USA Progress Report On
ITER Test Program

Presented by

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US View on the ITER Test Program

"The development of a viable Test Program on ITER is vital to the mission success of ITER and to the US interests for the successful development of fusion energy."

(Dr. C. Baker, US Home Team Leader)

-----------------------------------------------------------------------------------

However

- Resources for the Test Program are very limited
- JCT credit (D2 and D3) is very small
- Coordination between Home Teams and JCT needs substantial improvement
USA Progress Report on ITER Test Program

Outline

• Framework for Fusion Nuclear Technology Development: US Perspective

• Requirements on Fusion Testing
  - Major Parameters
  - Engineering Features

• Benefits of ITER Basic Device Operation

• Test Port Design, Configuration, Maintenance [Integration Issues]

• Test Program Description
  - Solid Breeder - Liquid Metals
  - Materials - Neutronics
  - Divertor - rf antenna

• Ancillary Equipment
  - Description - integration requirements

• International Program Approach and Issues
Components and Technical Areas for Test Program

1. Blanket / First Wall

2. Plasma Interactive and High Heat Flux Components
   - Divertors, Limiters
   - PFC parts of Plasma Heating, Current Drive (rf antennas, launchers, etc.)

3. Materials

4. Shield

5. Neutronics

6. Tritium Processing System

7. Instrumentation and Control

8. Heat Transport and Power Conversion
A DEMO Plant is one that demonstrates dependability and reliability. The size, operation and performance of DEMO must be sufficient to demonstrate that there are no open questions about the economics of prototype/first commercial reactor.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron wall loading</td>
<td>2 - 3 MW/m²</td>
</tr>
<tr>
<td>Fluence</td>
<td>10 - 20 MW.y/m²</td>
</tr>
<tr>
<td>Fuel cycle</td>
<td>Self sufficient</td>
</tr>
<tr>
<td>Plasma mode of operation</td>
<td>Steady state or very long burn, short dwell</td>
</tr>
<tr>
<td>Net plant availability</td>
<td>&gt; 50% (demonstrate reliability and maintainability)</td>
</tr>
<tr>
<td>Thermal conversion efficiency</td>
<td>&gt; 30%</td>
</tr>
<tr>
<td>(gross electric/thermal power)</td>
<td></td>
</tr>
<tr>
<td>Disruption resistance</td>
<td>One major disruption during lifetime</td>
</tr>
</tbody>
</table>
Figure 1. Types and role of experiments and facilities for fusion nuclear technology
Figure 2. Stages of fusion nuclear testing in fusion facilities
Fusion Nuclear Technology Development Approach

Design Requirements

Design Options

Data Base + Technology Experience

Begin Testing in Fusion Environment

Testing in Non-Fusion Facilities

Scoping Tests

Pass Test Plan & Min. Function

Design Improvement Test Article Fabrication

Data Analysis/Performance Margin

Test terminated at 0.3 MW-yr/m²

Performance Verification Tests

Test terminated at 1 MW-yr/m²

Optimum Design Concept

Reliability Growth Tests

Reliability Growth Test Plan [> 4 MW-yr/m²]

DEMO
Scope of Testing in ITER

Information Obtained from Basic Device
Divertor Operation
Heating and Current Drive Systems
Protective Armor and Limiters
Neutronics and Shielding
Magnet Systems
Tritium Processing
Remote Maintenance
Subsystem Interactions

Testing in Specialized Test Ports

Blanket Test Modules
  Screening Tests
  Performance Verification
  Reliability Growth

Materials Test Module
  Material Properties Specimen Matrix

Divertor Test Modules
  Engineering Performance
  Design Improvements and Advanced Divertor Testing

Alternate Current Drive and Heating Launchers
# Fusion Nuclear Technology Testing Requirements on Fusion Testing Facility Parameters

