning. Little is known about the effectiveness of such methods in high particle and heat flux components covered with special materials and constituting convoluted surfaces, as in the case of limiters. Tandem mirrors are often designed with the vacuum boundary encompassing major components, giving rise to large and convoluted surfaces with narrow gaps. Some of the components may not be able to withstand vacuum baking and cannot be reached by hydrogen discharge cleaning. Thus, the effects of surface conditioning on plasma control, especially following commissioning and maintenance procedures, need to be better understood.

Potential Impact: (UL,RL) Surface conditioning is mainly a concern of plasma control during start-up after major interventions and is, thus, an operational problem. Once the device is operating there could still be an influence on the disruption frequency and on arcing erosion, which could reduce the components lifetime.

Design Specificity: (generic) In tokamaks, the surface conditioning is of particular importance for the first wall due to its large surface, on limiters and divertors due to the high particle flux and surface temperature, and possibly on RF heating components due to the introduction of special insulating materials. In mirror devices, the large and convoluted surface seems to be the major conditioning problem.

Overall Level of Concern: (medium) Near-term devices will contribute to a better understanding of the importance of surface conditioning for future fusion reactors. It is expected that in a long-term run, the need for in-situ surface conditioning will tend to diminish due to a self-cleaning effect. This has to be proven and makes the issue an important one.

Operating Environment/Neutrons: (--) No neutron effect is anticipated.

Operating Environment/Parameters: (PMI,G,I,T) Impurity release during start-up is a matter of plasma-material interaction. For tokamaks, the particle flux and energy at the first wall is typically in the order of $10^{20}$ to $10^{21}$ $m^{-2}s^{-1}$ and up to several keV for charge-exchange particles, respectively. At the limiter or divertor, the corresponding parameters are $10^{22}$ to $10^{23}$ $m^{-2}s^{-1}$ and about 10 to 1200 eV. The geometry is important in the case of covoluted surfaces. The surface chemistry is a key factor in the effectiveness of conditioning processes and depends on the material and the applied fabrication and finishing techniques. The temperature is important in chemical reactions and is typically around 300°C for first walls and 400° to 1000°C for high heat flux components.

Issue II.A.5 Safety

Issue II.A.5.a Tritium Permeation and Inventory

Description: Tritium permeation through first walls, limiters, or divertors subjected to energetic tritium ion or charge-exchange neutral bombardment is a concern for advanced D-T reactors operating at elevated temperatures. A high concentration of tritium in the near surface region can be reached by implantation of tritium atoms combined with a relatively slow recombination into molecules at the plasma/wall interface. Because of the large concentration of mobile tritium near the plasma wall surface, a concentration gradient is established, causing tritium to diffuse into the bulk and eventually to the outer wall surface where it can enter the coolant.

The two main processes involved in tritium transportation in the bulk of the material, solubility and diffusivity, are well understood for metal walls, and the data base is adequate for most HHFC candidate materials with undisturbed atom latice. In this case, the permeation rate is strongly temperature and material-dependent and, for many applications, undesirably high. However, in real wall structures, there are a number of mechanisms effective, which can alter the tritium permeation rate by several orders of magnitude. Among these inherent and unpredictable effects are: surface conditions (e.g., oxide layers, cracks), bulk impurities, irradiation damage, latice defects, grain boundaries, and alloying at composite interfaces. Most of these effects tend to inhibit tritium permeation. Other tritium barriers can be intentionally introduced such as ceramic surface layers, doping or bonded metal composites. All these effects cause large uncertainties in tritium permeation predictions. On the other hand, an effective trapping would increase the tritium inventory in the component.

Potential Impact: (DW,US) High tritium permeation would result in larger tritium reprocessing systems, additional shielding requirements, access problems for maintenance. All this could pose serious safety questions and require back-fitting. It also is a pathway for potential tritium losses from the fuel cycle. In designing tritium barriers, the tritium component inventory has to be considered in order to minimize tritium losses (particularly for short life components), and the activation problem.

Design Specificity: (generic) Tritium permeation is generic to high heat flux components when exposed to energetic tritium bombardment, especially when operated at elevated temperatures. In the case of copper, molybdenum, tungsten or beryllium as heat-sink or plasma-side materials, permeation might not be a serious problem. For hydride forming materials like tantalum, the tritium inventory can be prohibitive.

Overall level of Concern: (critical) Since safety questions are involved and engineered safeguards as well as operational and design limits have to be established in a conservative manner, the reduction of permeation and inventory calculational uncertainties by extensive test programs is most important.

Operating Environment/Neutrons: (D) The materials damage by neutron irradiation seems to be an important factor in tritium permeation. However, many of the above mentioned non-neutron effects have to be investigated separately or in combination with neutron damage.

Operating Environment/Parameters: (PMI,F,T,$\sigma$,q) Energetic tritium bombardment requires a plasma-materials interactive environment with particle energies in the order of 10 eV up to 1000 eV, depending on the envisaged plasma edge conditions. At beam dumps, the particles may have energies of 100 to 200 keV. If radiation damage is investigated, the fluence should be in the order of 20 to 50 dpa for anticipated limiter/divertor lifetimes. The temperature range is $< 1000^{\circ}C$ for plasma-side materials and $400^{\circ}C$ to $750^{\circ}C$ for heat sink materials. Mechanical stress close to the yield strength might be important. The heat flux, typically 5 to 10 $MW/m^2$ for limiters or divertors and up to 20 $MW/m^2$ for beam dumps, have to be considerable for tritium permeation because of the temperature gradient. The most important parameters seem to be surface conditions, choice of tritium barriers and possibly fabrication techniques in composite materials.

Issue II.A.5.b  Tritium Inventory Behaviour During Maintenance

Description: In order to replace a divertor or limiter plate, the 1st wall or the blanket, the vacuum boundary must be opened. Tritium implanted or absorbed in these structures will be reemitted to the reactor room unless some kind of cover is used to seal the opening. If the amount of tritium reemitted is large, the tritium will contaminate the reactor room and result in releases to the environment. If the amount of tritium reemission during maintenance operations is large, prior baking of the limiter plate. 1st wall or blanket may reduce the tritium reemision.

Potential Impact: (IC) Depending on the amount of tritium to be reemitted, baking of the structures prior to maintenance operations or the implementation of design changes, such as addition of a cover structure, become necessary.

Design Specificity: (generic)

Level of Concern: (high) The level of concern is high because this will cause considerable changes in the maintenance procedures.

Operating Environment/Neutrons: (D) Surface reemission is dependent on the surface condition which is affected by neutron damage.

Operating Environment/Parameters: Neutron flux, spectrum, fluence, temperature, particle flux.

Issue II.A.5.c  Eroded Activation Product Behavior in the Vacuum Chamber

Description: Calculations indicate that neutron sputtering and direct daughter recoil will cause radioactive particles to be introduced into the vacuum chamber. Experiments are needed to verify calculations of the sputter yield at fusion conditions, the transport behavior of the products, their deposition rates, and releasibility from surfaces in transients or during maintenance.

Potential Impact: (IC,RS) Inaccurate prediction of sputter product formation, transport, deposition, and releasibility could cause inaccurate prediction of activity levels in serviced components or of activity mobilizable in a transient or during maintenance. This is particularly important for those systems where designers previously have not strongly considered the presence of activity in the vacuum chamber and pumping systems. Such inaccurate predictions run the risk of over-conservatism in predicting radiation fields in systems external to the blanket with associated economic design costs or the risk of under-estimating these fields with the associated costs of excessive occupational maintenance exposure, inability to maintain and/or decommission an unexpectedly hot system.

Design Specificity: (generic)

Overall Level of Concern: (medium)

Operating Environment/Neutrons: (R) Neutrons with appropriate energy are needed to produce sputter and direct daughter recoil reactions. Sufficient fluence is needed to measure yield.

Operating Environment/Parameters: For the vacuum chamber, the influence of wall geometry should be investigated; a real fusion plasma is needed to establish the appropriate particle contribution, interaction with neutron sputtering, and transport of sputtered material.

## B. LIMITER/DIVERTOR SPECIFIC ISSUES

### Issue II.B.1 Maintenance and Replacement

Description: Limiters and divertors are pertinent to frequent replacements and/or repair due to their limited predicted lifetime. The whole component is therefore divided into manageable segmented modules corresponding to the toroidal pattern of the TF coils, allowing module replacement without moving the coils. And yet, each module is part of the vacuum boundary and has numerous supply lines for coolant, vacuum, instrumentation and control, which have to be disconnected and reconnected for module replacement. The coolant as well as parts of the limiter/divertor module are contaminated, requiring complete remote operation within reasonable times.

The most obvious techniques to be developed involve: coolant removal from the module, afterheat removal and control during maintenance, remote handling and leak checking of pipe joints, remote handling and leak checking of large vacuum boundary seals, means to avoid spilling of particulate or dust contaminants from the vacuum duct, removal of module edge bonding caused by redeposited material (if required), module handling and precision realignment, repair of worn-off parts or small leaks, insitu leak detection, insitu protection layer attachment checking, and overall quality assurance and quality control procedures for maintenance.

Potential Impact: (DW,UL,IC) Scheduled replacement of all limiter/divertor modules could be performed in an optimized rotating step-by-step mode. Failure of the planned sequence could result in a prolonged plant down time.

Design Specifity: (generic) Several maintenance procedures mentioned above are generic to HHFC and to blanket modules in tokamaks and mirror devices. Some of the procedures are specific to the limiter and divertor design.

Overall Level of Concern: (high) The maintenance procedures as a whole in connection with the yet unknown design are subject to reveal unforseen problems, which might require substantial back-fitting of the whole plant. Therefore, maintenance schemes have a high priority from the very beginning of any device design.

Operating Environment/Neutrons: (D) Neutrons have no effect on most of the maintenance program. However there are special effects that need to be considered, i.e., swelling and creep deflections, activation, damage of elastomere seals, and instrumentation equipment.

Operating Environment/Parameters: [G,(PMI,F)] Maintenance procedures are normally performed at room temperature, in an inert atmosphere, and are remotely controlled. Geometric configuration and available space for access are very important. For module removal the damage at the limiter blade or divertor plates due to erosion/redeposition and swelling might be important. Typical neutron fluences at end of life are 20 to 50 dpa.

## Issue II.B.2 Choice of Limiter vs. Divertor

Description: An important issue in the near term involves the need for poloidal divertors for impurity control and ash removal. It is desireable to use pumped limiters; however, it is unclear whether or not they will work in long pulse, auxiliary heated devices. Clearly this issue is intimately connected with plasma edge control and strongly influences the overall reactor design (for example, by the additional poloidal field coils in the divertor case) as well as the exhaust system design.

The implications on plant design have to be considered in conjunction with the plasma physics concern. For instance, the location of the limiter or divertor involves a trade-off between the physical performance and the impact on the overall tritium breeding by occupying potential blanket space. The location also is a key entry in maintenance schemes and exhaust duct dimensioning, giving rise to neutron losses due to streaming effects. The selection of limiter/divertor coolant and its operating temperature also link component design issues (e.g., material selection, thermal hydraulics, coolant boundary integrity) to plant safety issues (chemical reactions) and to plant performance issues, e.g., degradation of tritium breeding by use of non-breeding coolants, and effects of operating parameters on heat recovery.

Potential Impact: (DW,UL) This issue has serious implications on plant design limits with respect to achieving specified plasma control. Therefore, it also has serious implicatons on operation and availability. The system performance might be degraded with respect to breeding and overall efficiency. Safety implications can possibly be involved depending on the coolant selection.

Design Specificity: (tokamak) This issue is generic to tokamak reactors.

Overall Level of Concern: (high) This issue has a high priority since it is part of the overall reactor design and determines the component development.

Operating Environment/Neutrons: (--) No effect.

Operating Environment Parameters: (PMI, G) Major parameters are set by the edge plasma conditions and corresponding plasma materials interactions (PMI) and by the overall design (geometric configuration, location, coolant).

Issue II.B.3 Effects of Misalignment

Description: In present limiter/divertor analysis for large tokamak devices, the plasma interactive components are assumed to be toroidal belt-type structures ideally shaped in the poloidal direction to match the theoretical particle and heat flux profiles in the edge plasma, and ideally, axisymmetric relative to the magnetic field in the toroidal direction. There are, however, numerous imperfections in both the plasma shaping, by the various sets of toroidal and poloidal field coils, and in the limiter/divertor shape and its position relative to the magnetic field. As a result, the actual particle and heat flux distribution may be significantly different from the computed ones, leading to hot spots and, conceivably to plasma instability.

There are various categories of imperfections to cause misalignment: (1) all design-and fabrication-related tolerances, involving global offsets between the limiter/divertor and the magnetic field (excentric, elliptic, height adjustment), and local perturbations (coil or limiter/divertor module misalignment, deviations from reference shape); (2) geometry changes during normal service, which can also be global or local, e.g., erosion/redeposition-related geometry effects, swelling and creep deflections (the erosion and redeposition mechanisms can be of a smoothing nature or a locally propagating nature); (3) deflections due to operating transients like bimetallic bending of the limiter structure or permanent deflections after plasma disruptions; (4) mismatch after maintenance and repair, e.g., module alignment, replaced (virgin) modules next to aged modules, in-situ repair procedures.

Potential Impact: (DW,RL) Limiter/divertor misalignment may have serious implications on plasma control and thus on achieving design limits. Geometry changes during normal service and due to operating transients can reduce the component lifetime.

Design Specificity: (tokamak) The issue is generic to tokamaks since the subjected component (limiter or divertor) is at the same time the plasma controlling component. Divertors may be less susceptible than limiters.

Overall Level of Concern: (medium) Since plasma control can be impaired or the component lifetime can be reduced resulting in extensive downtimes of the plant, the alignment issue is ranked as medium priority.

Operating Environment/Neutrons: (D) Most of the described effects are not related to neutrons and can be investigated in near-term tokamaks. The swelling effects may be assessed analytically when better material data are available.

Operating Environment/Parameters: (PMI,G,q,B,B) The operating environment for a test component can only be a tokamak device of DEMO characteristics or scalable size and edge plasma conditions, causing typical heat flux, particle flux and temperature distributions. The as-built geometric imperfections should be documented extensively for later interpretation. Deliberately installed misalignments (e.g., an adjustable module) are desirable.

## C. VACUUM SYSTEMS

### Issue II.C.1 Compound Cryopump Helium Pumping and Regeneration Lifetime

Description: Since the primary pumping load from the vacuum chamber consists of a low pressure DT/He mixture (10% He), cryopumps are strong candidates on the basis of their proven high DT or helium throughput at low pressures. However, a number of improvements are needed. Present cryopumps have some helium pumping capacity, but it is severely degraded in the presence of hydrogen. Two-stage or compound cryopumps must be developed which first remove the hydrogen, yet still have high speed for helium at a second stage. Cryosorption is generally preferred over cryocondensation for helium due to the high helium vapor pressure over its liquid state around 2-4 K. The pumps must be periodically regenerated to refresh their surfaces and reduce the tritium inventory. This regeneration could be done in stages, with helium unloaded first and then hydrogen, thus saving a step in the fuel cleanup process.

Uncertainties include the lifetime of the cryopump surfaces (particularly molecular sieves) with plasma impurities; tritium or neutron radiation heat loads; effects of thermal cycling during regeneration; and the overall reliability of the mechanical design for regenerating the cryopumps. The latter in particular needs some careful design since it may involve multiple large panels moving or rotating every few hours under high vacuum and cryogenic temperatures.

Potential Impact: (RP,IC,RS) Reduced performance under reactor conditions would force the addition of further panels, more frequent panel changeout, or reduced regeneration frequency (and thus increased tritium inventory).

Design Specificity: (generic) These concerns apply to any device using cryopumps as the main vacuum pump. Depending on the throughput and exhaust pressure, turbopumps or two-stage Roots blowers may be usable, but would require some development of their own.

Overall Level of Concern: (medium) Considerable development work needs to be done, particularly in the area of pump regeneration. However, the present uncertainties are probably more due to the lack of attention given to this problem than to any inherent engineering difficulties. Because of its general importance, though, it is a medium level of concern.

Operating Environment/Neutrons: (H,D) Depending on the location of the pumps, there may be some neutron-induced heating and materials damage, or heating from activated materials.

Operating Environment/Parameters: (p,T,I,G,$\sigma$,t,F) The primary conditions are the temperature and gas pressure that are to be pumped, as well as the basic composition of the gas including impurities. The mechanical design must allow sufficient surface area to provide enough pumping, avoid direct exposure to plasma or neutron radiation, and provide a mechanically reliable regeneration method over many pump cycles. Typical parameters are 3000 $m^3/s$ DT, 3000 $m^3/s$ He with 4 K He cryosorption surfaces, regeneration temperatures up to about 100 K, DT/He (10% He) at 300-600 K and less than 1 Pa total pressure.

## Issue II.C.2 Vacuum Chamber Outgassing and Leak Rates

Description: Present machine designs generally place the vacuum boundary away from the first wall. This alleviates concerns about vacuum integrity under plasma and neutron fluence, but leaves concerns regarding the general ability to obtain a good, reliable vacuum seal over a large area with many penetrations. Furthermore, the components inside the vacuum boundary will present a large, convoluted surface area that may be an appreciable outgassing load on the vacuum pumps. Even if the pumps are sized to handle the gas throughout during startup after a vacuum break, the narrow spaces will limit the conductance and thus pumpdown rate.

Uncertainties include the reliability of the vacuum boundary, particularly size, frequency and throughput rate of the leaks, as well as difficulties in locating and repairing leaks. Uncertainties also include the outgassing rate from the in-vessel components, and the limiting conductance or pumpdown rates.

Potential Impact: (RP,RS) Any residual gas load from leaks or outgassing will be a source of impurities that will reduce plasma performance, require additional pumping capacity for startup and operation, and be a possible safety hazard (oxidation of hot in-vessel surfaces, leakage of tritium or activated products outside vacuum vessel).

Design Specificity: (generic) Most magnetic fusion devices operate at high vacuum, and have a large, complex vacuum boundary.

Overall Level of Concern: (medium) Although difficult to accurately predict for a fusion reactor, there is already some experience with large vacuum systems (e.g., space simulation and operations). Methods of solution include increased pump capacity, close attention to good vacuum design practices, and allowing sufficient pumpdown capacity and time during startup after vacuum breaks.

Operating Environment/Neutrons: (--) The vacuum boundary, by design, is assumed to be placed away from any neutron fluence. Only neutron streaming may raise some materials damage concern if not properly shielded.

Operating Environment/Parameters: (G,$\sigma$,T,P) The geometry is important since total surface area dominates concerns over outgassing and likelihood of vacuum leak. Stresses at penetrations are a concern for causing cracks that may eventually lead to vacuum leaks. Outgassing is primarily a function of temperature and local vapor pressure. Typically, the first wall area in a reactor will be 200-500 $m^2$. The vacuum outer boundary will have approximately this much area also, with multiple penetrations. Convoluted surfaces inside the vacuum boundary shell will increase the effective surface area for outgassing by factors of 2-10.

## Issue II.C.3 Large-Diameter Vacuum Valve Reliability

Description: Large diameter (over 0.25 m) valves are necessary to isolate components of the vacuum system - for example, neutral beam injectors, vacuum ducts, regenerating vacuum pumps. Reliable valves with polymer-seals are presently available at least up to 0.25 m in diameter, but metal seals are preferred when tritium is present. However, present large-diameter metal-sealed valves are very unreliable. Dust entering the seal region typically reduces their effective lifetime to only a few cycles.

Engineering development is necessary to produce more robust metal-sealed valves, or to provide adequate tritium protection to polymer-sealed valves. Some allowance for neutron-induced swelling or damage may be necessary in some locations, such as neutral beam injection lines. Large, fast-acting shutter valves will also need development for neutral beam injectors.

Potential Impact: (UL) Failure of vacuum valves could result in shutting the machine down for part replacement, or reduced isolation between systems (having to bring more system up to atmosphere during vacuum breaks than desired, for example). This reduces the machine availability.

Design Specificity: (generic) Present magnetic fusion systems use high vacuum and will have large ducts for high pumping speed.

Overall Level of Concern: (low) Development of metal-sealed or tritium-resistant valves is desirable, along with increases in size, but this should be fairly straightforward engineering.

Operating Environment/Neutrons: (D) For particular valves, such as on neutral beam lines, neutron induced swelling or damage may interfere with the required tight tolerances. Most valves, however, can probably be located away from neutrons.

Operating Environment/Parameters: (t,I,G,F) The primary factors are the cycling of valves with component operation (startup/shutdown, NBI operation, vacuum pump regeneration), and the presence of dust or other impurities that can prevent good seals from being formed. Fluence may matter if the valve is exposed. The relevant size is 1.5 m diameter.

## Issue II.C.4 Vacuum Pump Operation under Thermal/Pressure Transients

Description: Gas pressure and temperature transients are possible due to changed plasma or exhaust conditions in the main chamber, or by the failure of an adjacent pump. These generally result in pulses of higher pressure gas, and also higher thermal loads (more and/or higher energy particles), which may overload the pump. Cryopumps are particularly sensitive to thermal loads since their refrigeration system usually does not have much excess capacity at operating conditions. Cryopumps as used in neutral beam lines have been shown quite robust against large pressure pulses, although cryosorption pumps (for helium) are undoubtedly more delicate. Mechanical pumps are sensitive to pressure changes since they may substantially change their effectiveness. Turbopumps operate best below 0.1 Pa, Roots pumps above 1 Pa; both show rapid drop-off in pump speed between 0.1-1 Pa. It is likely that the actual operating pressure will be close to this range near the plasma, so small variations may be critical.

Uncertainties arise due to expected thermal or pressure pulses and the limits of pump capacity in handling these transients.

Potential Impact: (IC,RS) If unable to cope with thermal/pressure transients, the vacuum pumps could be expected to overload quickly and cease functioning. This would shut the plasma down, but could also release large tritium inventories into the vacuum chamber (as cryopumps heat up) or even mechanical damage (if turbopumps overheat at too-high pressures).

Design Specificity: (generic) Any high vacuum system may experience thermal or pressure pulses from leaks, operation (startup/shutdown, starting up of neutral beams or fuellers) or accidents (disruptions, major leaks). Some tolerance must be included in the design.

Overall Level of Concern: (low) The capabilities of the pumps to handle transients can be experimentally or theoretically estimated. Although the exact thermal or pressure transients may not be qualifiable yet, the designer can add reasonable conservatism to the vacuum system design.

Operating Environment/Neutrons: (--) Vacuum pumps should not be directly exposed to neutrons so should not directly see neutron power transients.

Operating Environment/Parameters: (p,Q,T,t) The primary variable is the neutral gas pressure at the pump inlet. Also of concern is the increase in thermal load associated with the increased pressure and possibly incrased temperature of the gas. Finally, the time duration of the pulse determines the overall energy input and the time available for instrumentation to respond (prevent pumps from overloading, add extra capacity, isolate cryopumps).

## D. RF COMPONENTS (AUXILIARY HEATING SYSTEMS)

### Issue II.D.1 RF Launcher Performance Requirements

Description: The purpose of the RF launcher system is to couple wave energy efficiently to the plasma while maintaining the structural integrity to survive the existing radiation environment. To accomplish this performance requirement, a tradeoff of lifetime and reliability versus coupling efficiency arises. Several design aspects must be considered: (a) the antenna must be well matched to the plasma to minimize wave reflection at the first wall; (b) high voltage arcing should be examined due to the high power requirements; (c) negative plasma confinement consequences could result if improper coupling exists (e.g., surface heating with ICRH in a tokamak); (d) cooling systems must be developed to stabilize the temperature during the burn cycle; (e) irradiation induces degradation of electrical properties will result in additional power losses; and (f) the structural integrity must be maintained during cyclic operation and in the event of additional transient loading during a disruption event.

Potential Impact: (UL,RL) The selection of launcher configuration is critical since it is generally located inside the first wall and it determines the auxiliary heating system availability, The launcher also affects the upstream design in terms of power requirements. Auxiliary heating systems affect plasma performance and the launching structure of these systems provides the major operational uncertainties.

Design Specificity: (generic) The use of auxiliary heating is generic to all fusion systems. Certain aspects of tokamak operation (e.g., cyclic operation and disruptions) may heighten concerns for tokamak applications over those expected with mirrors. However, neutral beam systems will require substantial development for use in mirrors.

Overall Level of Concern: (critical) The generic use of RF systems and the performance implications concerning the launching structure make this a critical issue.

Operating Environment/Neutrons: (H,R,D) Neutrons will significantly impact the cooling requirements of the launching structure while degrading the mechanical and electrical properties.

Operating Environment/Parameters: ($B,\dot{B},F,Q,\sigma,G,\phi,S$) The plasma-interactive nature of the launching structure implies a dependence on the plasma parameters, structural behavior, and electrical properties.

## Issue II.D.2 Window and Feedthrough Performance

Description: Ceramic windows are required for most transmission lines to separate a gas-filled region from a vacuum. Additionally, the window must absorb a minimum amount of RF power, have good heat transfer properties, and minimize power reflection. This must be accomplished in a high neutron/gamma flux level which tends to adversely affect the ceramics design properties. The location of this window is critical to overall system performance. The window may be pulled back from the plasma, or located around the bend and shielded, but at the cost of increasing the vacuum section which is prone to breakdown.

Potential Impact: (UL,RP) Windows in RF systems are known to be potential "weak link" components in terms of performance impact and availability aspects. Neutron and gamma heating and flux-induced conductivity increase results in extra power absorption leading to thermal stresses causing fracture. Neutron-induced swelling of even modest proportions can result in microcracking which threatens vacuum integrity. Increased power relection will increase the VSWR and reduce transmission efficiency.

Design Specificity: (generic) The use of auxiliary heating sytems is generic to all fusion reactors.

Overall Level of Concern: (critical) The potential for severe damage induced by irradiation in ceramics, coupled with design implications introduced by remote location of the window, results in a critical level of concern.

Operating Environment/Neutrons: (H,R,D) Ceramics are generally notorious for structural and electrical property degradation at low fluence (< $10^{26}$ $n/m^2$) levels. Neutron flux effects include heating and instantaneous conductivity increases which have major design emphasis. Finally, the bonding of the ceramic-to-metal may be threatened by irradiation exposure.

Operating Environament/Parameters: ($\phi$,S,F,G,T) Geometry and operating temperature are the remaining important parameters.

## Issue II.D.3 RF Transmission Systems Performance Requirements

Description: The major issues for transmission lines revolve around power loss, voltage breakdown effects, material selection, and cost. They involve known technology and are expected to be substantially less demanding than those associated with the launcher. However, their application in a highly intense 14 MeV neutron fluence has uncertain consequences. The possibility of breakdown is likely to be enhanced. Therefore, a safe margin will have to be established between the maximum power rating and the operating parameters. Power attenuation will be increased from neutron effects on surface resistivity. Additionally, if spacers are structurally required in the coax line, its consequences on power reflection and structural integrity will be influenced by irradiation.

Potential Impact: (RP,RL) Increased power reflection or absorption will result in increased cooling requirements and decreased coupling efficiency. Breakdown can result in power surges which may damage components and reduce system availability.

Design Specificity: (generic) The transmission of RF waves is a generic issue for fusion systems.

Overall Level of Concern: (medium) The uncertainty over radiation consequences warrants a medium level of concern on these critical components.

Operating Environment/Neutrons: (R,D,H) Structural and electrical property changes will result from the displacement damage and transmutations caused by the 14 MeV neutron fluence.

Operating Environment/Parameters: ($\phi$,S,F,G,T) The metal resistivity (and hence, the power absorption) is very sensitive to temperature changes in the conductor.0

# III. SHIELD

## Issue III.1 Shield Effectiveness

### Issue III.1.a Protection of Sensitive Components

Description: The combined thickness of the blanket and bulk shield is a significant factor in determining the fusion power and economics of a reactor. This sensitivity is extremely strong on the inboard side of a tokamak where protection must be afforded the inner TF coils (at a point of maximum magnetic field).

It is generally cost beneficial to incorporate local shielding in addition to bulk shielding to protect components that are most seriously affected by the radiation field. Cryopanels are an example of such components. In order to avoid excessive heating, extra neutron and gamma shielding are required. Local shielding will affect the overall system design and the need must therefore be identified and incorporated early in the component design.

Potential Impact: (RL,IC,RS) The necessary inclusion of shield materials ultimately complicates overall system designs in a complex manner. Fusion performance, system cost, and environmental acceptance can be equally affected.

Design Specificity: (generic)

Overall Level of Concern: (high) The complicated interdependence of system performance and shield thickness indicates a high level of concern is appropriate.

Operating Environment/Neutrons: (R,D,H) The transport of neutrons and their generated gamma rays are are essential in all shielding applications.

Operating Environment/Parameters: ($\phi$,F,S,t,G) Besides the irradiation environment, geometry is the only major variable.

Issue III.1.b Biological Dose During Operation and Maintenance

Description: Occupational exposure limits must be maintained at a reactor site. The exterior shield and component surfaces will may require the inclusion of extra shield material to maintain consistency with exposure limits, maintenance requirements, work station environments, and system availability needs. Primary uncertainties in the actual dose arise from assembly error and tolerances, distortions resulting from thermal and radiation sources, and neutron streaming through access ports and ducts. This latter effect can be influenced by the selection of duct wall material.

Potential Impact: (RS) If the shield is found to be insufficient, it generally requires additional shielding or considerable change in the component arrangement. This could result in delayed plant operation or reduced period of operation, imposing an economic penalty.

Design Specificity: (generic)

Overall Level of Concern: (high)

Operating Environment/Neutrons: (D,R) Fusion neutrons are required as a source of radiation at low fluences, and to cause activation and materials damage at high fluences.

Operating Environment/Parameters: Neutron flux, spectrum, fluence, and impurities are important.

Issue III.1.c Analytical Techniques/Data Base

Description: The sensitivity of reactor performance and cost to the shield dimensions indicates an importance on the availability of methods and codes to accurately predict (a) neutron (and gamma) transport and (b) nuclear responses. Uncertainty in estimating the operating environment of sensitive components can best be relieved by additional conservatism in shield thickness. Better estimates of damage can reduce the required conservatism and, therefore, the overall system cost.

Potential Impact: (RL,IC,RS) The necessary inclusion of shield materials ultimately complicates overall system designs in a complex manner. Fusion performance, system cost, and environmental acceptance can be equally affected.

Design Specificity: (generic)

Overall Level of Concern: (high) The complicated interdependence of system performance and shield thickness indicates a high level of concern is appropriate.

Operating Environment/Neutrons: (R,D,H) The transport of neutrons and their generated gamma rays are essential in all shielding applications.

Operating Environment/Parameters: ($\phi$,F,S,t,G) Besides the irradiation environment, geometry is the only major variable.

## Issue III.2 Shield Compatibility with Blanket Including Assembly and Disassembly

Description: Shields are generally heavy, weighing more than 50 tonnes apiece. They must be fitted together with such accuracy that the slit width between them is small enough to maintain the level of radiation streaming through the slits below a certain specified level. The design of support mechanisms for the blanket, shield and magnets must consider various factors such as the cometition for space, the difference in the amount and direction of thermal expansions, the electromagnetic stress, the clearance against earthquakes, etc. Additionally, the activation of the shield material can result in remote maintenance complications.

Potential Impact: (RS,IC) The mechanical interactions between components can lead to mechanical failures. From a safety viewpoint, if the precision of the assembly/disassembly is not high enough neutron streaming can result.

Design Specificity: (generic) Generic to all kinds of reactors.

Overall Level of Concern: (high) The complexity and serious consequences on the mechanical issue rate a high level of concern. Although a certain amount of radiation streaming through the slits between the shield seems to be inevitable, reduction of the streaming by providing steps in the slit or by adding some additional shield may be feasible.

Operating Environment/Neutrons: (H,R,D) Although irradiation creep has some effect on mechanical failure, the dominant role of neutrons is nuclear heating of the blanket and shield causing thermal expansions. Neutrons are the source of concern for streaming and activation considerations.

Operating Environment/Parameters: $(\psi, S, F, T, G, \dot{B})$ Geometry is the other major parameter. A changing magnetic field will introduce transient stresses.

## Issue III.3 Time Constant of Magnetic Field Penetration through Shield for Plasma Control

Description: For a tokamak fusion reactor with the vertical position control coil placement external to the shield, the magnetic field needs to penetrate through the shield with an adequately small time constant. The shield also acts as a part of the passive shell for vertical position stabilization. In addition to the electromagnetic force on the shield, the magnetic field penetration and passive shell effect of shield must be known.

Potential Impact: (RP) If the magnetic field effect related to shield is not estimated with sufficient accuracy, system failure could occur.

Design Specificity: (tokamak)

Level of Concern: (medium)

Operating Environment/Neutrons: (--) No effect of neutrons.

Operating Environment/Parameters: $(\dot{B},\sigma,G)$ Transient magnetic field, stress and geometry will dominate as the important paramenters.

## Issue III.4 Shield Compatibility with the Vacuum Boundary and One-Turn Resistance

Description: In some tokamak reactor designs, the plasma vacuum boundary is placed at the inner or outer surface of the shield. To provide necessary one-turn resistance for plasma ramp-up, ceramic breaks (or bellows) are required in the vacuum boundary which introduce additional complexity in the design.

Potential Impact: (RP) Radiation streaming may cause the dielectric or mechanical property of the ceramic break to degrade below the allowable limit.

Design Specificity: (design) Limited to tokamak reactor with ceramic breaks to provide one-turn resistance of the vacuum boundary.

Level of Concern: (low) The level of concern is low because the issue is strongly design dependent.

Operating Environment/Neutrons: (D) Neutron damage is the cause of the problem.

Operating Environment/Parameters: $(\phi,S,F,G)$ Geometry is an important factor.

