

USA Progress Report on
Tasks for IEA Study on
High-Volume Plasma-Based
Neutron Source (VNS)

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Task 2.a.
Summary of Key Technical Issues

Table 2. Summary of Critical R&D Issues for Fusion Nuclear Technology

1. D-T fuel cycle **self sufficiency**
2. **Thermomechanical** loadings and response of blanket components under normal and off-normal operation
3. Materials **compatibility**
4. Identification and characterization of **failure modes, effects, and rates**
5. Effect of imperfections in electric (MHD) **insulators** in self cooled liquid metal blanket under thermal/mechanical/electrical/nuclear loading
6. **Tritium inventory** and recovery in the solid breeder under actual operating conditions
7. **Tritium permeation** and inventory in the structure
8. Radiation Shielding: accuracy of prediction and quantification of radiation production requirements
9. Plasma-facing component thermomechanical response and lifetime
10. **Lifetime** of first wall and blanket components
11. Remote maintenance with acceptable machine shutdown time.

List of Blanket/First Wall Testing Issues

Blanket/first-wall issues

A. Structure

1. Changes in properties and behavior of materials
2. Deformation and/or breach of components
 - a. Effect of first-wall heat flux and cycling on fatigue or crack growth-related failure
 - b. Magnetic forces within the structure (including disruptions)
 - c. Premature failure at welds and discontinuities
 - d. Failures due to hot spots
 - e. Interaction of primary and secondary stresses and deformation
 - f. Effect of swelling, creep, and thermal gradients on stress concentrations (e.g., in grooved surfaces)
 - g. Failure due to shutdown residual stress
 - h. Interaction between surface effects and first-wall failures
 - i. Self-welding of similar and dissimilar metals
3. Tritium permeation through the structure
 - a. Effectiveness of tritium permeation barriers
 - b. Effect of radiation on tritium permeation
4. Structural activation product inventory and volatility
5. Hermiticity of SiC

B. Coolant

1. MHD pressure drop and pressure stresses
2. MHD and geometric effects on flow distribution
3. MHD insulating coating fabrication, integrity, and in-situ self-healing
4. Stability/kinetics of tritium oxidation in the coolant
5. Helium bubble formation leading to hot spots
6. Coolant/purge stream containment and leakage
7. Activation products in Pb-Li
8. Liquid metal purification

C. Breeder and Purge

1. Tritium recovery and inventory in solid breeder materials
2. Liquid breeder tritium extraction
3. Temperature limits and variability in solid breeder materials
 - a. Temperature limits
 - b. Thermal conductivity changes under irradiation
 - c. Effect of cracking
 - d. Effect of LiOT mass transfer
4. Breeder behavior at high burn-up/high dpa

D. Coolant/structure interactions

1. Mechanical and materials interactions
 - a. Corrosion
 - b. Mechanical wear and fatigue from flow-induced vibrations
 - c. Failure of coolant wall due to stress corrosion cracking
 - d. Failure of coolant wall due to liquid metal embrittlement
2. Thermal Interactions
 - a. MHD effects on first-wall cooling and hot spots
 - b. Response to cooling system transients
 - c. Flow sensitivity to dimensional changes
3. Coolant/Coatings/Structure interactions

E. Solid breeder/multiplier/structure interactions

1. Solid breeder mechanical and materials interactions
 - a. Clad corrosion from breeder burnup products
 - b. Strain accommodation by creep and plastic flow
 - c. Swelling driving force
 - d. Stress concentrations at cracks and discontinuities
 - e. Thermal expansion driving force
2. Neutron multiplier mechanical interactions
 - a. Beryllium swelling (Swelling driving force in Be)
 - b. Strain accommodation by creep in beryllium
 - c. Mechanical integrity of unclad beryllium
3. Thermal interactions
 - a. Breeder/structure and multiplier/structure interface heat transfer (gap conductance)

F. General blanket

1. D-T fuel self-sufficiency
 - a. Uncertainties in achievable breeding ratio
 - b. Uncertainties in required breeding ratio
2. Tritium permeation
 - a. Permeation from breeder to blanket coolant
 - b. Permeation from beryllium to coolant
 - c. Permeation characteristics at low pressure
3. Chemical reactions
4. Tritium inventory
5. Failure modes and frequencies
6. Nuclear heating rate predictions
7. Time constant for magnetic field penetration for plasma control
8. Blanket response to near blanket failures
9. Assembly and fabrication of blankets
10. Recycling of irradiated lithium and beryllium
11. Prediction and control of normal effluents associated with fluid radioactivity
12. Liquid-metal blanket insulator fabrication, effectiveness, and lifetime
13. Tritium trapping in beryllium

Task 2.b.
Role and Limitations of Non-Fusion Facilities

- Non-Neutron Test Stands
- Fission Reactors
- Accelerator-Based Neutron Sources

Test Categories for Blanket R&D

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: (a) pellet-in-can test of the thermal stress/creep interaction between solid breeder and clad; (b) electromagnetic response of bonded materials to a transient magnetic field; (c) tritium production rate in a slab of heterogeneous materials exposed to a point neutron source**

Multiple-effect/multiple interaction test

- **Explores 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 "integration test" information, but without some important environmental condition to permit large cost savings**
- **All key physical elements of the component; not necessarily full scale**
- **Example: liquid-metal blanket test facility without neutrons if insulators are not required. (For concepts requiring insulators, tests without neutrons are limited multiple effect.)**

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: (a) an isolated blanket module with its own cooling system in fusion test reactor; (b) a complete integrated blanket in an experimental power reactor**

Types and role of experiments and facilities for fusion nuclear technology

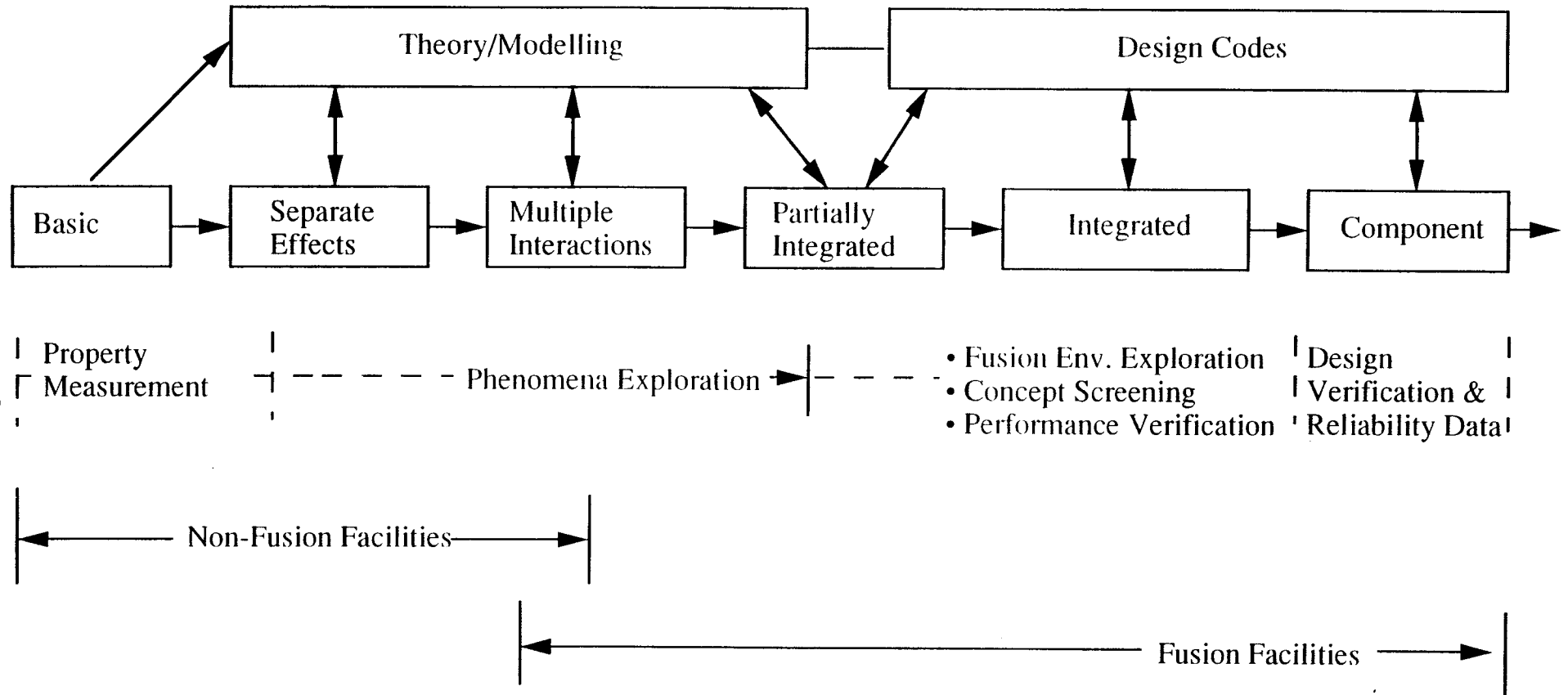


Table 14. Capabilities of Non-fusion Facilities for Simulation of Key Conditions for Fusion Nuclear Components Experiments

	Neutron Effects ⁽¹⁾	Bulk Heating ⁽²⁾	Non-Nuclear ⁽³⁾	Thermal/ Mechanical/ Electrical ⁽⁴⁾	Integrated Synergistic
Non-Neutron Test Stands	no	no	partial	no	no
Fission Reactor	partial	partial	no	no	no
Accelerator-Based Neutron Source	partial	no	no	no	no