<table>
<thead>
<tr>
<th>Device Parameter</th>
<th>Minimum for a useful Test Facility</th>
<th>Needed Prior to DEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average neutron wall load at the test module, MW/m²</td>
<td>1</td>
<td>1-2</td>
</tr>
<tr>
<td>Average surface heat flux at the test module, MW/m²</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Annual neutron fluence (at the test module), MW-yr/m²</td>
<td>&gt; 0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Total neutron fluence (at the test module), MW-yr/m²</td>
<td>≥ 1</td>
<td>4</td>
</tr>
<tr>
<td>Device total neutron fluence (average at the first wall), MW-yr/m²</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Plasma burn time</td>
<td>≥ 1000 s</td>
<td>1 - 3 hours (to steady state)</td>
</tr>
<tr>
<td>Dwell time</td>
<td>*</td>
<td>≤ 20 s</td>
</tr>
<tr>
<td>&quot;Continuous&quot; test duration</td>
<td>≥ 1 week</td>
<td>2 weeks</td>
</tr>
<tr>
<td>Number of &quot;continuous&quot; tests per year</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Average availability</td>
<td>10 - 15%</td>
<td>30 %</td>
</tr>
<tr>
<td>Number of ports</td>
<td>5</td>
<td>7 (+ segment or sector)</td>
</tr>
<tr>
<td>Minimum port size</td>
<td>2 - 3 m²</td>
<td>outboard segment</td>
</tr>
<tr>
<td>Total test area</td>
<td>10 m²</td>
<td>20 - 30 m² (+ segment or sector)</td>
</tr>
</tbody>
</table>

* Minimum acceptable dwell time is highly dependent on the design concept, and is difficult to specify. Further analysis in this area is recommended.
Fusion Nuclear Technology Testing Requirements on Configuration and Engineering Features of Testing Facility

1. Need exposure of test module first wall to plasma.

2. Need easy access to place and remove test article (access to inside of vacuum vessel without welding and rewelding).

3. Sufficient space at the first wall:
   
   - adequate dimensions in the poloidal and toroidal directions for test articles (varies among design concepts to be tested).
   
   - space around test modules for boundary conditions.
   
   - space for manifolds, and access lines (purge streams, etc.), and instrumentation.

4. Space outside the reactor for ancillary equipment supporting the test program (heat rejection, tritium processing, etc.).
Present Issues for ITER Test Program Activity

1. Plasma Dwell Time:

   Desirable: < 50 S
   Acceptable: < 200 S
   ITER: ~ 1200 S

   Can plasma dwell time be reduced in ITER?

   Burn time:

   ITER: 1000 S

   Acceptable but some tests can be more useful if burn time is increased (longer burn is particularly more crucial for long dwell time).
Present Issues for ITER Test Program (Cont'd)

2. **Fluence:**

   Needed by the year 2015: \( >3-4 \ \text{MW y/m}^2 \)
   
   ITER BPP: \( 0.1-0.3 \ \text{MW y/m}^2 \)
   
   by the year 2015
   
   • Can something be done to enhance BPP fluence?
   
   • We should try hard to have test program start from day one of DT operation during BPP

3. **COT and Test Campaign Definition for BPP**

   Needed: \( >1 \)-week periods of back to back cycles (i.e. device availability 100%).

   ITER BPP: Only 1 month integrated burn time during BPP?

   • What is the resolution here? What can we assume for ITER operation?
Present Issues for ITER Test Program (Cont'd)

4. **Plasma Exposure**

- Most test modules need to be exposed to the plasma. Is this acceptable from ITER Basic Design Viewpoint?

- Be coating redeposition on test module surfaces may be an issue. Need analysis.

5. **Test Port:** Shape, Size and Access

CDA: $1 \times 2 \, \text{m}^2$, rectangle, horizontal, single-motion maintenance.

EDA: $0.7 \times 6 \, \text{m}^2$, odd shape, complex withdrawal procedure.