# IV. TRITIUM PROCESSING AND CONTAINMENT SYSTEMS

## Issue IV.1 Impurity Removal in the Fuel Cleanup Process

Description: Impurity removal is the first stage in processing the tritium collected from the plasma exhaust or breeder extraction systems. The Fuel Cleanup Unit (FCU) must be able to handle a range of impurity contents (composition and concentration) and hydrogen throughputs because of variations in plant operating conditions (power level, startup/shutdown, disruptions, aging or backfitting changes), and because of present uncertainties in the actual throughput and impurity mix. Furthermore, due to differences in flow rate, composition, impurities and isotopic abundances, the plasma exhaust and the breeder extraction flows will likely enter the FCU at different points. The output of the FCU, however, is a stream of hydrogen isotopes that are sent on to an isotope separator.

The concern is efficient handling of the known inputs, as well as allowing for their uncertainties (e.g., flow rate, impurities, $T_2/T_2O$ ratio). Present options include combinations of uranium beds, molecular sieves, catalytic oxidation, cryogenic strippers, palladium diffusers and electrolysis cells. However, for the high tritiated vapor throughputs anticipated, uranium beds are reasonably well understood but expensive, molecular sieves are less well-known, and reliable electrolysis cells are not available. TSTA is addressing many of these development and demonstration concerns. However, performance with breeder feed streams (from solid or liquid breeders) is not presently being tested, actual impurity levels are not certain until operation of a DT-burning device, inlet dust and activation product filters are not considered, and some components need to be developed.

Potential Impact: (UL,RP,IC) The primary impact is reduced performance of the tritium processing system.

Design Specificity: (generic) Impurity removal is necessary in all devices.

Overall Level of Concern: (high) There is presently some experience with the components, and some basis for estimating the likely range of throughputs and composition. In general, while the components themselves are not expensive, the engineering and assembly required to minimize tritium leaks, or provide redundancy, may be. It is an important process that needs some development to establish reliable and efficient methods so has been given a High level of concern.

Operating Environment/Neutrons: (R) The processing system is not exposed directly to plasma neutrons. Indirect effects may include neutron-induced radiolysis ($T_2/T_2O$ ratio in the feed stream), or neutron-induced sputtering (impurity composition).

Operating Environment/Parameters: (V,G,C,I,T,$\phi$,F) The primary parameters are the throughput or flow rate of the feed streams, the hydrogen content and form, the types and amounts of impurities, and the overall inlet/operating temperature (a design choice). Neutron flux and fluence are indirect contributors to the feed stream composition through neutron-induced radiolysis of $T_2O$ and through neutron sputtering. Plausible plasma exhaust conditions are 1-10 kg/d/1000 MWth $T_2$ and $D_2$ (each), with around 4% He, 1% C, 0.1% H, 0.1% O, 0.1% N, and smaller amounts of other materials.

## Issue IV.2 Tritium Monitoring and Accountability

Description: Present DOE criteria may call for 100 Ci (0.01 g) accuracy in tritium processing systems. However, in a fusion reactor with 1 kg/d circulating tritium and several more kilograms in storage, this implies 0.0001% accuracy. Futhermore, tritium is subject to decay, burnup, creation and permeation over a large surface area of piping, and will be present in a variety of phases and chemical compounds.

Clearly while tritium inventory must be accountable, present criteria are technically unrealistic. Part of this issue is a regulatory issue - deciding exactly what is important to monitor and what tritium uncertainties are appropriate to meet the real concerns. For example, from the safety viewpoint, it is the vulnerable tritium inventory that must be controlled, and this may only be 10% of the total. Or it may be acceptable to treat the reactor as a black box and monitor very carefully for tritium crossing the boundaries.

The second part of this issue is technical. The requirements will always be stringent, and it is necessary to develop reliable real-time tritium monitors with good resolution even under fusion reactor conditions. This may be coupled with a comprehensive computer model of the tritium inventory. For example, tritium implanted in limiters or divertors could be as much as 1 kg, and would have to be measured or modelled. At present, periodic shutdown might be necessary to check specific inventories.

Potential Impact: (UL,RS) Appropriate regulatory guidelines need to be developed for fusion that realistically address tritium concerns. On-line tritium monitoring and dynamic modelling must be developed to meet these criteria. It is possible that meeting the accountability guidelines may require periodic shutdown of the reactor.

Design Specificity: (generic) All DT fusion devices will face this issue.

Overall Level Of Concern: (high) Elements of both monitoring and modelling are being developed at TSTA and in CANDU power stations. Accurate on-line accounting has been developed for fission fuel processing and the techniques may be extended to fusion. However, given the importance of the issue (both physical and public perceptions), the tight requirements that will have to be met, and the present abilities to predict and measure tritium in a activated, on-line system, this has a high level of concern.

Operating Environment/Neutrons: (H,R,D) High tritium accountability requires accurate assessment including regions exposed to neutrons. Effects include neutron heating (affecting permeation), specific reactions (tritium production) and neutron damage (permeation, trapping, detector accuracy).

Operating Environment/Parameters: (V,G,I,C,t,$\phi$,F) Flow rates, overall geometry, tritium concentrations, and impurities all directly affect the accountability. Secondary concerns are variation with time (consumption, decay, operational transients, instrumentation response times, monitor lifetime), and neutron flux (radiolysis) and fluence (permeation, trapping, detector damage).

Issue IV.3 Tritium Losses in Solid Waste

Description: While tritium losses through gaseous and liquid effluents will be strictly controlled to within 100 Ci/d, it is possible for larger amounts to be disposed of with solid waste. These could arise from several sources, including the waste stream from the fuel cleanup system and from discarded components (such as limiters) with an appreciable tritium inventory. For example, TSTA has about a 1% process loss in the primary fuel cleanup loop, with the secondary waste treatment system designed to reduce the final loss to about 100 Ci/yr. Also, there may be ~ 1 kilogram of tritium implanted in the first wall and HHFCd structure.

Possible approaches include include additional stages in the impurity removal step, better technologies in the waste treatment (recovery of tritiated water), baking of highly tritiated components before disposal, and modifications to the fuel cleanup process (only processing 10% of the plasma exhaust on each pass if the burnup is very low, or partially bypassing the isotope separator stage). Quantifying the source terms, and addressing these reprocessing and disposal questions has not received enough attention yet.

Potential Impact: (RP,IC,RS) Strategies to control losses economically with minimal impact on operations need to be addressed. Major uncertainties include the costs of controlling tritium losses to acceptable levels.

Design Specificity: (generic) The fuel cycle is similar in all magnetic confinement machines. However, extraction processes that yield tritium oxide (more likely for solid than liquid breeders), might be inherently less efficient than processes yielding elemental tritium. Machines of different designs might also involve different impurities, such as argon or iodine, which affect process design or efficiency. Overall, machines with high fractional burnups (say, 5%) are less affected.

Level of Concern: (high) Since this may have an appreciable influence on most designs and has not yet been considered in detail, it is given a high level of concern.

Operating Environment/Neutrons: (--) The tritium processing systems will operate outside of the neutron field. Possible concerns on overall losses are the effects of neutron-induced trapping and neutron-enhanced permeation losses in the breeder region.

Operating Environment/Parameters: (I,C,PMI,F,t) The processing system efficiency is related to the tritium concentrations and impurities (which affect system performance) and time (aging, operational transients). Plasma and neutrons will influence the amount of tritium trapped in discarded components.

## Issue IV.4 Tritium Extraction from Water Coolant

Description: Since water is a desirable coolant, the possibility of tritium permeating into the water within the hot blanket or plasma interactive region and then transferring out of the primary loop across a heat exchanger is a serious safety concern. If substantial tritium permeation into the water is inevitable (depending on the effectiveness of surface barriers and the influence of the first wall), then it will be expensive to remove. There may also be a general need for tritium removal from water in the secondary containment and waste treatment systems.

Presently developed methods require some scaling, possibly with extra containment or leak attenuation. Although the cost is somewhat uncertain, a MARS-type extraction facility would be about 10 M$ based on the Darlington CANDU Tritium Removal Facility. Novel extraction methods such as laser separation, which primarily supply energy to the tritium atoms, are necessary to economically meet more stringent 0.001 Ci/L goals.

Potential Impact: (US) The availability of a full-scale, economic method to maintain low levels of tritium in water would appreciably enhance the viability of water-cooled reactor components. This is important since water has excellent and well-understood cooling capabilities for the high heat fluxes anticipated in many fusion components.

Design Specificity: (water coolant) This issue is specific to components cooled with water that are exposed to large amounts of tritium, especially plasma interactive components (limiter/divertor, first wall, direct converter), blanket modules, and hot tritium processing components.

Overall Level of Concern: (high) Present water-cooled designs presume that surface barriers (natural or artificial) will be able to control tritium permeation to manageable levels. However, this remains to be seen under fusion reactor conditions. If an acceptable tritium removal system could be demonstrated, then a major drawback to water coolants would be removed.

Operating Environment/Neutrons: (--) The tritium extractor could be placed outside the neutron field.

Operating Environment/Parameters: (V,C,I,G,T) The primary factors are water coolant flow rate, tritium concentration, and impurity level. The overall geometry and temperature might also add constraints on size and process.

## Issue IV.5 Tritium Processing System Integration

Description: An integrated system demonstration is desirable to prove system performance, including plasma exhaust, vacuum system, breeder extraction system, fuel cleanup, isotope separation, tritiated waste treatment, secondary containment, and particularly overall instrumentation and control. There is a need to identify the necessary redundancy for reliability and safety. The secondary containment size and integrity must be traded off against cost and maintainability. The potential for mixing explosive amounts of hydrogen and oxygen must be assessed.

Potential Impact: (RP) The system integration step will identify any unknown or unexpected interactions among components, as well as operating procedures, that could reduce system performance.

Design Specificity: (generic) All DT devices must process tritium although the actual system will vary according to expected throughputs, impurities and tritium form.

Level of Concern: (high) The bulk of the tritium processing system can be sufficiently far removed from the rest of the reactor that interactions are most likely to be felt through variations in the inlet conditions and have been treated as separate issues. However, the need to verify overall performance and safety of this subsystem, including instrumentation and control, in near full-scale conditions gives this a high level of concern. TSTA will be able to perform much of the system integration verification on a test reactor scale (1 kg/d), but does not presently incorporate a breeding blanket input, or some secondary recovery systems (especially treatment of tritiated water), or activated material filters.

Operating Environment/Neutrons: (--) The tritium processing system is away from the neutron environment.

Operating Environment/Parameters: (V,G,t,I) The important variables are the flow rate, overall geometry, interconnectedness with other fusion systems, time effects (aging, wear, operational transients), and impurity effects which might foul up the chemical processing system.

## Issue IV.6 Atmospheric Cleanup Process

Description: In the event of tritium spills inside the containment building, emergency atmospheric cleanup procedures must be used to reduce the tritium hazard to personnel and to the public. Given the large size of typical containment buildings and the large amounts of surface area on walls and equipment, a large number of Atmospheric Cleanup Units (ACU) are necessary. These generally oxidize any hydrogen present into water vapor (using high temperature catalysts), which is then condensed and trapped.

It will generally be difficult to clean the containment atmosphere in less than a day. Consequently, tritium can be expected to soak in to exposed surfaces. The rate of soaking in and the rate of soaking out again as the atmosphere is cleaned are not well known and can dominate the time to return to normal operating concentrations. There is a need to develop more efficient - and preferably non-oxidizing - ACU's as well as surface decontamination procedures. Present uncertainties in the rate of conversion of HT/HTO (HTO is more likely to adsorb onto surfaces), of soak-in/soak-out rates, and the degree of mixing in the containment atmosphere are orders of magnitude, leading to a factor of 10-100 uncertainty in the cleanup time. TSTA will be performing ACU tests, but will be using a comparatively small room, and may not include smoke or soot (which can clog the catalyst).

Potential Impact: (RP,IC,RS) The number of ACU's installed in the containment building is based on a trade-off between economics and a safety concern for personnel. Furthermore, as long as the containment is tritium contaminated, personnel access to repair the original problem will be limited, thus increasing the time to repair and reducing the availability.

Design Specificity: (generic) All DT fusion reactors are affected.

Overall Level of Concern: (medium) Atmospheric clean-up has been practiced for several years with systems one or two order of magnitude smaller ($0.5 m^3/s$) than needed for fusion reactor halls. Since these same units (although more of them) will be used and since bubble-suited personnel/remote access may be inevitable after major releases, this is a Medium level of concern.

Operating Environment/Neutrons: (--) The neutron fluence in the containment building (i.e., outside the radiation shield and outer vacuum boundary) should be negligible.

Operating Environment/Parameters: (C,G,t) The effectiveness of the atmospheric cleanup and the extent of soak-in is a function of the size of the spill (and thus tritium concentration in the building atmosphere), the geometry (concentration, volume to be processed, exposed surface area), and the time scales (spill, ACU startup/throughput, soak-in/soak-out). Typical flow rates are 3 containment volumes/day, with 4 days to reduce an 8 g $T_2$ spill in a STARFIRE sized containment down to 100 $\mu Ci/m^3$.

Issue IV.7  Breeder Tritium Extraction Stream Characteristics

Description: Since all the tritium needed to sustain the reactor is processed from the breeder (solid or liquid), this is an important input stream to the tritium processing system and is different from the plasma exhaust. For example, the purge from a solid breeder will be largely helium gas with less than 1% hydrogen, while the plasma exhaust will be almost 100% hydrogen with about 5% helium.

Uncertainties include the $T_2/T_2O$ ratio, isotopic abundances, impurity concentrations and type, and tritium phase and chemical compound flow rate. This will vary between blanket designs (self-cooled Li versus $Li_2O$, for example) but also within any given design. In solid breeder blankets, protium gas may be deliberately added to enhance the amount of tritium present as hydrogen gas versus water vapor. Furthermore, the degree of oxidation of $T_2$ and radiolytic decomposition of $T_2O$ are not certain.

Potential Impact: (RP,IC) The nature of the breeder tritium output stream affects the fuel cleanup system primarily, since the hydrogen will just be an additional load on the isotope separator, while the characteristics of the breeder extraction stream will require special processing before being mixed with the rest of the fuel cycle. Uncertainties in the breeder output - especially the amount of protium and the $T_2O/T_2$ ratio - are a performance and cost concern for the tritium processing system.

Design Specificity: (generic) The breeder tritium extraction processing stream is common to all blanket designs. Since there has been little demonstration of tritium extraction to date, the uncertainties are comparable for all blankets.

Level of Concern: (low) There is some understanding of the nature of the breeder output from present blanket designs, and enough flexibility in impurity removal systems to handle the uncertainties (with some economic penalty).

Operating Environment/Neutrons: (R,D) Neutron reactions produce tritium, transmute other materials and possibly cause decomposition of $T_2O$. Neutron sputtering and material damage will contribute to the impurity level. In solid breeders, neutrons will also influence tritium recovery and the overall purge flow behaviour, which gives rise to uncertainties in the output rate and content.

Operating Environment/Parameters: (V,G,C,I,$\phi$,F) The breeder tritium output is a function of the purge/breeder flow rate, geometry, tritium concentration and impurities, and breeder temperature. To the extent that neutrons are important, neutron flux and fluence are additional parameters determining flow rate, impurity levels and tritium concentrations.

## V. MAGNETS

### Issue V.1 Structural Overloading and Quenching from Dynamic Interaction During Plasma Disruption

Description: A plasma disruption will impact magnet design due to the mutual coupling between the plasma and the magnets. Dynamic shock loading results in the PF coils from the induced voltage and overcurrents during a disruption sequence. Torque changes in the TF coils will also occur but at a lesser relative increment over normal operation. Additionally, magnet quench may occur from the AC losses induced in the magnet systems from the disruption.

Potential Impact: (UL,IC) Plasma disruption considerations will directly affect magnet design through dynamic structural loading, local heating singes, induced voltages and I&C.

Design Specificity: (tokamak) Tokamak operation suggests disruptions are a design certainty.

Overall Level of Concern: (high) The AC losses following plasma disruption must be quantified as it can lead to magnet quench. Cooling systems and quench detection systems must be adequately designed. Structural design must allow for dynamic forces which, in addition, will be distributed in a non-uniform manner.

Operating Environment/Neutrons: (--) No direct influence.

Operating Environment/Parameters: ($B,\dot{B},\sigma,T,G$) Forces originating from electromagnetic sources depend upon the magnetic field strength, current and geometry. A plasma disruption will result in rapidly varying magnetic fields and associated varying forces.

Issue V.2 Internal Cooling Requirements and Cryostability

Description: A primary consideration in superconducting magnet design is the ability to avoid quenches and emergency discharges. Transiently stable conditions can be relatively easily achieved. However, unconditional cryostability may require excessive refrigeration power. A prime concern for magnet stability degradation is nuclear heating. Other credible events leading to the presence of resistive regions need definition.

Potential Impact: (IC) The power needed to run the refrigerators for the magnets should be kept as small as possible. At most, no more than ~ 5% of the plant electrical power should be used for that purpose. Higher values present an economical penalty. At least six orders of magnitude reduction in neutrons and gamma ray levels are required to reach this limit with proper choice of shield materials.

Design Specificity: (generic) Generic to all reactor types.

Level of Concern: (high) Since several hundreds Watts are required to remove one Watt during the magnet cooling process, it is essential to keep the heat deposition rate level as low as practical by proper shield design. Higher level (> 5% plant power outage) presents a higher level of concern.

Operating Environment/Neutrons: (H,R) Most of heat deposited in magnets is due to gamma ray heating. Inclusion of high-Z material (e.g., Fe, Ta, Pb, W, etc.) in the shield will both moderate neutrons through inelastic scattering and attenuate the gamma ray radiation that reaches the magnets. Additionally, neutron damage can reduce the cryostability margin.

Operating Environment/Parameters: ($\phi$,S,T,B) Heat deposition rate in the magnet components is a strong function of the neutrons and gamma ray fluxes, spectra, and flux emerging from the shield.

Issue V.3  Radiation Damage and Recovery Process for Magnet Components

Description: Degradation in the performance of the cryogenic magnet components is caused by the radiation damage induced by neutrons and gammas leaking from the shield preceding the magnets. If the damage rate to magnet components is high due to improper shield design, several annealing processes may be required to retain material properties. Some of the radiation damage to the magnet components can be recovered by bringing the magnet to room temperature. Lower partial recovery occurs at lower temperature.

Issue V.3.a  Critical Current Density

Description: The superconductor (NbTi, $Nb_3Sn$ etc.) will suffer a decrease in the critical density $J_c$, with a degree depending on neutron fluence and spectrum. In the case of $Nb_3Sn$ superconductor, the critical current density degrades rapidly above the fluence of $3 \times 10^{18}$ n/cm$^2$ ($E_n > 0.1$ MeV). A lower level ($\phi = 10^{17}$ n/cm$^2$) has been observed for the NbTi superconductor case. The impact is a reduction in the performance of the superconducting magnets with an increase in cost to accommodate for the decrease in $J_c$.

Issue V.3.b  Electrical Resistivity of the Stabilizer

Description: Radiation damage to the stabilizer (usually copper) is mainly due to the accumulated atomic displacements leading to an increase in the electrical resistivity, $\rho_r$. The heat generated by the $I^2R$ resistivity should be removed. An increase in $\rho_r$ of ~ 10% is reasonable and results from an accumulated displacement of ~ $1.8 \times 10^{-4}$ dpa.

Issue V.3.c  Radiation Damage to the Insulator

Description: Magnet lifetime is limited by the damage level in the insulation material (mylar, epoxy, etc.). The mylar and epoxy can operate satisfactorily for doses up to $1.2 \times 10^8$ and $3 \times 10^9$ rad, respectively. Since replacing the interlayer insulation between conductor and structure is impractical, exceeding this damage level due to improper shielding will result in component lifetime reduction and severe economical penalty.

Issue V.3.d Annealing of Radiation Damage

Description: The annealing process can take several months in a large coil, and with each anneal, the level of recovery is only about 80% of the previous level. In the annealing process, warming the magnet up only to temperatures just enough for 70-80% recovery will result in substantial savings in the power requirements needed to cool down the magnet. (Note: specific heat of copper, for example, increases with temperature.) Frequent annealing substantially reduces plant availability and, hence, has direct impact on the system operating cost.

Design Specificity: (generic) Generic to all kinds of reactor type.

Level of Concern: (high) Some radiation damage effects (reduction in the critical current, increase in the stabilizer resistivity) can be partially recovered by annealing. In most cases, the limiting factor in designing an adequate shield is the damage level to the insulator since the effect is irreversible. This sub-issue presents higher concern.

Operating Environment/Neutrons: (R,D) Neutrons of high energy leaking from the shield cause a higher level of atomic displacements in the stabilizer and higher degree in the critical current reduction due to various neutron reactions. Both neutrons (high and low energy) and gamma rays increase the energy deposition in the insulation material.

Operating Environment/Parameters: ($\phi$,F,S,$\sigma$,T) Damage parameters in magnet components are a strong function of neutron and gamma rays flux, fluence and spectrum.

## VI. INSTRUMENTATION AND CONTROL

### Issue VI.1 Definition of Transducer Lifetimes and Hardening Requirements

Description: Instrumentation at or near the first wall will experience radiation levels for which there is very little experience. The effects of this radiation on the lifetime of the instruments needs to be defined. A corollary to this is to determine and develop the radiation hardening necessary to provide adequate lifetime.

Lifetime of transducers and sensors may be limited by several effects; many of them are listed as separate issues. Synergistic relationships of various effects may impact lifetime significantly more than would be predicted for individual issues.

To accurately determine lifetime or test hardening techniques will require testing in fusion facilities and other irradiation devices.

Potential Impact: (UL) As this issue is specifically related to lifetime, it is not considered to have serious design window or safety implications. It does have the potential, however, of limiting availability as it is anticipated that instrument failure could force shutdown.

Design Specificity: (generic)

Overall Level of Concern: (high) Due to the generic nature of this issue, there is a high level of concern.

Operating Environment/Neutrons: (D,R,H) Neutrons have significant impact through damage and reactions; furthermore, some problems may be created or compounded through bulk heating.

Operating Environment/Parameters: Instruments will be affected by many operating parameters, including spectrum, flux, plasma interaction, magnetic fields, the full range of operating temperatures, and heat load.

Issue VI.2 Breakdown of Insulation Resistance

Description: The performance of many instruments relies on maintaining effective insulation between electrical conductors. Ionizing radiation can significantly degrade this insulation resistance resulting in erroneous readings and cable noise.

Potential Impact: (UL,RP) Reduced system performance or increased cost because of necessary replacements are the potential impacts of this issue.

Design Specificity: (generic)

Overall Level of Concern: (medium) The level of concern is medium because of the generic nature of the issue.

Operating Environment/Neutrons: (R) It has not been clearly shown that neutrons impact insulation resistance; ionizing radiation such as charged particles and gamma radiation may prove more damaging.

Operating Environment/Parameters: 1) Temperature over the full operating range. 2) Prototypic ionizing radiation including charged particles from plasma.

Issue VI.3 Decalibration of Instrumentation through Transmutations

Description: The 14 MeV neutrons produce several reactions including n-p, n-2n, and n-$\gamma$. These reactions can significantly alter sensor behavior through transmutations resulting in impurities which can change the behavior of sensor elements. Significant levels of transmutations in thermocouples may result in loss of calibration. Thermocouple testing at the RTNS facility has yielded mixed results at fluences of $10^{18}$ n/cm$^2$. There is a great deal of uncertainty about the effect at fluence levels of $10^{22}$-$10^{23}$ n/cm$^2$. Similar effects may be observed in devices such as bolometers or other devices which rely on understanding basic elemental properties.

Potential Impact: (RL) As this process should be a relatively gradual one, it is seen as having reduced component lifetime implications.

Design Specificity: (generic)

Overall Level of Concern: (medium) Though this issue is generic, its limited impact results in a medium level of concern.

Operating Environment/Neutrons: (D) Neutron damage is the driving force for this issue.

Operating Environment/Parameters: Both flux and spectrum are critical to this issue.

## Issue VI.4 Ceramic Insulator/Substrate Seal Integrity

Description: The mechanical strength and vacuum integrity of a ceramic-to-metal seal are interrelated through bond strength. The effects of high energy neutrons on this bond region are not well characterized. Recent difficulties with seals in the fast fission neutron spectrum in-vessel in boiling water reactors show that the bond region of seals may be seriously affected by high energy neutrons. Recent tests on seals at RTNS-II to fluences as low as $2 \times 10^{18}$ n/cm$^2$ (14 MeV) suggest the possibility of unexpected damage to bond regions as well. This is in spite of work (although limited) by LANL and others suggesting vacuum integrity of seals in fast neutrons can be achieved to $3 \times 10^{21}$ n/cm$^2$. These mixed results suggest that the present data base on high energy neutron damage to seal bond regions is too limited to form reliable design criteria.

Potential Impact: (RL) Ceramic-to-metal seals form critical components in many instrument channels and are often projected to form part of the primary vacuum boundary in fusion reactors and accelerators. The loss of these seals may impair instrument functions or contaminate the plasma. This would result in reduced system performance and/or increased system costs.

Design Specificity: (generic)

Overall Level of Concern: (medium) Because of the generic nature of this issue, it does carry a medium level of concern. Not only is it generic to all plant designs, but it is also generic to many instrument designs.

Operating Environment/Neutrons: (D,R) The mechanism of bond failure has not been clearly defined; neutrons are needed for damage and possibly reactions.

Operating Environment/Parameters: In addition to the neutrons, temperature is a critical parameter and will have to be prototypic over the full expected operating range.

Issue VI.5 RF Transmission Losses; Horns, Antennae, Wave Guides, Windows

Description: Caution must be used in designing instrumentation which utilizes RF signals, e.g., microwave resonant cavities. Though the signal generating and detection equipment can be located sufficiently remote from the high radiation zones, it may be difficult to reliably transmit these signals. As an example, microwave propagation may be affected by ionizing radiation in the wave guides. Radiation damage to RF windows may result in prohibitive loss tangents; ionization-created neutron and gamma radiation may significantly affect antennae operations.

Potential Impact: (RP) This issue has the potential of reducing system performance.

Design Specificity: (generic)

Overall Level of Concern: (medium) Though generic to all designs, the level of concern is considered to be medium.

Operating Environment/Neutrons: (R,D,H) Neutrons contribute to this issue through damage and, to a lesser extent, the generation of ionizing radiation. Bulk heating of these components may also contribute to problems.

Operating Environment/Parameters: Neutron fluence, flux, and spectrum are important to this issue. Also important are temperature and bulk heating.

## Issue VI.6 Optical Windows, Lens, Prism Darkening

Description: Many instrument systems have been proposed which utilize some type of optical sensing. These systems often require windows, prisms, lenses, and reflecting surfaces. These components may be extensively damaged by the radiation field. Darkening of the components occurs over a range of $10^5$-$10^9$ rads and self-annealing is temperature dependent. Thus, the damage limit will be a function of use and temperature. Sputtering of surfaces may distort signals to an unacceptable level. Fiberoptic devices have significant transmission losses at doses higher than $10^6$ rads.

Optical systems may have great utility in a fusion device, but there are considerable problems to overcome. Their use will require extensive development and testing to achieve reliable performance levels.

Potential Impact: (RL) The potential impact of this issue is reduced component lifetime or, in cases where damage is rapid and severe, reduced system performance.

Design Specificity: (generic)

Overall Level of Concern: (medium) There is a medium level of concern for this issue. It is important, and it is generic to all machine designs. However, the potential impact is not as severe as other issues.

Operating Environment/Neutrons: (D,R,H) Neutron irradiation will result in reactions, damage, and bulk heating, all of which contribute to this issue.

Operating Environment/Parameters: In addition to the neutrons, the temperature of these components is important to their behavior.

## Issue VI.7 Shielding of Instrument Penetrations

Description: Many types of instrumentation will require some type of penetration. Shielding of these penetrations may prove difficult. A good example is the use of optical components. In order to minimize the damage to the component, it may be necessary to position it in some type of duct located behind the first wall. Though this reduces the radiation damage to the optical component, it significantly increases the radiation levels behind it.

Potential Impact: (IC,RS) The principal impact of this issue is the increased cost to provide additional shielding. In extreme cases, there may be safety implications.

Design Specificity: (generic)

Overall Level of Concern: (low) As this is a design problem with probable design solutions, the overall level of concern is considered low.

Operating Environment/Neutrons: (D,R) Neutrons are the primary source of this issue.

Operating Environment/Parameters: Neutron flux and spectrum are critical parameters to be considered.

## Issue VI.8 Radiation Effects on Electrical Components beyond the First Wall and Shield

Description: Though generally we consider the instrumentation and control issues to be associated with those components in the high radiation level areas, there may be some pr blems with supporting electronics in relatively shielded regions. Solid-state devices, for example, are significantly damaged at doses of $10^8$ rads. Imaging devices may require some sensors and arrays to be located as close to the source as possible. Care must be taken to be certain they are not seriously degraded by the radiation field.

Care in design should be able to eliminate most of these problems; however, some difficult tradeoffs may be necessary.

Potential Impact: (RL,IC) Primary impact is reduced lifetime of components or increased system cost to provide adequate shielding.

Design Specificity: (generic)

Overall Level of Concern: (low) There is a low level of concern for this issue as proper design should eliminate most problems.

Operating Environment/Neutrons: (D,R) Neutrons directly or indirectly are the source of the damaging radiation.

Operating Environment/Parameters: Flux, fluence, and spectrum are critical to this issue.

## Issue VI.9 Cable Noise from RF, Magnetic Fields, Charged Particles, Etc.

Description: The fusion environment is extremely harsh with many aspects which may degrade instrument performance or interfere with signal transmission. Magnetic fields have been shown to introduce significant errors into thermocouple measurements when the thermocouple cable traverses a magnetic field in a temperature gradient region. The intense level of RF and charged particles may also interfere with signal generation and transmission. It is expected that adequate provisions can be made in the design of a fusion machine to counter these effects. However, this is yet to be demonstrated.

Potential Impact: (RP) The loss or degradation of instrument signals could impact system performance.

Design Specificity: (generic)

Overall Level of Concern: (low)

Operating Environment/Neutrons: (R) Neutrons can lead to ionizing radiation which may aggravate this issue.

Operating Environment/Parameters: 1) Magnetic field — steady state and time varying. 2) Radio frequencies. 3) Plasma interaction.

## 3.5 Safety and System Interfaces

### 3.5.1 Safety Issues Cross References

Safety issues appear throughout the blanket and other systems of the reactor. Because of the importance of safety as an issue in itself, all of the safety issues are compiled here in one place. Each issue corresponds to an entry in the main issues table; therefore, a detailed description already exists. Table 3.5-1 lists the safety issues together with the location cross reference to the main table.

### 3.5.2 Subsystem Interfaces

In many cases either a design-driving environmental condition and/or an important source of common-mode failures would be provided by an ajoining or interfacing subsystem in the fusion reactor. Consequently, to assure the development of reliable components, such interactions should be recognized and taken into account in the development of a given subsystem. This consideration will be relevent regardless of whether the component is to be developed in a non-nuclear test stand environment or in an integrated fusion reactor environment. The requirement for such integration will, to a great extent, be determined by the extent, complexity, and potential consequences of subsystem interactions in the ultimate application.

The following subsections provide a top level listing of many of the potential subsystem interactions for tokamak and tandem mirror applications. The individual interactive issues are ordered by both the impacted system (first) and the impacting system (second). The list is constrained to those issues which cross over between subsystems (i.e., inter-component). Many of the issues on the list are also discussed in Sections 3.2 and 3.3 in more detail and when applicable, a cross-reference to the issue listing of that section is provided.

Table 3.5-1 Safety Issues Cross References

Tritium Issues:

| | |
|---|---|
| I.A.3.a | Effectiveness of Tritium Permeation Barriers |
| I.A.3.b | Effect of Radiation on Tritium Permeation |
| I.B.4 | Stability/Kinetics of Tritium Oxidation |
| I.C.4 | Tritium Release Form from Solid Breeder |
| I.F.2.a | Permeation from Breeder to Blanket Coolant |
| I.F.2.b | Permeation Characteristics at Low Pressure |
| I.F.3 | Tritium Inventory Behavior during Transients |
| II.A.5.a | Tritium Permeation and Inventory for In-Vessel Components |
| II.A.5.b | Tritium Inventory Behavior during Maintainance |
| IV.2 | Tritium Monitoring and Accountability |
| IV | Tritium Processing System Failures |

Activation Product Issues:

| | |
|---|---|
| I.A.4 | Structural Activation Product Inventory |
| II.A.5.d | Eroded Activation Product Behavior in the Vacuum Chamber |
| I.D.1.a | Corrosion and Sputter Product Behavior |
| I.F.10 | Prediction and Control of Normal Effluents Associated with Fluid Radioactivity |
| III.1.b | Biological Dose during Operation and Maintainance |

Transient Responses

| | |
|---|---|
| I.A.2.b.1 | Response to Plasma Disruptions (also II.A.3.e) |
| I.D.2.b | Response to Cooling System Transients |
| I.F.4 | Lithium Chemical Reactivity |
| I.F.5 | Uncertainties in Failure Modes and Frequencies |
| I.F.7 | Response to Near-Blanket Failures |
| II.A.5.c | Chemical Reactions, including Vanadium Oxidation |
| V.1 | Magnet Response to Plasma Disruptions |
| V.3.e | Magnet Failures due to Radiation Damage |

### 3.5.2.1 Issues Involving Impacts on the First Wall/Blanket Due to Interfaces with Other Subsystems

#### Shield Impacts on the First Wall/Blanket

##### Structural Support and Afterheat Removal (Generic)

In most cases, the blanket would be mechanically supported by the shield. This mechanical support must permit sufficient flexibility to address the issue of differential thermal expansion (i.e., the blanket and shield will not, in general, operate at the same temperature although both are assembled at room temperature). Also, during a loss of primary coolant event, transfer of the first wall/blanket afterheat to the shield coolant is often specified to prevent blanket overheating. These two requirements can be conflicting because the afterheat cooling requirement implies a high degree of thermal contact.