(1) radiation damage, tritium and helium production

(2) nuclear heating in a significant volume

(3) magnetic field, surface heat flux, particle flux, mechanical forces

(4) thermal-mechanical-electrical interactions (normal and off-normal)

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Key Limitations of Fission Reactors

1. Small test volume
 - a. small size per location
 - b. small number of existing locations
2. Lack of non-nuclear conditions
 - a. magnetic field
 - b. surface heat
 - c. particle flux
 - d. mechanical forces
3. Different radiation damage simulation
 - a. neutron spectra
 - b. He/dpa ratio
 - c. types and rates
4. Power density
 - a. magnitude
 - b. spatial profile
5. Lithium burn up rate
 - a. magnitude
 - b. spatial profile
6. Reactivity considerations limits on size and type of experiments
7. Availability of fission test reactors for testing (rapid downward trend)

Capabilities of Available Fission Reactors for Blanket Tests

Reactor	Location	Reactor Power (MW)	Fast Flux (n/cm ² s)	Thermal Flux (n/cm ² s)	Dimension of Irradiation Channel (cm)	Effective Core Height (cm)
ATR	US	250	3.7x10 ¹³ 5.25x10 ¹⁴ 1.9x10 ¹⁴	2.48x10 ¹⁴ 4.64x10 ¹⁴ 8.8x10 ¹⁴	3.81 (circular) 1.59 (circular) 6.05 (7 flux traps)	122
HFIR	US	100	1.5x10 ¹⁵	2.3x10 ¹⁵	3.7 (circular)	51
EBR-II	US	62	2.0x10 ¹⁵		7.4 (circular)	36
RBT-10	Russia	10	4.4x10 ¹³	2.3x10 ¹³	15.8 x 23.7	35
IVV-2M	Russia	20	9.3x10 ¹³	5.5x10 ¹³	14.7 x 25.5	50
SM-3	Russia	100	2.2x10 ¹⁴	8.8x10 ¹³	16 (circular) 6 (circular)	35
OSIRIS	France	70	5.0x10 ¹⁴	1x10 ¹⁴	8.4 (circular)	60
SILOE	France	35	5.0x10 ¹⁴	4.0x10 ¹⁴	8.0 (circular)	60
BR-2	Belgium	60	6.0x10 ¹⁴	1.0x10 ¹⁵	20 (circular)	96
HFR	Netherlands	20	5.0x10 ¹⁴		14.5 (circular)	60
KNK	Germany	60	2.0x10 ¹⁵	2.0x10 ¹⁴	10 (circular)	60
JRR-2	Japan	10	1.0x10 ¹⁴	1.0x10 ¹⁴		
NRU	Canada	125	4x10 ¹³	2.4x10 ¹⁴	10 (circular)	300

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Accelerator-Based Neutron Sources

1) D-T Sources (e.g. FNS)

- 14 MeV Neutrons
- Limited in Yield ($\sim 10^{13} \text{ s}^{-1}$)
- Suitable Only for Neutronics Tests

2) D-Li Source (e.g. IFMIF)

Advantages

- Higher Yield (but is it enough?)
- Experience with Accelerator Technology

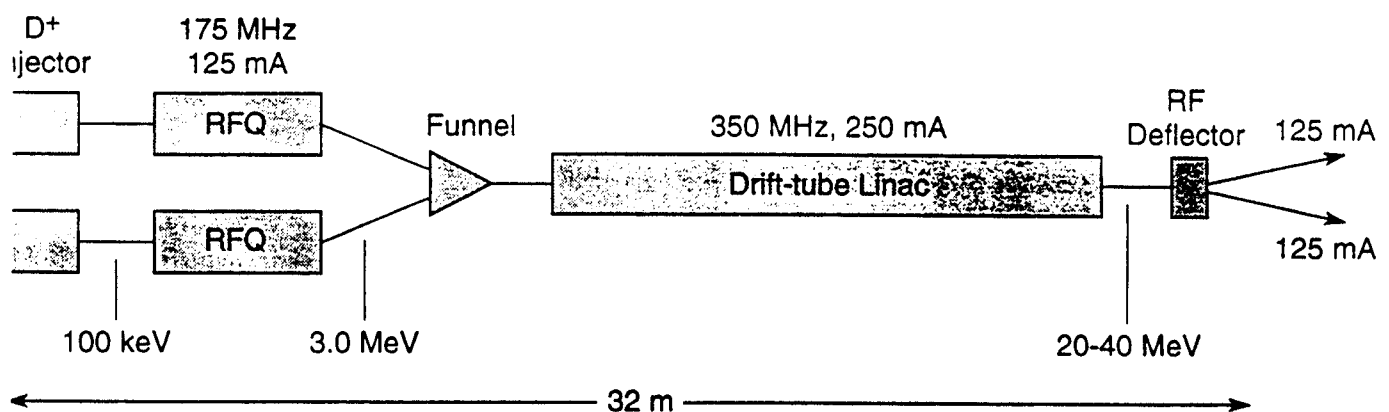
Concerns

- Surface Area and Volume Available for Testing Too Small
- Flux and Dose Rate?
- Neutron Spectrum Not Fusion
- Steep Flux

Comparison of Present DT Point Neutron Source to (FNS)
 Present Plasma-Based Device (TFTR)

	TFTR	FNS
Neutron Yield	2×10^{18} n/shot	5×10^{12} n/s
Pulse Length	~ 1 s	variable
Irradiation Frequency	~ 10 cycles per day	~ 10 hours per day
Neutron Flux, n/cm ² •S	<u>at the first wall</u> 2×10^{12}	<u>at 5cm from target</u> 6.4×10^9 <u>at 1 m from target</u> 1.6×10^7

Proposed Accelerator System for International D-Lithium Neutron Source



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

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

Neutron Generation Rate and Average Neutron Energy
from D-Li Source

	Incident Deuteron Energy		
	30 MeV	35 MeV	40 MeV
Total Neutron Generation Rate for a 250 mA D-beam (neutrons/sec)	6.46×10^{16}	8.36×10^{16}	1.035×10^{17}
Average Neutron Energy (MeV)	5.36	6.06	6.71
Percentage of Neutrons born in Each Energy Range:			
0-15 MeV	91.9	88.1	84.3
15-50 MeV	8.1	11.9	15.7

Surface Area Available for Testing with D-Li Neutron Source
(35 MeV, 250 mA deuteron beam) to Simulate First Wall Conditions
of a Fusion Reactor

(Equivalent) Neutron Wall Load	Maximum Surface Area Available for Testing ^a	Comments
1 MW/m ²	200 cm ²	b
3 MW/m ²	50 cm ²	c

- a- Area perpendicular to beam direction
- b- Possible with beam spot area 20cm x 20cm
- c- Possible with beam spot area 10cm x 10cm

Test Volume Available with dpa Rate Per Year Greater Than Specified Threshold For D-Li Neutron Source with 35 MeV, 250 mA Deuteron Beam

dpa/yr.*	Beam Cross Sectional Area (cm x cm)	
	10 x 10	20 x 20
30	10cm ³	0
20	100cm ³	0
10	300cm ³	7cm ³

* Assuming a plant factor of 70% and stainless steel as typical material

Space Requirements for Material Property Specimen Tests for "Material Science" Information on Radiation Effects on Four Candidate Structural Materials

Test Description	Specimen Configuration	Size (mm)	Material Variables	<u>Irradiation Environment</u>				Multiplicity	Total Specimens	Vol./Spec. (cm ³)	Total Vol. (cm ³)
				Temp.	Fluence	Flux	Stress				
Charpy-v	1/3 CVN	(3.3x3.3x23.6)	4	7	4	1	0	8	896	0.26	235
Tensile	Flat	(0.76x25.4x5.0)	4	7	4	1	0	15	1680	0.10	162
Creep	Tube	(4.57 dia.x23.0)	4	7	1	1	6	1	168	0.38	63
Swelling	Disc	(3.18 dia.x5.0)	144	7	4	1	0	6	24192	0.002	48
Fracture Toughness	Compact Tension	(160 dia.x2.5)	4	7	4	1	0	16	1792	0.5	901
Stress Corrosion Cracking	CERT SS-3	(0.76x25.4x5.0)	4	7	4	1	0	24	2688	0.10	259
Fatigue	Constant Amplitude/ High Cycle	(6.35 dia.x38)	4	7	4	1	0	3	336	1.2	404
Total for all Specimens (does not include volume for coolant and support)								----	31752	----	2072

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SiC/SiC COMPOSITE COMPONENT TEST MATRIX

(PRIMARY ISSUES ONLY)

Test Description	Specimen Configuration	Size (cm)	Material Variables	IRRADIATION ENVIRONMENT			Volume (cm ³)
				Temp. (°C)	Fluence (dpa)	Stress*** (MPa)	
Creep	ALL*	10-50	M/F/I**	350 - 1200	1-10	1-15	200-1,000
Tensile	ST/DT/MT	50	M/F/I	"	"	"	1,000
Swelling	ST/MT	50	M/F/I	"	"	"	1,000
Fracture Toughness	ST/MT/MA	50	M/F/I	"	"	-	25,000
Elongation	ST/DT/MT	50	M/F/I	"	"	-	1,000
Fatigue	ALL	50	M/F/I	"	"	1-15	25,000
Thermal Shock	ALL	50	M/F/I	"	"	1-15	25,000
Hermiticity	ALL	50	Sealants/Coatings	"	"	1-15	25,000
SiC/Breeder	ST	10	M/F/I	"	1-10	0.1	100-1,000

*ALL refers to:

Single Tube (ST)
 Double Tubes (DT)
 Multiple Tubes (MT)
 Manifold Assembly (MA) (see previous slide)