- Implications on test module design and prototypicality.
- Implications on access, removal and replacement.
Present Issues for ITER Test Program (Cont'd)

6. **Safety Restrictions**
   e.g. Liquid Metal Compatibility with Water

7. **Approach to International Test Program and Test Port Allocation**
Other Issues for Test Program

A. Resources to develop and analyze details of test programs.

B. Distributing responsibilities and coordination among parties and JCT.

C. R & D for developing Test Module (Hardware).
Benefits of ITER to Fusion Components Development

• Benefits (to DEMO and beyond) come from two areas:

1.) Information form operation of Basic Device components (e.g. TF coils, plasma heating system test program)

2.) Information from test program experiments (specific test articles, e.g. blanket modules)

• Benefits from Basic Device:

1.) Construction and Short Term Operation

• Confirmation of analytical techniques, manufacturing processes, environments and operational characteristics.
• Validation of performance in early life

2.) Long Term Operation

• Failure Mode Identification
• Failure Rate Data
• Failure Recovery Time
• How to Obtain Benefits from Operating Basic Device:

To obtain these benefits, a special purpose goal-oriented program must be established for:

1.) **Documentation**
Document information and lessons from construction, assembly, operation, failures, etc.

2.) **Instrumentation**
Special purpose instrumentation to measure performance parameters (e.g. on ITER basic components, temperature, strains, etc.) during operation.

3.) **Failure Mode Characterization**
Detection systems and analysis program to identify failure modes, causes and effects.

4.) **Reliability Data**
Program to collect and analyze "reliability" data and to extrapolate to DEMO. Requirements can be quantified here to obtain useful data. [work in progress]
FIG. XII.4-1. A constant failure rate is the standard choice for reliability demonstration

ITER BLANKET TEST-PORT CONFIGURATION, REPLACEMENT, AND MAINTENANCE APPROACH

M. Abdou
A. Ying, S. Sharafat, M. Tillack

ITER Blanket Test Program Meeting
Garching, Germany
April 1994
Fig. 6.1: ITER section showing the space allocation for blanket test modules.
Test Port Design, Configuration and Maintenance

- Using present ITER configuration
  [6 ports, each is half outboard segment 0.7 m x 6 m x 0.6 m]

- we suggest three different configurations:

  1) 6-12 submodules arranged within the port

  2) 2-3 subsections, each section occupying the full poloidal length of the test port

  3) only one module occupying the test port

- we developed engineering design details

- we identified several serious concerns and problem areas

- Alternative test port for ITER

  we began to identify other alternatives to the present test port configuration design
ITER BLANKET TEST-MODULE PORT

Port Envelope Only

Device Eqitorial Plane

Plasma-Facing Blanket Test Module Openings

Plasma

Divertor Region

Port Envelope Side

Access Port
ITER BLANKET TEST - MODULE PORT

Cut Envelope Module Piping All 12 Modules

Blanket Test Modules

Blanket Module Coolant Pipes

Access Port

(port shell cooling, purge pipes, diagnostics, & support structure not shown)

Plasma

Divertor Region
ITER BLANKET TEST - MODULE PORT

Half of Port Envelope Module Piping
6 of 12 Test Modules

Blanket Test Modules

Blanket Module Coolant Pipes

(port shell cooling, purge pipes, diagnostics, & support structure not shown)

Access Port

Plasma

Divertor Region
ITER BLANKET TEST-MODULE PORT

Half of Port Envelope
Internal Module Support
6 of 12 Test Modules

Blanket Test Modules

Access Port

Blanket Module Support Structure

Plasma

Divertor Region
ITER BLANKET TEST-MODULE PORT

Independent Plasma Facing Blanket Test Modules

Divertor Region
ITER BLANKET MODULE TEST PORT
POLOIDALLY-COOLED BLANKET MODULES

Access Port

Blanket Test Modules

Plasma

Divertor Region
ITER BLANKET MODULE TEST PORT
POLOIDALLY-COOLED BLANKET MODULES

Access Port

Blanket Test Modules

Test Module Coolant Pipe

Plasma

Divertor Region

(port shell cooling, purge pipes, diagnostics, & support structure not shown)
ITER BLANKET MODULE TEST PORT

POLOIDALLY-COOLED BLANKET MODULES
(closeup view)

Device Equatorial Plane

Blanket Test Modules

Access Port

Blanket Module Coolant Pipes

(port shell cooling, purge pipes, diagnostics, & support structure not shown)
ITER BLANKET TEST-MODULE PORT

Toroidally-Cooled Full-Length Modules

Independent Plasma Facing Blanket Test Modules
Drawbacks of Present ITER Test Port

• Access and Maintenance

  - present test port configuration requires removal of entire test port for replacement of any single submodule
  - once the test port is removed, replacement of the submodules is difficult and time consuming:
    • removal of many submodules to gain access to "lower" submodules
    • may need to break port envelope structure