##### Electromagnetic Forces Resulting From Coupled Current Paths (Tokamaks)

During a tokamak plasma disruption or other electro-magnetic transient event, currents can flow through the structure of the first wall, blanket, shield, limiter/divertor, and the sector-to-sector connectors. These currents result in $\underline{J} \times \underline{B}$ body forces on these components. The current path provided by any of these components affects the others (i.e., parallel circuit analogy). The shield current path affects the current path in the first wall/blanket. Related Issues: I.A.2.b.(1), II.A.3.f.

#### Magnetic Field Coil Impacts on the First Wall/Blanket

##### Consequences of Control Coil Placement (Tokamaks)

In current tokamak experiments, control coils located near the first wall are required to provide plasma stability. If near-plasma control coils are required for future tokamaks, the accommodation of such coils within the blanket will impact the mechanical design, cooling, and tritium breeding of the blanket.

Electromagnetic Forces Resulting from Field Transients (Tokamaks)

During startup/pulsing, the transient magnetic fields generated by the OH and other PF coils will result in $\underline{J} \times \underline{B}$ body forces in the blanket. Related Issues: I.A.2.b.(1).

Magnetic Forces in Ferritic Steels (Ferritic Steels)

If ferretic steel blankets are selected, the steady state magnetic fields can result in significant body forces on the structure. Related Issues: I.A.2.b.(2).

MHD Effects in Liquid Metal Blankets (Liquid Metal)

If liquid metal coolants are used, magnetohydrodynamic (MHD) effects will dominate the coolant pressure drop and will seriously impact heat and mass transfer. Related issues: I.B.1, I.B.2.

Coolant Breakdown and Enhanced Corrosion due to MHD Voltages (Non-Conducting Coolants)

If non-conducting coolants are used, flow through the magnetic field can result in an induced voltage drop through the fluid. This voltage drop can cause breakdown of the coolant and enhanced corrosion. Related Issues: I.B.6.

Requirements on Blanket Configuration due to Field Ripple Constraints (Generic)

Magnetic field ripple constraints determine the required number of toroidal field coils (tokamaks) and the axial separation and/or size of central cell solenoid coils (tandem mirror). As the coils become more numerous and/or smaller, the blanket sector/module configurations must conform to the spatial requirements provided by the coils.

## Plasma Interactive Component Impacts on the First Wall/Blanket

### Electromagnetic Forces Resulting from Coupled Current Paths

The current path provided by the limiter/divertor can influence the $\underline{J} \times \underline{B}$ force experienced by the first wall/blanket during plasma disruptions. Related Issues: I.A.2.b.(1), II.A.3.f.

### Impact on Tritium Breeding (Generic)

All plasma interactive components in tokamaks (e.g., limiter, divertor, RF launchers) and tandem mirrors (e.g., direct convertor, halo scraper, beamlines, RF launchers, and the end plug in general) will provide neutron streaming paths which will lead to increases of the tritium breeding requirements of the blanket. Related Issues: I.F.1.a.

### Effect of Penetrations on Mechanical Design and Erosion (Tokamaks)

First wall/blanket penetrations in tokamaks (e.g., for RF launchers and/or pumped limiters) can complicate mechanical design by interrupting the load paths. Local charge exchange heat and particle fluxes associated with such penetrations can exacerbate first wall heat flux/erosion issues. Related Issues: II.A.2.a.

### Safety Implications of Water-Cooled Components (Generic, most critical for liquid metal cooled blankets)

Plasma interactive components typically experience high heat loads and low temperature water cooling is usually specified. The rupture of a water coolant channel (e.g., in the limiter/divertor of a tokamak or the high field copper choke coil of a tandem mirror) with consequent spray/splashing on the hot first wall can lead to thermal shock and can result in the rupture of the first wall with mixing of the blanket coolant and water. The safety implications are particularly serious for reactive liquid metal blanket coolants. Related Issues: I.F.3.

First Wall Heat Load due to Armor Tiles (Tokamaks)

The armor tile of the tokamak limiter/divertor might operate at temperatures high enough to provide significant radiation to the first wall, thereby increasing the heat load. The extent and uniformity of this additional heat load is a concern. Related Issues: I.A.2.d.

## Tritium System Impacts on the First Wall Blanket

### Corrosion from Process Chemicals (Tritium recovery using chemical process)

Tritium bred in the blanket must be extracted via chemical and/or physical processes in the tritium process loop. For some concepts (e.g., tritium extraction from lithium), there is a concern that trace quantities of process chemicals (e.g., halides from the molten salt extraction process) could cause enhanced corrosion and activation product transport. Related Issues: I.C.2.

### Safety Implications of Tritium System Pressure Loss (Pressurized tritium recovery loops)

Some blanket concepts rely upon a pressurized tritium purge system to resist buckling of thin tritium breeder containers within the blanket. The loss of pressure is a safety reliability concern. Related Issues: I.B.7.

### Impact of Tritium Processing Losses on Net Tritium Breeding (Generic)

Tritium processing losses, particularly in the plasma-side tritium recovery system (which has a high recycle requirement to address low tritium burnup in the plasma) can seriously impact the blanket tritium breeding requirements. Related Issues: I.F.1.b.

### 3.5.2.2 Issues Involving Impacts on the Shield Due to Interfaces with Other Subsystems

#### First Wall/Blanket Impacts on the Shield

##### Electromagnetic Forces Resulting From Coupled Current Paths (Tokamaks)

The current path provided by the first wall/blanket can influence the $\underline{J} \times \underline{B}$ force experienced by the shield during plasma disruptions. Related Issues: I.A.2.b.(1), II.A.3.f.

#### Magnetic Field Coil Impacts on the Shield

##### Consequences of Control Coil Placement (Tokamaks)

If near-plasma control coils (and other shield penetrations) are required for future tokamaks, their accommodation will impact the design and effectiveness of the shield.

##### Electromagnetic and Electrostatic Forces (Tokamaks)

During startup/pulsing, electrical currents can be induced in the shield. These currents will result in $\underline{J} \times \underline{B}$ body forces. Changes in the mechanical properties of the shield structure due to neutron irradiation are a complication. If the shield contains ferromagnetic structure and/or filler materials, steady-state body forces will also result. Related Issues: I.A.2.b.

#### Plasma Interactive Component Effects

##### Electromagnetic Forces Resulting from Coupled Current Paths (Tokamaks)

The current path provided by the limiter/divertor can influence the $\underline{J} \times \underline{B}$ force experienced by the shield during plasma disruptions. Related Issues: I.A.2.b.(1), II.A.3.f

### 3.5.2.3 Issues Involving Impacts on the Heat Exchanger/Primary Loop due to Interfaces with Other Subsystems

#### First Wall/Blanket Impacts on the Heat Exchanger/Primary Loop

##### Mass Transfer (Generic, more important for liquid metal blankets)

Mass transfer in the primary loop will be a key concern for some coolants (e.g., the liquid metals). As the heat exchanger will provide a larger and colder surface than the blanket, it will receive most of the transferred structural material. Possible consequences include tube pluging and reduced heat transfer in the heat exchanger as well as thinning in the blanket. Related Issues: I.D.1.a

##### Mass Transfer/Activation (Generic)

As the structural and other mass transfer products will be subject to high neutron fluxes in the blanket, activation of the heat exchanger and the primary loop is a concern. Related Issues: I.D.1.a

#### Magnetic Field Coil Impacts on the Heat Exchanger/Primary Loop

##### MHD Effects in Liquid Metal Blankets (Liquid Metal Coolants)

For liquid metal coolants, MHD flow in the inlet/outlet piping of the blanket can dominate the overall blanket pressure drop these pressure drops depend upon the details of the piping and magnetic field. Related Issues: I.B.1

##### Electromagnetic and Electrostatic Forces (Generic, most important for ferritic steel piping)

If the primary loop is constructed of a ferretic steel, a body force will be exerted upon the entrance/exit piping during normal (steady-state) operation. Forces on the piping due to pulsed fields and/or disruptions are not expected to provide an important concern, but any piping configuration which can conduct electrical currents should be checked in this regard. Related Issues: I.A.2.b

Tritium System Impacts on the Heat Exchanger/Primary Loop

Corrosion/Activation due to Process Chemicals (Tritium recovery using process chemicals)

If process chemicals are used in the blanket tritium recovery process, trace quantities of these can cause corrosion and activation problems in the heat exchanger/primary loop. Related Issues: I.C.2

Tritium Permeation Control (Generic)

Effective tritium control for several coolants (e.g., lead-lithium, helium) may require the use of a double-walled heat exchanger. Related Issues: I.F.2

3.5.2.4 Issues Involving Impacts on the Magnetic Field Coils due to Interfaces with Other Subsystems

First Wall/Blanket Impacts on the Magnetic Field Coils

Magnetic Field Penetration (Tokamaks)

For tokamaks, the coupling of a pulsed poloidal field to the plasma can be delayed by torodial currents induced in the first wall/blanket. Related Issues: III.3

Shield Impacts on the Magnetic Field Coils

Magnetic Field Penetration (Tokamaks)

The coupling of a pulsed poloidal field to the plasma can also be delayed by toroidal currents induced in the shield. Related Issues: III.3

### 3.5.2.5 Issues involving Impacts on the Plasma Interactive Components due to Interfaces With Other Subsystems

#### First Wall/Blanket Impacts on Plasma Interactive Components

##### Electromagnetic Forces Resulting from Coupled Current Paths (tokamaks)

$\underline{J} \times \underline{B}$ body forces on the limiter/divertor which occur during plasma disruptions (and, to a lesser extent, startup) depend, to some extent, upon the current path provided by the blanket. Related Issues: I.A.2.b.(1), II.A.3.f

##### First Wall/Plasma Interactive Component Heat Flux Tradeoffs (Tokamaks)

The fraction of heat and particle flux on the limiter/divertor relative to the first wall can be decreased by enhancing the radiative heat flux to the first wall via high Z (e.g., Xenon) seeding of the plasma. The maximum first wall heat flux (and plasma engineering considerations) will determine the extent of such practices.

##### Erosion/Redeposition (Tokamaks)

Erosion rates for tokamak first wall systems are predicted to be high. Some of the eroded material (e.g., steel) will deposit on the plasma side of the impurity control system. If the deposition is nonuniform, heat transfer (hot spot) problems can result. The potential impact on surface properties (e.g., enhanced cracking and corrosion, spectral emissivity) is also a concern. Related Issues: II.A.2

#### Shield Impacts on Plasma Interactive Components

##### Vacuum System Conductance Reduction due to Shielding (Tokamaks)

Effective shielding of large penetrations will require a series of duct bends to reduce neutron streaming. These bends will increase flow impedence to the vaccum system and can reduce the pumping efficiency of a tokamak limiter/divertor.

Electromagnetic Forces Resulting From Coupled Current Paths (tokamaks)

J x B body forces on the limiter/divertor which occur during plasma disruptions depend to some extent, upon the current path provided by the shield. Related Issues: I.A.2.b.(1), II.A.3.f

Magnetic Field Coil Impacts on Plasma Interactive Components

Electromagnetic Forces Resulting from Field Transients (Tokamaks)

During startup/pulsing, the transient magnetic fields generated by the OH and other PF coils will cause J x B body forces in the limiter/divertor. Related Issues: I.A.2.b.(1)

Dependence of Heat Flux and Erosion/Redeposition on Field (Tokamaks)

The magnetic field lines in the plasma volume determine the pattern of erosion/redeposition and heat flux on the limiter/divertor surface. Related Issues: II.A.2, II.A.3.e

3.5.2.6 Issues Involving Impacts on the Tritium Processing System due to Interfaces with Other Subsystems

First Wall/Blanket Impacts on the Tritium Processing System

Erosion Product Transport (Tokamaks)

During steady-state operation of a tokamak, the first wall surface is expected to erode (typically, several millimeters over its lifetime). The erosion products will, for the most part, be collected in the vacuum/tritium processing system. The throughput of these products will be large (typically, $\sim 1\ m^3/yr$) and they will be activated. An impact on process efficiency and maintenance can be expected. Related Issues: II.A.5.c, II.A.2

Tritium Permeation to the Primary Coolant (Isolated tritium recovery loop)

In many blanket concepts, the blanket tritium recovery loop would be isolated from the primary coolant. Nevertheless, tritium leakage, permeation, and release to the primary loop is a serious operational concern and will determine the need for a tritium cleanup system for the primary loop. Related Issues: I.F.2.a

Transport of Activated Blanket Materials (Generic)

The blanket tritium recovery loop will interface to the primary loop or a separate tritium purge system. In either case, the transport of activated materials (structure of breeder) through the loop to the tritium processing equipment can cause activation or maintenance concerns. Related Issues: I.D.1.a

LiOT Transport ($Li_2O$ Breeders)

For $Li_2O$ breeders, the generation and transport of LiOT can cause corrosion problems in the blanket tritium recovery system. Related Issues: I.C.3.d, I.E.1.a

Effects of Temperature Transients on Tritium Release (Solid Breeders)

For many solid tritium breeding materials, a blanket temperature transient would result in the release of more tritium than expected during normal operation. The chemical form (e.g., $T_2$ vs. $T_2O$, metal hydrides) could also be a concern. Related Issues: I.F.4, I.C.4

Coolant Leakage to the Cleanup System (Generic)

Depending upon the blanket coolant (e.g., liquid metals) pin-hole leaks into the plasma vessel might not be catastrophic to plasma operation. Such leaks, however, would be expected to have an impact on the vacuum tritium cleanup system performance and/or maintenance. Related Issues: I.B.7

Shield Impacts on the Tritium Processing System

Tritium Permeation (Generic)

Tritium removal from the shield coolant will be determined by permeation from the blanket and plasma (through penetrations) into the shield. Related Issues: I.F.2, II.A.5.a

Heat Exchanger/Primary Loop Impacts on the Tritium Processing System

Tritium Permeation (Generic)

The effectiveness of the heat exchanger as a tritium barrier can determine the tritium cleanup system requirements on both sides of the heat exchanger. Related Issues: I.F.2

Plasma Interactive Component Impacts on the Tritium Processing System

Activated Erosion Product Transport (Generic)

Activated erosion products from high heat flux components (e.g., limiter/divertor in tokamak, halo scraper in tandem mirror) will be transported to the vacuum tritium recovery system. These activated products can impact the performance and maintainability of the tritium process system. Related Issues: II.A.5.c

Tritium Permeation (Generic)

Tritium removal from the plasma interactive component coolant streams will be determined by tritium permeation into those coolants. Related Issues: I.F.2, II.A.5.a

# CHAPTER 4

# SURVEY OF TESTING NEEDS

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# 4. SURVEY OF FUSION NUCLEAR TECHNOLOGY TESTING NEEDS

## 4.1 Introduction

The development of fusion to the commercial reactor stage will require resolving the many known issues, as well as the many presently unknown ones. The first step is to identify these concerns, the second is to identify the tests that are needed to resolve these concerns, and the third is to implement a test program to perform these tests. The known nuclear technology issues have been characterized in some detail, and are described in Chapter 3. In this chapter, the fusion nuclear technology testing needs up to the engineering demonstration stage are identified.

For this survey, "test" is used in the generic sense to mean a process of obtaining information through physical experiment and measurement - i.e., not through design analysis or computer simulation. A "testing need" refers to a need for a certain class or type of information that must be obtained through testing. There are different kinds of testing needs, including:

- developing a property data base (to allow quantitative predictions and quantitative modelling);
- understanding underlying phenomena (to make predictions, interpret component behaviour, and allow design improvements);
- verifying component performance.

The survey relied on experts from many technical disciplines in order to identify the tests that should be performed. It is based largely on a limited number of representative blankets which are expected to indicate most of the needed tests. Other blanket concepts (e.g., molten salt designs) may add some further testing needs, but are not likely to substantially change the results. These tests must address the issues and unknowns with minimum overlap, and have test goals that can be measured under the relevant environmental conditions. The identified tests are presented in a format that is intended to make assumptions and judgements explicit.

The structuring of the tests and their descriptions are first given in this Introduction. Then the tests are summarized in Section 4.2, Summary Tables, and some characteristics of the important tests discussed in Section 4.3, Critical Testing Needs. Finally, a more complete description of the tests themselves is given in Section 4.4, Test Descriptions.

4.1.1 Organization of Tests

There are several possible ways to organize the tests - for example, type of information, need for neutrons, or experiment time frame. This survey of testing needs is organized by component and by type of information (Table 4-1). The first level distinguishes between the components, which generally have different functions, different operating conditions, and thus different testing needs. It is also compatible with the organization of the issues in Chapter 3. The second level of organization distinguishes between types of test such as basic property measurements versus full component verification. This level also provides a rough measure of test complexity and a loose chronological ordering since generally the simpler tests will be performed first. There is presently no third organizational level. Although it will ultimately be useful and necessary to establish priorities for the different tests, this has not yet been done.

There are different ways to describe the test categories within the context of type of information gained. For example, some test categories emphasize information learned directly towards developing a particular component - Specimen, Unit Cell, Module and Component Tests. Here, the adopted test categories reflect the full range of test results from data, to understanding, to concept demonstration, to component verification: Basic, Single Effect, Multiple Interaction, Partially Integrated, Integrated and Component Tests. Table 4-2 summarizes the definitions of these categories.

Basic Tests measure basic or intrinsic property data such as thermal conductivity of a solid breeder material. Single Effect Tests are experiments with a single environmental condition to develop understanding and models of single phenomena or issues. Since the effect is poorly understood or under extrapolated conditions, the number of other phenomena or interactions is strictly limited.

At some point, however, additional phenomena and interactions must be added to demonstrate and explore any synergistic effects. These Multiple Effect/Multiple Interaction Tests involve both interactions among the effects of multiple environmental conditions as well as direct interactions among different physical elements.

Partially Integrated Tests attempt to obtain Integrated Test information but without some key environmental condition. This category emphasizes a

Table 4-1. Organization of Tests

I. Blanket
   A. Basic Tests
      e.g., Structural Material Irradiated Properties
   B. Single Effect Tests
      e.g., Single and Multiple Channel Liquid Metal MHD Effects
   C. Multiple Effect/Multiple Interaction Tests
      e.g., Solid Breeder Unit Cell Heat Transfer
   D. Partially Integrated and Integrated Tests
      e.g., Verification of Tritium Breeding Ratio

II. Plasma Interactive Components
   A. Basic Tests
   B. Single Effect Tests
   C. Multiple Effect/Multiple Interaction Tests
   D. Partially Integrated and Integrated Tests
   E. Component Tests

III. Shield

IV. Tritium Processing System

V. Magnets

VI. Instrumentation and Control

VII. Balance of Plant

VIII. Component Interactions

Table 4-2. Test Categories for Single Component Development

**Basic Test**

- **Basic or intrinsic property data;**
- Single material specimen;
- Examples: thermal conductivity; neutron absorption cross section.

**Single Effect Test**

- **Explore a single effect, a single phenomenon or the interaction of a limited number of phenomena, in order to develop understanding and models;**
- Generally a single environmental condition and a "clean" geometry;
- Examples: 1) pellet-in-can test of the thermal stress/creep interaction between solid breeder and clad; 2) electromagnetic response of bonded materials to a transient magnetic field; 3) tritium production rate in a slab of heterogeneous materials exposed to a point neutron source.

**Multiple Effect/Multiple Interaction Test**

- **Explore multiple environmental conditions and multiple interactions among physical elements in order to develop understanding and prediction capabilities;**
- Includes identifying unknown interactions, and directly measuring specific global parameters that cannot be calculated;
- Two or more environmental conditions; more realistic geometry;
- Example: testing of an internally cooled first wall section under a steady surface heat load and a time-dependent magnetic field.

**Partially Integrated Test**

- **Partial "integrated test" information, but without some important environmental condition** due to large cost savings;
- All key physical elements of the component; not necessarily full scale;
- Example: liquid metal blanket test facility without neutrons.

**Integrated Test**

- **Concept verification** and identification of unknowns;
- All key environmental conditions and physical elements, although often not full scale;
- Example: blanket module test in a fusion test device.

**Component Test**

- **Design verification and reliability data;**
- Full-size component under prototypical operating conditions;
- Examples: 1) an isolated blanket module with its own cooling system in a fusion test reactor; 2) a complete integrated blanket in a demonstration power reactor.

particular range of tests in the continuum between Multiple Effect/Multiple Interaction and Integrated Tests. It is particularly relevant for fusion where costs may limit complete simulation of all important variables such as neutrons. It may be difficult to quantitatively resolve contributing effects in these and later tests. For example, there is no direct way to determine how much of a particular stress is due to pressure, temperature profile or magnetic forces. Rather, these tests are used to establish the validity of models that predict the individual contributions in such a way as to produce the observed overall stress state. Or, for phenomena that are poorly understood, these tests provide empirical relations for gross behaviour.

Integrated Tests demonstrate that a concept is feasible; they are the "proof-of-principle" experiments. With all key environmental conditions and physical elements present, they specifically indicate any major unanticipated interactions. However, they are often performed under scaled size or environmental conditions. Depending on the degree of scaling, a given test may emphasize one aspect of component performance over another, such as a test that simulates thermomechanical behaviour but cannot also simulate full tritium breeding behaviour because of the changes in the module needed to accommodate the available test conditions.

Component Tests verify that the component operates as expected, and requires full-sized components under complete prototypical conditions. This brings out all interactions and any remaining unknowns, and yields definitive reliability and performance data.

As the test categories progress, there is clear differentiation in the test conditions. Basic Tests require only the state conditions (e.g., temperature, fluence, pressure) necessary to the intrinsic properties being measured. Single Effect Tests include a single environmental conditions (e.g., neutron flux or surface heat flux) that are necessary for the phenomena of interest. Multiple Effect/Multiple Interaction Tests include several environmental conditions (e.g., neutron flux and magnetic field) in order to explore the interactions between the effects of each environmental condition. Partially Integrated Tests supply all conditions except some key environmental condition, generally absent due to the large cost of providing this condition (e.g., neutron flux). Integrated Tests provide the full environmental conditions, although often scaled from the commercial operating values. Component Tests are conducted in a complete prototypical environment.

There is also a progression in the geometry of the tests. Basic Tests are small coupons or specimens since intrinsic properties generally apply down to microscopic dimensions. Single Effect Tests are idealized tests with "clean" geometry so that the phenomena of interest are not obscured by complex geometrical effects. Multiple Effect/Multiple Interaction Tests begin to explore the interactions between different physical regions of a component, and so have more realistic geometries such as multiple unit cells. The Partially Integrated and Integrated Test categories contain all key physical elements of the hardware, although possibly scaled in size. The Component Tests involve full components with the complete geometry and structure.

### 4.1.2 Description of Testing Needs

Each testing need is characterized by:

- importance of neutrons;
- importance of fusion neutron energy spectrum;
- other required environmental conditions;
- typical test article size;
- number of test articles;
- usefulness and limitations of non-nuclear test stands, point neutron sources and fission reactors as test facilities.

A complete description of these entries is given in Table 4-3.

The test article size and number are intended to be approximate guidelines. The actual size will vary, but appreciably different sizes probably imply a different type of test. The number of tests are probably accurate to within an order of magnitude. In some cases, additional phenomena will be discovered in the course of testing that will require more data - a linear relationship is often assumed in estimating the numbers of tests needed to establish a relationship, leading to about three data points per independent variable. In practice, more complicated relations are possible.

Some information is not yet present in enough detail, but will eventually be needed to better define the tests. These include defining the test measurements and the instruments to confirm that these tests are realistic; estimating the time, flux and fluence requirements for each test; and the sequencing of the tests. Tests that require destructive assays (such as tritium inventory measurement) would require multiple modules to reach a given goal fluence while understanding the processes at intermediate fluences.

Table 4-3. Description of Entries in Test Summary Tables

TESTS:

- Types of tests that are needed, grouped according to the issues addressed and the nature of the test

IMPORTANCE OF NEUTRONS:
IMPORTANCE OF FUSION SPECTRUM:

- Critical: Tests have little value without this environmental condition.
- High: Most important test condition, but test still partially addresses main issues without it present.
- Medium: One environmental condition among others that contribute; main issue is addressed regardless of the presence of this condition although it has some lower order or synergistic effect
- Low: Not applicable to test or not believed to influence test.

OTHER REQUIRED ENVIRONMENT:

- Non-neutron environmental requirements for the test:

| | |
|---|---|
| B - magnetic field strength | p - pressure |
| $\dot{B}$ - transient magnetic fields | q,Q - surface,volumetric heating |
| C - chemical environment | t - time |
| G - geometry | T - temperature |
| H - hydrogen; $H^3$ tritium | v - velocity |
| I - impurities | Vac - vacuum |
| N - cycling | $\gamma$ - gamma radiation |
| PMI - plasma-materials interaction | $\sigma$ - stress |

TEST ARTICLE SIZE:

- Overall size of a typical test article
- First two dimensions refer to the area towards the plasma, if applicable

NUMBER OF TEST ARTICLES:

- Approximate number of test articles required to resolve the issues.
- The number of test articles will be related to the number of test conditions that must be examined, and whether multiple conditions can be examined with the same test article. Test conditions refer to specific combinations of test variables such as materials, temperature and fluence.
- Does not include multiple test specimens that may be needed to establish statistical variations, off-normal operation

USEFULNESS AND LIMITATIONS:

TEST STANDS
POINT NEUTRON SOURCES
FISSION REACTORS

- High: Test facility able to resolve most/all test issues.
  Medium: Test facility able to resolve some test issues.
  Low: Test facility able to resolve few/none of test issues.
- Examples of Limitations:
  No neutrons - Test facility lacks neutrons
  Size - Test facility lacks sufficient test volume
  Spectrum - Test facility does not have the appropriate neutron spectrum
  Need device - A fusion of DT fusion device is needed
  Neutrons - Test facility neutrons are an unnecessary test complication

## 4.2 Summary Tables

The characteristics of the testing needs are summarized in Table 4-4. The type of information and the organization of the tests has been previously described. From these summary tables, a total of 74 testing needs were identified, with 45% blanket related, 20% plasma interactive components, and 35% for the remainder of the components and component interactions. Three specific tokamak tests were identified related to plasma interactive components, while no mirror specific testing needs were defined. Also, there were about seven solid breeder, two multiplier and three liquid breeder specific testing needs.