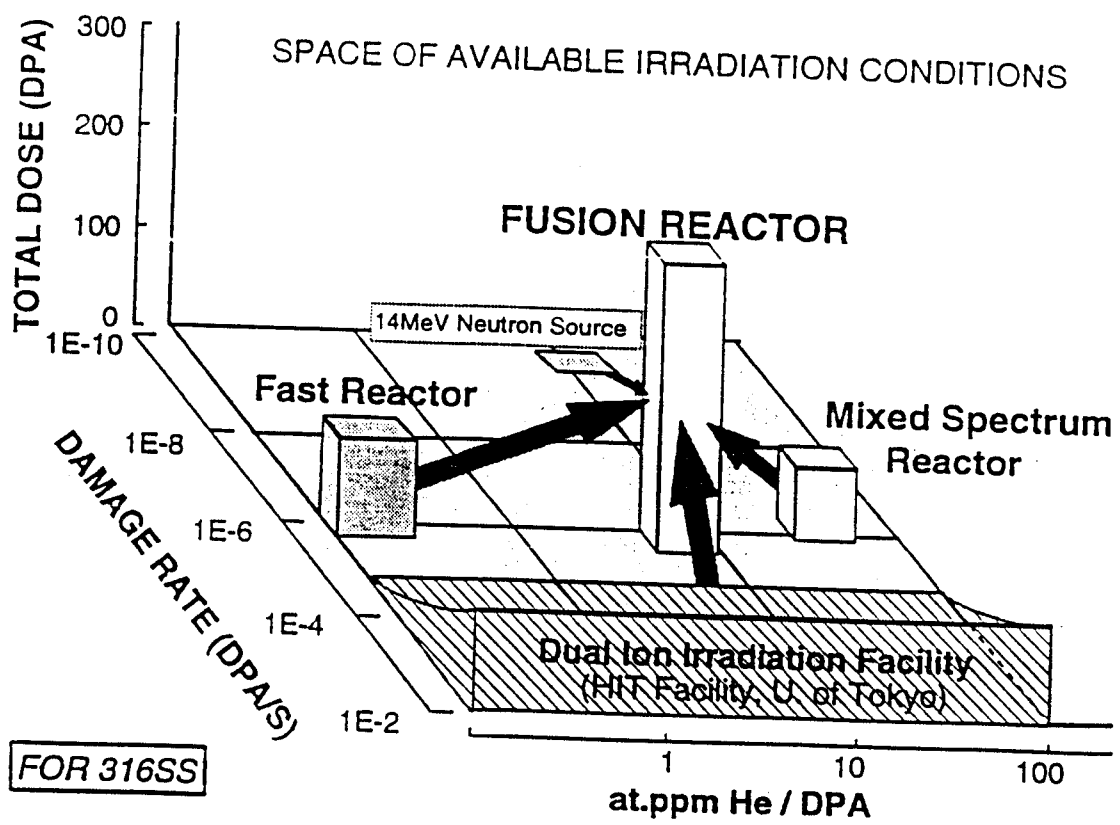
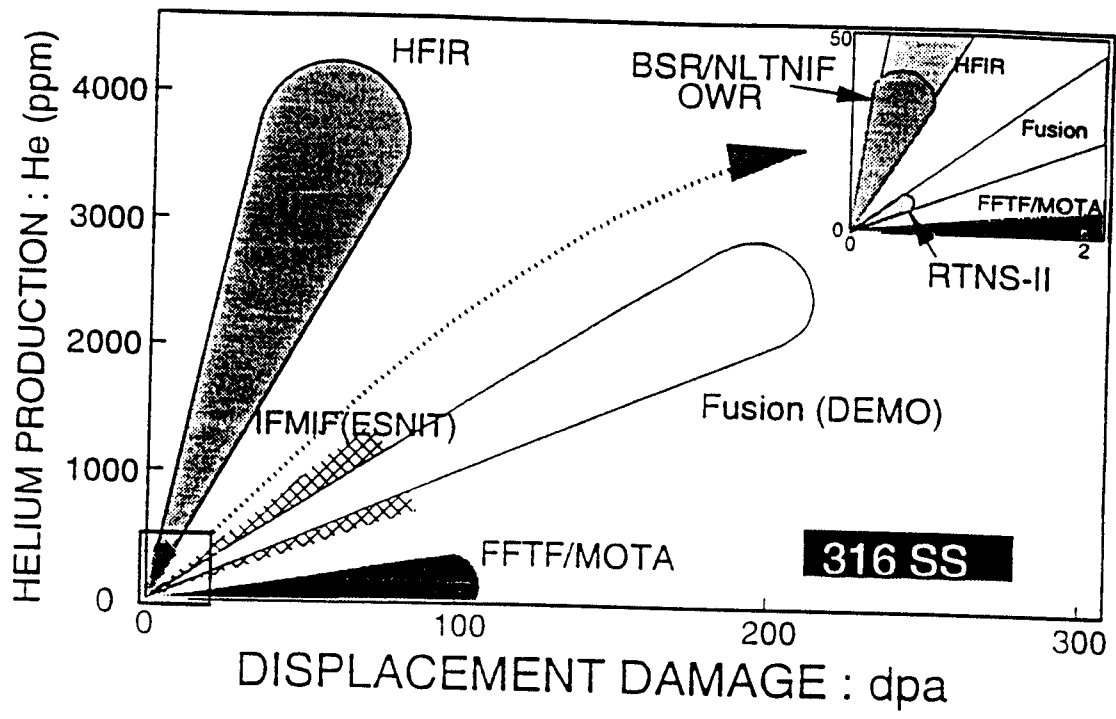
**M/F/I refers to:

M: Matrix
 F: Fibers
 I: Interface material

***He-Coolant Pressure:
 1 to 15 MPa

Several important conclusions can be reached regarding the usefulness and limitations of a D-Li neutron source: 1) present concepts for the source are clearly limited in both neutron flux/power density and test area/volume; representative maximum test area/volume are $200 \text{ cm}^2/300 \text{ cm}^3$ at an equivalent neutron wall load of 1 MW/m^2 . Such wall load is comparable only to ITER and is a factor of 3 to 5 lower than that for DEMO/power reactors, 2) it is clearly not suitable for testing submodules of components, 3) it is not suitable for testing important non-structural materials such as breeder and multipliers as the key issues for such materials require testing in a volume (e.g. tritium release and transport in solid breeders), 4) it can be used for some structural material irradiation specimen testing; the major advantage relative to ITER is expected to be higher availability ($\sim 70\%$ compared to $< 10\%$ in ITER); however, the test volume is not sufficient to do all the required material science specimen irradiation tests for one material. Since the flux in D-Li source test region is not high, considerations of test space - test time matrix need to be carefully analyzed, and 5) results from specimen irradiation tests are generally meaningful only if performed in parallel to component tests; therefore, an IFMIF-type facility will be useful only if submodule tests and module tests are carried out in parallel in fusion facilities.

HELIUM PRODUCTION VS dpa FOR VARIOUS NEUTRON SPECTRA



RADIATION EFFECTS DATABASE EXTRAPOLATION

UCLA

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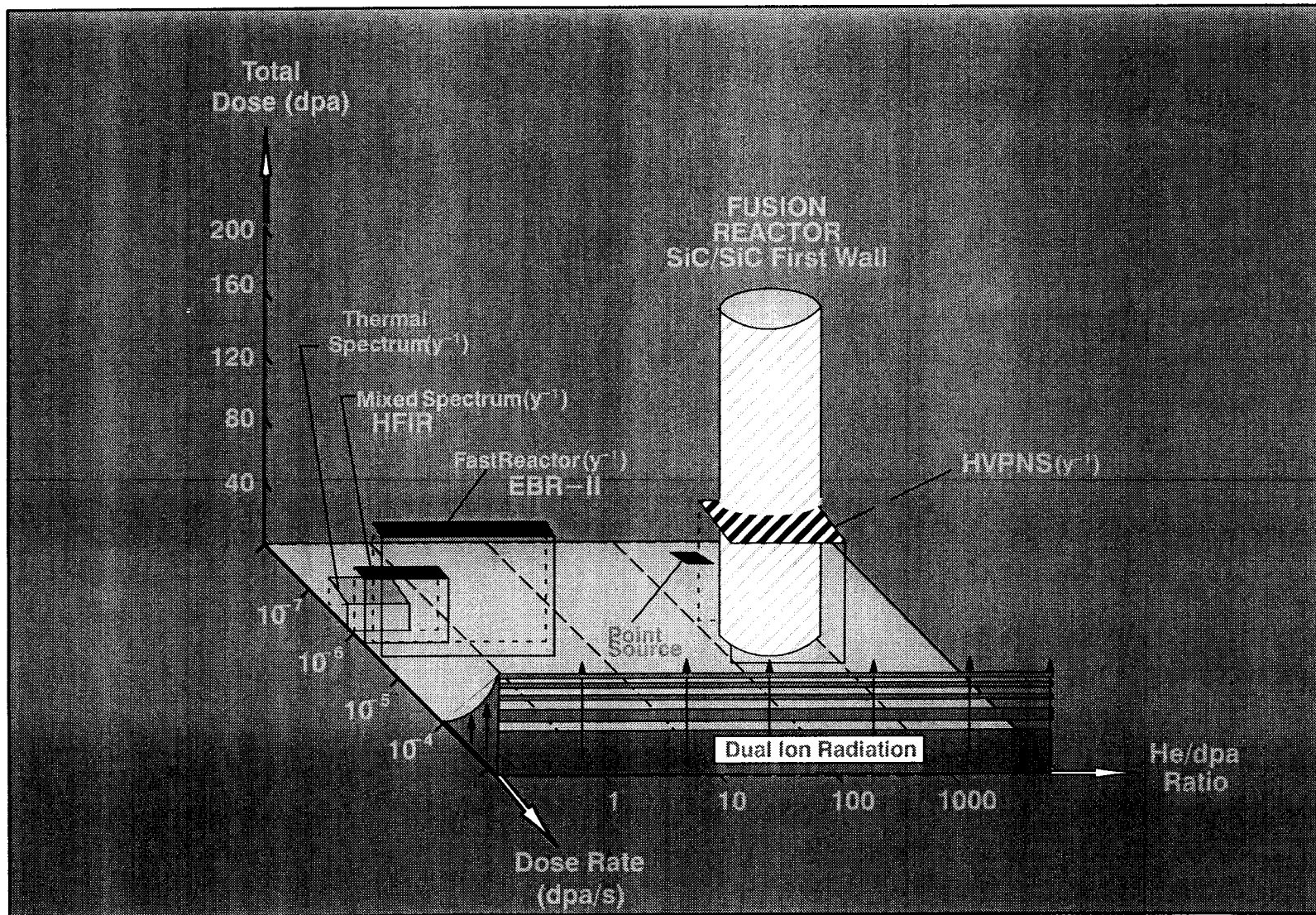