Note: Direct access to remove individual submodules independent of other submodules is crucial because
  - replacement schedule (e.g., fluence interval) varies greatly among submodules
  - individual submodules may fail
• **Size and Shape**

- all supply lines (coolant, gas purge, etc.) for all test submodules must pass through a single opening of the test port

Nearly impractical: overcrowding, have to handle all supply lines in order to extract one single submodule

- width in toroidal direction not enough for some toroidally cooled test modules

- need for "time-independent" boundary condition may limit severely the size and number of submodules

- difficult to design "support" of submodules

• Need to cool the test port structure envelope

• **Vacuum Seal**

Interface between test port and vacuum vessel needs to be studied.

Does it account for "open port" for module exposure to plasma?
Suggested Alternative to ITER Test Port Configuration

- Need configuration that allows
  - rapid insertion/removal
  - operations on one submodule should be independent of other submodules
  - avoid welding/rewelding of vacuum seals

- Suggested Option

Horizontal Submodule Removal Concept
A Preferred Alternative to the ITER Test Port Design

Twelve Horizontally Removable Blanket Test Modules
A Preferred Alternative to the ITER Test Port Design

Twelve Horizontally Removable Blanket Test Modules

Test Module
Coolant Pipe

Module
Removal Tray

Blanket Test Modules

Module Support Structure

Plasma

Divertor Region

(pot shell cooling,
purge pipes, diagnostics, &
support structure not shown).
Possible Vacuum Seal Concept to Accommodate the Horizontal Test Port Configuration
Suggested Additional Test Port Configuration for High Heat Flux Component Testing

*fig. 3* Cross-section through a divertor cassette showing the baffle, the dome, the power exhaust region and the energy dump targets
Test Program

Description
Test Program Description [Type and Size of Test Articles, Test Article Design, Test Matrix, Test Schedule, etc.]

- Solid Breeder Blanket Test Program
- Liquid Metal Blanket Test Program
- Fuel Cycle Tests
- Neutronics Tests
- Materials Tests
- Divertor Tests
- Plasma Heating Engineering (e.g. rf antenna tests)
- Safety Tests
- Overall Schedule
## Blanket Options for DEMO

<table>
<thead>
<tr>
<th>Breeder</th>
<th>Coolant</th>
<th>Structural Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Solid Breeders</td>
<td>He or H2O</td>
<td>Fs, V alloy, SiC</td>
</tr>
<tr>
<td>Li2O, Li4SiO4, Li2ZrO3, etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. Self Cooled Liquid Metals</td>
<td>Li, LiPb</td>
<td>FS, V alloy with Electric Insulator (SiC with LiPb only)</td>
</tr>
<tr>
<td>Li, LiPb</td>
<td>Li, LiPb</td>
<td></td>
</tr>
<tr>
<td>C. Separately Cooled Liquid</td>
<td>He</td>
<td>FS, V alloy</td>
</tr>
<tr>
<td>Metals</td>
<td>He or H2O</td>
<td>FS, V alloy, SiC</td>
</tr>
<tr>
<td>Li, LiPb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- All options have feasibility and performance issues.
- Resolving many of these issues requires testing of material combinations in subcomponents in the fusion environment (n, γ, B, T, V, etc.).
- R & D needs: basic properties, material interactions, synergistic effects; technology for alloy production, fabrication, etc.
## Solid Breeder Blanket Test Matrix