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| I. BLANKETS | | | | | | | |
| I.A BASIC TESTS | | | | | | | |
| 1. Structural Material Irradiated Properties | Critical/High | T,$\sigma$,C | 1 x 1 x 2 | 20,000 | Low/No neutrons | High/Size | High/Spectrum |
| 2. Solid Breeder Irradiated Properties | Critical/ High | $H^3$,T | 1 x 1 x 2 | 1200 | Low/No neutrons | High/None | High/Spectrum |
| 3. Radiation Damage Indicator Cross-sections | Critical/ High | T | 1 x 1 x 0.5 | 500 | Medium/ No neutrons | Medium/Fluence | Low/Spectrum |
| 4. Beryllium Multiplier Irradiated Properties | Critical/Low | T,$\sigma$,N | 1 x 1 x 3 | 160 | Low/No neutrons | High/Fluence | High/Spectrum |
| 5. Oxidation, Volatility and Energy Release | | | | | | | |
| a. Solids | Medium/Medium | T,p,I | 1 x 1 x 0.1 | 50 | High/None | Medium/Neutrons | Medium/Neutrons |
| b. Liquids | Low/Low | T,p,I | 1 x 1 x 0.1 | 50 | High/None | Low/Neutrons | Low/Neutrons |
| 6. Long-lived Isotope Activation Cross-sections | Critical/High | None | 1 x 1 x 0.1 | 200 | Low/No neutrons | High/Fluence? | Medium/Spectrum |
| 7. Neutron Sputtering Rate Cross-Sections | Critical/High | None | 1 x 1 x 0.1 | 30 | Low/No neutrons | High/None | Low/Spectrum |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| I.B SINGLE EFFECT TESTS | | | | | | | |
| 1. Structure Thermomechanical Response Experiments | | | | | | | |
| a. Radiation Effects | Critical/High | T,p,σ | 10 x 10 x 10 | 50 | Low/No neutrons | Medium/Size | High/Spectrum |
| b. Surface Damage Effects | Medium/Low | T,p,PMI,σ | 10 x 10 x 10 | 50 | High/Plasma, No neutrons | Medium/Plasma | Medium/Plasma |
| c. Thermal Effects | Low/Low | T,p,σ,t,N | 10 x 10 x 10 | 50 | High/None | Low/Neutrons | Low/Neutrons |
| 2. Weld Behavior Experiments | Critical/High | T,p,σ,$H^3$ Vac | 10 x 10 x 5 | 50 | Medium/ No neutrons | Medium/Size | High/Spectrum |
| 3. Liquid Metal MHD Effects on Heat Transfer, Pressure Drop and Corrosion | Low/Low | G,B,v,q,Q, T,C,I | 20 x 20 x 200 | 30 | High/Bulk heating | Low/Size | Medium/Magnetic field, Size, Complexity |
| 4. Solid Breeder Tritium Recovery Experiments | Critical/Medium | $H^3$,C,T,p | 2 x 2 x 4 | 480 | Low/No $H^3$ generation | High/Size | High/Spectrum |
| 5. Solid Breeder/Structure Mechanical Interaction | Critical/Medium | Q,p,N | 3 x 3 x 8 | 80 | Medium/Bulk heating, | Medium/Size, Swelling | High/Spectrum |
| 6. Tritium Permeation Processes through Structural Material | High/High | p,T,I,C,N | 10 x 10 x 2 | 100 | High/No neutrons | High/Surface conditions | High/Surface conditions |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| 7. Environmentally-Assisted Cracking | | | | | | | |
| a. Stress Corrosion | Medium/Low | T,σ,I,N | 1 x 2 x 2 | 30 | High/No neutrons | High/None | High/Spectrum |
| b. Liquid Metal Embrittlement | Medium/Low | T,I,N | 1 x 2 x 2 | 60 | High/No neutrons | High/None | High/Spectrum |
| 8. Self-Welding of Similar and Dissimilar Metals | High/Low | T,p,σ | 1 x 2 x 2 | 180 | High/No neutrons | High/None | Medium/Spectrum |
| 9. Breeder and Multiplier Fabrication/Reprocessing | Medium/Medium | I | 1 x 1 x 4 | 120 | High/Burnup | Medium/Fluence | High/Spectrum |
| I.C MULTIPLE EFFECT/MULTIPLE INTERACTION TESTS | | | | | | | |
| 1. Solid Breeder Unit Cell Heat Transfer | | | | | | | |
| a. BOL Performance | High/Low | G,Q,T,C,v,σ | 5 x 30 x 5 or | 15 | Medium/ No neutrons | Low/Size | High/None |
| b. MOL/EOL Performances | High/Medium | | 2 x 30 x 40 | 15 | | | |
| 2. Breeder Thermomechanical Interactive Effects | | | | | | | |
| a. Thermal Effects (BOL) | Low/Low | T,p,Q,G,N | SB:25 x 50 x 10 | 2 | High/Bulk heating | Low/Size | Medium/Bulk heating |
| b. Radiation Effects (MOL/EOL) | Critical/Medium | T,p,G | LB:50 x 100 x 20 | 8 | Low/No neutrons | Low/Size | High/Bulk heating, Spectrum |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| 3. Submodule Thermal, Corrosion and Stability Interactive Effects Experiments | Medium/Medium | G,B,q,Q,v, T,C,I | SB:10 x 50 x 30<br>LB:100 x 100 x 30 | 20 | Medium/ Bulk heating, Radiation damage | Low/Size | Medium/ No magnetic field, Size |
| 4. Tritium Permeation into Breeder Coolant | High/Medium | $H^3$,p,T,G, I,C,N | 10 x 50 x 10 | 3 | Medium/ No neutrons | Medium/Size | High/Spectrum |
| 5. Neutron Multiplier Unit Cell Thermomechanical Performance | Critical/Medium | T,σ,N,G,C | 30 x 30 x 10 | 4 | Low/No neutrons | Low/Size, Flux, Gradients | Medium/Spectrum |
| 6. Verification of Submodule Thermomechanical Behavior under Complex Loadings | Critical/High | q,Q,PMI,p,B | 25 x 50 x 10 | 3 | Medium/ No neutrons | Low/Size | Medium/Size, Heating, Spectrum |
| 7. Submodule Thermal and Corrosion Verification | | | | | | | |
| a. BOL Performance | Critical/Low | G,q,Q,T,p, v,B,C,σ | SB:10 x 50 x 30<br>LB:100 x 100 x 30 | 5 | Low/No neutrons | Low/Size | High/None |
| b. MOL Performance | Critical/High | | | 5 | Low/No neutrons | Low/Size | High/None |
| c. EOL Performance | Critical/Critical | | | 5 | Low/No neutrons | Low/Size | Medium/Spectrum, |
| 8. Solid Breeder Tritium Behavior in Thermal and Flow Transients | Critical/Low | $H^3$,T,p,v, I,G,t | 10 x 50 x 10 | 10 | Low/No neutrons | Low/Size | Medium/Spectrum |
| 9. Blanket Response to Coolant Transients | Medium/Low | G,v,q,Q,B | 10 x 50 x 100 | 3 | High/None | Low/Size | Low/Size, Magnetic field |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| | Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|---|
| 10. | First Wall Response to Plasma Thermal Transients | Medium/Medium | G,q,PMI | 10 x 10 x 2 | 3 | High/None | Low/Size | Low/Plasma |
| 11. | Helium or Water Cooled First Wall Temperature Verification | Low/Low | G,q,T,v,P,σ | 30 x 30 x 30 | 1 | High/None | Low/Complexity | Low/Complexity, Surface heating |
| 12. | Mechanical Behaviour of Grooved First Walls | Medium/Low | q,PMI,B,Vac | 5 x 5 x 2 | 100 | High/No neutrons | Low/Size | Medium/Size, Spectrum |
| 13. | Reaction Rates under Accident Conditions | Low/Low | G,T,p,I | 5 $m^3$ | 20 | High/None | Low/Neutrons | Low/Neutrons |
| I.D | INTEGRATED AND PARTIALLY INTEGRATED TESTS | | | | | | | |
| 1. | Verification of Neutronic Predictions<br>a. Tritium Breeding<br>b. Nuclear Heating during Operation<br>c. Induced Activation | Critical/ Critical | G | 50 x 50 x 100 | 4 | Low/No neutrons | High/Size, Fluence | Low/Spectrum |
| 2. | Full Module Thermal and Corrosion Verification | | | | | | | |
| | a. BOL Performance | Critical/High | q,Q,p,v, | LB:900 x 300 x 80 | 1 | Low/No neutrons | Low/Size | Medium/Size |
| | b. MOL Performance | Critical/Critical | I,C,B,t | SB:100 x 100 x 80 | 1 | Low/No neutrons | Low/Size | Low/Spectrum, Size |
| | c. EOL Performance | Critical/Critical | | | 1 | Low/No neutrons | Low/Size | Low/Spectrum, Time, Size |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| 3. Solid Breeder Module Tritium Recovery | Critical/High | Q,p,v,t, G,C | 60 x 60 x 60 | 3 | Medium/ No neutrons | Low/Size, Gradients | Medium/Spectrum |
| 4. Module Thermomechanical Non-nuclear Integrity | Low/Low | q,Q,PMI,B, v,p,N | SB:30 x 100 x 80<br>LB:900 x 300 x 80 | 3 | High/Bulk heating | Low/Size | Low/No plasma, Size, Spectrum, Cycling |
| 5. Module Thermomechanical Lifetime | Critical/ Critical | q,Q,PMI,B, v,p,N | 100 x 100 x 50 | 3 | Low/No neutrons | Low/Size | Low/No plasma, Size, Spectrum, Cycling |
| 6. Blanket Response to Magnetic Field Transients | Low/Low | G,B,$\dot{B}$ | 100 x 50 x 50 | 3 | High/None | Low/Size | Low/No magnetic field, Size |
| 7. Blanket Steady Magnetic Field Interaction | Low/Low | B,G | SB:15 x 50 x 25<br>LB:100 x 30 x 10 | 2 | High/None | Low/Size | Low/No magnetic field, Size |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| II. PLASMA INTERACTIVE COMPONENTS | | | | | | | |
| II.A BASIC TESTS | | | | | | | |
| 1. Plasma Interactive Materials Irradiated Properties Measurement | Critical/High | T | 1 x 1 x 5 | 4500 | High/No neutrons | High/Size | High/Spectrum |
| II.B SINGLE EFFECT TESTS | | | | | | | |
| 1. Plasma Materials Interactive Effects | Low/Low | PMI,Vac,B, $H^3$ | 10 x 10 x 5 | 300 | High/Plasma size, Surface heating | Low/No plasma | Low/No plasma |
| 2. Surface Coating Bond Integrity | High/Medium | PMI,q,σ,P, Vac | 2 x 2 x 0.5 | 100 | High/No neutrons | Medium/Size | High/Spectrum |
| 3. Plasma Disruption Induced Surface Erosion | Low/Low | q,PMI,Vac, B,$\dot{B}$ | 2 x 2 x 0.5 | 160 | High/Plasma | Low/No plasma | Low/No plasma |
| 4. HHFC CHF and Heat Transfer Experiments | Low/Low | q,Q,G | 1 x 10 x 1 | 20 | High/None | Low/Neutrons | Low/Neutrons |
| 5. Tritium Surface Re-emission Control | Medium/Medium | T,PMI,Vac | 10 x 10 x 2 | 50 | High/No neutrons | Low/No plasma | Medium/No plasma |
| II.C MULTIPLE EFFECT/MULTIPLE INTERACTION TESTS | | | | | | | |
| 1. RF Transmission Systems Fusion Environment Effects | High/High | PMI,G,T,q,Q | 10 x 10 x 50 | 20 | High/ No neutrons | Medium/No plasma, | Medium/No plasma |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| 2. RF Window and Feedthrough Performance | High/High | PMI,q,Q, frequency | 10 x 10 x 20 | 20 | Low/No neutrons | Medium/Fluence | Medium/Spectrum |
| 3. HHFC Thermomechanical Element Experiments | Medium/Medium | q,PMI,p | 10 x 10 x 5 | 100 | High/No neutrons | Low/No plasma | Low/No plasma |
| II.D PARTIALLY INTEGRATED AND INTEGRATED TESTS | | | | | | | |
| 1. Limiter/Divertor Performance | High/High | PMI,G,q | DT tokamak | 3 | Low/Need device | Low/Need device | Low/Need device |
| 2. Verification of HHFC Thermomechanical Behavior under Complex Loadings | Medium/Medium | Q,PMI,p,B | 100 x 100 x 30 | 8 | High/No neutrons | Low/Size | Low/Size, Surface heating |
| 3. Plasma Erosion Product Transport in Vacuum Chamber and Exhaust | Medium/Medium | PMI,B,Vac,T | fusion device | 4 | High/Need device | Low/No plasma | Low/No plasma |
| 4. Measurement of First Wall Heat Flux Variations | Low/Low | PMI,G | DT device | 1 | Low/Need device | Low/Need device | Low/Need device |
| 5. RF Launcher Performance | High/High | PMI,G,Q,q | DT device | 10 | Low/No plasma | Medium/Fluence | Medium/Spectrum |
| 6. Development of Methods for Limiter/Divertor Maintenance | Low/Low | G | 30 $m^3$ | 20 | High/None | Low/Neutrons | Low/Neutrons |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| 7. Measurement of Realistic Vacuum System Loads | Low/Low | PMI,G | DT device | 3 | Low/Need device | Low/Need device | Low/Need device |
| II.E COMPONENT TESTS | | | | | | | |
| 1. Vacuum Component Verification | Low/Low | p,C,I | 150 x 150 x 150 | 10 | High/None | Low/Neutrons | Low/Neutrons |
| III. SHIELD | | | | | | | |
| 1. Shield Effectiveness in Complex Geometries | Critical/High | G | 50 x 50 x 200 | 50 | Low/No neutrons | Low/Flux | Low/Source characteristics |
| 2. Plasma Control through Blanket and Shield | Low/Low | G,$\dot{B}$ | DT device | 2 | Low/Need device | Low/Need device | Low/Need device |
| 3. Development of Methods for Shielded Sector Assembly and Disassembly | Low/Low | G | 30 $m^3$ | 2 | High/None | Low/Neutrons | Low/Neutrons |
| IV. TRITIUM PROCESSING SYSTEM | | | | | | | |
| 1. Tritium Processing | | | | | | | |
| a. Component Development | Low/Low | T,p,C,I,v, $H^3$ | 2 $m^3$ | 100 | High/None | Low//Neutrons | Low/Neutrons |
| b. System Verification | Low/Low | | 100 $m^3$ | 3 | High/Inlet characteristics | Low/Neutrons | Medium/Inlet characteristics |
| 2. Liquid Breeder Tritium Extraction Verification | Low/Low | I,T,p,v | 2 $m^3$ | 4 | High/Inlet characteristics | Low/Neutrons | Low/Neutrons |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| 3. Tritium Monitoring and Accountability | Medium/Medium | $\gamma$,PMI,T, p,G | 100 x 100 x 50 | 10 | Medium/Plasma, No neutrons | Medium/No plasma | Medium/No plasma |
| 4. Tritium Permeation and Leakage from Purge and Coolant Loops | Low/Low | $H^3$,p,T,G, C | 20 $m^3$ | 3 | High/None | Low/Flux (use as $H^3$ | Medium/Flux source) |
| 5. Tritium System Inlet Conditions | | | | | | | |
| a. Blanket Output | High/Low | G,p,T | 50 x 50 x 20 | 10 | Medium/ No neutrons | Low/Size | High/Size, Flux, Spectrum |
| b. Plasma Exhaust | Low/Low | PMI | DT device | 3 | Low/Need device | Low/Need device | Low/Need device |
| 6. Atmospheric Cleanup System Verification | Low/Low | C,p,v,G,$H^3$ | 1000 $m^3$ | 3 | High/None | Low/Neutrons | Low/Neutrons |
| V. MAGNETS | | | | | | | |
| 1. Neutron and Gamma Degradation of Properties | Critical/Low | T,B,He | 1 x 2 x 10 | 500 | Low/No neutrons | Low/Fluence | High/None |
| 2. Nuclear Heat Removal and Cryostability | Medium/Low | T,B | 10 x 10 x 20 | 15 | Medium/ Bulk heating | Low/Flux | Low/No B |
| 3. Plasma Disruption Induced Magnet Overload | Low/Low | B,$\dot{B}$, G,t | DT device | 1 | High/Plasma | Low/Need device | Low/Need device |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| VI. INSTRUMENTATION AND CONTROL | | | | | | | |
| 1. Transducer Development and Lifetime | Critical/Critical | T | 1 x 1 x 2 | 70 | Low/No neutrons | High/Size | Medium/Spectrum |
| 2. Insulator Breakdown | Medium/Medium | $T,\gamma,H^3$ | 1 x 1 x 2 | 20 | Low/No neutrons | Medium/Size | High/Spectrum |
| 3. Fusion Environment Effects on Optical Components | Critical/High | $T,PMI,\gamma$ | 2 x 2 x 2 | 50 | Low/No neutrons | Medium/Size, No plasma | Medium/Spectrum, No plasma |
| 4. Insulator/Substrate Seal Integrity | Critical/ Critical | $T,\sigma,p,C,N$ | 1 x 1 x 2 | 20 | Low/No neutrons | High/Size | Medium/Spectrum |
| 5. Fusion Environment Noise Effects | Low/Low | $RF,PMI,\dot{B}$ $\gamma,H^3$ | 1 x 1 x 200 | 20 | High/No neutrons | Low/Size | Low/Size, No $\dot{B}$, No RF |
| 6. Radiation Effects on Electronic Components | Critical/ Critical | $T,\gamma,H^3$ | 1 x 1 x 1 | 20 | Low/No neutrons | High/None | Low/Access? |
| 7. Instrumentation Performance and Lifetime Verification | Critical/ Critical | $\gamma,B,RF,H^3$, C,PMI,Vac | 5 x 5 x 5 | 100 | Low/No neutrons | Medium/ No B,RF,plasma | Medium/Spectrum, No B,RF,plasma |

Table 4-4. Summary of Fusion Nuclear Technology Testing Needs (contd.)

| Tests | Importance of Neutrons/ Fusion Spectrum | Other Required Conditions | Typical Test Article Size ($cm^3$) | Number of Test Articles | Test Stands Usefulness/ Limitations | Point Sources Usefulness/ Limitations | Fission Reactors Usefulness/ Limitations |
|---|---|---|---|---|---|---|---|
| VII. BALANCE OF PLANT | | | | | | | |
| 1. Liquid Metal Pump Development | Low/Low | T,p,v,I | 10 $m^3$ | 5 | High/None | Low/Neutrons | Low/Neutrons |
| VIII. COMPONENT INTERACTIONS | | | | | | | |
| 1. Mass Transfer and Leakage in Coolant and Purge Loops | Medium/Medium | B,G,v,C,T | 30 $m^3$ | 3 | High/No neutrons | Low/Size | Medium/Size |
| 2. Biological Dose Rate Profile Verification | Critical/ Critical | G,γ | DT device | 1 | Low/Need device | Low/Need device | Low/Need device |
| 3. Afterheat Profile Verification | Critical/ Critical | G,γ | DT device | 1 | Low/Need device | Low/Need device | Low/Need device |

## 4.3 Critical Testing Needs

From this assessment of the overall testing needs, it would be useful to determine which are more important in order to set program priorities and allocate limited resources. However, there are several difficulties in trying to extract this information. For example, are basic property measurements generally more or less important than integrated tests? Is it even fair to pose such a question, or can priorities only be objectively established within a test category?

As in the development of any complex new technology, it seems clear that fusion nuclear technology has to proceed through stages of R&D. In the early stages, fusion emphasized basic and single effect tests. Now, there is a need to begin performing many interactive tests; some of which will require upgrades of existing non-neutron test stands or construction of new ones, while others require designing and constructing experiments for use in available fission reactors and point neutron sources. In the early 1990's, more complex interactive experiments will have to be carried out. In cases such as self-cooled liquid metals, it appears plausible to construct a new facility that simulates all aspects of the fusion environment except neutrons. Such a facility will cost under 50 M$ and will provide much needed information on the complex fluid flow, MHD, corrosion and other aspects of the thermomechanical loading and response. In the mid to late 1990's, the construction of a fusion facility for engineering experiments will provide the necessary transition to more complex interactive and integrated tests.

Thus, fusion nuclear technology should proceed through the above stages in terms of the types of experiments. However, the number and detailed design of the experiments for each stage involves considerations of benefit, cost and risk. In an accelerated fusion R&D program, higher risks can be acceptable in moving more rapidly from the lower cost simple experiments to the more costly and more complex tests which provide engineering design data. The degree of risk in an accelerated program can, of course, be reduced by providing additional funds to perform more experiments in a shorter time period. On the other hand, a normal pace R&D program will take lower risk by emphasizing the understanding of phenomena and development and verification of models in each stage.

It must be clearly recognized, however, that there are large uncertainties introduced by the many new phenomena and the substantial change in the characteristics of old ones brought about by the unique and complex fusion environment. It is possible that definitive data to establish the feasibility and judge the safety and economic potential of concepts may come only from the more elaborate interactive and integrated tests. Such a possibility will demand more rapid transition from the simple to the more representative types of experiments.

## 4.4 Test Descriptions

In this section, the descriptions of the full list of testing needs are given. These descriptions are intended to give the rationale for the assumptions and judgements that went into characterizing each test. These tests are organized in the same format and order as the summary tables in Section 4.2.

## I. BLANKET

### I.A BASIC TESTS

#### I.A.1 Structural Material Irradiated Properties Measurement

In these tests, the basic properties of structural materials would be measured under neutron irradiation, including, for example, yield strength, fracture toughness and swelling. These tests could use the standard techniques and small specimens developed by the fission reactor industry.

Importance of Neutrons: (Critical) Virtually all material properties of interest to reactor designers vary with neutron irradiation. Material properties are dependent upon the microstructure and physical chemistry of the material, and neutron irradiation directly impacts both via atomic displacements and nuclear transmutations. For example, the ability of a material to yield or plastically deform is a function of the defect population in the microstructure which continually evolves as the irradiation produced point defects recombine and migrate within the material.

Importance of Fusion Spectrum: (High) The correct neutron spectrum is of high importance because the neutron energy distribution impacts both the magnitude and type of point defects, and the rate and type of transmutation. Radiation-induced creep and swelling are clearly properties that have been found to be spectrum dependent in fission reactor testing. For example, on a dpa basis, the rate of swelling in materials exposed to a higher energy breeder reactor spectrum is lower than that in a water moderated fission reactor. Tensile and fatigue properties are anticipated to be less sensitive to neutron spectrum than creep or swelling; however, the impact of copious amounts of transmutation-produced elements in the fusion irradiated materials will undoubtedly result in significant material property changes.

Other Required Environmental Conditions: $(T, \sigma, C)$ The test results with greatest reliability and usefulness will be those closest to the operating conditions anticipated in the fusion device. The correct temperatures and stress are required for virtually all properties and for those sensitive to the surface condition of the material (e.g., crack growth, fracture toughness), a prototypic chemical environment is required. Duplicating the cyclic or time histories of the temperature, stress, and neutron flux magnitude is often of secondary importance because this significantly adds to the complexity and uncertainties in data interpretation.

Test Article Size: An average material property test specimen requires an irradiation volume of approximately 1 x 1 x 2 $cm^3$.

Number of Test Articles: The number of test articles is very large - on the order of 20,000 - due to the many specimen types (e.g., tensile, swelling, creep) and test parameters (e.g., temperature, time stress, fluence).

Test Facilities:

Test Stands: Test stands are required to obtain baseline material properties data; however, their usefulness is low when neutron irradiation data is required since they lack neutrons.

Point Neutron Sources: The usefulness of point neutron sources has been determined to be high for the testing of changes in material properties. During 1983, a panel of U.S., Japanese, European, and Canadian materials experts comprehensively reviewed the miniature specimen tests planned for the Fusion Materials Irradiation Test (FMIT) facility and concluded that the data from small material test specimens utilized in a point neutron source (e.g., FMIT) would be of good quantity and of high value. The major limitation of point neutron sources is the size of the irradiation volume.

Fission Reactors: The usefulness of fission reactors is high for the measurement of material property changes in a neutron environment. In fission reactors, the correct atomic displacement rates and temperatures can be obtained and sufficient volume is available to test extensive matrices of engineering materials. Furthermore, the ability to efficiently utilize fission reactors for material property change testing has been clearly demonstrated. The limitation of fission reactors is the neutron spectrum. The fission reactror neutron energy is not sufficiently high to produce comparable quantities of the nuclear transmutation products (e.g., hydrogen, helium) that will be produced in fusion reactors. The type of displacement damage and cascade events will also be somewhat different in the fusion devices due to the higher amounts of energy transferred to the metal lattice via the fusion neutrons. This difference, while not as important as transmutation events, needs to be characterized and understood for reliable reactor designs.

### I.A.2 Solid Breeder Irradiated Properties Measurement

Issues involving tritium recovery, mechanical interaction and temperature variability all require supporting property measurements, including thermal conductivity, creep, strength and surface character. Material properties obtained without irradiation effects are initially of considerable value, but are not considered here because of the comparative ease by which they can be obtained and their limited long term value. Measurements would typically be post-irradiation determination of standard properties such as thermal conductivity, heat capacity and tritium diffusivity.

Importance of Neutrons: (Critical) Since the emphasis is on neutron irradiation effects, neutrons are critical to the evaluation of these properties. The transmutation and displacement damage processes might be simulated by other forms of irradiation but the extrapolation is typically too difficult to be worthwhile.

Importance of Fusion Spectrum: (High) The fusion neutron spectrum may be of high importance because the damage processes can be dependent on energy-sensitive displacement and transmutation cross sections. It may be possible, however, to duplicate these cross sections without actually obtaining the exact spectrum of energies produced by a fusion source.

Other Required Environmental Conditions: ($H^3$,T) Some means of tritium release from the sample is required although an exacting purge environment is not deemed necessary. Temperature control is necessary in one form or another in order to achieve the isothermal conditions necessary for intrinsic property measurements.

Test Article Size: Since properties are by definition intrinsic down to a "microscopic" level, it is possible to use very small specimens - 1 x 1 x 2 $cm^3$, for example. The size is only limited by the size of the microstructure and testing capabilities.

Number of Test Article: It is assumed that after thorough fission reactor testing (not considered here), six material variables remain unspecified and that 50 environment parameter conditions are required to evaluate these variables. The environmental parameters would be expected to contain sets of nine temperatures at three fluences and four flux levels within the blanket. Since reduced sets would be used at lower flux regions, a total number of test elements of 600 would be used. If more than one property could not be evaluated on each specimen, then an even larger number of specimens would be needed. An overall number of 1200 is suggested. In-situ property measurements, if possible, could reduce this number considerably.

Test Facilities: Neutron test facilities are required. Since these test articles are sufficiently small, testing in point neutron sources is feasible. However, test volumes may not be adequate for a complete evaluation of all parameters. It seems more logical to use these sources to pinpoint if spectral effects are important. Fission reactors could readily provide sufficient testing volume, time, fluence, flux, etc. to explore all the variables. From this extensive data set, point source or fusion data would only confirm the extrapolation to that spectrum.

## I.A.3 Radiation Damage Indicators Cross-Section Measurement

The effect of radiation damage on structural properties is usually correlated against parameters such as dpa or He production, but neither this connection nor the measurement of the parameters themselves is direct. There is a need to develop better understanding of radiation damage indicators and better data for their cross-sections. There is, for example, no simple measure for dpa, even though it is often used in correlating irradiated property changes. Existing data is largely from metals, and the application to ceramics is also unclear. These tests may require instrumentation and theoretical development, as well as basic cross-section measurement.

Importance of Neutrons: (Critical) Neutrons are the source of radiation damage of concern, although some theoretical understanding may proceed with charged particle beams.

Importance of Fusion Spectrum: (High) Tests must be performed which include high energy fusion neutrons to obtain the appropriate cross-sections. It should be noted, however, that accelerators with very high energy components ($E > 15$ MeV) will have higher charged particle production through spallation reactions, which may complicate the data interpretation at lower energies.

Other Required Environmental Conditions: (T) Cryogenic conditions are preferred in order to "freeze" the damage and study the microscopic situation just after the initial damage cascade.

Test Article Size: ($1 \times 1 \times 0.5\ cm^3$) Since microscopic properties are being measured, test articles just large enough to handle and avoid edge effects are needed.

Number of Test Articles: (500) Due to the present lack of data, and the variety of tests and materials that could be performed, it is likely that the number of test articles will be between 100-1000, with 500 as a rough estimate.

Test Facilities: Test stands have no neutrons, but are still useful for some analyses, especially charged particle beam tests to explore the post-PKA microscopic situation. Fission reactors can provide much data at lower energies. The usefulness of point DT neutron sources is very good. They can measure reaction rates such as (n,p) or (n,He) as caused by 14 MeV neutrons. Using activation techniques and mass separation of He, cross sections of some of these reactions can be determined even at relatively low fluences. However, directly measuring many other transmuted nuclides may require a larger fluence.

### I.A.4 Beryllium Multiplier Irradiated Properties Measurement

The four tests needed to complete the Be radiation damage data base are swelling, irradiation creep, mechanical properties, and recycling of irradiated beryllium. Tests must be conducted in the temperature range of about 400°C to 600°C. Fast neutron fluences required for these tests vary from 2 - 5 MW-yr/$m^2$ equivalent neutron wall loading. Standard post-irradiation measurements should give the properties, while the irradiated Be could be subjected to proposed recycling processes (e.g., temperatures, grinding, chemistry) to determine the effects.

Importance of Neutrons: (Critical) All tests require fast neutrons. Helium could possibly be implanted but helium distribution within the Be would be near surface and not throughout the bulk.

Importance of Fusion Spectrum: (Low) In most cases, 14 MeV neutrons are not believed to be needed since high rates of helium production occur at low energies, although it is possible that some mechanical properties may be sensitive.

Other Required Environmental Conditions: (T,$\sigma$,N) Temperature is important for all tests. Pre-stress conditions are required for the creep tests, and cycling may be needed for some mechanical properties.

Test Article Size: Most tests require test pieces 1 cm diameter by 3 cm long, although the creep test pieces could be smaller, 0.5 cm diameter by 2 cm long.

Number of Test Articles: Each test will require multiple samples at various temperatures, neutron fluence, and stresses for the creep tests. All will require baseline data from non-irradiated specimens which have received similar temperature profiles. Minimum number of samples for each test vary from 30 to 50, for an estimated total of 160 test articles.

Test Facilities: Test stands are of no value to tests which require large fast neutron fluence. Point neutron sources may not have sufficient fast neutron fluences. Radiation damage in Be caused by fusion blanket spectrum neutrons does not differ from the damage caused by fast fission neutrons. More damage is caused by a 14 MeV neutron than a fission neutron but use of a larger fission neutron fluence will in most cases provide the same damage. Dpa rates are higher in fission irradiations but damage effects due to high helium content will overshadow dpa effects. Therefore, fission reactors are highly useful. Mechanical property tests may be a possible exception because of transmutation products and damage mechanisms.

### I.A.5 Oxidation, Volatility and Energy Release Measurements for Solids and Liquids

Fusion reactors are expected to contain large inventories of activated materials, which are not normally mobile. During accident conditions, the potential release is determined by thermal sources, such as reactions of lithium or lithium lead with air or water, and the presence of oxidizing environments. These small sample tests would measure the basic volatility of chemically active materials under plausible fusion operating or accident conditions. Measurements would include temperature, calorimetry and weight loss.

Importance of Neutrons and Fusion Spectrum: (Medium) The primary concern is for reactions involving the bulk material. Chemistry changes due to neutron irradiation may be important in some cases - e.g., decomposition of salt-based coolants, high burnup of solid breeders - although generally less so for liquids where the accumulation of reaction products can be limited. Tests on releases are normally destructive and best done away from a neutron source.

Other Required Environmental Conditions: (T,p,I) The reaction rate may be affected by the temperature of the material, the partial pressure of oxygen or other gases above the material, and by impurities in the material itself that may interfere directly with the chemistry or form surface layers that inhibit further reactions.

Test Article Size: (1 x 1 x 0.1) Small samples are sufficient to measure the reactions and their energies.

Number of Test Articles: Possibly 10-100 combinations of materials and environment (temperature and composition) are needed for both solids and liquids, or nominally 50 tests each.

Test Facilities: Test stands can be used to provide the temperature and environment needed to simulate off-normal reactor conditions. In addition, facilities are available where tests on energy release from materials interactions can be safely conducted. In some solid structural materials, neutrons would be useful in producing activation products for eventual testing. Since high energy neutrons are needed, a point source such as FMIT would be suitable. Fission reactors could be used to produce samples of activated material for testing. Release tests would best be done away from the reactor.

### I.A.6 Long-Lived Isotope Activation Cross-Section Measurement

These tests consist of irradiations of coupons of materials in point neutron source and fusion facilities to determine isotope cross-sections and to determine radioactivation of real engineering materials. Passive tests, i.e., not requiring instrumentation or cooling leads, can be done with examination of specimens following irradiation and removal from the irradiation facility. The tests would measure the decay gamma spectrum and count rate, as well as characterize the activating neutron fluence and spectrum.

Importance of Neutrons and Fusion Spectrum: (Critical/High) The general level of need for such tests is small because an extensive set of data exists from previous nuclear programs. However, some added testing can be expected in order to obtain more accurate values for activation cross-sections of certain long (>10 years) half-life isotopes in a fusion reactor spectrum so that more accurate estimates can be made of required decay time before disposal. Also, special low activation alloys, such as first wall materials, should be tested in a fusion reactor spectrum to verify predicted activation properties.

Other Required Environmental Conditions: None.

Size and Number of Test Articles: Test samples can be small coupons of material, on the order of 1 $cm^2$ area by 0.1 cm thick. The total number of samples may be on the order of 100 - 1000, with a rough estimate of 200.

Test Facilities: Inasmuch as fusion-spectrum neutrons are required, test stands are not useful, and fission reactors are of marginal usefulness. Point neutron sources would be highly useful, and should be adequate for most of the tests except those that need a modified spectrum such as would exist farther away from the plasma.

### I.A.7 Neutron Sputtering Rate Cross-Section Measurement

Neutron-induced sputtering is a contributor to activated material transport. In some systems, such as helium-cooled blankets, where corrosion is very small, neutron sputtering can be the dominant source of activated material. These specimen tests would be intended to quantify the rates of neutron sputtering. The measurements would include monitoring fluid chemistry, filtering, and post-test examination of exposed surfaces.

Importance of Neutrons: (Critical) Neutrons cause the sputtering.

Importance of Fusion Spectrum: (High) Neutron sputtering will be very dependent on the neutron energy, and may be much worse under fusion conditions. Thus, it is important that tests include sufficient high energy neutrons.

Other Required Environmental Conditions: (None)

Test Article Size: Small samples of about 1 x 1 x 0.1 $cm^3$ would be appropriate if the neutron flux is high enough. A larger area might be necessary to measure low rates due to material resistance or weak neutron source intensity.

Number of Test Articles: (30) Sputtering rates need to be measured for materials (structure, multiplier and breeder) that may be in contact with the coolant or purge loops and exposed to neutrons. Allowing 10 materials tested in 3 different flux/spectrum conditions gives a total of about 30 test articles.

Test Facilities: Test stands are of little usefulness since neutrons are needed. Point neutron sources are a very appropriate test facility since the correct spectrum could be provided, and only small volumes are necessary. There may be some question as to the required flux for a measurable sputtering rate in a small sample. Information on neutron spectrum effects would be provided by performing both thermal and fast reactor tests. These could calibrate codes and reduce the need for testing in a fusion spectrum.

## I.B SINGLE EFFECT TESTS

Note that while primarily single effect tests are described here, some of these tests actually extend into the multiple effects stage.

### I.B.1 Structure Thermomechanical Response Experiments

a. Radiation Effects

b. Surface Damage Effects

c. Thermal Effects

Various interactive effects on structural components may be examined under ideal geometry or environmental conditions in order to develop a quantitative understanding of the response of the structure to particular effects. The number of conditions should be limited in order not to complicate the tests. Three particular areas of concern are radiation effects, surface damage effects, and thermal effects. Measurements would include primarily stress, deflection and analysis of failed articles for the failure mode.

Importance of Neutrons: (Low - Critical) Neutrons are critical for determining radiation effects. Other element tests should not include neutrons, at least initially, in order not to complicate their interpretation.

Importance of Fusion Spectrum: (Low - High) For tests involving neutron-induced radiation damage, there are concerns over the importance of neutron spectrum. If radiation damage is related primarily to the dpa and dpa/He parameters, and if these can be simulated in a non-fusion spectrum, then the importance of a fusion spectrum is reduced. However, it is in fundamental tests such as these that differences due to spectrum effects can directly be evaluated since the tests are small (allowing some irradiation in point neutron sources) and designed to yield quantitative information on the structural behavior.

Other Required Environmental Conditions: ($T,\sigma,P,PMI,t,N$) In general, a simple temperature and stress field are required, possibly from pressure loads. Surface damage tests will need a plasma, and some tests will run for long times to see creep, stress relaxation and deformation, or for multiple cycles to observe crack growth and fatigue.

Test Article Size: ($10 \times 10 \times 10$ $cm^3$) Small, simple geometry are desired. However, there must be enough volume that support or end effects, welds, manufacturing procedures and instrumentation do not dominate the test - unless intended to!

Number of Test Articles: At present, there is not a clear picture of the number and type of these tests that will be required. However, since several of each type are probably needed to interpret submodule or module tests, an overall estimate is 10-100 test articles for each category, or about 50.

Test Facilities: Tests stands will be very useful for many of these tests. There will be some limitations based on the need for fusion-relevant plasmas (not directly simulated by ion beams, for example) and for neutrons. Tests needing neutrons may be tested in accelerator-based sources, within the constraints of size and possibly fluence. Fission reactors are useful for irradiating test articles, although spectrum effects would need to be checked in other facilities. Some feel for the importance of neutron spectrum may be provided by irradiation in different fission reactors. High energy neutron effects, if significant, may be limited in terms of fluence.

### I.B.2 Weld Behavior Experiments

Tests are necessary to demonstrate that reliable welds can be routinely achieved with the candidate structural materials under fusion conditions. Clean geometry tests can be used to determine if the weld region will respond differently than the parent material in a neutron environment. If differential swelling does occur, these element tests will help determine the resulting stresses and effects. Measurements would include stress, strain and post-test examination for failure modes.

Importance of Neutrons: (Critical) Neutrons are required for testing to produce specific reactions and to produce material damage. Neutrons are also required to determine the effects of differential swelling between the weld and the parent material.

Importance of Fusion Spectrum: (High) Neutron spectrum can affect the amount of swelling and creep that can take place, so is of high importance.

Other Required Environmental Conditions: $(T,p,Vac,H^3,\sigma)$ The temperature of the test, stress level in the component at the weld, and the atmosphere (potential for stress corrosion cracking) will affect the weld behaviour.

Test Article Size: To achieve the correct response of a weld in a fusion environment, an act-alike module is required which will put the welds under the expected temperature, stress and chemistry in a fusion reactor. However, it will be difficult to quantitatively evaluate any weld failures in such a test. Thus module tests must be accompanied by weld tests under idealized geometries and conditions which allow evaluation of contributing effects. These tests may be fairly small, perhaps 10 x 10 x 5 $cm^3$.

Number of Test Articles: (50) The number of test articles is related to the number of types of welds and the number of large-scale tests that may need these tests for interpretation purposes. Assuming at least 10 large-scale tests, and/or 10 distinct weld conditions in a given blanket design, an estimated number of such tests is 10-100, or nominally 50 test articles.

Test Facilities: The usefulness of test stands for experiments to resolve the effects of welds in fusion environment is medium. Since basic welding procedures for some alloys are uncertain (e.g., vanadium), substantial non-nuclear testing of weld mechanical strength may be performed. However, test stands do not have the ability to test with neutrons. The usefulness of point neutron sources to resolve this issue is medium. The main limitation is size. Point neutron sources can be used for small elemental weld specimens to establish basic material properties and potentially to establish the effects of differential swelling between the weld region and the parent material. The usefulness of fission reactors to resolve this issue is medium. The main limitation again is neutron spectrum.

## I.B.3 Single and Multiple Channel Liquid Metal MHD Effects on Heat Transfer, Pressure Drop and Corrosion

There are currently many fundamental uncertainties concerning the flow of liquid metals through magnetic fields. The most significant of these includes pressure drop, flow distribution, and velocity profiles. These properties are highly interactive with many other blanket phenomena, such as temperature profiles, stresses and corrosion. Therefore it is imperative to develop a better understanding of the basic thermal and hydraulic properties of liquid metal MHD flow. Both single channel and multiple channel experiments in an assortment of geometries will be needed. There are aspects of MHD flow which can be drastically altered by the existence of multiple channels. Standard measurements include bulk and surface temperatures (and distribution), bulk flow rate, and pressure drop profile. It would be very desirable, but possibly more difficult, to also measure velocity distribution, eddy currents or electric potentials, and local magnetic flux density.

Importance of Neutrons: (Low) For a large number of tests, neutrons are unimportant. Possible exceptions arise in the study of corrosion, bulk heating effects on temperature profiles, or changes in MHD thermal hydraulics due to irradiation effects. Overall, the importance is low.

Importance of Fusion Spectrum: (Low) The neutron energy spectrum in not important for this class of tests.

Other Required Environmental Conditions: (G,B,v,q,Q,T,C,I) Geometry and magnetic field are critical for addressing MHD issues. For thermal behavior, velocity profiles, surface and bulk heating are important. For corrosion issues, temperature, chemical environment, and impurities may be needed.

Test Article Size: Most transport phenomena require long entry lengths for development. In fact, temperatures and mass concentrations never become fully developed in realistic blanket designs. The channel width and depth requirements are less stringent. For multiple channel tests, the size may be 20 x 20 x 200 $cm^3$ or greater.