Table 15. Contribution of Nonfusion Facilities to Resolving Critical Issues for Fusion Nuclear Technology

Critical Issue	Non-neutron Test Stands	Fission Reactors	Accelerator Based Neutron Sources	
			D-T	D-Li
1. D-T fuel cycle self sufficiency	none	none	partial	none
2. Thermomechanical loadings and response of blanket components under normal and off-normal operation	small	small	none	none
3. Materials compatibility	some	some	none	none
4. Identification and characterizations of failure modes, effects and rates	none	none	none	none
5. Effect of imperfections in electric (MHD) insulators in self cooled liquid metal blanket under thermal/mechanical/ electrical/nuclear loading	small	small	none	none
6. Tritium inventory and recovery in the solid breeder under actual operating conditions	none	partial	none	none
7. Tritium permeation and inventory in the structure	some	partial	none	none
8. Radiation shielding: accuracy of prediction and quantification of radiation protection requirements	none	small	partial	small
9. Plasma-facing component thermomechanical response and lifetime	some	some	none	some
10. Lifetime of first wall and blanket components	none	partial	none	partial ^a
11. Remote Maintenance with acceptable shutdown time	none	none	none	none

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Summary of Role and Limitations of Non-Fusion Facilities

It is important to assess the overall contribution of non-fusion facilities to the development of fusion nuclear technology. Table 14 summarizes the capabilities of non-fusion facilities for simulation of key conditions for fusion nuclear component experiments. The most important conditions are: 1) neutron effects (radiation damage, tritium and helium production), 2) bulk heating (nuclear heating in a significant volume), 3) non-nuclear conditions (e.g. magnetic field, surface heat flux, particle flux, mechanical forces), 4) conditions for simulating thermal-mechanical-chemical-electrical interactions, and 5) conditions for integrated tests and synergistic effects. A very important conclusion is that non-fusion facilities are not able to simulate partially integrated or integrated conditions. Their capabilities are limited mostly to single environmental conditions and some multiple effect/multiple interaction experiments.

From the FNT development viewpoint, the most important question is the contribution of facilities to resolving the critical issues, which were presented earlier in Table 2. Table 15 shows the contribution of non-fusion facilities to resolving the FNT critical issues. The most striking result is that there is no critical issues that can be fully resolved by testing alone in non-fusion facilities. The second most striking conclusion is that there are critical issues for which no significant information can be obtained from testing in non-fusion facilities. An example is identification and characterization of failure modes, effects and rates. Therefore, the feasibility of blanket concepts can not be established prior to testing in fusion facilities.

The word "partial" in Table 15 designates a contribution which is substantial when supplemented by fusion tests; otherwise, in the absence of fusion tests, no judgment can be rendered on the resolution of the critical issue.

It should be emphasized here once again that the above conclusions do not suggest that non-fusion facilities should be used. They only suggest that their usefulness in resolving the critical issues is severely limited. Non-fusion facilities can and should be used to narrow materials and design concept options and to reduce the costs and risks of the more costly and complex tests in the fusion environment. The cost of tests in non-fusion facilities tends to be much smaller than that expected in the fusion environment; with the only possible exception is tests in a D-Li source since none exists at present and both the capital and operating costs are substantial.

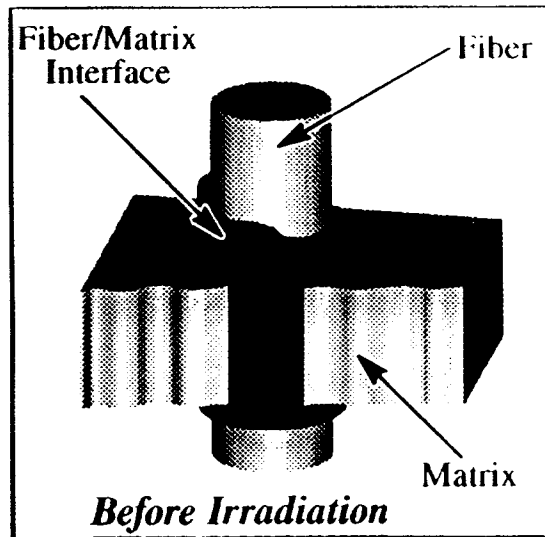
The key conclusion from here is that fusion nuclear technology development does require fusion testing facilities.

Appendix A

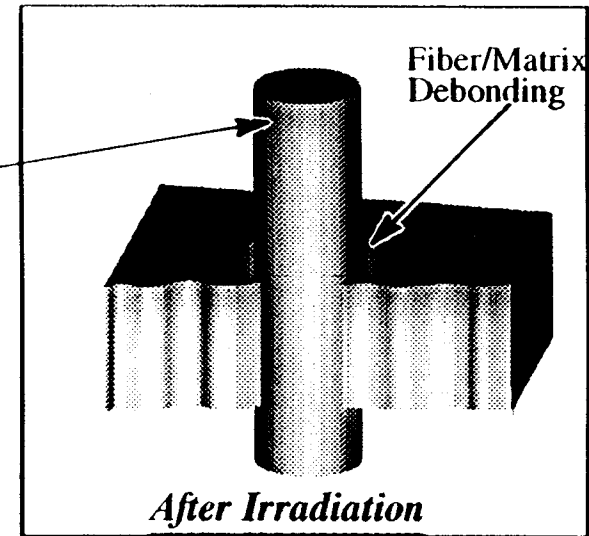
Silicon Carbide Composites Testing Needs

- SiC composites represent one of only two materials that provide true low activation.
- It has special needs for testing that have not been considered yet in detail.
- In particular, composites generally require larger test volume than metallic alloys.

SiC/SiC COMPOSITES SPECIAL TESTING NEEDS



Pre-Ceramic
Polymer Based
Fibers
(NICALON)
Shrink During
Irradiation



- SiC/SiC composites have three components:

MATRIX

FIBERS

MATRIX/FIBER INTERFACE

- Testing of all three materials, as a composite structure *SYSTEM* is essential

SiC/SiC COMPOSITES HAVE ADDITIONAL TESTING REQUIREMENTS OVER METALLICS

- Composite Material Properties are not “Scaleable”:
 - ▶ Coupon–size test results can not be extrapolated to large structures.
 - ▶ The geometric details of a composite structure (sizes, bends, joints, etc.) play a very important role in composite response to loads.

■ TO DEVELOP ADVANCED SiC/SiC COMPOSITE MATERIALS FOR FUSION APPLICATIONS, ENTIRE SUB–MODULES MUST BE TESTED
(COUPON TESTS ARE NOT INDICATIVE OF LARGER COMPONENT RESPONSES)

SiC/SiC COMPOSITES REQUIRE SPECIAL ASSEMBLY APPROACHES

- Joining Techniques for SiC/SiC Composites:
 - Brazing
 - Special Adhesives
 - Self-Propagating High Temperature Sintering

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- SiC/SiC Composites are not leak tight:
 - Sealants
 - Coatings
 - Sleeves

■ RADIATION DAMAGE RESISTANT, LOW ACTIVATION BRAZES, ADHESIVES, SEALANTS AND COATINGS HAVE TO BE DEVELOPED AND TESTED.

SiC/SiC COMPOSITES DIFFER GREATLY IN THEIR MANUFACTURING REQUIREMENTS OVER METALLICS

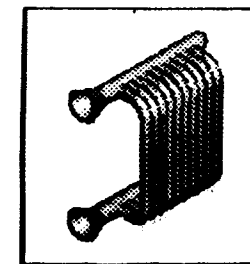
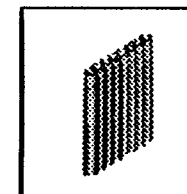
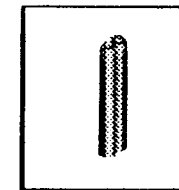
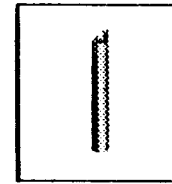
- Composite Material Structures have to be designed and manufactured as a *integrated system* which includes structures, manifolds, and joints:
 - ▶ Coolant channels are manufactured as TUBE-BANKS not as individual tubes.
 - ▶ Flanges are often manufactured as an integral part of the component (this approach minimizes joints).
 - ▶ Structural supports should be designed as part of the component (not as a unit to be added later).