<table>
<thead>
<tr>
<th>Tests</th>
<th>Number of Test Articles</th>
<th>Total Number</th>
<th>Element Size (Test Size)</th>
<th>Volume FW Area</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic Tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid breeder irradiated properties (4 properties)</td>
<td>4 x 2 x 3</td>
<td>3072</td>
<td>1 x 1 x 2 cm (2 x 2 x 3 cm)</td>
<td>0.037</td>
<td>0.077</td>
</tr>
<tr>
<td>Be irradiated properties (4 properties)</td>
<td>2 x 3</td>
<td>768</td>
<td></td>
<td>0.009</td>
<td>0.019</td>
</tr>
<tr>
<td><strong>Single Effect Tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid breeder tritium recovery</td>
<td>4 x 2 x 2</td>
<td>256</td>
<td>2 x 2 x 4 cm (3 x 3 x 5 cm)</td>
<td>0.012</td>
<td>0.014</td>
</tr>
<tr>
<td>SB/structure interaction</td>
<td>4 x 2 x 1</td>
<td>384</td>
<td></td>
<td>0.013</td>
<td>0.022</td>
</tr>
<tr>
<td>Be tritium inventory &amp; rec.</td>
<td>2 x 3</td>
<td>96</td>
<td></td>
<td>0.004</td>
<td>0.005</td>
</tr>
<tr>
<td>SB/Be interaction</td>
<td>4 x 2 x 1 2 x 1</td>
<td>768</td>
<td>0.035</td>
<td>0.043</td>
<td></td>
</tr>
<tr>
<td>Be/structure mechanical inter.</td>
<td>2 x 1</td>
<td>96</td>
<td></td>
<td>0.004</td>
<td>0.005</td>
</tr>
</tbody>
</table>
## Solid Breeder Blanket Test Matrix, cont'd.

| Tests                                      | SB | Be | Structure | Config. | Total (Test size) | Element Size m$^3$ | Volume m$^2$ | FW Area
|--------------------------------------------|----|----|-----------|---------|-------------------|-------------------|--------------|---------
| **Multiple Effect Tests (submodule)**      |    |    |           |         |                   |                   |              |         |
| Thermal:                                   |    |    |           |         |                   |                   |              |         |
| water                                      | 4  | 1  | 1         | 2       | 8                 | 10 x 50 x 30 cm   | 0.288        | 0.48    |
| helium                                     | 4  | 1  | 1         | 2       | 8                 | (15 x 60 x 40 cm) | 0.288        | 0.48    |
| Corrosion:                                 |    |    |           |         |                   |                   |              |         |
| water                                      | 4  | 1  | 1         | 2       | 8                 |                   |              |         |
| helium                                     | 4  | 1  | 1         | 2       | 8                 |                   |              |         |
| Tritium Recovery and Permeation:           |    |    |           |         |                   |                   |              |         |
| water                                      | 4  | 1  | 1         | 2       | 8                 |                   |              |         |
| helium                                     | 4  | 1  | 1         | 2       | 8                 |                   |              |         |
| **Integrated Tests:**                       |    |    |           |         |                   |                   |              |         |
| Module:                                    |    |    |           |         |                   |                   |              |         |
| Full module                                |    |    |           |         |                   |                   |              |         |
| performance verification:                  |    |    |           |         |                   |                   |              |         |
| water                                      | 2  | 1  | 1         | 2       | 4                 | 1 x 1 x 0.5 m     | 4.03         | 3.36    |
| helium                                     | 2  | 1  | 1         | 2       | 4                 | (1.2 x 1.2 x 0.7 m)| 4.03         | 3.36    |
| Qualification (5 x selected configuration) |    |    |           |         |                   |                   |              |         |
| Lifetime (1 x initial preferred conf.)     |    |    |           |         | 5                 |                   |              |         |
| Sector Prototypical full sector test       |    |    |           |         | 1                 |                   |              |         |

* Preliminary assumption is that all submodules and modules require plasma interface.
Example Test Sequence for Solid Breeder Blankets

ITER | BPP | EPP | ??
--- | --- | --- | ---
Fluence MW·a/m² | 0.3 | 1.0 | 6.0

Elements
- Irradiated Properties
  - 1cm x 1cm x 2 cm
  - Solid Breeder (3072)
  - Be (768)
- Single Effect (2cm x 2cm x 4cm)
  - Tritium Release (SB and Be) (352)
  - Material Interaction (SB/Be/Struct.) (1248)

Submodules (10cm x 50cm x 30cm)
- Thermal (4 SB x 2 conf. x 2 cool.)
- Corrosion (16)
- Tritium Recovery (16)

Modules (1m x 1m x 0.5m)
- Helium (4) (2 SB x 2 configurations)
- Water (4) (2 SB x 2 configurations)
- Qualification (5) (5 x Selected configuration)
- Lifetime (1) (Initial preferred configuration)