Number of Test Articles: (30) Different geometries should be explored, including bends, obstructions, contractions and expansions. In addition, since velocity profiles are thought to be highly sensitive to small geometry changes, it would be prudent to repeat tests or intentially vary the geometry in small increments to study this sensitivity. Since this subject has many non-fusion applications and is not constrained by a need for neutrons, there are potentially many interesting tests. However, the actual number of distinct test configurations directly needed for a given liquid metal blanket design is probably around 30.

Test Facilities: A test stand is the preferred facility. Fission reactors would be useful for providing bulk heating, if necessary, since spectrum is not critical. Point neutron sources lack the required volume

### I.B.4 Solid Breeder Tritium Recovery Experiments

These single and multiple effect tests include basic tritium recovery, tritium permeation and mass transfer within the solid breeder since they require the same type of measurement capabilities and conditions, and may occur simultaneously. These tests will address solid breeder issues of solubility, diffusivity, surface migration, desorption, purge flow effects, LiOT mass transfer, tritium recovery and permeation losses from the blanket. Measurements will include purge chemistry ($H^3$ activity, Li content, $T_2O/T_2$ ratio), coolant or sweep gas tritium activity (for permeation), post-test exam for mass transfer and tritium inventory, and neutron flux and spectrum dosimetry.

Importance of Neutrons: (Critical) Neutrons are critical to the evaluation of the integrated tritium recovery process. Tritium recovery involves a set of kinetically-limited, and potentially non-equilibrium phenomena acting in series which requires a steady state throughput of tritium in order to be maintained. It might seem that permeation studies could be conducted without neutrons; however, damage to any barriers and the establishment of the correct thermodynamic environment may only be feasible under neutron irradiation. LiOT requires a steady state release of $T_2O$ which is internally generated in order to simulate the blanket environment.

Importance of Fusion Spectrum: (Medium) The fusion neutron spectrum is thought to be of medium importance because the distribution of tritium and the relative magnitude of displacement and transmutation damage may be highly sensitive to energy-dependent neutron cross sections. It seems possible, however, that similar spectrum-averaged cross sections can be obtained in other spectra. In particular, the spectrum behind a neutron multiplier is significantly different than that at the first wall, perhaps closer to that of a fission spectrum rather than a "fusion" spectrum.

Other Required Environmental Conditions: ($H^3$,C,T,p) The presence of tritium is obvious, but it is also necessary that purge gas flow through these tests be maintained and the purge gas chemistry must be prototypical of blanket designs. Not only must additives ($H_2$) be considered but also chemical reactions with structural component surfaces. In addition, tritium permeation losses require a coolant interface to exist with appropriate temperatures and thermodynamic conditions.

Test Article Size: The minimum test element size is about 2 x 2 x 4 $cm^3$ which reflects the typical dimensions calculated from presently believed temperature limits, thermal conductivity and heat generation rates at the first wall. Larger test volumes (6 x 6 x 10 $cm^3$) are required to evaluate regions of the blanket with lower heat generation. However, interest in those regions is less due to their low tritium production.

Number of Test Article: (480) The number of tests aimed at tritium recovery is specifically determined by the measurement technique, i.e., in-situ versus incremental postirradiation data collection. In-situ tritium recovery tests yield a large quantity of data but are only useful at low fluence levels in viable solid breeder materials. At high fluence levels, measurement of the tritium inventory retained and LiOT transport in the solid breeder may be the only approach to accurately measuring tritium release even though it requires a larger number of test elements. Tritium permeation testing appears to be easily addressed by in-situ recovery testing with continuous data collection. Closed capsule tests are economically attractive for scoping diffusivity and solubility comparison for materials variables, but do not evaluate surface and purge flow effects. Step change tritium recovery experiments are similarly useful for scoping but not for developing correlations.

After or while conducting scoping studies on material variables (300), it is anticipated that at least 30 analytical tests aimed at deriving either empirical or phenomenological correlations for prediction of tritium recovery will be required on six different materials, so that a further 180 test conditions would be required. Purely empirical correlations would need a much smaller test matrix, but more tests are necessary to support phenomenological extrapolation of the results.

Test Facilities:

Test Stands: Tritium permeation tests conducted in test stands could provide the first information on tritium releases; however, the tests might be more economically pursued along with actual fission reactor tests of recovery, such as attempted in the TRIO experiment. LiOT mass transfer in laboratory tests may be very difficult to extrapolate.

Point Neutron Sources: Selected tritium recovery tests and permeation tests conducted in point neutron sources are a high priority in order to evaluate spectrum effects. But availability and volume constraints are expected to limit such testing to the minimum.

Fission Reactors: Fission reactor testing of one form or another is anticipated to represent the bulk of the tritium recovery testing. Fission reactor spectrum possess spectral average cross section, tritium production rates, heat generation rates, etc. close to those found in blanket designs. The major uncertainties associated with the spectral effects on tritium recovery and permeation (i.e., damage) may remain for confirmation in a fusion environment, perhaps 30 tests.

Fusion Reactors: Considering the importance of tritium recovery to the operation of fusion devices, the need for verifying tritium recovery at the first opportunity in an actual fusion environment is very high. The difference between a fusion test environment and other test environments may or may not be small depending upon the rate controlling phenomena but the remaining uncertainty could never be tolerated.

### I.B.5 Solid Breeder and Structure Mechanical Interaction Experiments

Solid breeder and structure mechanical interaction will no doubt be observed in tritium recovery tests, however, these tests may intentionally limit mechanical interaction in order to pursue their main purpose. Another class of testing is anticipated which directly addresses mechanical interaction issues. Strain accommodation is expected to influence purge flow distribution and tritium migration within the porosity of the solid breeder. Measurements would include stress and strain in the structure; cracking and redistribution in the breeder; and overall deformation and failure modes.

Importance of Neutrons: (Critical) Neutrons are critical to the evaluation of the swelling driving force for mechanical interaction but may be only a convenient source of heat for conducting tests aimed at understanding thermal expansion driven interactions.

Importance of Fusion Spectrum: (Medium) For thermal expansion, heat generation in some other neutron spectra are adequate unless heat transfer changes could yield a second order effect on temperature profiles. For swelling (and creep), spectral difference may be of high importance in controlling the damage rates simultaneously in metal and solid breeder materials.

Other Required Environmental Conditions: (Q,p,N) For thermal expansion driven mechanical interaction, cyclic loading between prototypic temperature gradients established by homogenous heating and design specific cooling geometries is needed. For simultaneous swelling and thermal expansion driven mechanical interaction, structural geometry is important in determining both stress concentration and accommodation. Other stresses, such as coolant pressure, contribute to the overall stress state in the solid breeder and blanket.

Test Article Size: Thermal expansion driven mechanical interaction is important in both larger (6 x 6 x 10 $cm^3$) cells deep in the blanket as well as smaller cells near the first wall ($2 \times 2 \times 4$ $cm^3$, or $3 \times 3 \times 8$ $cm^3$ with space for cooling and instrumentation). Swelling driven mechanical interaction tests will be limited to the high fluence region near the first wall.

Number of Test Articles: (80) Temperature is important to thermal expansion mechanical interaction but is dependent upon the heat generation rate and geometry. Consequently, the major parameters to consider in thermal expansion driven mechanical interaction are heat generation (3), geometry (3), material variables (6), fluence (2) and cycling frequency (3) which would lead to 324 conditions, but by systematic reduction less than 150 test conditions would be necessary and in fact 50 may suffice if chosen correctly.

At higher fluence levels, thermal expansion mechanical interaction and swelling mechanical interaction may function together and will be tested together on three material variables ($Li_2O$ only), three geometries, and at nine fluence levels. But since swelling will dominate only at or near the first wall (or neutron multipliers) only one flux level is necessary. Hence, a test matrix of 81 which could be reduced to 30 test articles.

Test Facilities:

Test Stands: Thermal expansion driven mechanical interaction experiments could be used as scoping studies for later irradiation studies, but homogeneous heat generation along with uninterrupted stresses may limit this approach.

Point Neutron Sources: For mechanical interaction testing, the steep gradients in flux and small volume of point neutron sources is difficult to take advantage of. Even with these shortcomings, the ability to irradiate structural materials adjacent to solid breeder materials would yield some insight into irradiation effects.

Fission Reactors: Fission reactors can be very useful in testing both thermal expansion and swelling driven mechanical interaction since heat generation rates and solid breeder swelling rates can be easily duplicated. It is more difficult to obtain fission reactor spectra in which damage rates in structural materials is proportional to damage rates (and burnup) in the solid breeder.

Fusion Reactors Testing in test stands, point neutron sources and fission reactors will all contribute to our understanding of mechanical interaction, but some fusion testing would be required for high availability.

## I.B.6 Tritium Permeation through Structural Material Experiments

There are a number of fundamental issues related to tritium permeation that need to be explored at the simple test level. These include basic permeation data (Sievart's constants, tritium diffusivity, Soret energy), changes in overall permeation mechanisms at low tritium partial pressures (domination of chemisorption, defects over bulk diffusion), effectiveness of surface barriers (natural and artificial), and the effects of radiation (defect density, He bubbles). Measurements would include tritium activity as a function of time and temperature, and post-test examination of tritium inventory and surface conditions.

Importance of Neutrons: (High) The potential importance of radiation in enhancing or degrading tritium permeation, either through bulk diffusion processes or affecting surface barriers and processes, is large enough for neutrons to be of High importance.

Importance of Fusion Spectrum: (High) The neutron energy may influence the damage, and thus permeation rates, so is important.

Other Required Environmental Conditions: (p,T,I,C,N) The important environmental conditions are the temperature (and profile) in the material, the tritium partial pressure and form, and the chemical environment, including impurities. Some samples may be cycled to observe the effects on surface barrier and cracks on permeation.

Test Article Size: (10 x 10 x 2 $cm^3$) A simple plate (or tube) geometry could be used, with about 100 $cm^2$ surface area to allow measurable tritium permeation rates even at low tritium partial pressures and to ignore end effects.

Number of Test Articles: (100) For 20 combinations of materials and surface conditions (5 materials, 4 surface conditions), and with 5 test articles each to cover different fluences, chemical environments and cycling, then a total of about 100 test articles are needed. These would each be tested under a few combinations of tritium form, pressure, and temperature profile.

Test Facilities: Test stands will be very useful for studying permeation in non-irradiated samples, and possibly for measuring permeation on pre-irradiated specimens. Point neutron sources can provide high-energy neutrons to explore radiation effects in a fusion nuclear environment. There may be some size limitations that make in- situ tritium permeation tests impractical. Fission reactors would be very suitable for studying tritium permetion in a fission neutron environment.

### I.B.7 Environmentally Assisted Cracking

a. Stress Corrosion

b. Liquid Metal Embrittlement

Both stress corrosion and liquid metal embrittlement are phenomena where the chemical environment degrades the ductility of the structural material and leads to early failure by crack growth. Stress corrosion has been observed in steel/hot water systems, while liquid metal embrittlement (LME) is a general concern for blanket designs with liquid metals. These tests involve "coupons" exposed to the appropriate environment and tested for loss-of-ductility in a post-test exam.

Importance of Neutrons: (Medium) Neutron irradiation is considered important to stress corrosion since it will enhance embrittlement via hardening effects and intergranular bubble production, but is not critical to the phenomenon of stress corrosion failure.

Importance of Fusion Spectrum: (Low) A fusion spectrum is considered to be of low importance for stress corrosion in austenitic steel because serious (essentially worst case) effects can be studied in the fission reactor environment in this nickel bearing alloy. For LME, a fusion environment may be of more importance because the helium and hydrogen might enhance the embrittlement of HT-9 and vanadium alloy.

Other Required Environmental Conditions: (T,$\sigma$,I,N) Temperature is a basic need for these tests. Stress, impurities (especially Cl for stress corrosion of water/steel systems) and stress cycling are also very important.

Test Article Size: Stress corrosion cracking and liquid metal embrittlement can largely be resolved via "coupon" testing in the appropriate environment. The test element size is of the order of 1 x 2 x 2 $cm^3$.

Number of Test Articles: Stress corrosion tests would require about 30 test conditions: three temperatures, two fluences and five stress levels. Liquid metal embrittlement would similarly require about 30 tests for each candidate alloy (HT-9 and V-15Cr-5Ti, at present)

Test Facilities: The effects of stress corrosion cracking and its consequences on component availability can be assessed quite well from the results of testing in nonfusion facilities, both test stands for pure stress corrosion, and in point neutron sources and fission reactors for the synergistic effects of neutrons (although the latter may miss some spectrum effects).

### I.B.8 Self-Welding of Similar and Dissimilar Metals Experiments

These tests determine whether materials in contact fuse together by welding or corrosive interaction, thereby affecting maintenance and component movement. The test measurements would be by post-test exam, particularly for changes at the contact surfaces.

Importance of Neutrons and Fusion Spectrum: (High/Low) Neutrons are considered to be of high importance in such testing primarily because, in addition to heating, they will enhance diffusive processes via displacement damage. A fusion spectrum would be nice to have for specific reactions but is of low importance overall.

Other Required Environmental Conditions: $(T,p,\sigma)$ The reaction rate is likely to be a function of temperature (which activates the diffusive processes) and contact pressure or stress (which relates to the degree of microscopic surface contact).

Test Article Size: These tests could be carried out on coupon samples of size $1 \times 2 \times 2\ cm^3$.

Number of Test Articles: Contact stress, temperature, and fluence are important test parameters, as well as the effects of hot water corrosion. Hence, for two materials, five stress levels, three temperatures and two fluences, with and without water exposure, one would need to test a total of 180 conditions. The need to examine the contact surface changes at each test condition (by sectioning the test article) might require separate test articles.

Test Facilities: Displacement damage is important to this test because the enhanced atomic diffusion processes will influence self-welding. Hence, test stands are of low usefulness. This issue can essentially be resolved via coupon testing in a neutron environment. Therefore, point neutron sources will be highly useful, without apparent limitation. Fission reactrors will be of medium to high usefulness, but testing in this environment will miss spectrum effects.

## I.B.9 Fabrication and Reprocessing of Solid Breeder and Multiplier

These tests explore the ability to fabricate and subsequently reprocess solid breeder and beryllium multiplier material. In particular, sphere-pack forms of solid breeder with desired grain sizes need to be produced, and existing fabrication methods for the other interesting breeder and multiplier forms evaluated in the context of suitability for remote handling. Measurements would be on the distribution of grain size, porosity and impurity levels in the materials.

Importance of Neutrons and Fusion Spectrum: (Medium) Neutrons will eventually activate the material and require remote handling, but will also change the local chemistry and possibly affect the reprocessing techniques. Initial fabrication can be explored without neutrons, remote handling does not need activated material to demonstrate the process suitability. However, chemistry and burnup related changes may require some irradiated material as input, unless these changes can be adequately characterized and simulated through the feed material.

Other Required Environment (I) These processes are carried out away from the reactor under whatever conditions are suitable for the particular process. The only influence is through impurities introduced through burnup.

Test Article Size: Most of these tests will be based around fabricating a few pellets (or equivalent) material at a time, or about 1 x 1 x 4 $cm^3$.

Number of Test Articles: Allowing 30 different fabrication/reprocessing procedures (e.g., two methods, 15 parameter variations), and four feedstock/end product combinations, the number of tests is about 120.

Test Facilities: Fabrication and reprocessing is done external to the reactor, so non-nuclear test stands are the appropriate facility. However, point neutron sources and fission reactors may be useful to pre-irradiate some materials to provide the burnup related changes in chemistry. Fission reactors may be a more cost-effective approach to reach a given fluence-related burnup since much of the reactions (lithium and beryllium burnup) can be activated by low energy neutrons, although there may be some high energy transmutation reactions that may be significant.

## I.C MULTIPLE EFFECT/MULTIPLE INTERACTION TESTS

### I.C.1 Solid Breeder Unit Cell Heat Transfer Experiments

a. BOL Performance

b. MOL/EOL Performance

These tests employ the smallest blanket unit cell, such as a single $Li_2O$ plate, as the test assembly. The tests specifically address, at least empirically, heat transfer in realistic solid breeder geometries. Multi-cell interactions are not addressed. Considerable data might also be expected in tritium recovery experiments. BOL tests will address initial performance, while MOL/EOL tests will include long-term changes. It is unlikely that blanket failure mechanisms will appear, as such, in unit cell tests, and therefore MOL and EOL testing are nearly synonymous. Measurements include temperature (breeder, coolant and purge), purge pressure drop, and post-test examination of the breeder structure and the gap dimensions.

Importance of Neutrons: (High) Neutrons will be useful for bulk heating and radiation effects on heat transfer such as thermal conductivity changes at high burnup or mass redistribution. Also, the formation of tritium may be important for LiOT mass transfer and any effect on gap conductance.

Importance of Fusion Spectrum: (Low - Medium) A fusion spectrum is not required since damage may not be too different from that in a fission environment, and other important processes such as cracking are independent of spectrum. For MOL/EOL tests, the fusion spectrum might be slightly more important due to more typical damage rates in the structure and the greater likelihood of simulating life-limiting effects.

Other Required Environmental Conditions: (G,Q,T,C,v,$\sigma$) The exact geometry, including breeder microstructure and surface roughness (if possible), mechanical boundary stress, coolant and purge temperature, pressure, velocity, power density, and purge chemistry must be simulated.

Test Article Size: For BOL solid breeder blanket designs, unit cells are, depending on the design, typically 3-10 cm diameter x 30 cm long (minimum), or 2 cm thick x 30 cm along the first wall x 40 cm deep.

Number of Test Articles: (30) Heat transfer experiments will be specific to a particular unit cell geometric design, but generic in the sense that observed phenomena could be present in other designs. Consequently, testing will be a function of the number of unit cell designs under consideration. Breeder temperature is not longer a test parameter but an output. The number of test articles may be reduced through semi-continuous in-situ experiments which yield data at many fluences and times.

Test Facilities: Test stands are of medium usefulness for BOL testing since, although bulk heating could be simulated, neutrons are still desirable. However, neutrons are definitely needed for MOL and EOL testing to incorporate damage effects. Point neutron sources generally have insufficient test volume for these tests, with strong gradients in heating and damage rates. Fission testing can fulfill almost all goals of unit cell testing. A small number of fusion EOL tests, possible 5, would be useful for assuring high availability.

I.C.2 Breeder Thermomechanical Interactive Effects Experiments

a. Thermal Effects (BOL)
b. Radiation Effects (MOL/EOL)

These would be the first tests performed under realistic geometry, temperature and stress states to study thermomechanical interactive effects on component behavior They would be somewhat simplified in terms of environmental conditions in order to obtain at least a qualitative understanding of the interactions. There would probably be two rough classes of tests: (1) heating or BOL, and (2) radiation effects or MOL/EOL. The heating tests would include thermal and pressure stresses, thermal creep and distortion, initial gap conductance, solid breeder cracking, sintering, or settling and hot spot effects. Radiation would then add radiation-induced thermal conductivity changes (affecting temperature profile), swelling, radiation-induced creep and sintering, and many other effects. These measurements would include temperature, stress, and post-test examination for gap size, cracking, sintering or settling, swelling and any other observable changes.

Importance of Neutrons: (Low - Critical) While not explicity needed for the first class of tests, it may be difficult to simulate the temperature profiles without neutron bulk heating. Neutrons would be required for the second series of tests.

Importance of Fusion Spectrum: (Low - Medium) The neutron spectrum is not significant for the BOL tests, provided that the bulk heating profile can be otherwise simulated. It would be desirable for the radiation effects tests, but appreciable information on mechanical interactions under irradiation should still be obtained.

Other Required Environmental Conditions: (T,p,Q,G,N) The breeder thermomechanical behavior will depend on the temperature, coolant and purge pressure, bulk heating, geometry and cycling.

Test Article Size: These tests should include a basic structural submodule of the blanket. For solid breeders, a few unit cells could be accommodated in a $25 \times 50 \times 10\ cm^3$, while a larger size, perhaps $50 \times 100 \times 20\ cm^3$ might be needed for the larger-structured liquid breeder blankets.

Number of Test Articles: Since these tests are intended to bring out interactive effects, perhaps 2 BOL tests would be needed to understand the thermal interactions, and then somewhat more (~8) to allow for four fluences.

Test Facilities: If a suitable non-nuclear bulk heating source can be provided, then test stands would be preferred for the thermal effects tests. Point neutron sources are limited in test volume. Fission reactors should be very useful for radiation effects testing, although it would be desirable to have high energy neutrons and there may be some difficulty in achieving bulk heating at higher than a 1 $MW/m^2$ equivalent neutron wall load.

I.C.3 Submodule Thermal and Corrosion Interactive Effects Experiments

a. Thermal Hydraulics

b. Corrosion, Coolant Stability and Mass Transfer

Interactive effects testing at the submodule scale emphasizes model development, including nonidealities that are not likely to appear in the single or multiple channel tests. The key additional feature is more realistic geometry. However, the geometry is still simplified from the actual component (and from other submodule verification tests) in order to allow a quantitative understanding of the behaviour. Measurements include coolant temperature, flow rate, velocity profile (for liquid metals, if possible), pressure drop, impurity content, and post-test examination of surfaces for corrosion.

Importance of Neutrons: (Medium) Bulk heating is more important than in element tests since whole blanket temperature distributions are emphasized rather than just channel profiles. Unlike the submodule verification tests, unexpected effects are not a dominating concern, so the overall need for neutrons is medium.

Importance of Fusion Spectrum: (Medium) Spectrum is only important to the extent that it is necessary to achieve the correct bulk heating profiles.

Other Required Environmental Conditions: (G,B,v,q,Q,T,C,I) Geometry and magnetic field are critical for addressing MHD issues. For thermal behavior, velocity profiles, surface and bulk heating are important. For corrosion issues, temperature, chemical environment and impurities may be needed.

Test Article Size: (SB: 10 x 50 x 30 $cm^3$, LM: 100 x 100 x 30 $cm^3$) For the solid breeder blankets, a scaled model of a full module is desired. For the liquid metal blankets, a scaled model of a full blanket sector is needed. Scaling by more than a factor of 2 - 4 is considered implausible for interactive effects.

Number of Test Articles: (20) Tests will be probably required to address several different areas within the blanket, and at different environmental conditions, including some outside the normal operating parameters.

Test Facilities: Large test stands with magnetic field (for the liquid metal blankets) could resolve many interactive issues, except for the lack of neutron bulk heating. Point neutron sources lack the appropriate volume. Fission reactors may be useful for submodule testing if magnetic field can be supplied. Size limitations may restrict their use.

### I.C.4 Tritium Permeation into Breeder/Multiplier Coolant

These tests might be performed in conjunction with other breeder or multiplier tests, but are described separately due to the different emphasis. This is to determine tritium permeation rates from the breeder region into the coolant under actual operating geometry and conditions. Thus, these tests differ from simpler element tests which may have measured local permeation rates under ideal conditions and geometries, and detemined the controlling processes. The primary outcome of these tests is a measurement of the net tritium permeation rate into the coolant. Measurements are primarily of tritium activity in the breeder purge gas and in the coolant, purge stream pressure and temperature, form of tritium in the purge (oxide or elemental), as well as clad temperature, and post-test examination of the clad surfaces to detemine the surface conditions.

Importance of Neutrons: (High) Since neutrons provide the source distribution and concentrations of tritium, are the prime source of heat, and may affect the permeation process itself (hopefully this is already known from the element tests), it is important to have neutrons. However, the dominant effects (local tritium partial pressure, clad temperature, chemical environment) may be simulated without neutrons.

Importance of Fusion Spectrum: (Medium) Since the exact contribution of neutrons to the permeation process is not known (e.g., $T_2/T_2O$ ratio, defect trapping or untrapping of tritium in clad material, embrittlement and cracking at joints), the importance of the neutron spectrum is also not certain. It is rated as Medium at present. However, for beryllium multiplier, the $(n,{}^3H)$ reaction threshold is 11.6 MeV, requiring high energy neutrons if the tritium source term is to be correctly simulated.

Other Required Environmental Conditions: ($H^3$,p,T,G,I,C,N) The test environment should include tritium (diffusion rates are different from other hydrogen isotopes by more than just the mass ratio) and simulate coolant, clad and purge pressures and temperatures, geometry (including joints and purge flow path), chemical environment and temperature cycling.

Test Article Size: The test article should include a few breeder/multiplier unit cells, typically requiring 10 x 50 x 10 $cm^3$.

Number of Test Articles: The test articles could be used over a range of test conditions. It is anticipated that no more than 3 would be needed, assuming that most of the development work in understanding permeation phemomena and surface barriers had already been performed.

Test Facilities: Some tests (especially for BOL) might be performed on non-nuclear test stands, with tritium pre-implanted or injected with the purge. Point neutron source are probably too small to provide the correct tritium and heating source terms over the few unit cells needed. Fission reactors could be very useful here, particularly if other tests show only a small effect of high energy neutrons on the processes. However, neutron damage over the life of the blanket and tritium production in beryllium are a strong function of neutron spectrum, and so fission reactor tests (for time and spectrum reasons) may not be a definitive test of EOL permeation rates.

### I.C.5 Neutron Multiplier Unit Cell Thermomechanical Performance

For blanket designs which incorporate distinct multiplier regions, some unit cell tests may be performed to verify mechanical behavior (structural integrity of unclad Be; interaction between Be and clad), temperatures (Be thermal conductivity, gap conductance), chemical compatibility, and possibly tritium permeation rate. Measurements would include beryllium temperature profile, stresses, and post-test examination for cracking, change in gap size, swelling, surface damage due to corrosion, and tritium inventory.

Importance of Neutrons: (Critical) Unirradiated beryllium properties are reasonably well-known and little submodule testing is required. The primary concerns that would be addressed here are the effects of neutrons, and thus neutrons are critical.

Importance of Fusion Spectrum: (Medium) Heat generation may be provided artificially or with fission neutrons, but radiation effects such as swelling (very large in Be) have some dependence on spectrum, so there is some need for fusion neutrons.

Other Required Environmental Conditions: (T,$\sigma$,N,G,C) It will be important to duplicate temperatures, stresses and chemical environment under the appropriate geometries. For unclad Be, multiple cycles would be useful to observe the fatigue life.

Test Article Size: (30 x 30 x 10 $cm^3$) A nominal multiplier unit cell should be used in the test.

Number of Test Articles: (4) Possibly 4 test articles would be used, allowing detailed destructive analysis after three fluence levels, and an additional article (possibly irradiated to some degree) tested separately for thermal corrosion and cycling response.

Test Facilities: Test stands would not be very useful due to the need for neutrons. Point neutron sources do not have sufficient volume. Except for spectrum differences, fission reactors are very useful.

### I.C.6 Verification of Submodule Thermomechanical Behavior under Complex Loading

These tests consist of a section of a full module (e.g., first wall section, several solid breeder plates), and subject it to similar stress conditions to the corresponding section in an operating blanket to verify the thermomechanical design. Measurements would include temperature, stress, and post-test examination for crack growth, deformation or other obvious changes.

Importance of Neutrons: (Critical) Neutrons are required as a source of heating, to produce specific reactions, and to produce material damage. Temperature gradients and neutron radiation can produce differential swelling and irradiation creep, resulting in excessive stresses in the first wall/blanket that can lead to failure. In addition, the neutrons damage can cause excessive distortion. The interaction of thermal creep, irradiation creep, and swelling will result in a complex time, temperature, and fluence-dependent stress history in the first wall/blanket module.

Importance of Fusion Spectrum: (High) The correct neutron spectrum is of high importance because the neutron energy distribution can impact the amount of creep and swelling that takes place. Therefore, neutrons can change the stress distributions and deflections of a component. Stresses from thermal effects and swelling relax during the plasma burn due to irradiation creep. Upon shutdown, these stresses will reverse, causing residual tensile stresses to remain during the nonburn portion of the cycle.

Other Required Environmental Conditions: (q,Q,PMI,p) Other required environments are bulk and surface heat flux, and plasma effects. The surface heat flux is important to establish the expected thermal gradients in the structure and the operating temperature. Irradiation creep and swelling are highly dependent on the temperature of the structure. The correct thermal gradient is required to establish the effects of differential swelling resulting from the thermal gradient.

Test Article Size: To investigate the interaction of thermal and irradiation effects on stresses in the first wall and distortion of the component, an act-alike submodule will give the primary stress distributions (coolant pressure and vacuum loading), secondary stress distributions (thermal gradients, swelling, and creep), and the distortions resulting from these loads. Typical dimensions might be 25 x 50 x 10 $cm^3$.

Number of Test Articles: Since an act-alike test module is used, the number of test articles will be less than three.

Test Facilities: The usefulness of test stands for experiments to resolve this issue is low since they do not include neutrons. Test stands can be used to resolve potential problems resulting from mechanical loadings and thermal gradients. However, neutrons are required to resolve the interaction effects of swelling and irradiation creep. The usefulness of point neutron sources to resolve this issue is low. The main limitation is size. The usefulness of fission reactors to resolve this issue is medium. The main limitations are neutron spectrum and size of test space in a fission reactor and ability to simulate PMI effects.

### I.C.7 Submodule Thermal and Corrosion Verification

a. BOL Performance

b. MOL Performance

c. EOL Performance

Submodule tests will employ assemblies with multiple unit cells or flow channels with realistic geometries. The issues addressed by these tests are similar to those for full-module tests, except that the issues are examined only in the submodule (as opposed to module-wide). For example, submodule tests may provide the first opportunity to verify flow distribution and stability between parallel channels, although only for a limited number of parallel channels. Other thermal-hydraulic issues which will be addressed include temperature fields, thermal/geometric instabilities, helium purge characteristics (Solid Breeder), interface conductivity (SB), parallel-channel MHD interactions (Liquid Metal) and manifold MHD effects (LM). Three levels of submodule testing are foreseen: BOL - to examine initial operational problems; MOL - to examine long-term effects which may degrade performance or possibly limit life; and EOL - to observe actual life-limiting mechanisms.

These verification tests are strongly component oriented, as opposed to the interactive effects tests which seek to develop and verify models and less to develop and verify design concepts. Measurements would include bulk fluid conditions (inlet and exit pressure, flow rate and temperature), a limited number of stresses and internal temperatures, coolant and purge chemistry (for corrosion products), and a detailed post-test exam for any changes in surfaces, breeder, structure.

Importance of Neutrons: (Critical) For all submodule tests, neutrons are considered critical. Neutrons are the only demonstrated method for providing submodule-wide bulk heating. In addition, neutron damage is a requirement for MOL and EOL tests.

Importance of Fusion Spectrum: (Low - Critical) It is important to note that at many locations in a blanket, the spectrum is softened considerably from the 14 MeV source. Also it is fairly straightforward to simulate fusion bulk heating in a submodule test using a fission neutron source. For these reasons, a fusion spectrum is of relatively lower importance than for a full module test.

Other Required Environmental Conditions: (G,q,Q,T,p,v,B,C,$\sigma$) For maximum utility in addressing both thermal-hydraulic and other issues, surface heat flux, power density/flux/damage rates, geometry, temperatures, magnetic field, coolant and/or purge velocity, pressure, and chemistry, and mechanical boundary stresses must be simulated.

Test Article Size: Test modules must contain multiple cells or flow channels. Since flow channels are long in one direction along the first wall, the test module must be similar. Dummy modules surrounding the test assembly may not be necessary. Estimated size is 10 x 50 x 30 $cm^3$ for solid breeders, and 100 x 100 x 30 $cm^3$ for liquid metals.

Number of Test Articles: Submodules must be tested over the range of conditions found in the blanket system, including variations in poloidal, toroidal, and blanket depth dimensions. It is estimated that approximately 15 test articles will be sufficient.

Test Facilities: Test stands are not useful since neutrons are needed. Point neutron sources are not useful since large test volumes are needed. Fission reactors can supply sufficient neutrons and test volume for submodule tests, and are very useful for BOL and MOL tests. However, they are less useful for EOL tests since spectrum effects may become important, and since long operating times are required. Fission testing can attain almost all the goals of submodule testing for low availability goals. For high availability, fission testing may miss important failure modes, particularly in long-term tests where radiation damage is important.

## I.C.8 Solid Breeder Tritium Behavior in Thermal and Flow Transients

These tests would involve at least one, but possibly more, solid breeder unit cells under transient thermal or flow conditions to determine the tritium inventory behaviour. These tests might be performed with the same test articles used in the steady-state tritium recovery tests, but are described separately since: (1) more than one unit cell may be used to include interactions, and (2) some transients may be severe and damage the test article. Measurements include temperature (breeder and coolant), coolant and purge tritium activity, and post-test examination for tritium inventory, cracking, or other solid breeder changes.

Importance of Neutrons: (Critical) It is important to have neutron damage effects in the solid breeder and the correct distribution of tritium prior to the transients. This could not be attained other than by neutron-generated tritium. Adding tritium in the purge and letting it soak into the grains will yield very different tritium concentration gradients in the grains and possibly the porosity. Some transients may also require heat and tritium generation during the tests.

Importance of Fusion Spectrum: (Low) The importance of a fusion spectrum, however, is not large as long as the tritium is correctly generated and reasonably similar damage or alterations are present (possibly more a function of the operating temperature than neutron spectrum).

Other Required Environmental Conditions: ($H^3$,T,p,v,I,G,t) The breeder temperature, coolant and purge conditions (flow, temperature, tritium partial pressure, impurities) should be reproduced in a similar geometry. The transient time scales should be adjusted to be consistent with the thermal and tritium recovery time scales of the test article (which may not be the same as in a reactor if the test articles are scaled).

Test Article Size: A typical size might be 10 x 50 x 10 $cm^3$, allowing for at least 2 unit cells and one long direction for purge flow effects.

Number of Test Articles: Therre will be a range of transients to consider, but since safety considerations will suggest severe transients (flow blockage, leak of coolant into breeder), and since a detailed and destructive post-test analysis will be required to locate the tritium inventory, each test would require a separate test article. Perhaps 10 such tests would be conducted.