- Fiber architecture plays a significant role in the composite response to loads (braiding, weaving, stitching, lay-up, ...)

■ THEREFORE, VARIOUS MANUFACTURING TECHNIQUES, FIBER ARCHITECTURES, MATRIX FORMATION APPROACHES MUST BE TESTED.

SiC/SiC COMPOSITE COMPONENT DEVELOPMENT PATH

- Single SiC/SiC Composite Tube
(ID \sim 1 to 2 cm, L \sim 10 to 30 cm)
- Several Tubes to demonstrate viability
of preform weaving techniques.
- A sub-module scale tube-bank
(10 to 20 coolant channels manufac-
tured as one unit)
- Complete assembly of tube-bank
plus manifolding system (typical di-
mensions of the order of 0.5 m).



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SiC/SiC COMPOSITES HAVE DIFFERENT OPERATING REQUIREMENTS OVER METALLICS

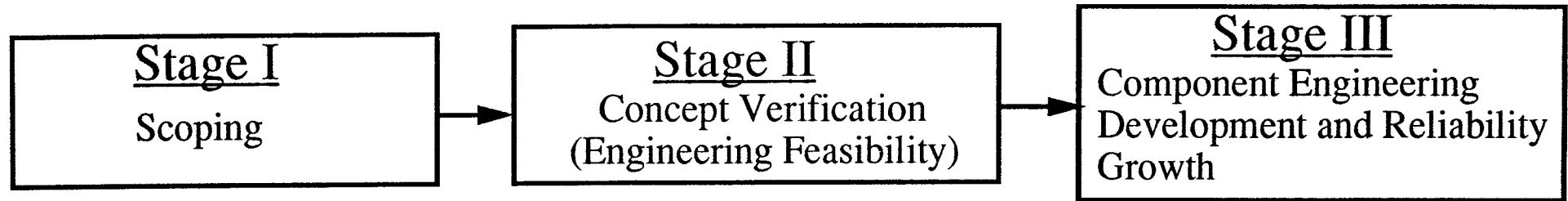
- ❑ Higher Temperatures: 800°C to 1000°C
- ❑ High Breeder/SiC Interface Temperatures: 500°C – 1024°C
study formation of SiO₂–Li₂O eutectics
- ❑ Different He–Coolant Chemistry:
Need 10⁻⁸ atm P_{O2} to form passive SiO₂ (T>700°C)
- ❑ Need high energy neutron flux to study transmutation effects
such as formation of He from C and from Si
(~1600 He–appm per 1 MW–y/m²; E_{th}>6 MeV)

STATUS OF SiC/SiC COMPOSITE MATERIALS FOR FUSION STRUCTURAL APPLICATIONS

<u>ISSUE</u>	<u>STATUS</u>
HERMETICITY	Identified as a concern, solutions identified but no test data. Small tubes successfully tested to 200 atm of helium.
THERMAL CONDUCTIVITY	NICALON fibers 7 W/m-K and 3 W/m-K AT 1000°C unirradiated and irradiated (25 dpa) respectively. Advanced SiC/SiC has k of ~75 W/m-K at RT and 35 W/m-K at 1000°C.
RADIATION STABILITY	Dimensional, thermal conductivity, fracture strength tested @ 400 to 1200°C up to 24 dpa, (NICALON fiber SiC/SiC). Results show low swelling (<0.1% between 800 and 1000°C); conductivity dropped by factor 20% at 1200°C, but dropped by factor of 4 at 500°C.
TRANSMUTATION EFFECTS	No He effects data. No solid transmutation data.
DAMAGE ANALYSIS	No universal damage code. New displacement cross-section developed.
IMPURITY EFFECTS	Commercial SiC available with <1 ppm metallic impurities.
CHEMICAL COMPATIBILITY	High temperature stability, passive oxide layer formation in air. Formation of Li ₂ O-SiO ₂ compounds between SiC and Li ₂ O (Tmetl=1024°C).
FATIGUE: THERMAL/MECH	Very limited data for high-temperature.
THERMAL SHOCK	Excellent thermal shock resistance in non fusion tests.
JOINING	No fusion specific data, some development for other materials, reduced activation brazing being evaluated.
PLASMA INTERACTIONS	Experiments proposed for DIII under the DIMES program
DESIGN CODES	Preliminary effort in progress at B&W/NASA and UCSB
REACTOR SAFETY	Preliminary evaluation performed under reactor design studies

Task 2c
Fusion Testing Stages

Stages of Fusion Testing

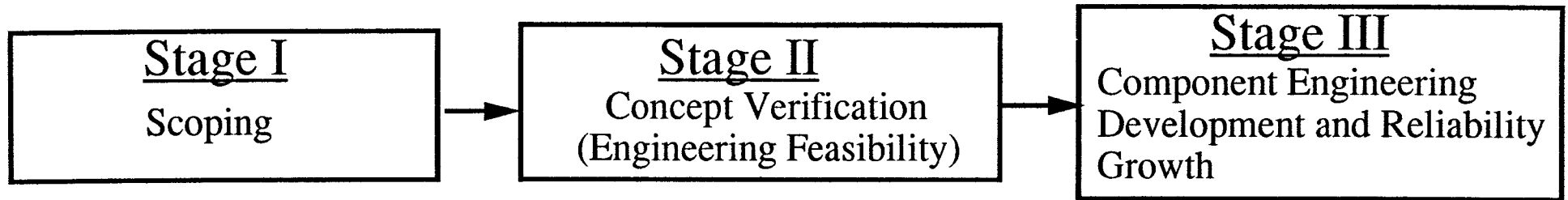


- Initial exploration of performance in fusion environment
- Calibrate non-fusion tests against performance in the fusion environment
- Initial check on codes and data
- Develop experimental techniques and test instrumentation
- Screen and narrow material combination and design concepts in the fusion environment

- Data on performance under normal operating conditions (temperature, stress, pressure drop, etc.)
- Data on initial failure modes and effects
- Select 2 or 3 concepts for further development

- Identify failure modes and effects
- Iterative design/test/fix programs aimed at improving reliability and safety
- Failure rate data: Obtain data base sufficient to predict mean time between failure with sufficient confidence
- Obtain data to predict mean time to replace (MTTR) for both planned outage and random failure
- Obtain data base to predict overall availability of FNT components in DEMO

Example of Number of Designs to Be Tested During Each Stage



20 Designs → 6 Designs → 2 (or 3) Designs

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Material combination
X Configuration
X Material form
X Fabrication technique

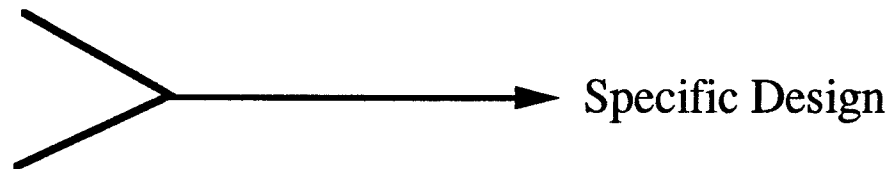
3 Material combinations
X 2 Configurations

2 (or 3) design points

Definitions

Specific Design (Everything is specified.)

Material combination
Configuration
Material form
Fabrication technique



Blanket Options for DEMO

- Material Combinations

Breeder	Coolant	Structural Material
A. <u>Solid Breeders</u> Li ₂ O, Li ₄ SiO ₄ , Li ₂ ZrO ₃ , Li ₂ TiO ₃	He <u>or</u> H ₂ O	FS [†] , V alloy, SiC Composites
B. <u>Self Cooled Liquid Metal Breeders</u> Li, LiPb	Li, LiPb	FS, V alloy with Electric Insulator, SiC Composites with LiPb only
C. <u>Separately Cooled Liquid Metal Breeders</u> Li LiPb	He He <u>or</u> H ₂ O	FS, V alloy FS, V alloy, SiC Composites

* almost all concepts use beryllium as neutron multiplier

† FS = Ferritic Steel

- Configurations

- Mixed Be and breeder
- Separated Be and breeder

- Material Form

- Pebble bed breeder & Be
- Sintered breeder & Be
- Pebble bed breeder, sintered Be

Task 2d

Quantifying FNT Testing Requirements on Major Parameters For Fusion Testing

Summary of FNT Requirements on Major Parameters for Testing in Fusion Facilities, with Emphasis on Testing Needs to Construct DEMO Blanket

Parameter	Value
Neutron Wall Load, MW/m ²	1-2
Plasma Mode of Operation	Steady State
Minimum Continuous Operating Time, Weeks	1-2
Neutron Fluence (MW•y/m ²) at Test Module	
Stage I: Scoping	0.3
Stage II: Concept Verification	1-3
Stage III: Component Engineering Development and Reliability Growth	4-6
Total Neutron Fluence for Test Device, MW•y/m ²	>6
Total Test Area, m ²	>10

Quantification of Test Requirements

General Observations of FINESSE Study Results

- In many cases, a true integrated test in the strictest sense cannot be performed under significantly scaled-down conditions for certain parameters (e.g., power density, surface heat load, geometry)
- Under scaled-down environmental conditions, the function of an integrated test module has to be divided into two or more "act-alike" tests. Each act-alike test emphasizes a group of issues/phenomena.
- While an overlap among the various act-alike tests can be included to account for certain interfaces, a concern about possibly missing some phenomena remains.
- Perfect quantitative engineering scaling is not possible because it requires complete quantitative models for all (including interactive) phenomena.
- If fusion testing will have to be carried out under scaled-down conditions, then:
 - Engineering scaling needs to continue to be nourished as a key technical discipline in fusion
 - The need for a more thorough understanding of phenomena and more analytical modeling will become more critical

Engineering Scaling In Act-Alike Test Modules Has Limitations

- Engineering Scaling Laws Must Be Followed
 - Preserve important phenomena
- Not All Parameters Can Be Scaled Down Simultaneously
 - Simulation is never perfect
 - Trade-offs among parameters results
- Complex Engineering Issues Are Involved
 - Large uncertainties in individual issues
 - Value judgments on relative importance of different issues and environmental conditions

Neutron Wall Load Requirements

Importance

- Neutron wall load is a primary source of both heating and nuclear reactions in the blanket
 - Bulking heating
 - Surface heating
 - Reaction rate (e.g., tritium production)
 - Fluence

Neutron wall load requirements determined by:

- Engineering scaling requirements
- Tradeoffs between device availability and wall load for a given testing fluence and testing time

Wall Load and Availability Required to Reach 6 MW•y/m² Goal Fluence in 12 Calendar Years

Wall Load (MW/m ²)	Availability
1	50%
1.5	33%
2	25%
2.5	20%

For pulsed plasma operation, this becomes the product of availability and plasma duty cycle. Therefore, at any given wall load, higher availability would be required.