Sector (1) (6m x 1m x 0.5m)
Final configuration choice

Test Requirements

<table>
<thead>
<tr>
<th>VOLUME (m³)</th>
<th>1.12</th>
<th>2.85</th>
<th>9.18</th>
<th>6.16</th>
<th>11.37</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW AREA (m²)</td>
<td>1.03</td>
<td>3.91</td>
<td>7.75</td>
<td>5.23</td>
<td>9.78</td>
</tr>
</tbody>
</table>

** total area will be larger to account for boundary conditions
Testing Schedule for Helium- and Water-Cooled Solid Breeder Blankets

* : submodules without plasma exposure
** : submodules with plasma exposure
*** : modules of half segment with plasma exposure
## Liquid Metal Blanket Test Matrix

<table>
<thead>
<tr>
<th>Tests</th>
<th>Typical Test Article Sizes (Toroidal x Poloidal x Radial: cm)</th>
<th>Number of Test Articles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic scoping tests (Specimen/Element)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural material irradiated properties</td>
<td>2.54 x 1 x 2.54</td>
<td>5000</td>
</tr>
<tr>
<td>Insulator material irradiated properties</td>
<td>2.54 x 1 x 2.54</td>
<td>500</td>
</tr>
<tr>
<td>Welds/brazed joints behavior experiments</td>
<td>10 x 10 x 10</td>
<td>100</td>
</tr>
<tr>
<td><strong>Multiple-effect/multiple interaction screening tests (Submodule)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrosion verification</td>
<td>25 x 25 x 25</td>
<td></td>
</tr>
<tr>
<td><strong>Welds/Brazed joints with flow</strong></td>
<td>25 x 25 x 25</td>
<td>2 x 2 x 3 (material x velocity x temperature x redundancy)</td>
</tr>
<tr>
<td><strong>Insulator self-healing</strong></td>
<td>25 x 25 x 25</td>
<td>5 x 2 x 3 x 3 (geometry x velocity x temperature x redundancy)</td>
</tr>
<tr>
<td><strong>MHD pressure drop</strong></td>
<td>25 x 100 x 25</td>
<td>5 x 3 x 3 (geometry x velocity x redundancy)</td>
</tr>
<tr>
<td><strong>Transient electromagnetic effect</strong></td>
<td>Variable x 25 x 25</td>
<td>5 x 3 (toroidal dimension x redundancy)</td>
</tr>
<tr>
<td>Performance Verification (Module)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated performance test - stage 1</td>
<td>100 x 100 x 50</td>
<td>5 x 3 (concept x redundancy)</td>
</tr>
<tr>
<td>Integrated performance test - stage 2</td>
<td>100 x 100 x 50</td>
<td>3 x 3 (concept x redundancy)</td>
</tr>
<tr>
<td><strong>Reliability Growth</strong></td>
<td>100 x 100 x 50</td>
<td>9</td>
</tr>
</tbody>
</table>

**Summary of Space Requirements:**

- Concept Screening: 10 m²
- Performance Verification: 15 m²
- Reliability Growth: 9 m²
## Example Test Sequence for Liquid Metal Blankets

<table>
<thead>
<tr>
<th>Fluence MW-a/m²</th>
<th>Concept Screening</th>
<th>Performance Verification</th>
<th>Reliability Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen/Element</td>
<td>Refractory Alloys</td>
<td>Li Corrosion</td>
<td>LiPb Water-cooled</td>
</tr>
<tr>
<td></td>
<td>Ferritic Alloys</td>
<td>LiPb Corrosion</td>
<td>Concept A</td>
</tr>
<tr>
<td></td>
<td>Insulator</td>
<td>Welds/Brazed joints with flow</td>
<td>Concept B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Insulator Self-Healing</td>
<td>Concept C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MHD- pressure drop</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transient electromagnetic effect</td>
<td></td>
</tr>
<tr>
<td>Module Scoping</td>
<td>Li self-cooled (conducting)</td>
<td></td>
<td>Optimum Concept, 9 test segments parallel testing</td>
</tr>
<tr>
<td></td>
<td>Li self-cooled (insulated)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Li He-cooled (conducting)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LiPb He-cooled</td>
<td>LiPb Water-cooled</td>
<td></td>
</tr>
<tr>
<td>Reliability Testing</td>
<td></td>
<td>Concept Evaluation</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Area (m²)</th>
<th>1</th>
<th>10</th>
<th>15</th>
<th>9</th>
</tr>
</thead>
</table>
Overview
Characteristics of Solid Breeder Test Program