Test Facilities: Test stands might be an appropriate test facility for certain transients if the tritium and damage profiles can first be provided by irradiation in another facility. Some means of retaining the correct initial and transient temperatures would be needed in the absence of neutron bulk heating. These tests would be particularly attractive for severe transients (which would complicate the design of an in-reactor test facility) and for transients accompanying loss of plama (so continued tritium and heat generation are not needed). Point neutron sources might be useful to pre-irradiate test articles, but probably lack the volume to do so over the full test article. Fission reactors would be very useful for these tests, possibly limited by the peak bulk heating rates attainable - thermal neutrons yield high but unrealistically sharp peaks near the first wall structure.

### I.C.9 Blanket Response to Coolant Transients

In these tests, a full or almost full module (the first wall or breeder might be separately tested) is subjected to loss of flow or loss of coolant conditions. Measurements include temperature, stress, coolant pressure and flow rate, and post-test examination for deformation and failure.

Importance of Neutrons and Fusion Neutrons: (Medium/Low) Neutrons per se are not important in the testing of coolant system transients, except inasmuch as they accurately simulate the volumetric heat generation rates which would occur in a fusion reactor. If heat generation and thermal inertia can be accurately modeled in an electrically heated test stand (for example), the course of cooling system transient can be adequately tested.

Other Required Environmental Conditions: (G,v,q,Q,B) The basic requirements are for geometry, coolant velocity and heating. In addition, the interaction of the escaping coolant in a loss of coolant accident with the materials of the breeding blanket and any purge gas needs to be measured and accounted for in testing. In addition, the weakened and possibly embrittled condition of coolant tubes and blanket structure due to neutron irradiation damage and the possibly sintered condition of the breeding materials need to be simulated. If lithium or another electrically conducting fluid is used as a coolant, a magnetic field would be required to accurately simulate cooling system transients.

Test Article Size: (10 x 50 x 100 $cm^3$) In order to accurately model the behavior of the component under a coolant transient, both the thermal capacity, which is proportional to volume, and the heat removal rate, which is proportional to surface area, must be present in the test article. This dictates that the test article be of roughly the same size as the corresponding component section.

Number of Test Articles: (3) A small range of transient conditions should be tested, including some mild ones where the test article can probably be reused, and some more violent ones where there may be failures. Except where flow instabilities in the entrie system are concerned, simultaneous testing of multiple modules is not necessary. The component response to the transient should not be of a statistical nature.

Test Facilities: Test stands are the most useful facilities for the testing of cooling transients and provide relatively economical data since working in a radiation environment is not necessary. Point neutron sources are of basically no usefulness in the testing of components during cooling transients because of the very small volume irradiated at high fluxes. Fission reactors have limited usefulness in simulating fusion reactor cooling transients. Volumetric heating rates in the blanket materials can be simulated if changes in isotopic enrichments are made to account for fission/fusion spectral differences. Surface heating phenomena cannot in general be simulated. In addition, the cost and complexity of operating the cooling loop within a fission reactor limits the number of transients which can be investigated.

I.C.10 First Wall Response to Plasma Thermal Transients

In fusion devices, loss of plasma confinement can lead to deposition of the plasma energy on first wall structures. The consequences of these events, include melting and volatization of material, and high thermal stresses. These tests observe the response of first wall sections to plasma transients. Measurements include surface temperature, first wall temperatures, coolant bulk temperature (total heat input), and first wall stresses, as well as post-test examination for cracking or deformation.

Importance of Neutrons and Fusion Spectrum: (Medium) The only value of neutrons would be to prepare samples for testing. Neutron irradiation changes material properties and mechanical stress tests would be needed.

Other Required Environmental Conditions: (G,q,PMI) Samples to be tested must be located in positions of maximum heat load from loss of plasma confinement. The presence of the plasma and magnetic fields will be necessary to determine shielding by the blow-off material and stability of the melt layer.

Test Article Size: A surface of 10 x 10 $cm^2$ would be required, with sufficient depth (2 cm) for cooling and instrumentation.

Number of Test Articles: (3) A small range of disruption conditions should be considered (time scale, energy content), as well as different first wall designs or materials. Depending on how reusable a test piece is (or how severe the transient is), the number of test articles might be about three.

Test Facilities: Test stands are currently available for simulating some aspects of the plasma interaction with the structure. More information is needed on plasma behavior before results based on these simulations can be applied to a specific device. Neutrons are only useful in preparing samples for mechanical tests.

I.C.11 Helium- or Water-Cooled First Wall Temperature Verification

An important issue for first wall/blanket designs is the performance of the first wall. For He or $H_2O$ cooled blanket concepts, the first wall can usually be tested separately from the blanket in initial tests. Such separate tests are necessary to support the full-module verification test, which includes first wall performance. Separate first wall tests are also attractive because they can probably be non-nuclear since bulk heating is less important than surface heating at the first wall, at least in tokamaks. These tests are primarily concerned with BOL performance. Measurements would be primarily surface temperature and first wall temperature, with coolant flow rate and bulk temperature rise to monitor the total power input.

Importance of Neutrons and Fusion Spectrum: (Low) The primary influence of neutrons is through bulk heating, which may be small compared to surface heating, depending on the device. Similarly, the spectrum is unimportant.

Other Required Environmental Conditions: ($G,q,T,v,p,\sigma$) Geometry, mechanical boundary stress, surface heat flux, coolant temperature, pressure, and velocity must be simulated.

Test Article Size: Typical first wall panels are approximately 30 cm wide and 30 cm deep. A section 30 cm long would be sufficient for testing.

Number of Test Articles: Approximately 20 separate test conditions will be required to represent the entire range of first wall heat fluxes, although these can be accommodated with one test article per first wall design.

Test Facilities: Test stands will be very useful. Point neutron sources may be limited in volume and in their ability to provide a surface heat flux. Fission reactors may be useful in that they have sufficient volume and flux to include neutron bulk heating. However, it is likely that the additional complications of nuclear test facilities will not be worth the additional information gained in these tests since the first wall temperature response is primarily (within 20% in tokamaks) driven by the surface heat flux.

## I.C.12 Mechanical Behavior of Grooved First Walls

These tests investigate a particular design of high heat flux components where surface grooves are added to relieve thermal stresses. These tests would be based on a section of the first wall and monitor bulk temperature (thermocouples?), surface temperature (infrared camera?) and stresses. Post-test examination would be necessary to observe crack initiation and growth at the groove tip.

Importance of Neutrons: (Medium) While radiation damage, especially embrittlement, may affect the response of a grooved first wall, the major design questions can be resolved without neutrons. These questions are the stress levels in the grooved part, stress concentration factor at the groove bottom, and the effects of groove geometry on stress levels and life. Therefore, neutrons are not required.

Importance of Fusion Spectrum: (Low) Since neutrons are not required, fusion spectrum is not important.

Other Required Environmental Conditions: (q,PMI,B,Vac) Other required environments are surface heat flux, plasma, magnetic fields, and vacuum. The surface heat flux is important to establish the expected thermal gradients and operating temperature of the structure. The stress distribution and concentration at the groove bottom are highly dependent on thermal gradients. The plasma may be required for determining the effects of erosion on a grooved surface. The plasma should be typical of plasmas that are expected in a fusion reactor. Electromagnetic fields may be important since they impact deposition rates.

Test Article Size: The response of a grooved surface in a fusion environment can be determined by using a test element that is approximately 5 x 5 $cm^2$ by 2 cm deep. The groove spacing can then be varied from 0.5 - 2 cm. It should also allow the center of the test specimen to be free from edge effects. A 2 cm depth would allow the first wall thickness to be varied and also allow for cooling of the first wall to establish thermal gradients.

Number of Test Articles: The major test parameters are surface heat loads, temperature, groove spacing, groove depth, groove geometry, first wall material, and cyclic operation. Testing for all these variables would require about 100 test conditions. Most test conditions would require a separate test article since they could lead to crack initiation, if not failure, and may be have to be destructively examined for crack initiation and growth.

Test Facilities: The usefulness of a test stand is high if it can provide the required surface heat flux, addressing the response of a grooved surface to a thermal gradient and the stress concentration factor at the groove bottom. In addition, the effects of groove geometry and spacing can be determined. However, the main limitation of a test stand is the lack of neutrons. Radiation damage could affect the response of a grooved surface. The usefulness of point neutron sources to resolve this issue is low due to size limitations. The usefulness of fission reactors to resolve this issue is medium. Fission reactors could be used to address the questions concerning radiation damage effects on a groove surface. The fission reactor must be able to provide the required surface heat flux. The main limitations are neutron spectrum and the size of test space in a fission reactor.

### I.C.13 Energy Release Measurements under Accident Conditions

These tests step beyond the basic reaction kinetics or thermodynamic tests, and explore the reaction rate and energy release under accident-like conditions. For example, these would consider realistic surface-to-volume ratios, air/water/reactant availability, amount of agitation and geometry. Measurements would include temperature and pressure during the transient, and a post-test exam to determine the reaction products, degree of reaction, and extent of movement of reactants or vaporized material.

Importance of Neutrons and Fusion Spectrum: (Low) Although the release of activated material is a concern, and neutron damage may contribute to the probability of accidents, neutrons do not change the reaction chemistry, and thus the evolution of the transient.

Other Required Environmental Conditions: (G,T,p,I) Important test parameters are the basic geometry, including surface-to-volume ratios and any geometry related limitations on heat and mass transfer. The initial temperatures, pressures and the presence of impurities will also affect the course of the reaction.

Test Article Size: Moderate scale tests are required to simulate the possible transient conditions, perhaps 5 $m^3$ for the test containment volume.

Number of Test Articles: Although the tests involve accident-related transients, it is anticipated that much of the test article will be reusable for different conditions of initial temperature, pressure and quantities of reactants. Perhaps 20 distinct test articles will be needed.

Test Facilities: Test stands are the preferred facility to test energy release and reactions under accident conditions. They can simulate all the necessary environmental conditions, and are not constrained by access or radioactivity hazard.

## I.D. PARTIALLY INTEGRATED AND INTEGRATED TESTS

### I.D.1 Verification of Neutronics Predictions

a. Tritium Beeding

b. Nuclear Heating during Operation

c. Induced Activation

In these tests, a complete full-scale module is tested to verify neutronics predictions for tritium breeding, nuclear heating and induced activation. Measurements include post-test exam for activation, tritium inventory and neutron fluence.

Importance of Neutrons and Fusion Spectrum: (Critical) Fusion neutrons are critical since the errors and uncertainties to be resolved are less than 20%.

Other Required Environmental Conditions: (G) Geometry is very important, since the nature of the module and its surroundings influence the local neutron field.

Test Article Size: (50 x 50 x 100 $cm^3$) Test article size depends on reactor design. Test modules should mock up the blanket module at least. In addition, the neutronic environment in test module should be equivalent to a full size reactor.

Number of Test Articles: (4) Number of test articles also depends on the design. It should include modules near, for example, limiters, diverter openings and ports. Multiple tests might be needed to establish the high accuracy required.

Test Facilities: Non-neutron test stands are meaningless for neutronics. Point neutron sources are useful if they are well-characterized and intense D-T neutron sources such as FNS or RTNS-II. Much useful data can be obtained from benchmark experiments using these point sources, but the data is ultimately limited by the source intensity, large flux gradients in the test volume, and total neutron fluence (tritium target lifetime). Fission reactors are not useful because they have no high energy neutrons.

I.D.2 Full-Module Thermal and Corrosion Verification

a. Beginning-of-Life (BOL) Performance

b. Middle-of-Life (MOL) Performance

c. End-of-Life (EOL) Performance

Full-module verification tests are required in order to develop the necessary confidence that the entire blanket module will function acceptably. Here, we allow for some partially integrated tests to concentrate on simulating thermal and corrosion behaviour in the full component, possibly at the expense of other features such as thermomechanics. Measurements would include bulk fluid temperature, pressure, flow rate, coolant/purge chemistry, local internal temperatures, some stresses, possibly some local flow rates, plus extensive post-test examination for any changes. There are three different test goals with specific issues and requirements:

BOL Performance: There are many uncertainties in the blanket flow and temperature fields which will exist during initial and early-in-life operation (zero to tens of days). These uncertainties stem from two main sources: unexpected design-specific synergisms, and poor modeling of the precise geometry of the module. Synergisms which can occur initially or early in the blanket lifetime will probably be directly related to design details which were not examined as part of earlier testing at reduced complexity; a typical example is a flow oscillation or flow-induced vibration which may first appear in the prototype itself or perhaps in the top-level integrated test as a result of an unexpected interaction between design features. The second cause of uncertainties, imperfect modeling, is closely related. It is often difficult to completely model a component as complex as a blanket module, particularly in specifying its geometry and boundary conditions (which may depend on the actual performance of related components, such as pumps, valves, and heat exchangers). Since assumptions and simplifications are always necessary, the potential exists for off-normal operation as a result of an imperfect assumption. Full-module verification testing is necessary to resolve these types of uncertainties. In the area of thermal-hydraulics, all issues must be addressed at this level, including: verification of module-wide temperature field, coolant flow instabilities, MHD pressure drop (liquid metal (LM) blankets only), thermal/geometric instabilities, interface heat transfer (including MHD effects for LM blankets) and helium purge system pressure drop/flow rate characteristics.

MOL Performance: Extended operation of a blanket (many days to several years) adds additional uncertainty to its projected performance, due to both nuclear and non-nuclear effects. Again, the uncertainties result both from unanticipated interactions, which in this case may include some which depend on specific aspects of the fusion environment and have therefore never been seen previously, and also from imperfect modeling. Because of the many mechanisms which may result in long-term changes, such as corrosion, creep, swelling, embrittlement, burnup, etc., perfect modeling of long-term performance is extremely difficult, and hence predictions are somewhat uncertain. Longer-term full-module testing will address the concerns. Again, in the area of thermal-hydraulics, all issues must be addressed at this level, with emphasis on performance changes which occur with extended operation. Examples include: burnup effects on the power density profile (and hence temperature field) in solid breeder (SB) blankets, creep/swelling effects on interface conductivity (SB), and corrosion/redeposition effects on heat transfer coefficients.

EOL Performance: The MOL full-module testing described above will probably suggest which effects will eventually prove life-limiting, by revealing their growth rates. However, as with all such extrapolations, there will be uncertainties until the EOL failure mechanisms are actually observed. Direct testing at the full-module level to observe EOL performance and failure mechanisms will be highly desirable to develop confidence in blanket lifetime estimates. Issues addressed in this type of testing are basically the same as those in MOL testing.

Importance of Neutrons and Fusion Spectrum: (Critical, High - Critical) For all full module tests, neutrons are considered critical. For BOL tests, the primary need is for accurate simulation of module-wide bulk heating, which is difficult or impossible to accomplish without neutrons; neutrons are also required if tritium breeding issues are among the test objectives. A fusion spectrum is of high importance in either function because of the difficulty in otherwise simulating these conditions over an entire module. For MOL and EOL tests, realistic radiation damage must also be produced. If a non-fusion spectrum is employed, uncertainty would be introduced due to the different damage rates and the potential for spectrum-related synergisms; thus, the fusion spectrum is considered critical for these tests.

Other Required Environmental Conditions: (q,Q,p,v,I,C,B,t) For all full module tests, all environmental aspects should be present. One possible exception might be that a magnetic field may not be required for testing SB blankets; this would, however, leave the potential for magnetic synergisms, and hence even in this case highest confidence is obtained if all environmental factors are present.

Test Article Size: Test modules must be full or nearly-full scale, complete blanket modules, probably surrounded with dummy modules to provide realistic boundary conditions. Overall size is approximately 100 x 100 x 80 $cm^3$ for solid breeders, including support structure, manifolds, and so on, and similarly 900 x 300 x 80 $cm^3$ for liquid breeders.

Number of Test Articles: (2) Tests need only be conducted at design conditions. For each blanket concept advanced to this stage, possibly two test articles would allow for detailed examination of the blanket at middle and end-of-life.

Test Facilities: Test stands are not useful since neutrons are needed. Point neutron sources have inadequate volume to irradiate a full blanket module. Fission reactors are also limited in volume. They are of medium usefulness for BOL testing, since the spectrum is different from fusion and potential spectrum-related synergisms need to be tested. The usefulness for MOL or EOL testing is low, since any spectrum effects will likely be more important, and since high fluence, long test durations are difficult to attain.

### I.D.3 Solid Breeder Module Tritium Recovery Verification

Although a full module test would ideally address all the performance issues of the blanket, scaling requirements may focus a module on "act-alike" tritium recovery at the expense of fully simulting thermomechanical or neutronic conditions. The requirements for such a test module are discussed here. Measurements would include in-situ tritium activity measurements in purge and coolant stream, neutron dosimetry, and post-test tritium assay to determine the location and magnitude of the tritium inventory.

Importance of Neutrons: (Critical) Neutrons are needed to produce tritium, and damage and swelling in the solid breeder and neighboring structural components. Neutrons also appear to be a reasonable source of heat generation within the blanket.

Importance of Fusion Spectrum: (High) For integrated module testing, it is desired that a fusion spectrum or one quite similar be used. The spatial distribution of heat generation, tritium production, damage and swelling are particularly sensitive to spectrum in a large module. If a nonfusion spectrum is used, "act alike" scaling must be developed in order to confirm the prediction based on individual issue tests. This may be possible in a fission reactor with suitable arrangements of spectral filters and $Li^7/Li^6$ ratio.

Other Required Environmental Conditions: (Q,p,v,t,G,C) Tritium movement in the blanket is essential to its functional operation. Purge and coolant flow through the blanket module establishes tritium recovery process and heat transfer processes prototypic of blanket operation.

Test Article Size: The test element size of the module is very specific to each design. A size of 60 x 60 x 60 $cm^3$ was selected to indicate the large volume necessary to duplicate a solid breeder module. Benchmark testing can be conducted with a much smaller test volume, but still requires extrapolation to full blanket size.

Number of Test Articles: (3) This is a very important issue for solid breeder blankets, and depending on the thoroughness of prior testing, a few full module tests or more would be desirable to identify any further unknowns, to correlate behaviour otherwise not well modelled, and to verify the models.

Test Facilities: Tritium recovery issues, mechanical interaction issues (swelling) and variations in the heat transfer are all driven by neutronic interactions such as tritium production, helium production and damage and heat generation. Point neutron such as FMIT are simply too small to conduct large component tests in high flux levels. Large volumes at low flux levels are available but would not be characteristic of blanket performance. If a much larger point neutron source could be created, it would be profitable for module testing. The use of fission reactor tests for integrated module testing is useful primarily as a "benchmark" of existing predictive capability. Such testing would confirm on a global scale the integrated effects of tritium recovery, heat transfer and mechanical interaction.

### I.D.4 Module Thermomechanical Non-Nuclear Integrity Verification

In these tests, a full-scale blanket module is subjected to a range of non-nuclear tests to verify fabrication and overall design integrity, especially stresses at startup before any radiation effects are significant. This module should also be subjected to multiple thermal cycles to determine the design's fatigue life in the absence of radiation, and to mechanical shaking to verify seismic safety. Measurements include local temperatures and stresses, and a post-test examination for any changes.

Importance of Neutrons and Fusion Spectrum: (Low) Neutrons are not needed since tritium and radiation damage are not considered. In fact, they would complicate the test. While there may not be an ideal non-nuclear simulator of bulk heating, the available techniques (e.g. electric heating, possibly microwave heating) should be adequate for these tests.

Other Required Environmental Conditions: (q,Q,PMI,B,v,p,N) The surface heat flux and bulk heating must be simulated. If possible, the surface heat flux should be plasma-related to simulate surface damage effects. Coolant conditions (velocity, pressure, temperature) should be reactor-relevant. Liquid breeder blankets would need a magnetic field for MHD effects, and the magnetic field body force would also be desirable for both solid and liquid breeder blankets.

Test Article Size: These tests should be nearly full-scale so that there are no concerns over size scaling effects. Since these modules are not intended for nuclear test facilities, size is not a major constraint, although practical limitations on magnetic field and non-nuclear heat sources may be important. Typical blanket dimensions are 30 x 100 x 80 $cm^3$ for solid breeder, and 900 x 300 x 80 $cm^3$ for liquid breeders.

Number of Test Articles: It is important to have a good design before it is subjected to the expense of nuclear testing. Possible three modules would be developed and tested here.

Test Facilities: These tests are specifically intended to be non-nuclear. Although the detailed simulation of surface and bulk heating by non-neutron sources may not be ideal, available techniques should be sufficient.

### I.D.5 Module Thermomechanical Lifetime Verification

These full module tests emphasize the thermomechanical performance through to end-of-life conditions. They should help establish structural failure modes. Measurements would include local temperatures and stresses, and a post-test examination for the cause of failure.

Importance of Neutrons: (Critical) Neutrons are required as a source of heating, to produce specific reactions, and to produce material damage. Temperature gradients and neutron damage can produce differential swelling and irradiation creep, resulting in excessive stresses in the first wall/blanket that can lead to failure. In addition, the interaction with neutrons can cause excessive distortion of the component.

Importance of Fusion Spectrum: (Critical) The correct neutron spectrum is of critical importance because the neutron energy distribution can impact the amount of creep and swelling that takes place. Therefore, neutrons can change the stress distributions and deflections of a component. Furthermore, although there may be reasons to believe that the same effects can be observed in different neutron spectra on the basis of material property tests, it is particularly the EOL structural failure that would remain uncertain.

Other Required Environmental Conditions: (q,Q,PMI,B,v,p,N) Other required environments are surface heat flux and plasma effects. The surface heat flux is important to establish the expected thermal gradients in the structure and the operating temperature. Irradiation creep and swelling are highly dependent on the temperature of the structure. The correct thermal gradient is required to establish the effects of differential swelling resulting from the thermal gradient. Magnetic stresses (including MHD), coolant pressure and thermal cycling would all have to be considered.

Test Article Size: To investigate the interaction of thermal and irradiation effects on stresses in the first wall and distortion of the component, an act-alike test module is required. Size of the module must be determined from scaling but will be large possibly 100 x 100 x 50 $cm^3$. An act-alike test module will give both the primary stress distributions (coolant pressure and vacuum loading) and secondary stress distributions (thermal gradients, swelling, and creep). The test will also give the distortions resulting from these loads.

Number of Test Articles: These tests will have to be subjected to extensive destructive examination at different fluences in order to understand their behavior with time, suggesting at least three test articles.

Test Facilities: The usefulness of test stands for experiments to resolve this issue is low since they do not include neutrons. The usefulness of point neutron sources to resolve this issue is low. The main limitation is size. The usefulness of fission reactors to resolve this issue is low. The main limitations are neutron spectrum and the size of test space in a fission reactor. Because neutrons and a fusion neutron spectrum is required there is strong need for testing in a fusion facility. The possibility of catastrophic structural failure due to unanticipated spectral effects would limit the confidence in the long-term performance of the structure otherwise.

### I.D.6 Blanket Response to Magnetic Field Transients

The testing of the response of the first wall, blanket and limiter to transient magnetic fields requires accurate modelling of the component geometry and electromagnetic characteristics. Components or suitable scale models are placed in a magnetic field which is rapidly changing in time and space, and the resultant stresses, deformations and resonances are measured.

Importance of Neutrons and Fusion Spectrum: (Low) The electromagnetic testing of first wall, blanket and limiter components in the presence of a neutron flux would add greatly and unnecessarily to the cost and complexity of the testing without appreciably adding to the quality of the data.

Other Required Environmental Conditions: $(G, B, \dot{B})$ As mentioned above, a strong magnetic field, up to 10 T, which can be rapidly varied at up to 200 T/s. is required to model the response of components to plasma disruptions and failures of the superconducting magnets. In addition, provision should be made to model the increased resistivity caused by neutron irradiation.

Test Article Size: Component models 100 x 50 x 50 $cm^3$ would accurately model the response of full scale components to transient magnetic fields if provision were made to scale the resistance, connections and time scale of the magnetic transient. Components of approximately this size can now be tested in FELIX.

Number of Test Articles: If scale models of actual reactor components are used, two or three different sizes may need to be tested in order to verify the scaling laws used. Otherwise, since the data is not of a statistical nature, multiple tests are not needed.

Test Facilities: Test stands incorporating strong magnetic fields are the only viable method for transient magnetic field testing. Neutrons add nothing to the testing except cost and complexity.

## I.D.7 Blanket Steady Magnetic Field Interaction Verification

The concern here is whether the complex states of stress induced in first wall/blanket components by strong magnetic fields are sufficient to cause premature failure. Measurements would be primarily the stress state and the magnetic field strength.

Importance of Neutrons and Fusion Spectrum: (Low) Neutron irradiation is less important because its effects on material properties can be determined in less expensive "coupon" tests.

Other Required Environmental Conditions: (B,G) A magnetic field of appropriate spatial variation and magnitude is required, as well as the same geometrical blanket configuration.

Test Article Size: This test could initially be performed with just a basic blanket model (structure and breeder), but with no heat sources or coolant. This simple test would yield stresses, strains and deformations due to magnetic forces alone to verify calculations and design margins. More complex testing of an act-alike module would be useful is the magnetic stresses are significant. Scaled dimensions of 15 x 50 x 25 $cm^3$ for solid breeders, and 100 x 30 x 10 $cm^3$ for liquid breeders might be sufficient.

Number of Test Articles: (2) Basically one test module would be tested to confirm the design calculations, with possibly a second if design modifications are required.

Test Facilities: Test stands are highly useful for this purpose, although they will miss irradiation effects that may enhance failure. Point neutron sources will be of little use because of serious size limitations and a lack of magnetic field. Fission reactors may provide more test space but are also missing the necessary magnetic field and are, therefore, of limited use.

# II. PLASMA INTERACTIVE COMPONENTS

## II.A BASIC TESTS

### II.A.1 Plasma Interactive Materials Irradiated Properties Measurements

The materials performance of high heat flux components is strongly dependent on the plasma parameters. For future tokamak reactors, questions concerning the most suitable edge plasma regime, and whether it can be realized, will be unresolved for a long time. Therefore the variety of candidate materials, material combinations, and special treatments is large, and the property data base is scarce or nonexistent. The goal of the materials test program is to establish this data base, with the testing needs in five areas: 1) plasma side material development; 2) heat sink alloys development; 3) fabrication and bond development; 4) irradiation effects of high heat flux materials; and 5) selection and development of refractory metals for high heat flux components. The tests described here focus on bulk properties - not the the surface properties for plasma side materials. These tests can use standard techniques for measuring mechanical and thermophysical properties, including irradiated properties.

Importance of Neutrons: (Critical) Neutron damage is of particular importance with respect to swelling and creep behavior, gas production (He), loss of ductility and fracture mechanics for both heat sink materials and heat sink/plasma side materials composites. A key current problem is the effect of low neutron doses on the integrity of bonds in composite materials.

Importance of Fusion Spectrum: (High) The $(n,\alpha)$ cross-section increases drastically with neutron energy for many materials (helium production is responsible for material swelling). The dpa rate also increases with neutron energy, but it is not clear that the dpa rate is a sufficient measure for material damage when extrapolating from fission reactor conditions to conditions anticipated in fusion high heat flux components. Therefore supplementary materials test in a fusion spectrum is very important.

Other Required Environmental Conditions: These involve high temperature testing and post irradiation tests in hot cells. The temperatures range from room temperature to ~750°C for heat sink materials and to ~1000°C for plasma side materials.

Test Article Size: ($1 \times 1 \times 5$ $cm^3$) The majority of the test specimens are small (typically less than 1 cm diameter and 5 cm length) and multiple specimens can be flexibly arranged in a test assembly with respect to coolant and flux goals. If tests are performed in fission reactors, the test assembly size might be typically 10 cm in diameter and 30 to 60 cm long. Fabrication and bond development may ultimately require large probes of the order of 100 x 100 $cm^2$ for non-irradiation tests.

Number of Test Articles: (4500) Assuming 50 different materials (including alloys and composite materials) and an average of two thermomechanical treatments for each material gives 100 material variations. If each variation is irradiated at three temperature levels, and up to three fluence levels, then we obtain a rough estimate of 900 conditions. Allowing a further 5 articles since some properties such as tensile strength will require destructive testing, then the total requirement is about 4500 test articles.

Test Facilities: Non-fusion test facilities are very useful because of their flexibility, test condition controllability and high availability. Many of the tests involved are standard non-irradiation tests, which have to be performed in appropriate test stands, i.e. measurements of physical properties, high temperature mechanical properties, fatigue tests, quality control measurements for fabrication techniques, corrosion tests, metallurgical tests. Most of the irradiation tests can be performed in fission reactors, preferably in fast reactors. Testing techniques for temperature and spectrum control as well as in-pile creep measurements are readily available. The effect of very high energy neutrons, (up to 14 Mev), which are not available in fission reactors, can be investigated in point neutron sources in a limited scale. If high component availability has to be guaranteed, there is more need for tests in point neutron sources or fusion facilities in order to avoid unforeseen spectrum effects.

## II.B SINGLE EFFECT TESTS

### II.B.1 Plasma Materials Interactive Effects Experiments

Plasma materials interaction (PMI) processes govern the material selection for high heat flux components, most importantly for the plasma side materials, but also with certain implications on heat sink materials. Of most concern is the surface erosion (physical sputtering, arcing, chemical erosion and blistering) due to its effect on component related lifetime and plasma impurity generation. Another point of interest is the tritium storage in and permeation through the wall. The tests should focus on candidate plasma side materials including low-Z candidates Be, C, SiC, and BeO, and high-Z candidates W, Ta, V, Nb, Mo, and possibly others. The purpose of the PMI effects tests is to broaden the data base and models for the processes involved in predicting erosion rates, impurity generation and tritium losses in high heat flux components.

Importance of Neutrons: (Low) For physical sputtering, arcing, chemical erosion and helium implantation neutron effects are not believed to significantly alter the PMI processes, at least not at low to medium fluence levels (possible influence of displacement damage affecting bubble nucleation?). For tritium permeation, supplementary tests with neutron damaged probes seem to be important.

Importance of Fusion Spectrum: (Low) Since neutrons are not believed to be important, the fusion spectrum is also not significant.

Other Required Environmental Conditions: (PMI,Vac,B,$H^3$) A well defined plasma stream with high density and variable particle energy and species is needed for the sputtering and arcing tests. The other phenomena also may require a plasma source rather than simply an ion beam since there may be synergistic effects due to the electrons. To measure sputtering/redeposition and arcing effects, a variable magnetic field is needed. Though most of the tritium permeation tests will be performed with H and D, the inclusion of tritium might be desirable in later experiments.

Test Article Size: (10 x 10 x 5 $cm^3$) Typical probe sizes may be 10 x 10 $cm^2$ facing the plasma and about 5 cm thick including the coolant channels. For special purposes such as sputtering at shallow angles, redeposition and leading edge designs the probes can be much larger (about 20 x 100 $cm^2$).

Number of Test Articles: (300) Accounting for the variety of effects to be measured, probe material variations, and surface treatment variations, about 150 different probes would be needed. Plasma energy, species, angle, fluence and other test parameters will have to be sporadically chosen and are not included. These might be estimated as requiring at least twice as many test articles, on average.

Test Facilities: Plasma test stands are the appropriate tools for PMI probe tests aimed at studying the phenomena and developing calculational models. Size and particle flux limitations will ultimately require device tests. Point neutron sources and fission reactors are not applicable due to the absence of plasmas.

### II.B.2 SURFACE COATING BOND INTEGRITY EXPERIMENTS

The integrity of surface coating/substrate bonds is a major concern due to differences in their intrinsic properties, such as thermal expansion, and the large temperature differences and fluences expected in fusion reactors. These tests would subject various coating/substrate material and bond processes to mechanical and irradiation testing to determine bond lifetime. Measurements would include direct observations of flaking or bond separation in the worst cases, and post examination by sectioning to determine smaller amounts of debonding.

Importance of Neutrons: (High) The importance of neutrons in testing the integrity of bonds in coated high heat flux components is high due to the sensitivity of the bond regions to changes in the physical, thermal, and mechanical properties of the coating and substrates. Since the bond region is typically a thin "joining" between two different materials, differences in thermal expansion, swelling rates, etc., will impose stresses over the bond region. Neutron induced reductions in properties such as the ductility and fracture toughness of the coating can lead to premature debonding and coating failure. Neutron induced changes in the thermal properties can result in larger temperture differences and resultant higher interface stresses.

Importance of Fusion Spectrum: (Medium) The importance of neutron spectrum is rated medium when testing bond integrity. While the gaseous and solid transmutation products from the high energy fusion spectrum will impact the bond region, it is anticipated that this may be less critical than the defect-produced changes in the material properties.

Other Required Environmental Conditions: (PMI,q,Vac,$\sigma$,p) The testing of the bond integrity requires plasma, vacuum and stresses (thermal and pressure).

Test Article Size: Bond integrity tests can be carried out on bayonet probes into the plasma chamber. The size of the test articles is estimated to be 2 x 2 x 0.5 $cm^3$

Number of Test Articles: Assuming 5 candidate coating materials, 5 candidate heat sink materials and 2-4 bonding/cooling schemes, a total of 50-100 test articles will be required, with a nominal value of 100 assumed.

Test Facilities:

Test Stands: Test stands consisting of ion and/or electron beams are of high value in the development of HHF bonds. Such test stands can accurately simulate the surface heat and particle fluxes that will be experienced in fusion devices. Since millimeter thick coatings are required, the stresses in the bond region resulting from the temperature gradients are virtually independent of the particle species that deposits the energy. Therefore, both ion and electron beam systems are useful in studying bond integrity. The principle limitation is the lack of neutrons which are important due to their effect on the material properties of the coating and substrate which directly effect the bond integrity.

Point Neutron Sources: Point neutron sources are of medium importance in the testing of bond integrity. The major limitation is the size of the irradiation volume. Useful testing can, however, be carried out on small bonded specimens in point neutron sources particularly when studying the microstructure in the bond region.