Importance of Steady State Operation for Nuclear Testing

- To Substantially Increase the Capability for Meaningful Nuclear Technology Testing
- To Reduce the Failure Rate and Improve the Availability of the Testing Device

Effects of Pulsed Plasma Operation on Nuclear Technology Testing

- Time-Dependent Changes in Environmental Conditions for Testing
 - Nuclear (volumetric) heating
 - Surface heating
 - Poloidal magnetic field
 - Tritium production rate
- Result in Time-Dependent Changes and Effects in Response of Test Elements that:
 - Can be more dominant than the steady-state effects for which testing is desired
 - Can complicate tests and make results difficult to model and understand

Examples of Effects

- Thermal conditions
- Tritium concentration profiles
- Failure modes/fracture mechanism
- Time to reach equilibrium

Pulsing Strongly Affects the Solid Breeder Temperature Distribution.

Figure II.1.3 Scaled-Up Li₂O Breeder Temperature Response To 1 MW/m² Pulsed Wall Load (Blanket Front Position, $q''' = 9.4 \text{ MW/m}^3$)

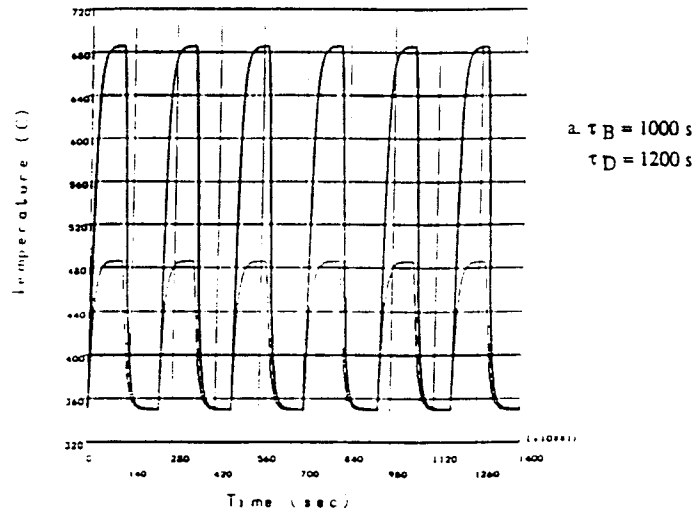
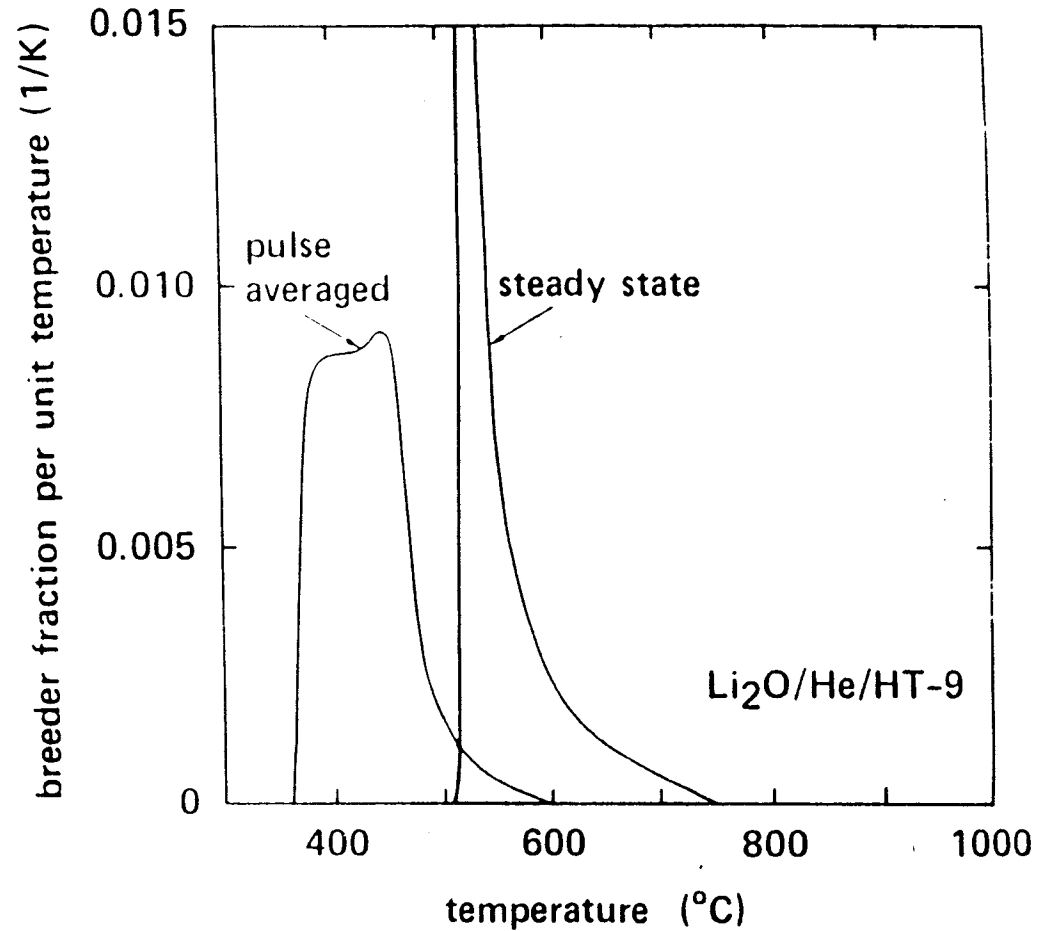
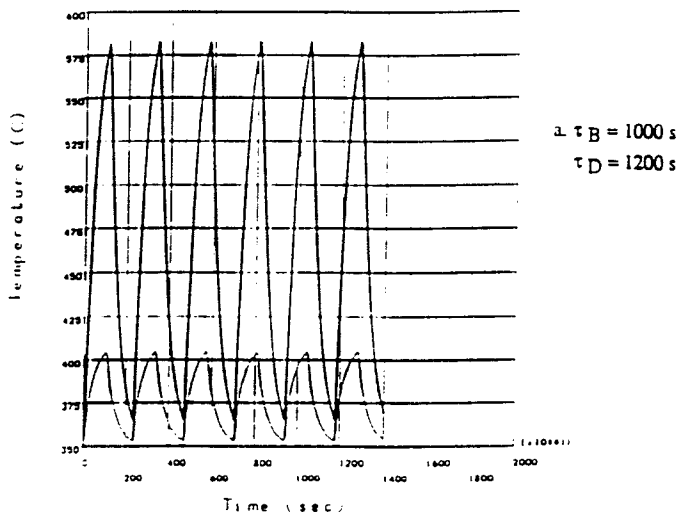


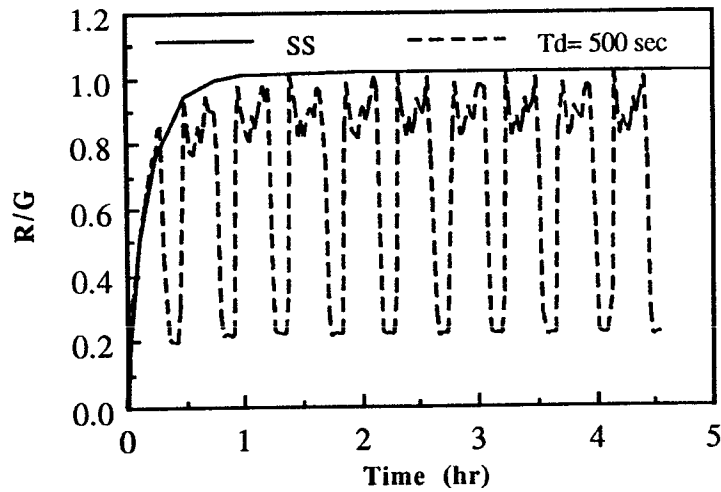
Figure II.1.4 Scaled-Up Li₂O Breeder Temperature Response To 1 MW/m² Pulsed Wall Load (Blanket Rear Position, $q''' = 2 \text{ MW/m}^3$)



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Pulsing Impacts Tritium Release and Inventory Tests

Figure II.2.6c Fractional Release



Blanket Front, $q''' = 15 \text{ MW/m}^3$
(Burn Time = 1000 sec)