- Test Phases & Decision Points
- Measurements
- Test Module Design and Physical Hardware
Objectives of Solid Breeder Blanket Testing

I. Calibration and Screening Phase:

- Calibrate fusion environment against results from nonfusion facilities
- Characterize and quantify the submodule blanket performance during operation for all relevant parameters and issues such as:
  - Tritium release rate
  - Thermomechanical performance
  - Thermalhydraulic performance
- Evaluate and screen concepts for further performance verification

II. Performance Verification Phase:

- Characterize performance and verify design details for the concepts identified
- Select best concept(s) for engineering development and reliability growth

III. Component Development and Reliability Growth
Criteria for Decision Points

A concept will be evaluated according to:

- Basic performance - such as tritium breeding recovery and thermal efficiencies
- Available safety margin
- Failure modes
- Environmental and safety features
A Large Number of Submodule Screening Tests is Needed

Breeder Materials

Li$_2$O, Li$_2$ZrO$_3$, Li$_4$SiO$_4$, LiAlO$_2$

Multiplier

Beryllium

Breeder/Multiplier Form

Pebble bed or Sintered product

Coolant

Helium
Water

Purge

Helium + %H$_2$

Structure

Ferritic/martensitic steels
Vanadium alloy
SiC

Configuration

- Beryllium mixed with breeder or separate
- BIT, BOT
- Different zones, coolant arrangement

Engineering Scaling

- Several of each one focusing on a group of issues
Types of Experiments Proposed for ITER Solid Breeder Tests During BPP

- Integrated Submodule Experiments With Plasma Exposure
  - To provide testing results for DEMO blanket concept selection and improvement
  - To evaluate accommodative performance of blankets to poloidal wall load distribution and thermo-mechanical integrity of large blanket structure

- Partially-Integrated Submodule Experiments With Plasma Exposure
  - Each submodule reproduces a critical section or unit cell of a blanket module
  - To characterize and quantify the submodule blanket performance during operation in the following aspects:
    - Tritium release rate
    - Thermomechanical performance
  - To evaluate and screen concepts for further performance verification

Conditions to be Simulated

- DEMO- like conditions
Example Solid Breeder Blanket Submodule Configurations to be Tested (with plasma exposure)

<table>
<thead>
<tr>
<th>Material</th>
<th>Configuration/Reference</th>
<th>Test configuration/ Frontal surface</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Helium-Cooled Solid Breeder</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li$_2$ZrO$_3$+Be+Ferritic</td>
<td>Packed bed in zone</td>
<td>Submodule/0.2x0.5</td>
</tr>
<tr>
<td>Li$_2$ZrO$_3$+Be+SiC</td>
<td>Packed bed in zone /ARIES</td>
<td>Submodule/0.2x0.5</td>
</tr>
<tr>
<td>Li$_2$O+Be+Ferritic</td>
<td>Sintered block</td>
<td>Submodule/0.2x0.5</td>
</tr>
<tr>
<td>Li$_4$SiO$_4$+Be +Martensitic</td>
<td>Packed bed</td>
<td>Submodule/0.2x0.5</td>
</tr>
</tbody>
</table>

**Water-Cooled Solid Breeder**

<table>
<thead>
<tr>
<th>Material</th>
<th>Configuration/Reference</th>
<th>Test configuration/ Frontal surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li$_2$O+Be+Ferritic</td>
<td>Sintered block</td>
<td>Submodule/0.2x0.5</td>
</tr>
<tr>
<td>Li$_2$ZrO$_3$+Be +Martensitic</td>
<td>BOT/BCSS (homogeneous SB/Be mixture)</td>
<td>Submodule/0.2x0.5</td>
</tr>
</tbody>
</table>