Fission Reactors: Fission reactors are considered to be of high usefulness in studying neutron effects on HHF bond integrity because composite specimens of prototype size can be irradiated in sufficient quantities. The major limitation is the low energy neutron spectrum which will not produce the correct type or amount of nuclear transmutations.

### II.B.3 Plasma Disruption Induced Surface Erosion Experiments

Since the short term but very high thermal load associated with plasma disruptions can melt and evaporate surface layers, tests are needed to determine the extent of the surface erosion and its subsequent settling or flow. The extent of evaporation would be monitored by weight loss measurements, and the extent of melting, melt layer stability, and form of redeposited vapors determined by post-test examination of sections through the surface.

Importance of Neutrons: (Low) Neutrons have little direct impact upon the interaction of the plasma and structure. Neutrons may play a secondary role, however, in the weakening of the structure and the eventual failure as a result of the plasma-wall interaction.

Importance of Fusion Spectrum: (Low) Since the neutrons have no direct role, the importance of a fusion spectrum is also low.

Other Required Environmental Conditions: ($q$,PMI,$T$,Vac,$B$,$\dot{B}$) The other required environments are surface heat flux, plasma interaction, vacuum and magnetic field. The surface heat flux and initial substrate temperature control the surface temperature and thus the melting, vaporization and mobility of the affected surface. The plasma should be typical in terms of particle species and energies. The magnetic field and vacuum are important since they influence the evaporation, redeposition and motion of melt layers that may occur.

Test Article Size: Surface erosion during disruptions can be simulated using specimen tests, with a size of about 2 x 2 x 0.5 $cm^3$. A set of these specimens can be mounted on a movable arm which can vary the distance between the coupons and the plasma center.

Number of Test Articles: (160) The major test parameters are the plasma thermal load, plasma characteristics, magnetic fields, and time scale of the disruption. Assuming at least four values for each of these, the total number of test conditions is 16 for each first wall alloy/coating combination. Since many of these tests may result in damage to the surface, or since destructive evaluation of the surface microstructure may be required after each test, the number of test articles is also about 16 per candidate surface structure. Considering 10 candidate surfaces at this point in the development, then the total number of tests is about 160.

### II.B.3 High Heat Flux Component Critical Heat Flux and Heat Transfer Experiments

Under heat flux conditions expected for plasma interactive components, there is a need for better correlations of heat transfer, Critical Heat Flux and pressure drop, especially for 0.1-0.3 $MW/m^2$ under one-sided heating. These tests are simple thermal-hydraulic tests of heat transfer under fusion conditions. Measurements include monitoring the coolant bulk temperature, component bulk temperature, component surface temperature, and the overall pressure drop. The onset of critical heat flux may be detected by a sudden rise in component temperature.

Importance of Neutrons and Fusion Spectrum: (Low) The primary influence of neutrons is as the source of bulk heating, which is secondary heat source in these components and may be simulated by non-nuclear sources anyway.

Other Required Environmental Conditions: (q,Q,G) The important parameters are the surface heat flux, and the bulk heating. These must be tested in prototypical geometries, including any heat-transfer enhancements, to establish useful design correlations.

Test Article Size: A typical test article would consist of a short length of one or two coolant channels, possible 1 x 10 x 1 $cm^3$.

Number of Test Articles: Since each test article could be used repeatedly, only different coolant channel geometries need be tested, leading to perhaps 20 test articles.

Test Facilities: Test stands are ideal for these tests, facilities such as ASURF at Westinghouse or PMTF at Sandia can supply the required test conditions. Neutrons would unnecessarily complicate the tests.

### II.B.4 Tritium Surface Re-emission Control Experiments

Tritium adsorbed or implanted on in-vessel components may be released during maintenance, with the potential for contaminating the reactor room and at least complicating the work. Tests are needed to establish the re-emission rates and the control of surface inventory. Measurements would include tritium inventory after exposure to tritiated plasma and neutrons, and measurements of the time evolution of adsorbed or implanted tritium after various surface cleaning techniques.

Importance of Neutrons: (Medium) Surface re-emission depends on surface conditions, which may be somewhat dependent on radiation damage. Bulk tritium trapping, perhaps in helium bubbles, may also be a factor. However, the overall inventory and surface conditions will likely be dominated by the plasma, so the importance of neutrons is rated Medium.

Importance of Fusion Spectrum: (Medium) To the extent that neutrons are important, there may be spectrum effects. However, it is plausible that the key variables are dpa and He which may be adequately simulated in non-fusion devices.

Other Required Environmental Conditions: (T,PMI,Vac) Tritium inventory re-emission will be a strong function of surface temperatures and surface damage due to plasma effects. The presence of a vacuum also influences the net tritium flow. Procedures to limit tritium re-emission by baking or surface cleaning would need to be tested, requiring additional plasma side test equipment.

Test Article Size: These tests can be performed on small plates exposed to a plasma source of about 100 $cm^2$ surface area to minimize end effects. Perhaps 2 cm thickness would be sufficient for internal coolant passages for temperature control.

Number of Test Articles: With 5 different coating/substrate surface materials (different components, as well as design differences for given components), and 20 combinations of surface and irradiation damage, the total number of test articles is about 50.

Test Facilities: Test stands are useful for non-irradiated tests, although the plasma conditions may not be prototypic. A better "test stand" might be non-DT fusion devices, or machines like TFTR and JET where small amounts of tritium are used. Point neutron sources and fission reactors have limited usefulness for in-situ testing because they cannot accommodate plasmas, but may be useful in irradiating test articles prior to tritium exposure.

## II.C MULTIPLE EFFECT/MULTIPLE INTERACTION TESTS

### II.C.1 RF Transmission System Fusion Environment Effects Experiments

These tests address the behaviour of major RF transmission system elements in the fusion environment. Measurements would include electrical resistivity, mechanical properties, and transmission efficiency.

Importance of Neutrons: (High) Neutrons are an important element in testing of RF transmission systems. Heating, transmutation effects on resistivity, degradation of spacer integrity and volumetric variations of these are important aspects affecting performance. Breakdown can also occur from electron emitting reactions of secondary gammas.

Importance of Fusion Spectrum: (High) A fusion spectrum is important since the higher energy neutrons cause higher rates of transmutation and gamma production.

Other Required Environmental Conditions: (G,PMI,T,q,Q) The geometry, temperature and transmitted power level are the remaining environmental considerations. The plasma interaction may affect the ceramic insulator resistivity.

Test Article Size: ($10 \times 10 \times 50$ $cm^3$) Tests involving cooling, peak power or impedance measurements should adequately be addressed in 1/2-meter long transmission length. Attenuation measurements may require longer samples.

Number of Test Articles: About 20 variations of temperatures, geometry, voltages and flux levels will provide sufficient operational information.

Test Facilities: Test stands should prove useful for all but the neutron degradation issues. The availability of a gamma source would benefit testing of breakdown related phenomena. Point neutron sources are limited to low fluence testing of transmutation reaction consequences. Fission reactors could be used for small scale testing of spacer structural integrity and resistivity variations with fluence.

## II.C.2 Rf Window and Feedthrough Performance

These tests address the behavior of the RF window and feedthrough components in the fusion environment. Synergistic effects, and especially the interaction of structural changes (damage microstructure, swelling) with electrical properties (resistivity, dielectric breakdown strength, loss tangent) are of primary concern. Measurements would include electrical resistivity, mechanical properties, and transmission efficiency. Since these are sensitive to ionizing flux as well as fluence, there is a need to monitor these quantities during irradiation.

Importance of Neutrons: (High) Neutrons are required for heating and damage. Vacuum integrity of windows is threatened by thermal stresses and by microcracking. Neutron induced changes in the dielectric constant and electrical conductivity can increase the reflected power and the absorbed power in the windows.

Importance of Fusion Spectrum: (High) There is speculation that ceramics may be very sensitive to differences between a fission and fusion spectrum. Until this is resolved, the importance must be considered as high.

Other Required Environmental Conditions: (Q,frequency) Important test features are the frequency of the transmitted wave for dose rate dependent measurement of the loss tangent, and the heat source magnitude and distribution (surface and volumetric).

Test Article Size: (10 x 10 x 20 $cm^3$) Windows are at thicknesses in near multiples of half wavelengths for optimal transmission. For ICRH, one-half of a wavelength is too long for a practical window and thin windows must be used. In all cases lengths less than 20 cm are needed with cylindrical outer diameters of the same order.

Number of Test Articles: Two materials at three frequencies and three dose levels would result in around 20 test conditions.

Test Facilities: Test stands could be useful for dose rate sensitivity studies using intense gamma-ray sources. Otherwise, only limited information can be obtained. Point neutron sources can provide microstructural information for correlating spectral differences in fission and fusion spectrums on these sensitive components. Fission reactors can provide very relevant data for all design considerations. Spectral differences would remain the outstanding technical issue.

## II.C.3 HHFC Thermomechanical Element Experiments

Since high heat flux components push the limits of thermal-hydraulic and structural design simultaneously, the design and testing of these components must be accompanied by a number of smaller element tests that seek to demonstrate basic thermomechanical behaviour. These would include critical heat flux measurements under the appropriate geometry, effectiveness of heat transfer enhancement methods, and demonstration of coolability under 1-10 $MW/m^2$ heat flux conditions. Measurements would include bulk temperature rise, surface temperatures (external by pyrometry, internal by thermocouples, perhaps), strains, the presence of two-phase flow or boiling and the onset of burnout (changes in coolant density, changes in turbulence or noise levels). Post-test examination could check surface damage, crack growth and failure modes.

Importance of Neutrons: (Medium) The lifetime of these components may be limited by the harsh heat flux and plasma interactions as much as or more than by radiation damage, although this certainly hastens the failure. Thus, it is important to assess the thermal effects even in the absence of radiation, and then to consider neutron damage as a further factor.

Importance of Fusion Spectrum: (Medium) Again, it is important to perform thermal and plasma effects tests in the absence of radiation to understand basic phenomena. The significance of neutron energy on radiation damage in candidate HHFC materials is difficult to assess at present, and is given an overall Medium importance here.

Other Required Environmental Conditions: (q,PMI,p) The most important parameters are the surface heat flux and the plasma interaction. Coolants should also run near the design pressures since the resulting stresses and the coolant behaviour (e.g., onset of boiling) are important.

Test Article Size: (10 x 10 x 5 $cm^3$) These tests would typically be much smaller than full modules or even sections of modules, but would explore the behaviour of small channels or cooled surfaces over dimensions at least as large as presently available high heat flux or plasma test stands can provide, typically 10 x 10 $cm^2$, with 5 cm for the coolant channels. Additional space would be needed for the inlet and exit manifolds and other hardware.

Number of Test Articles: (100) Due to their simplicity, many of these tests should be performed to aid in the design of the complete components. Considering the number of candidate heat sink materials, surface coating materials, surface bonding processes, mechanical design of the surface, coolants, and coolant flow enhancements, it is likely that about 100 test articles will eventually be needed.

Test Facilities: Test stands are particularly useful for these tests in the absence of a need for radiation damage. High heat flux and plasma facilities are presently available for interesting heat fluxes and dimensions to provide useful information. Point neutron sources are difficult to use directly in that space limitations prevent high surface heating and plasmas, but might be useful for pre-irradiating samples in fusion-like spectra. Similarly, the primary usefulness of fission reactors would be to provide high fluence levels of radiation damage.

## II.D PARTIALLY INTEGRATED AND INTEGRATED TESTS

### II.D.1 Limiter/Divertor Performance Verification

The choice of limiter or divertor and the particular design of the exhaust system are intimately related to the capability of achieving favorable plasma edge conditions. These in turn influence the helium removal as well as other impurity introduction into and removal from the plasma. These fundamental physics and design issues can only be resolved in a steady state DT burning tokamak plasma. From the viewpoint of the limiter or divertor design, one can distinguish between short-term performance tests (showing the adequacy of the overall design with respect to heat removal, pumping capability, plasma burn characteristics, operating transients) and lifetime performance tests (which add erosion effects, material degradation, swelling and creep deflections, and fatigue phenomena). The short-term tests can be performed in physics test devices with sufficiently long burn times (e.g. TFCX), whereas, the lifetime performance tests require an ETR type test facility with substantial neutron fluence. The latter would be at the same time proof tests for most of the other plasma interactive components issues.

Importance of Neutrons: (High) Neutrons are not needed in the short term tests, which are considered to be the majority and the more flexible part of the whole test program. During this phase, the neutron damage information will be obtained from separate material properties tests and from the thermo-mechanical module tests. However, neutrons will be most definitely needed for the ultimate lifetime tests.

Importance of Fusion Spectrum: (High) This corresponds to the importance of neutrons described above.

Other Required Environmental Conditions: (PMI,G,q) A steady state DT burning tokamak approaching prototypic plasma conditions will finally be needed. However the whole chain of fusion test facilities must contribute to an increasing understanding of plasma edge control and pumping capability in tokamaks.

Test Article Size: The test object is the exhaust system and the whole tokamak plasma. Therefore, it is expected that the tests can only be performed with a complete exhaust system. No additional test volume would be necessary.

Number of Test Articles: (3) It is anticipated that 5-10 different limiter/divertor sets will have to be tested, with perhaps three under significantly long pulse conditions. Minor modifications, adjustments or other parameter variations are not included.

Test Facilities: Point neutron sources and fission reactors are not applicable. Plasma test stands are useful in an early stage to investigate particle transportation (pumping) in a fundamental and flexible way. Fusion facilities are the primary test facility, however.

## II.D.2 Verification of High Heat Flux Component Thermomechanical Behavior under Complex Loadings

In high heat flux component design, particular for limiters and divertors, safety margins with respect to thermal-hydraulic performance (critical heat flux, flow distribution, temperature rise) and mechanical behavior (primary and secondary stresses, cycling, deflections, erosion) are small and the need for testing large. Module tests need to be performed in several stages with increasing complexity and size. Initially, they should verify the thermal-hydraulic behaviour, possibly with a non-nuclear heat source, as well as materials and fabrication aspects. Mechanical tests concentrating on aging and fatigue phenomena in other modules can be conducted in parallel. Finally the synergistic thermomechanical effects have to be tested in integrated module tests.

Importance of Neutrons: (Medium) Neutron damage is important with respect to the mechanical behavior and will be needed in the integrated module tests. The thermal hydraulic tests, however, and many of the mechanical module tests can reveal valuable information about the design, fabrication techniques and overall performance without neutrons.

Importance of Fusion Spectrum: (Medium) The effect of fusion spectrum on neutron damage is not well understood for most of the HHFC candidate materials. The materials test program will provide a better understanding. According to present knowledge the effect of fusion spectrum cannot be ignored.

Other Required Environmental Conditions: ($Q$,PMI,$p$,$\dot{B}$) The test environment must include high surface heating, plasma materials interactions, internal pressure stresses, and magnetic field transient forces. Extensive heating of a large surface can possibly only be achieved by an energetic particle stream in a high heat flux test stand. The mechanical loading conditions at critical joints should be simulated by either thermal cycling or by mechanical load mechanisms. The study of the mechanical response to plasma disruptions requires transient magnetic fields.

Test Article Size: (100 x 100 x 30 $cm^3$) The test module should comprise a significant portion (possibly bordered by lines of symmetry) of a full size limiter or divertor section. The module tests will be preceded by appropriate tests of smaller size.

Number of Test Articles: (8) The number of test modules with significantly different design features (e.g., coolant channel pattern, manifold arrangements, support structure, heat sink/plasma side material combination) might be in the order of eight to ten. This number does not include ad hoc modifications in the course of the test. Neither does it account for the numerous accompanying or preceding element tests.

Test Facilities: High heat flux test stands are the appropriate tools for elements and module tests. However the lack of neutrons limits their usefulness to non-irradiation tests. Point neutron sources are not applicable due to their narrow size limitations. Fission reactors cannot provide the size and surface heat load required for module tests. The thermomechanical HHFC development requires a flexible and broad stepwise non-fusion test program up to the level of the these module tests, but definitely needs performance tests in fusion facilities such as TFCX for short term effects and ETR for lifetime performance, including radiation damage effects.

### II.D.3 Plasma Erosion Product Transport Experiments in Vacuum Chamber and Exhaust

The high particle and neutron fluence on first wall, limiter and divertor will cause substantial sputtering and redeposition of activated and non-activated material. The amount of relocated material in a DEMO type reactor has been estimated to be several $m^3$/yr, most of which will probably deposit near its origin. Nevertheless, the gross material transport is substantial. The physical and chemical transport, deposition rates in duct-chamber systems, and release in transients or during maintenance have to be studied. The experiments could be performed in two categories: (1) bulk physical transport processes for large amounts of essentially non-activated material (transport lengths, paths, channel plugging); and (2) surface chemistry driven phenomena important to the smaller amounts of activated material (including tritium) with regard to safety issues. Measurements include direct visual observation of exposed surfaces, weight loss/accumulation measurements on probes or vacuum system filters, spectroscopy of type and density of impurities in the plasma edge, and activity measurements of activated material transport.

Importance of Neutrons: (Medium) For the physical transport tests, the importance of neutrons is low, since the transport processes are not affected by neutrons, although the presence of activated material may make the measurements easier. Also many of the surface chemistry tests can be done with non-active simulation isotopes. Neutrons might be needed to assess the actual type and amount of activation products, and because surface damage related effects may contribute to the in-vessel debris.

Importance of Fusion Sectrum: (Medium) As with the overall importance of neutrons, the bulk of the transport processes should be plasma controlled and independent of neutrons. To the extent that activation and surface damage (e.g., blistering from gas production) are of concern, then higher energy neutrons are probably needed.

Other Required Environmental Conditions: (PMI,B,T,Vac) Plasma materials interaction in a magnetic field govern sputter/redeposition processes and are therefore indispensable for the transport processes. For the surface-related processes, the simulation of the temperature field and the surface chemistry is important. Both test categories require a large vacuum chamber.

Test Article Size: (fusion device) A typical vacuum chamber/exhaust duct system has to be simulated, possibly in a 1/3 to 1/2 scale, probably several $m^3$ in volume. However, since plasma-related transport and redeposition are probably very important, a prototypical fusion plasma device is needed, although not necessarily a DT-burning one. However, any fusion device capable of providing high levels of heating and long pulses would probably already have an exhaust system, so this would not impose additional test volume requirements.

Number of Test Articles: (3) It is likely that measurements in a few machines with appreciable mass transport will be needed to understand the transport processes and rates, although they should be fairly different in conditions, configuration or size to allow extrapolation to reactor conditions.

Test Facilities: Simple plasma test stands offer simplicity and potentially high erosion rates, but will be strictly limited by their simulation of reactor plasma confinement and conditions. Non-DT fusion devices would simulate the transport, but may be limited in the amount of sputtered material. Point neutron sources and fission reactors are not applicable. The issues should also be pursued in any fusion test facilities. Tests in an fusion facility with high particle flux and fluence would be desirable.

### II.D.4 Measurement of First Wall Heat Flux Variations

These tests will instrument a DT device to determine variations in space and time of the heat source, as needed to adjust the local first wall design. Measurements could include bolometry and infrared camera observations of the vacuum chamber surfaces, and thermocouples imbedded in the vessel.

Importance of Neutrons: (Low) Neutrons are not important in determining the first wall heat source uncertainties due to local hot spots (time or space), including disruptions, since surface heating is dominant or any neutronic related variations are generally spread out over wide areas (e.g., outboard versus inboard in a tokamak).

Importance of Fusion Spectrum: (Low) Neutron spectrum is not important for heating variations.

Other Required Environmental Conditions: (PMI,G) The important conditions are the plasma configuration and the plasma/wall interaction.

Test Article Size: A prototypical DT device is necessary to provide realistic first wall load distributions. No additional test volume would be needed.

Number of Test Articles: A hot, long pulse and preferably DT device would reduce the uncertainties in the first wall heat flux time and spatial distributions, especially if operated over a range of plasma conditions.

Test Facilities: The first wall hot spot and disruption load distributions cannot be resolved without a fusion device. A DT-burning plasma in a prototypical reactor device is necessary to provide information that can allow tailored first wall modules or armor to be placed where needed, with minimal impact on the overall tritium breeding ratio. Present devices (including TFTR, JET, MFTF-B and JT-60) will provide some information, but may not operate long enough (length of pulse, number of DT pulses) or be instrumented enough to resolve these heat flux distribution issues. Thus, there is an appreciable need for a DT-burning test device, since the DEMO first wall may not have much room for design conservatism.

### II.D.5 RF Launcher Performance Experiments

These describe tests on the performance of RF launchers. The nature of the launcher and plasma interaction will eventually require fusion device operation. Measurements during launcher development will include power transmitted to plasma, power absorbed in the launcher structure, launcher temperatures, and post-test exam of some components for plasma and neutron-related degradation.

Importance of Neutrons: (High) Launching structures may be directly exposed to the plasma, so neutron exposure will be severe. Neutrons will significantly impact the cooling requirements of the launching structure both by direct heating and through resistivity changes resulting in increased power absorption. The changes in resistivity will have a minor effect on impedance matching. Structural materials will experience mechanical property variations that could be important during transient operation. Neutrons also threaten welds and joining interface integrity.

Importance of Fusion Spectrum: (High) The fusion spectrum effects are most notable for resistivity changes due to transmutation reactions and for damage to sensitive interface areas.

Other Required Environmental Conditions: (PMI,G,Q,q) A DT fusion device offers the only complete environment for launching structure testing. The critical nature of the physics of absorption and plasma response coupled with the plasma interactive effects on the exposed structure require more than a plasma test stand.

Test Article Size: Launching structures can require about a 1 $m^2$ area on the surface of a DT fusion device, with a transmission line of comparable area running outside of the device. If the device was RF heated through these launchers, then no additional test volume would be needed.

Number of Test Articles: (10) While it is probably not practical to test loop antennas, waveguides and cavity launchers in one DT fusion device, they are representative options for launching structures. More likely, test conditions will center on geometry, Faraday shielding and surface effects for a total of around 10 variations.

Test Facilities: Test stands have limited applicability for testing RF launchers. Fabricability, cooling, and power capabilities could be demonstrated, but the important test issues revolve around energy coupling and its consequences on stability and neutron irradiation effects. Point neutron sources could find applicability in transmutation consequences at low fluence. However, the majority of issues would remain unresolved. Materials damage could be tested on a smaller scale to obtain mechanical property information. The obtained data would be useful, but limited. Basically, plasma interactive testing in a fusion facility is felt mandatory even for 10% availability goals for DEMO, due to the integrated nature of the component and the plasma interaction.

### II.D.6 Development of Methods for Limiter and Divertor Maintenance

The numerous procedures involved in the replacement and/or repair of a limiter or divertor segment have yet to be developed and tested in a prototypic environment. This is very design specific and requires an advanced design state of the demonstration reactor. However, many procedures can be standardized and should be developed in separate module or component mock-up tests. These involve, for example, remote handling and leak checking of pipe joints or large vacuum boundary seals, replacement of thermal insulation, handling of effluent contaminants from removed components, repair of worn-off parts, in-situ leak detection and repair, in-situ erosion measurements, and module geometry measurement and alignment methods.

Importance of Neutrons: (Low) Neutrons cause the activation problem and determine the amount of remote handling needed. However available calculation methods are sufficient to estimate the isolation necessary in these tests. A neutron test environment is not needed.

Importance of Fusion Spectrum: (Low) Since neutrons are not needed in the test, the spectrum is of no concern.

Other Required Environmental Conditions: Besides sizeable mock-ups and possibly an inert gas or evacuated atmosphere (to check the equipment), no special environmental conditions are foreseen.

Test Article Size: Tests have to be performed with full-size parts, modules and components according to the particular test goal. In some cases a partial system mock-up might be needed to simulate the accessibility. A sector mock-up of 3 x 3 $m^2$ cross-section and 3 m width might be needed (30 $m^3$), with more floor space for the access entry point and the operator console.

Number of Test Articles: (10) Different mock-ups might be needed for appreciably different sectors or different devices, perhaps three. Possibly several major modifications to these mock-ups might be made for different procedures or maintenance approaches. Small modifications may be tested in a single configuration. For instance, developing a welded seal for a particular purpose requires a variety of materials, shapes, welding parameters and so on. The number of such test conditions is not estimated here.

Test Facilities: The maintenance tests will be performed primarily in non-fusion mockups. Point neutron sources and fission reactors are only of interest in the field of material development, e.g. elastomere seals. The program will benefit from experience gained in present and near-term fusion devices.

## II.D.7 Measurement of Vacuum System Load

These tests would verify the gas composition and loads to the vacuum pumping system. Measurements would include gas composition (mass spectrometry), pressure, energy content (calorimetry, rate of consumption of cryogenics in thermal shields?) and throughput (pressure rise and fall on forepump or vacuum side during cryopump operation and regeneration, rate of regeneration?).

Importance of Neutrons and Fusion Spectrum: (Low) Neutrons are not a significant contributor to uncertainties in the actual load on the vacuum system, although it is possible that there is some indirect effect through neutron damage to exposed surfaces affecting recycling, outgassing or sputtering.

Other Required Environmental Conditions: (PMI,G) The uncertainties arise from the complex surface area, surface conditions and treatment, plasma behaviour and divertor operation, which will need to be simulated.

Test Article Size: A prototypical DT device is required to determine the actual loads on the vacuum system, including the interaction between vacuum system and plasma edge conditions.

Number of Test Articles: (3) A small range of device conditions (device configuration and size) is desirable to indicate the range of exhaust conditions. In each case, sufficient operating time under different operating conditions (power, disruptions, startup/shutdown, other transients) is needed to characterize the vacuum system loads and interactions.

Test Facilities: The complex surface geometry and plasma behaviour in a fusion device cannot convincingly be simulated in a test stand. Point neutron sources and fission reactors are not appropriate since there is little need for neutrons and a large need for volume, plasma and vacuum conditions. Extrapolations from present machines (especially TFTR, JET and JT-60), and reasonable conservatism in design should allow the vacuum system to achieve good performance without testing in a new fusion device.

## II.E COMPONENT TESTS

### II.E.1 Vacuum Component Verification

Vacuum science is sufficiently well-established that the issues are more component developmental than fundamental. The primary need is to develop larger-scale vacuum components, with some new features such as separate $H_2$ and He pumping, and tritium-proof seals.

Importance of Neutrons: (Low) Vacuum components are not generally exposed to neutrons. Any direct effect would be heating (by direct exposure, neutron streaming down ducts, or gammas from neutron-activated material) and could be simulated. The amount or type of dust in the system, primarily controlled by the plasma, might be affected by neutron damage to the surface material.

Importance of Fusion Spectrum: (Low) The neutron spectrum is not important.

Other Required Environmental Conditions: The important factors are the nature of the gas (composition, impurities, pressure, energy) and any dust present.

Test Article Size: (150 x 150 x 150 $cm^3$) A full-scale test of a section of the vacuum system is desirable, with perhaps two or three 1 $m^2$ panels to test simultaneous pumping and regeneration through many cycles. A large vacuum tank could also test full-scale valves (1.5 m diameter).

Number of Test Articles: (20) Test conditions should include multiple designs (10 pumps, 10 valves) tested under a range of DT/He ratios, impurity conditions, transients (with variations in pressure, energy and time scale), and multiple pump/regeneration cycles.

Test Facilities: A vacuum test stand would be an effective way to test full-scale vacuum system components. The primary limitation is in uncertainties related to overall integration with the fusion plasma and other systems in an operating environment. Neutrons are not important, so neither point neutron sources nor fission reactors are appropriate. Near-term fusion devices (DT-burning or not) will require and test many features of these components.

# III. SHIELD

## III.1 Shield Effectiveness Experiments in Complex Geometries

These tests aim to improve shielding calculation accuracy in the important areas of streaming and deep penetration, particularly with 14 MeV neutrons. Measurements would include standard neutron dosimetry methods for neutron flux, as well as neutron spectrum. There is some need for instrumentation development here to improve the measurement accuracy consistent with the desired calculational accuracies and the intensities of available neutron sources.

Importance of Neutrons: (Critical) The transport and attenuation of neutrons and their generated gamma rays is the design issue for shield applications.

Importance of Fusion Spectrum: (High) The fusion spectrum is an important feature of shielding effectiveness testing. Deep penetration shield thicknesses are largely determined by the 14 MeV neutrons. Neutron streaming tests can be adequately determined with neutrons of lesser energy.

Other Required Environmental Conditions: Varied geometries are needed for testing. These include thick bulk shields, streaming in access ports, local shielding around very sensitive components and biological shielding. Combinations of these geometries are also important.

Test Article Size: ($50 \times 50 \times 200\ cm^3$) To minimize side leakage of neutrons from the test article, a minimum face $50 \times 50\ cm^2$ would be required for all but local shielding tests. Shielding depths of up to two meters can be important for deep penetration and neutron streaming problems.

Number of Test Articles: The numerous geometries and potential shield materials could lead to many as 50 test arrangements.

Test Facilities: Test stands may only be useful for testing biological shields against gamma sources. The source strength of point neutron sources generally limits them to low attenuation geometries. A well-characterized neutron source is desirable for accurate interpretation of the data. Fission reactors would not allow this detail.

## III.2 Plasma Control Verification through Blanket and Shield

In order to control the plasma, magnetic fields from the control coils located outside the neutron shielding must quickly penetrate through the blanket and shield. This will be accommodated by suitable arrangements of the structure, such as insulating breaks in the vacuum boundary.. In this test, the plasma control will be verified in a complete system with blanket, shield and other connections. Measurements would include time-dependent vacuum magnetic field observations in the core, as well as direct observations of plasma behaviour during operation.

Importance of Neutrons and Fusion Spectrum: (Low) Neutrons may indirectly influence the magneitc field permeation by increasing the resistivity of the structure, degrading insulators or leading to deformations (thermal or swelling) that cause unexpected contacts and current paths. However, these are not presently believed to be important.

Other Required Environmental Conditions: $(G,\dot{B})$ It is important to use the same geometry and magnetic field change time scales.

Test Article Size: A prototypic reactor device is needed, complete with plasma, blanket, shield and magnets.

Number of Test Articles: One or two devices should be sufficient to verify plasma control.

Test Facilities: Since this is fusion device oriented, test stands, point neutron source and fission reactors are not suitable. Some information on blanket module magnetic time constants can be obtained in the tests of blanket response to magnetic transients such as disruptions. Other integrated system information may be obtained from non-DT experiments, though TFTR, JET, JT-60 and MFTF-B and similar devices will not have a full blanket and shield as would be required on DT machines. And even if integral blanket and shield structures were added, the additional complexity would not justify the information and concerns might still remain over the control requirements of ignited plasmas.

### III.3 Development of Methods for Shielded Sector Assembly and Disassembly

The blanket and shield in each sector form a heavy mass (~50 Mg) that must fit tightly together during operation to minimize radiation streaming, yet loosely enough that they will not jam from handling procedures or from distortions occuring during operation. These tests will use a blanket and shield sector to verify assembly and disassembly procedures and tolerances. Actual neutron penetration will be separately measured in a DT device.

Importance of Neutrons and Fusion Spectrum: (Low) Neutrons are not needed to test the basic assembly and dissassembly procedures, although eventually they may impact sector maintenance through swelling or other distortions.

Other Required Environmental Conditions: (G) The primary test requirement is to simulate the sector and access gometry. The appropriate masses might also be needed to check inertia, operator "feel" and equipment capabilities.

Test Article Size: A sector mockup within a factor of 2 of full-scale would be about 4 x 4 $m^2$ across the plasma, and 2 m axial thickness, or about 30 $m^3$ total, plus additional floor space for the operator console.

Number of Test Articles: Only a few such sector mock-ups would be built, to cover different sectors, although they might be modified as experiments and reactor designs progress.

Test Facilities: The appropriate test is a non-nuclear mockup. Some information will also be gained on any fusion experiment requiring shielding inside the magnetic coils. Although neutron-induced activation in a reactor will ultimately require remote operations, activation does not need to be present to test procedures and hardware.

# IV. TRITIUM PROCESSING SYSTEM

## IV.1 Tritium Processing System Verification

a. Component Development

b. System Integration

Some of these issues are component-related and early designs can be tested with hydrogen on a component basis (particularly impurity removal components such as electrolysis cells, getter beds and molecular sieves). However realistic tests with tritium require a loop with inlet and waste streams, tritium pumps and storage, and protection against tritium permeation and leaks. Such tritium loop tests naturally address, at least in part, issues such as waste losses, permeation, instrumentation and system integration.

Importance of Neutrons: (Low) The Tritium Processing System is not directly exposed to neutrons. There may be some indirect effect through the amount, type and activation of impurities brought into the tritium systems from neutron-exposed regions. These should, however, be filtered out early.

Importance of Fusion Spectrum: (Low) Neutrons are not considered important.

Other Required Environmental Conditions: ($T,p,C,I,v,H^3$) The tritium components and systems should be tested under realistic inlet conditions (temperature, pressure, composition and throughput).

Test Article Size: (2 $m^3$ glove box for components and small loop tests, TSTA room size for full-scale system test) It should be possible to test full-scale components (2 cm ID transfer lines, 5000 $cm^3$ typical dimensions at TSTA). Simple component and loop tests at the 100 Ci/d level can address basic design issues, but full tests with 1 kg/d equivalent throughput such as TSTA are needed to demonstrate system safety and availability prior to installation on DEMO.

Number of Test Articles: The system should be operated for long enough to determine component and system behaviour, failure modes, and rates (at least one year), with various component designs, and with a range of inlet conditions (with variations in temperature, pressure, composition, impurities and throughput representing present uncertainties in plasma performance and blanket choice). Considering the number of components, there may be about 100 component tests needed, but only perhaps 3 large-scale system tests.

Test Facilities: Since the tritium processing system is outside the fusion environment, the entire system can be setup and checked out on a test stand. The limitations are due to uncertainties in the actual inlet conditions, which depend on the fusion device operation, and on any interactions with other fusion system components (with respect to possible failure modes). Neutrons are not needed for the tritium system itself, so point neutron sources and fission reactors are not directly useful. However, if a large-scale breeder blanket test was conducted with appreciable tritium generation, it would be very useful to couple a tritium processing loop into the test.