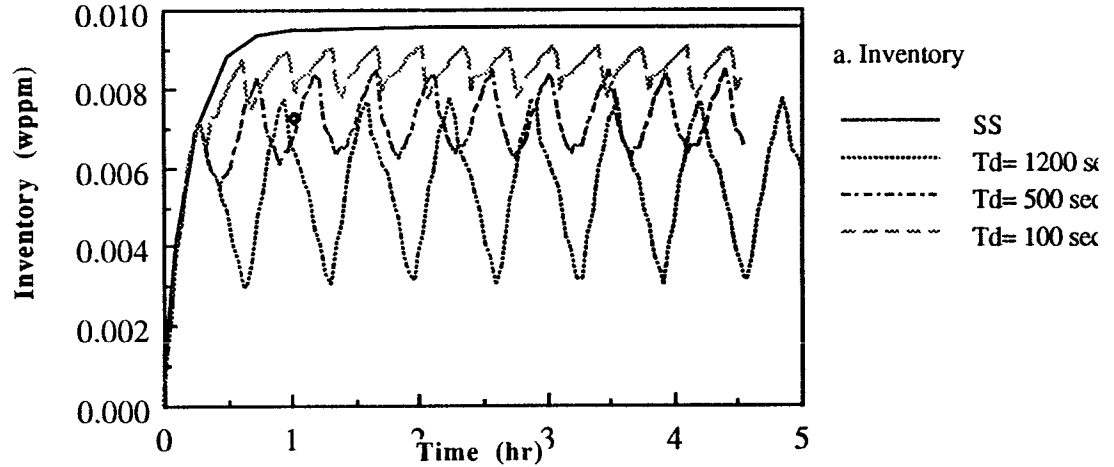


Figure II.2.6d Fractional Release

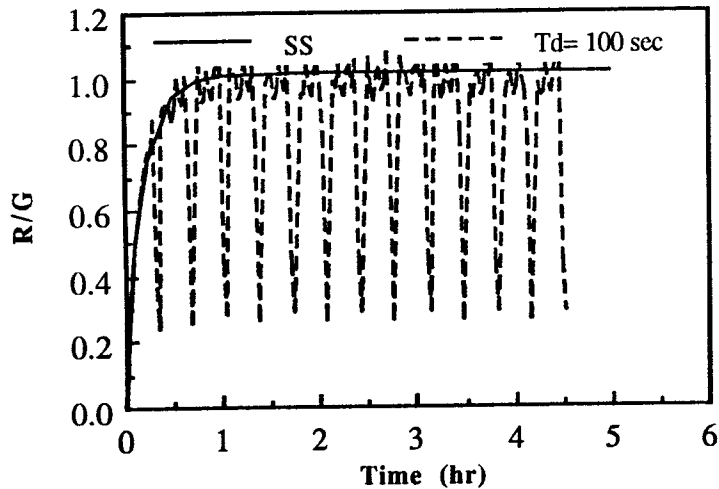
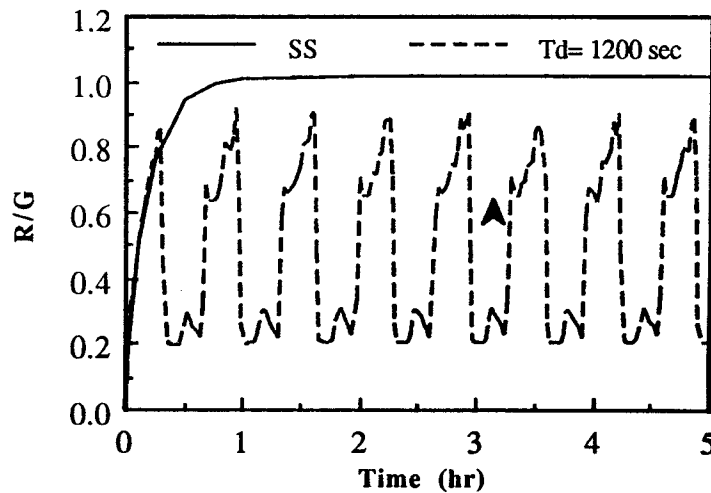


Figure II.2.6b Fractional Release



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Device Fluence vs Test Module Fluence

- Must make a distinction between:
 - Fluence achievable at test module
 - Test facility "lifetime fluence"
- Benefits to FNT testing as a function of neutron fluence have been recognized:
 - Many issues show continuous increase in benefits at higher fluences
 - Some issues show distinct fluence regions of highest benefit
- There is inevitably a long period of fail/replace/fix for test module
- Time required to perform the three testing stages. The reliability growth testing phase is the most demanding on fluence requirements.

Testing Fluence

- Previous studies emphasized radiation effects and lifetime

They concluded that $\sim 5 \text{ MW}\cdot\text{y}/\text{m}^2$ is required.

- In this study, we derive fluence directly for each of the three stages of fusion testing

Stage I: Scoping ($0.3 \text{ MW}\cdot\text{y}/\text{m}^2$)

Just enough time to explore environment, develop instrumentation, and get initial data

Stage II: Concept Verification ($1-3 \text{ MW}\cdot\text{y}/\text{m}^2$)

$1 \text{ MW}\cdot\text{y}/\text{m}^2$ is barely enough to establish engineering feasibility ($\sim 10\%$ of minimum life)

Stage III: Engineering Development & Reliability Growth ($4-6 \text{ MW}\cdot\text{y}/\text{m}^2$)

This fluence is derived from detailed analysis of reliability growth testing.

Figure 1 Fluence-Related Effects in Blanket Structural Materials

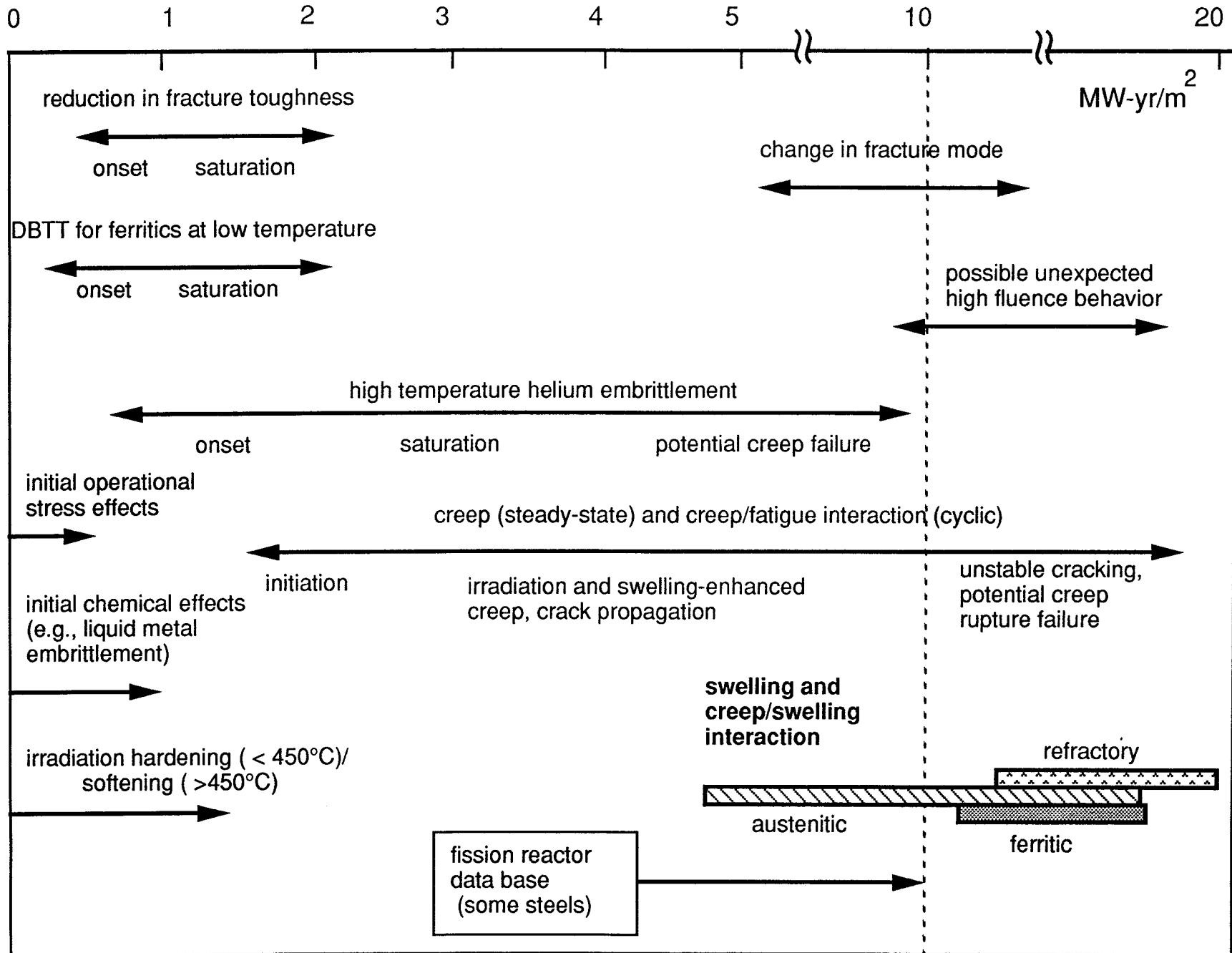
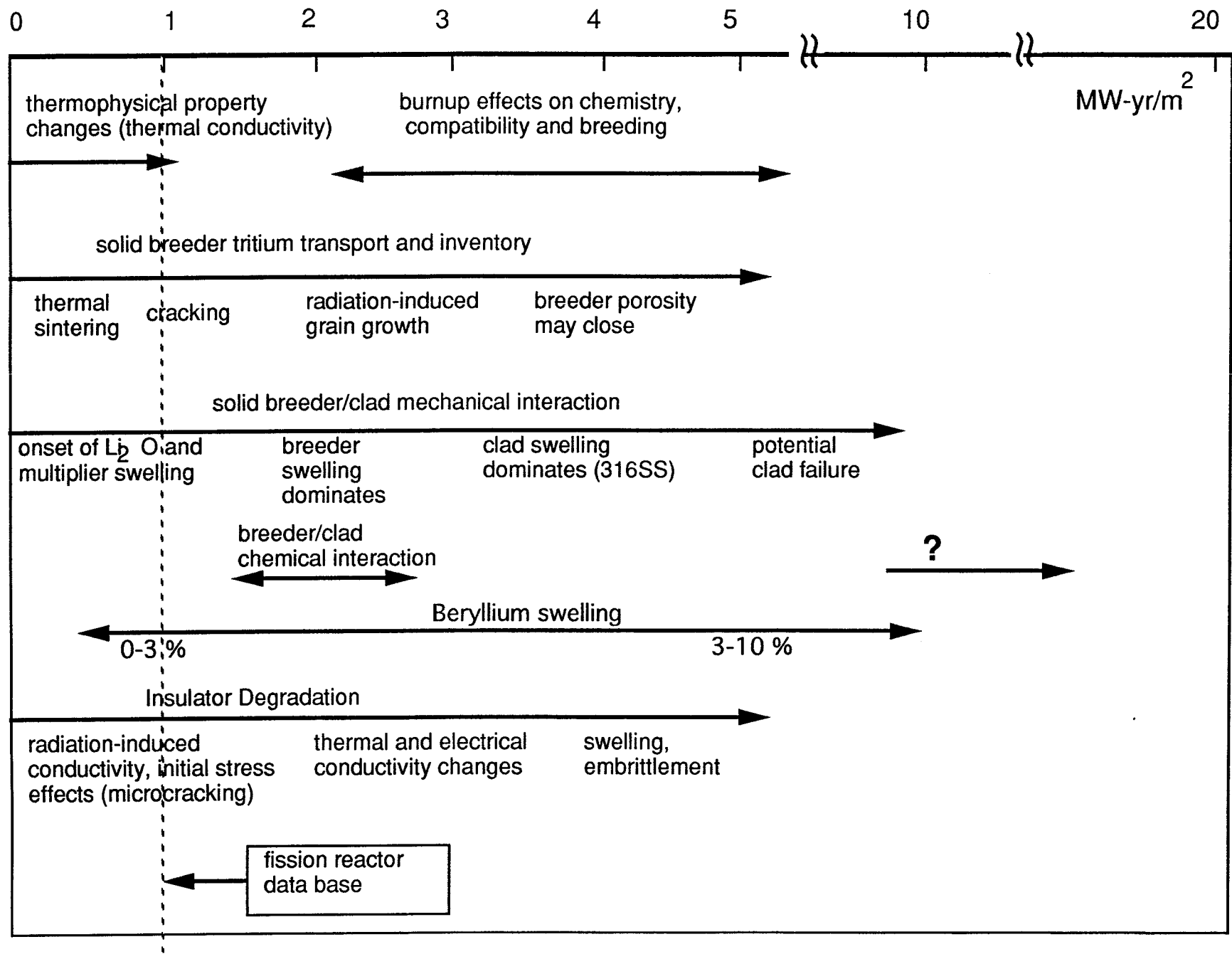