## IV.2 Liquid Breeder Tritium Extraction Verification

These tests would confirm the extraction processes to remove tritium from circulating liquid breeders. Measurements would include flow rates, temperatures and tritium activity both into and out of the extractor and for both the liquid breeder and the extraction fluid. Samples of the liquid breeder and extraction fluid might be separately removed and analyzed for impurity content to determine the degree of separation of the two fluids.

Importance of Neutrons: (Low) Neutrons are not necessary to test the operation of the external tritium extraction system used with liquid breeder blankets. Tritium may be injected from any source, although neutrons may be the most convenient. Neutrons may, however, affect the impurity levels in a realistic loop, and there may be some benefit from passing the inlet line through a neutron field if the uncertainties in impurities cannot be bounded and shown to be unimportant for tritium extraction.

Importance of Fusion Spectrum: (Low) Neutrons should not affect the operation of the external tritium extraction system except as noted above.

Other Required Environmental Conditions: (I,T,p,v) The tritium extraction system should be tested with a wide range of possible impurities, and under realistic temperatures, pressures and flow velocities.

Test Article Size: (2 $m^3$) The test should be of a full component or a full-scale cell of a commercial reactor extractor. Exclusive of the piping, pumping, storage tank and so on, the basic extractor cell may be very roughly on the order of 2 $m^3$ in volume.

Number of Test Articles: Possibly 10 different impurity compositions and levels, and 10 combinations of pressure, temperature and flow rate would comprise the test matrix for a given design. At least one test should be run to long times. Depending on the extractor design, the liquid breeder conditions (pressure and temperature) in the extractor may be controlled independently of the primary loop conditions, which could reduce the number of p,T,v combinations to check. A total of 4 test articles is plausible allowing for some evolution of the designs with the experiments.

Test Facilities: Separate liquid metal test loops with externally injected tritium should be quite sufficient to resolve all but possibly interactive or neutron-related effects. These would most likely show up as unexpected levels or types of impurities, and a sufficiently robust design and test stand program should verify a substantial safety margin on these uncertainties. Point neutron sources and fission reactors are not useful except if they are used to generate tritium and any neutron effects in a loop entering a tritium extraction test stand. Point neutron sources might even then be limited by their intensity.

## IV.3 Tritium Monitoring and Accountability Experiments

These tests would address questions related to the location of the tritium inside the device. They require testing for the tritium inventory in various components, measuring tritium permeation rates, monitoring overall tritium losses, and the development of models and instruments to provide real-time indications of the tritium. There are a variety of existing hardware for measuring tritium, although these could use some improvement in discrimination ability or accuracy in a fusion environment.

Importance of Neutrons: (High) A major concern for monitoring tritium is the effect of radiation damage on surface barriers, and on producing trap sites to hold the tritium, as well as on the monitoring instruments themselves.

Importance of Fusion Spectrum: (High) Although the importance of spectrum on permeation, trapping and instruments is not well-known, there are enough concerns regarding the high gas production, activation, gamma production and material damage that the spectrum has a High importance.

Other Required Environmental Conditions: ($\gamma$,PMI,T,p,G) Many factors may influence the tritium inventory and transport, and the instrumentation accuracy. However, of particular concern are the background gamma level, plasma interaction related inventory, and overall geometry, temperatures and tritium partial pressures.

Test Article Size: A range of test articles is needed, from small specimens exposed to tritium, to large-scale components. However, many of these tests can be obtained in other tests such as permeation in plasma interactive components. Here we are more concerned with monitoring tritium at the component level. Typical dimensions might be on the order of 100 x 100 x 50 $cm^3$, for significant fractions of the components and to allow full scale monitoring instruments to be tested in typical conditions.

Number of Test Articles: Approximately 10 tests for different components might be needed. These would have to examined in post-test assays to determine the tritium content.

Test Facilities: Test stands would be used to develop and benchmark tritium monitoring instruments, including gamma background, but have neither adequate plasma nor neutrons to resolve related questions. Point neutron sources could test 14 MeV neutron effects on the instruments and on small samples, but lack the volume to properly irradiate components. Fission reactors could also take appreciable sized components out to high fluence, but could not test plasma related inventory. DT device are the preferred route to properly address these issues since representative components would be used, and since tritium can be monitored at all levels of interest for establishing accountability - at the plasma interface, at the blanket output, and at the outer boundary of the nuclear island.

## IV.4 Tritium Permeation and Leakage Experiments from Coolant and Purge Loops

Operational losses occur from leaks or minor spills of fluids containing radioactivity. The extent of the losses is determined by the effectiveness of fluid processing systems and leak rates of valve, seals, and fittings. Losses result in contamination of the facility with accompanying occupational dose, and releases to the environment. These tests seek to measure and locate these losses on typical coolant and purge loops. Measurements include standard tritium activity monitoring, with bagging around suspected leaks and samples.

Importance of Neutrons and Fusion Spectrum: (Low) Neutrons are of little importance since tritium can be added to fluids and neutrons have little effect on fluid chemistry.

Other Required Environmental Conditions: ($H^3$,p,T,G,C) Other required environmental conditions include tritium itself, at the appropriate pressure, temperature, geometry and gas composition.

Test Article Size: (20 $m^3$) A basic loop with breeder "source" term, and piping, joints, valves, pumps, seals, pressurizers, heat exchangers and any other components is desirable. At least 3 x 3 x 2 $m^3$ would probably be needed. This test could be piggy-backed onto a blanket test such as for tritium recovery or even simply corrosion product transport, as long as there is an external loop with pumps, valves, seals and piping.

Number of Test Articles: (3) At least two distinct loop arrangements are needed allowing for differences in the coolant and purge loop fluids, materials and components.

Test Facilities: Fluid loops with processing systems could be effectively tested for radioactivity losses on test stands. Neutrons are of little value except to produce tritium in breeder materials. Point sources would probably not be adequate in intensity for such tests. Fission reactors could produce the tritium and provide the radiation environment needed to simulate fusion systems. Tests could be piggy backed on other module tests to reduce costs.

IV.5 Tritium System Inlet Condition Measurements

a. Blanket Output

b. Plasma Exhaust

These tests address uncertainties related to the inlet conditions into the tritium processing system from the major sources - the blanket and the plasma. Measurements would include tritium concentrations, tritium form ($T_2O/T_2$), hydrogen isotope and impurity concentrations (mass spectrometry), as well as pressures.

Importance of Neutrons: (High) Neutrons are the source of tritium in the blanket and influence the recovery (especially in solid breeders) and permeation rates (including possible protium permeation into the tritium streams). They may influence the tritium form through radiolysis or rate effects on the local thermodynamics (making the solid breeder oxidizing). They may affect the plasma exhaust some through weakening the surface and making it more susceptible to erosion.

Importance of Fusion Spectrum: (Low) The primary influence is through the production of tritium in the blanket. This can be simulated with appropriate isotopic tailoring of lithium or by adding tritium to the breeder externally, so the exact spectrum is not needed. The materials damage that influences breeder or wall inventory or permeation may be only grossly sensitive to spectrum, such as through the He/dpa ratio. Furthermore, much of the blanket may actually see few high energy neutrons, yet be as important in terms of total tritium inventory and surface area for tritium permeation or impurity pickup. Thus, the overall importance of a fusion spectrum on the uncertainties in tritium permeation and stream composition is considered low.

Other Required Environmental Conditions: (G,p,T,PMI) A typical breeding blanket module is needed, with coolant and breeder geometrical arrangement, and relevant operating conditions of temperature, pressure, flow rates and tritium concentrations. On the plasma side, a prototypical device with exhaust system is the prime environmental condition since the plasma dominates surface erosion and transport.

Test Article Size: A blanket module or section is needed, with anticipated dimensions of about 50 x 50 x 20 $cm^3$ in order to provide appreciable tritium generation rates, and include geometric effects on tritium permeation due to the varying temperature and tritium production profiles. A DT device is needed to determine the exhaust composition.

Number of Test Articles: Several different blanket module configurations should be tested (10), with different operating conditions (perhaps 25, including purge stream composition, flow rates, temperature ranges, startup/shutdown, power ramp, other transients), and some tests performed with multiple cycles or to high fluence. At least three hot, long pulse fusion devices would be desirable to establish equilibrium plasma exhaust conditions for a range of plasma parameters, device configurations and device size. Remaining uncertainties in tritium system inlet conditions can be accommodated by conservative design.

Test Facilities: Some uncertainties in blanket output can be resolved with a test stand utilizing non-nuclear heat sources and externally added tritium to explore some chemistry and thermally-activated processes important for tritium extraction, inventory and permeation. These tests would be more useful for self-cooled liquid breeders or ex-situ processed solid breeders, where the tritium extraction takes place external to the neutron field. Neutron-related issues are important, however. Point neutron sources generally lack the volume to do these tests. Fission reactors have sufficiently large neutron fluxes and volumes that some testing can be performed. Since plasma exhaust uncertainties require a fusion device, neither test stands, nor point neutron

## IV.6 Atmospheric Cleanup System Verification

These tests would demonstrate the performance of the Atmospheric Cleanup System. Measurements would be primarily room tritium activity as a function of time. The ratio of HTO/HT would also be useful to monitor, as well as the general room humidity, temperature, and dust content.

Importance of Neutrons and Fusion Spectrum: (Low) The containment is not exposed to neutrons.

Other Required Environmental Conditions: $(C,p,v,G,H^3)$ The containment gas composition and pressure, volume turnover rate with respect to the cleanup system, and surface conditions (tritium adsorption, release and chemistry characteristics) must be included.

Test Article Size: (1000 $m^3$) A full-scale cleanup unit should be tested, both separately to verify operation and in a reasonable size room (15 x 15 x 5 $m^3$) to measure cleanup rates, flow circulation patterns, and effects of surface conditions, tritiated vapor release, adsorption and change of form, and suspended smoke or dust.

Number of Test Articles: (3) Differing designs (3) could be tested under a small range of conditions (perhaps 5) representing different size tritium spills under different accidents (and thus other released materials).

Test Facilities: Test stands are the preferred way to test these safety systems. Accident performance cannot be tested on a fusion device since this is an important safety system and must be verified before installation on any machine that might rely on it. Sufficiently broad operating conditions must be tested to assure that plausible (and implausible) accident conditions are adequately handled. There is no need for neutrons, so point neutron sources and fission reactors are not directly useful. However, some performance data under realistic reactor hall conditions could be obtained by operating a cleanup unit in a reactor environment such as a CANDU reactor.

# V. MAGNETS

## V.1 Neutron and Gamma Irradiated Magnet Material Properties Measurements

Although not directly ionizing, there is an electronic component of energy loss from neutrons that can affect the insulator resistivity. Long-term neutron damage will further degrade the the insulator and stabilizer resistivity. These will affect the magnet vulnerability to faults and their propagation through the magnet. Electrical resistivity, thermophysical and standard mechanical properties of the stabilizer, insulator and superconductor under neutron and gamma irradiation need to be measured.

Importance of Neutrons: (Critical) Neutrons are critical for providing the radiation damage to the insulator, stabilizer and superconductor.

Importance of Fusion Spectrum: (Low) Since the magnets are located behind the blanket and shield, the energy spectrum of the leakage neutron current closely resembles a hard spectrum in a fission reactor.

Other Required Environmental Conditions: (T,B,He) Cryogenic temperatures are necessary for both irradiation and testing to prevent annealing of the neutron induced damage. Further, irradiation and testing should occur without any intervening warming, if not concurrently. The presence of a magnetic field and liquid helium (with representative impurities) may also be important since performance may be limited by surface conductivity or breakdown.

Test Article Size: (1 x 2 x 10) Nuclear damage tests can be performed on small samples, with provisions to keep the materials at 4.2 K.

Number of Test Articles: (500) Numerous samples of superconducting material, stabilizer material and insulating material will have to be irradiated to various fluence levels, resulting in 100-1000 test articles.

Test Facilities: Test stands lack neutrons. Point neutron sources would not provide adequate test fluence. Excellent damage testing can be accomplished for magnet materials in fission reactors.

V.2 Magnet Nuclear Heat Removal and Cryostability Experiments

These tests address the ability of superconducting magnets to remove any nuclear heating that reaches them. The tests would determine the cryostability limits of magnet sections to possible heat inputs. Measurements would have to characterize the magnet response to heating (coolant pressure, flow rate and magnet electrical resistivity), as well as the amount and localization of the heat input (more difficult since only small amounts of heat at these temperatures are sufficient to quench the magnet).

Importance of Neutrons: (Medium) Neutrons are the source of nuclear heating in magnets either directly or through generated gamma rays, however any heat source can be used to test magnet cryostability limits.

Importance of Fusion Spectrum: (Low) Due to the presence of a shield, the neutron spectrum at the magnet is 'softened', generally below that of a fission source. Hence, a fusion spectrum is not essential.

Other Required Environmental Conditions: (T,B) Operating temperature and required magnetic field influence normal heat sources that would add to the nuclear effect.

Test Article Size: (10 x 10 x 20 $cm^3$) Sections of superconducting magnets can be used since the destabilizing heat input is usually localized.

Number of Test Articles: Cryostability tests would be needed for a range of superconductor designs, with perhaps 15 large test articles to explore major design variations, influence of test length, and influence of manufacturing processes. Numerous smaller test articles - single cable sections about 2 x 2 x 20 $cm^3$ - would explore other variables. Each test article can test a range of conditions of current, magnetic field, coolant temperature and flow rate.

Test Facilities: Test stands can test surface heating easily, but providing volumetric heating may require artificially enhancing the resistive heat generation and limit the usefulness of these tests. Point neutron sources are limited by intensity, while fission reactors lack magnetic fields.

## V.3 Plasma Disruption Induced Magnet Overload Experiments

These tests address the ability of the magnets to withstand electromagnetic forces resulting from plasma disruptions. A complete magnet would need to be subjected to equivalent forces, with measurements of stresses or strains and cryostability (through the electrical resistivity).

Importance of Neutrons and Fusion Spectrum: (Low) Neutrons are not needed since the concern is through the electromagnetic coupling of plasma and magnets.

Other Required Environmental Conditions: ($B,\dot{B},G,t$) Forces originating from electromagnetic sources depend upon the magnetic field strength, current and geometry. A plasma disruption will result in rapidly varying magnetic fields and associated varying forces.

Test Article Size: At a minimum, a full magnet coil is needed, along with some accounting of the ability of the blanket and shield to interfere with the permeation of the magnetic field changes, and absorb some of the energy, and corresponding eddy currents and forces. Accurate force simulation, including a realistic disruption-type of magnetic field transient and the presence of intermediate structure may require a DT device.

Number of Test Articles: Testing of a few coil designs under a range of plausible transients is desirable if this has a major impact on the magnet design. Otherwise, operation of several coils in a single DT device, again for a range of disruptions, would be sufficient.

Test Facilities: Test stands could provide valuable information on the transient response of superconducting magnets to a plasma disruption. Torques and overcurrent conditions can be provided. Their shortcoming is the plasma time scales and interactive nature of the response. Point neutron sources and fission reactors are not relevant since there is no need for neutrons. The first fusion device will likely be overdesigned for this transient and operation information obtained to design future systems more cost effectively.

## VI. INSTRUMENTATION AND CONTROL

There is a large class of testing needs for instrumentation, sensors and leads in a fusion reactor environment. Some tests are of a generic nature, such as development of reliable insulators, while others reflect the need to develop specific capabilities, especially under radiation, tritium, gamma and EM loads. No attempt is made here to completely describe all the specific developmental needs for particular components. Rather, the emphasis is on describing the generic needs of instruments for operation in a fusion reactor.

In addition to instrumentation, there may be active control systems near the nuclear environment (as in control rods and their drives in fission reactors) to control plasma operation or any of the internal hardware. These could include valves on gas injectors, vacuum systems, and neutral beam lines; active manipulation of limiters or divertor plates to adjust their angle or operation relative to the plasma; or perhaps components that are only active during maintenance or dwell time (getters, coaters, surface cleaning) that are installed inside the vacuum chamber. Such systems have not been defined yet for fusion reactor systems, so no estimate of the amount and type of testing needed can be provided.

### VI.1 Transducer Development and Lifetime

Instrumenting fusion machines will require the development of new transducers and/or the qualification of existing designs in the fusion environment, particularly allowing for the intense radiation. These tests address the development of transducer elements and their demonstration under fusion conditions. The measurements could check the transducer output signal before, during and after testing against calibrated conditions.

Importance of Neutrons: (Critical) The design of transducers is generally based on an understanding of basic material properties. Material properties are dependent upon the microstructural and physical chemistry of that material, and neutron irradiation directly impacts both via atomic displacements and nuclear transmutations. It is critically important that development and testing of these transducers be performed in a neutron environment.

Importance of Fusion Spectrum: (Critical) The correct neutron spectrum is critical because the neutron energy distribution impacts both the magnitude and type of point defects and strongly affects the production of new transmutation-produced elements. As the cross-section for these reactions is highly energy dependent, prototypic spectrum testing is essential.

Other Required Environmental Conditions: (T) The most critical environmental factor other than neutrons is the operating temperature. Many material property changes during irradiation are temperature dependent.

Test Article Size: ($1 \times 1 \times 2\ cm^3$) The size of transducers varies considerably. However, their size must be minimized wherever possible. A conservative average size (for the transducer, not the entire instrument) is estimated at $1 \times 1 \times 2\ cm^3$.

Number of Test Articles: (70) A variety of transducers must be tested, and at this stage it is difficult to predict the number of required tests. A best guess is 70 tests not including multiple tests for statistical purposes.

Test Facilities: Test stands are not considered useful because of the lack of neutrons. Point neutron sources have proven to be quite effective - the main limitation being lack of volume. Since much instrumentation may be used in regions of low fluence, it is possible to perform some of the testing outside of the limited high flux region of point sources. Fission reactors are of medium usefulness; they provide good scoping information on radiation effects. However, as many of the reactions are energy dependent, the fission reactor spectrum limits the test usefulness.

## VI.2 Insulator Breakdown

Most instruments make extensive use of insulators to maintain signal viability, including very low voltage/low current applications such as thermocouples and strain gauges, and high voltage devices such as radiation monitoring instruments. These tests seek to understand the limits of insulator performance under fusion conditions. Since electrical properties are sensitive to ionizing flux as well as fluence, measurements of electrical resistivity and dielectric breakdown strength must be made during as well as after irradiation.

Importance of Neutrons and Fusion Spectrum: (Medium) Neutrons do not seem to directly affect insulation resistance or breakdown characteristics. Ionizing radiation, however, is significant. Consequently neutrons have some importance since ionizing radiation may be released as a secondary reaction from neutron irradiation. Similarly, spectrum is of medium importance since these secondary reactions are dependent on the neutron energy.

Other Required Environmental Conditions: ($\gamma$ ,T,$H^3$) Ionizing radiation is a critical parameter. Temperature is also of importance; both insulation resistance and breakdown voltage are functions of temperature. Tritium may be a local source of ionizing radiation if the concentration is substantial.

Test Article Size: (1 x 1 x 2 $cm^3$) These test articles can be relatively small, although long cable sections must be tested in some instances. The average test size is 1 x 1 x 2 $cm^3$.

Number of Test Articles: (20)

Test Facilities: Test stands are not useful since they lack neutrons. Point neutron sources are of medium usefulness due to limited ionizing radiation and size limitations. Fission reactors are of high usefulness, limited only by spectrum concerns which are considered of secondary importance.

## VI.3 Fusion Environment Effects on Optical Components

Several instruments have been proposed which utilize optical or laser devices. These require windows, lenses, prisms or other optical components which may darken, distort or otherwise lose their ability to transmit optical signals. These tests would address the behaviour of the optical materials and components under radiation and other fusion environmental conditions. Measurements could be based on measuring the efficiency in transmitting the signal before, during and after exposure to the environmental conditions, as well as strain measurements or post-test examination for distortion.

Importance of Neutrons and Fusion Spectrum: (Critical) The primary concern is radiation damage of all types. Neutrons produce reactions as well as secondary ionizing radiation resulting in darkening or clouding of the components, or swelling. Many of these reactions are energy dependent so spectrum is also considered critical.

Other Required Environmental Conditions: ($\gamma$,T,PMI) Gamma radiation is a major source of damage and must be present for testing. Temperature has a significant effect on the rate the damage is annealed. For those components that interface with the plasma, the plasma interaction is also critical. Sputtering of a window surface, for example, would make it useless. Temperature gradients due to bulk or surface heating may be a source of distortion.

Test Article Size: ($2 \times 2 \times 2\ cm^3$) Simple coupon tests should be sufficient for most purposes, although coupons should be large enough to allow including prototypic temperature gradients.

Number of Test Articles: (50) A variety of materials must be tested first to qualitatively identify the best candidates. From these, about 50 further tests would be needed to characterize their limitations.

Test Facilities: Test stands are not useful since they have no neutrons. Point neutron sources are of medium usefulness, but lack the size and plasma needed. Fission reactors are of medium usefulness because of spectrum and plasma concerns.

## VI.4 Insulator/Substrate Seal Integrity Experiments

Many instruments rely on seals between the insulator and some substrate to maintain vacuum boundaries or special material isolation. For example, flux monitors often contain special gases between two insulated electrodes. There is considerably fission reactor experience that shows that these seals are damaged by neutrons. These tests would consist of representative seals placed under irradiated conditions. They could be monitored for pressure changes, weight loss, chemical reactions or visible signs of leakage.

Importance of Neutrons and Fusion Spectrum: (Critical) The primary factor is believed to be neutrons. Light water reactor industry experience points to an energy dependence that also makes the spectrum critical.

Other Required Environmental Conditions: (T,$\sigma$,p,C,N) Other critical parameters are temperature, neutron flux, pressure, chemical environment and cyclic operation.

Test Article Size: (1 x 1 x 2 $cm^3$)

Number of Test Articles: (20)

Test Facilities: Test stands are not useful since they have no neutrons. Point neutron sources are excellent irradiation devices and considered highly useful, but may be limited in available test volume. Fission reactors are of medium usefulness, limited by spectrum concerns.

## VI.5 Fusion Environment Noise Effects Experiments

The environment of a fusion reactor is extremely noisy from an instrument standpoint, each source potentially contributing to noise and possibly a DC shift in the signal. These tests would investigate the susceptibility of the instrument to fusion environmental noise sources, and potential modifications or shielding that would reduce the sensitivity. Measurements would monitor the instrument signal at zero level (to determine the background noise level), as well as over the full operating range (in case of potential synergistic effects) to observe changes between non-fusion and fusion conditions.

Importance of Neutrons and Fusion Spectrum: (Low) Neutrons are not considered a significant contributor to this problem (given that the transducer itself is not physically degraded by neutrons). Neutrons can generate some ionizing radiation which may need to be considered.

Other Required Environmental Conditions: (RF,PMI,$\gamma$,$H^3$,$\dot{B}$) All potential sources of electrical noise and ionizing radiation must be considered.

Test Article Size: (1 x 1 x 200 $cm^3$) For effective testing, long instrument leads with prototypic routing through the environment are required.

Number of Test Articles: (20)

Test Facilities: Test stands are extremely useful, and would only be limited in that any remaining secondary concerns over neutron effects could not be tested. Most point neutron sources would not be able to resolve these issues because their size prevents applying the other more significant conditions (although some sources such as "Super FMIT" could be applicable). Fission reactors are further limited in that they can carry no transient magnetic field or RF effects.

## VI.6 Radiation Effects on Electronic Components

It is likely that some electronics will be placed as close to the reactor as possible. Although not in a high radiation field, the impact of low level irradiation may be significant, and some testing is needed to establish operating limits. These tests will place full electronic component under irradiation and monitor the performance through the output signals.

Importance of Neutrons: (Critical) These components will be placed in as much shielding as possible, so the dose is expected to be low. However, the purpose of these tests is to establish the operating limits and shielding needs.

Importance of Fusion Spectrum: (Critical) 14 MeV radiation is the source of the damaging radiation and should be simulated, although the neutron spectrum may be softened in some locations due to shielding.

Other Required Environmental Conditions: ($T,\gamma,H^3$) All forms of damaging radiation are required, as well as prototypic operating temperatures.

Test Article Size: ($1 \times 1 \times 1$ $cm^3$)

Number of Test Articles: (20)

Test Facilities: Test stands are not useful since they lack neutrons. Point neutron sources are highly useful. Shielding will be required to provide prototypic conditions, but this should be easily accommodated. Fission reactors could provide valuable information, but access to prototypic radiation zones may be difficult.

## VI.6 Instrumentation Performance and Lifetime Verification

While other tests address aspects of instrumentation behaviour in an operating fusion reactor, these tests specifically place full instrument in prototypical conditions to verify the performance and lifetime, monitoring the signal for drift, noise and eventual degradation due to interactions with the environment or surrounding hardware. These tests may be required for safety considerations prior to operating a large fusion device, and in fact may usefully be performed as the instrumentation in other tests - for example, a test blanket module could verify the behaviour of installed temperature-monitoring thermocouples as well as the behaviour of the blanket itself.

Importance of Neutrons and Fusion Spectrum: (Critical) Considering the ability of neutrons to affect material properties and cause ionizing radiation, the presence of neutrons, especially high energy neutrons, is critical to verifying instrument performance and lifetime.

Other Required Environmental Conditions: ($\gamma$,B,RF,$H^3$,T,C,PMI,Vac) Gamma and ionizing radiation, and EM fields (magnetic, RF, global eddy currents from plasma transients or liquid metal MHD effects) will influence the performance of the instruments. The chemical, mechanical and plasma interactive boundary conditions will affect the component lifetime and must be tested.

Test Article Size: (5 x 5 x 5 $cm^3$) The size of the test article varies considerably with the type of instrument, but a median size would be about 5 x 5 x 5 $cm^3$, allowing space for the mechanical construction of the device, the transducer and its coupling apparatus (if any), and any cabling connections.

Number of Test Articles: (100) Assuming 10 basic types of measurements within the nuclear environment (e.g., pressure, temperature, strain, neutron flux) and 10 variations each for different operating ranges, fluences and measuring method, the total number of test articles is about 100. Of course, each test article could be operated in a variety of test conditions after a given fluence, for example.

Test Facilities: Although very useful in developing the instruments and testing aspects of their performance and lifetime, neutrons are eventually needed. Point neutron sources could test individual instruments to reasonable fluences, but could not simultaneously apply other environmental conditions. Fission reactors could provide some high fluence information, but would also be severely limited in environmental conditions such as RF or plasma. Although a prototypical fusion environment is desired for these verification tests, the importance of these instruments from an operational safety point requires substantial testing and verification prior to their need in a fusion device.

# VII. BALANCE OF PLANT

## VII.1 Liquid Metal Pump Development

Sodium technology provides a good basis for the initial designs of lithium or lithium-lead pumps, but development is still required. Pump design is heavily dependent on materials issues and on the resolution of pump head requirements. Measurements of pumps would include power requirements, motor temperature, liquid metal flow rates and pressure head, post-test examination of the pump blades and cavity, and possibly non-destructive tests for crack presence and growth.

Importance of Neutrons: (Low) Neutrons are not directly important for pumps, but may produce transmutation products that will be transported from the blanket and embrittle the pumps.

Importance of Fusion Spectrum: (Low) Neutrons are not generally believed to be important, unless the transmutation products cause serious embrittlement.

Other Required Environmental Conditions: (T,p,v,I) The environmental factors are temperature, pressure, coolant velocity and coolant impurities.

Test Article Size: (10 $m^3$) Very large systems can be required for the testing of scaled down prototypic equipment and plant sized equipment. A plausible scaled pump size might be 10 $m^3$.

Number of Test Articles: (5) Extrapolating from experience with sodium and smaller loop or corrosion tests with lithium and lithium-lead to limit the number of pump tests, about 5 large scale pumps might be built.

Test Facilities: Test stands would be the preferred test facility, although there may be some concern over the lack of proper impurities until an irradiated loop test can be performed. Point neutron sources may have some value in identifying potential impurities present in the coolant loop resulting from transmutation reactions in the structure, but fission reactors would not be useful because of the low neutron energy.

# VIII. COMPONENT VERIFICATION

## VIII.1 Mass Transfer and Leakage in Coolant and Purge Loops

These tests consist of integrated tests of sputtering and corrosion product formation, transport and leakage. Formation and transport within the blanket require that part of the tests address the blanket. However, a substantial part of the overall problem occurs outside the blanket in the coolant and purge piping, valves, seals, pumps, pressurizers, heat exchanger and other components. Net mass transfer is typically between the hot blanket and colder external surfaces. Leakage of activated crud may be a problem in the external piping. These tests must involve both the blanket and the external hardware, although given tests may emphasize one or the other aspect in more detail. Measurements will include weight gain or loss on inserted probes, removal and analysis of the impurity content of the coolant, and post-test examination of the surfaces of different parts of the loop.

Importance of Neutrons and Fusion Spectrum: (Medium) Neutrons are required for sputtering tests, but may not be required for corrosion tests. Neutron-enhanced corrosion has not been observed in sodium, but has been in cesium. It is possible that high energy neutron irradiation may damage the material (e.g. phase segregation) and influence corrosion rates. The neutron spectrum is important for sputtering, and probably would be important for corrosion if there is any effect (water and helium cooled systems apparently see no effect with lower energy neutrons).

Other Required Environmental Conditions: (B,G,v,C,T) There is presently a need to confirm that the existence of intense magnetic fields does not enhance corrosion. Realistic geometries, flow conditions and temperatures are required if the transport and deposition is to be correctly simulated.

Test Article Size: (30 $m^3$) A blanket module or sub-module would be suitable for sputter and corrosion tests. This would be part of an overall coolant and/or purge loop to include system wide effects. A complete loop might be 3 x 3 x 3 $m^3$ in volume.

Number of Test Articles: (3) Corrosion and mass transfer on a system-wide scale should be tested in at least three loops to explore the range of conditions and interactions possible - there are a number of components and configurations that could be used in an commercial reactor loop.

Test Facilities: Corrosion testing can be performed using test stands since neutrons may not be needed. The effects of EM fields on corrosion can also be tested using test stands. Point neutron sources can provide useful data on the physics of sputtering. However, integrated system tests with the correct magnitude of neutron flux are needed to measure the combined formation, transport and deposition of the sputtered products. The operation of the FMIT-like point neutron source can be expected to provide useful data on the sputtering, corrosion, and transport of the products in a lithium cooled system. Fission reactors are of limited usefulness for sputter testing because they have the wrong neutron spectrum. However, preliminary tests of transport and deposition of sputter products in simulated coolant/breeder fluid systems can be made in fission reactors because some neutron sputtering can be induced. Furthermore, other tests of tritium recovery and thermomechanics, for example, would involve module tests in fission reactors. It would be natural to piggyback a corrosion transport and leakage test onto these. The effect of the intense gamma ray field in fission reactors, and the absence of EM field, would have to be accounted for. Inasmuch as sputter products are expected to be greater than the corrosion products in the coolant stream of a helium cooled system, and sputtering is so dependent on neutron spectrum, fission reactor tests are probably somewhat less accurate for helium cooled systems than for other systems.

## VIII.2 Biological Dose Rate Profile Verification

This test addresses the biological dose rates (including neutrons and gammas) around the perimeter of the reactor during operation. Measurements would be based on standard neutron and gamma dosimetry techniques.

Importance of Neutrons: (Critical) Neutrons are fundamental contributors.

Importance of Fusion Spectrum: (Critical) The amount of induced activity depends strongly on the neutron field characteristics. The neutron and gamma spectrum and spatial distribution in the test area are all significant contributors to biological dose. These require fusion neutrons to generate the correct penetration and activation source terms.

Other Required Environmental Conditions: (G,γ) Contributions to the dose rate from all of the blanket modules should be accounted for in this test. Exact bulk shield system must be used as well as the complete blanket modules, magnets and other systems that will affect neutron and gamma penetration.

Test Article Size: A full-sized DT device sector is needed, which effectively implies a DT device.

Number of Test Articles: It would be desirable to monitor the dose contours around a few DT devices to understand the likely variability. However, the nature of the dose rate may be bounded, for DEMO purposes, through one DT device with sufficient flux and fluence.

Test Facilities: Test stands are not useful since they have no neutrons. Point neutron sources do not have the volume to irradiate full size reactor sectors (including the bulk shield) with sufficient neutron intensity to provide sufficient flux and fluence. Fission reactors do not have the high energy penetrating neutrons. Near-term fusion devices like TFTR and JET will provide useful information related to neutron and gamma penetration, although they will not have full blanket and shields and will not reach enough fluence for activation to be significant.

## VIII.3 Gamma Decay Afterheat Profile Verification

After reactor shutdown, the heat load from radioactive decay and the associated gammas may be about 1% of the full reactor power, depending on the design, materials and fluence. The distribution of the heat source must be known to assure that adequate cooling is available. Due to the complex geometry, materials variations and gammag ray mean free path, a test of afterheat distribution must include loads from other module or other regions. This large scale test would provide verification based on activation and gamma decay modelling of reactor sectors. Measurements would include calorimetry and gamma ray detectors.

Importance of Neutrons: (Critical) Neutrons are fundamental.

Importance of Fusion Spectrum: (Critical) The correct distribution of gammas depends on the type of activation and transmutations, which requires a high energy fusion spectrum.

Other Required Environmental Conditions: (G,$\gamma$) The influence of gamma decay is not local, but is affected by the gamma emissions of surrounding components and structure. Thus, the overall geometry is important.

Test Article Size: To correctly simulate the source distribution of gamma decay, the principle afterheat source (beta decay also contributes), a full-sized sector is required with blanket and shield segments. Source distribution between modules and regions may also be important in accurately determining the shutdown heat loads.

Number of Test Articles: One test per reactor design is desirable, although there will be variations from sector-to-sector.

Test Facilities: Test stands are not useful since they have no neutrons. Point neutrons do not have sufficient volume or flux. Fission reactors have neither the volume, flux or spectrum. Any uncertainties must be resolved with a fusion device.