Figure 2 Fluence-Related Effects in Solid Breeders, Beryllium and Insulators

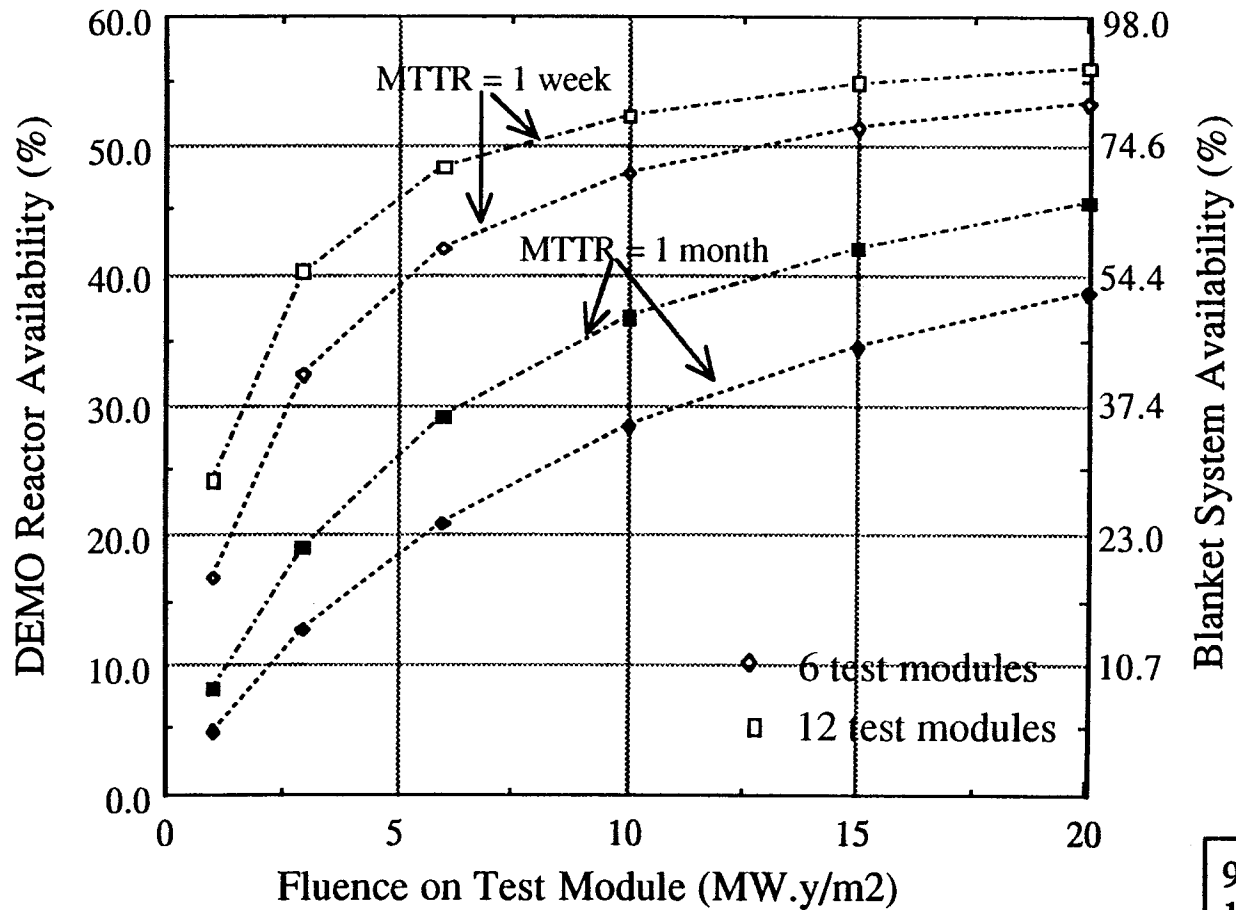
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Achievable DEMO Reactor and Blanket System Availabilities Depend on:

- Testing Fluence at the Blanket Test Module
- Achievable Mean Time To Replace (MTTR) for Blankets

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90% confidence
1 failure during the test
experience factor = 0.8

Findings of Testing Fluence Requirements on Achievable Reactor Availability Analyses

- Achieving a fluence of $\sim 5\text{-}6$ MW.y/m² at the test modules with $\sim 6\text{-}12$ test modules is crucial to achieving DEMO reactor availability on the 40% to 50% range with 90% confidence,
- Achieving DEMO reactor availability of 60% with 90% confidence may not be possible for any practical blanket test program,
- The mean downtime (MTTR) to recover (or replace) from a random failure in the blanket must be on the order of one week or less in order to achieve the required blanket and reactor system availabilities, and
- The length of MTTR must be by itself one of the critical objectives for testing in fusion facilities.

FNT Fluence Requirements

	Suggested Fluence Goals (at Test Modules)
Scoping:	0.3 MW•y/m ²
Concept Verification:	1-3 MW•y/m ²
Component Engineering Development and Reliability Growth	4-6 MW•y/m ²
Allowance (for failure/fix, enclosure attenuation, etc.)	

Recommended Neutron Fluence for FNT:

$$\geq 6 \text{ MW}\cdot\text{y}/\text{m}^2$$

COT Requirements

- Test Schedule Issues
 - It is desirable to complete a test campaign before the machine is shut down for a long period of time
 - The objective of design/test/fix iterative program requires timely data acquisition as input to redesign and construction of new test modules. It is therefore desirable to complete test campaigns as quickly as possible.
- Requirements on Environmental Control
 - The level of control over conditions within test modules and ancillary systems during shutdown is uncertain.

Recommended COT for FNT:

$\geq 1-2$ weeks

Device Surface Area Requirements

- No. of Modules per Specific Design Concept
 - Need for Engineering Scaling and Statistics
 - A large number of test modules lead to a faster reliability growth and a higher precision level
- Full scale test preferable
 - There are many problems that were solved only after setting up a full scale test.
 - There are also many problems that surfaced only in the full scale test but did not show in the reduced scale.
- If each module first wall area is about 1 m^2
 - Test area required = $(6 - 12) \times A$ (for engineering scaling) m^2 per concept
- If test 3 concepts, use 6 modules per concept; or 2 concepts use 12 modules per concept.

Total test area at the first wall required: $> 10 \text{ m}^2$