**Note**

- The U.S. believes intelligent concept screening requires fusion testing.
- A robust development program would test several conditions.
# Measurements Required to Address Critical Blanket (Performance) Issues

<table>
<thead>
<tr>
<th>Performance Issue</th>
<th>Measurements to be Performed</th>
<th>Number of Diagnostics per module</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Integrated tritium retention, release and recovery</strong></td>
<td>Tritium concentration and gas species in purge stream&lt;br&gt;Purge gas flow rate, control&lt;br&gt;Post-examination of tritium concentration in breeder, multiplier and structure</td>
<td>In-situ: 1&lt;br&gt;Ex-situ: X</td>
</tr>
<tr>
<td><strong>Integrated mechanical interactions</strong></td>
<td>Breeder/structure, breeder/multiplier, multiplier/structure deformation and strain&lt;br&gt;Post-examination of structural thermomechanical behavior&lt;br&gt;Post-examination of material microstructure</td>
<td>5-10</td>
</tr>
<tr>
<td><strong>Thermal performance for breeder, multiplier, conductance gap and interfaces</strong></td>
<td>Temperature in breeder, multiplier, structure and coolant</td>
<td>10-20</td>
</tr>
<tr>
<td><strong>Tritium permeation</strong></td>
<td>Coolant flow tritium concentration</td>
<td>1</td>
</tr>
<tr>
<td><strong>Structural response of the blanket module</strong></td>
<td>Structural deformation, stress and strain&lt;br&gt;Post-examination of structural thermomechanical behavior</td>
<td>5-10</td>
</tr>
<tr>
<td><strong>Material interactions</strong></td>
<td>Purge chemistry, coolant chemistry, PIE</td>
<td>1</td>
</tr>
</tbody>
</table>
Test Article Design

- ITER testing is limited because of the environmental conditions and test port configuration.

- It is necessary to maximize the test benefit.

- 3 types of test article design:
  - DEMO Look-Alike (useful only for neutronics)
  - DEMO Act-Alike (majority of tests)
  - ITER optimized blanket concept (useful during BPP to test basic breeding blanket for EPP)
Act-Alike Design Strategy

The test article to be tested in ITER is designed to preserve aspects of DEMO blanket behavior by using an engineering scaling process.

Example: Partially Integrated Submodule Tests

- Tritium release and inventory
- Thermomechanical performance

- Breeder/multiplier/structure temperature and temperature difference
- Purge gas characteristics and chemistry
- Coolant operating temperature and pressure
- Breeder/multiplier/structure thermomechanical boundary

- Breeder/multiplier needs to be 4-sides cooled
- The scaling law of preserving $\hat{T}$ in the case of same temperature difference in the breeder region requires that:

\[
(T_c + \Delta T_{\text{film}} + \Delta T_{\text{interface}} + \Delta T_{\text{clad}} + \Delta T_{\text{gap}})_{\text{DEMO}} = (T_c + \Delta T_{\text{film}} + \Delta T_{\text{interface}} + \Delta T_{\text{clad}} + \Delta T_{\text{gap}})_{\text{ITER}}
\]

- Alter material thickness to account for a lower heat generation rate

\[
\Delta_{\text{ITER}} = \Delta_{\text{DEMO}} \times \left(\frac{Q_{\text{ITER}}}{Q_{\text{DEMO}}}ight)^{0.5}
\]

\[
= \Delta_{\text{DEMO}} \times \left(\frac{N_{\text{DEMO}}}{N_{\text{ITER}}}ight)^{0.5}
\]
How Many Test Modules (per Concept)?

- When the number of test modules are small, it is difficult to resolve whether the observations are real or practically significant. Furthermore, a small sample size makes the statistics too dependent on the precise value of a few individual observations or a high uncertainty interval in estimating both mean and variance.

Example: A mean value of TBR for a blanket design option is to be estimated within $\pm f\%$ at some confidence level

![Graph showing the number of test articles required as a function of the uncertainty band for different confidence levels.](image)

Number of test articles required as a function of required uncertainty band for different confidence levels
Additional Issues of Test Module Design

1. The need of plasma exposure
   - Surface heat flux is crucial.
   - The blanket first wall and the first few centimeter blanket zone away from the first wall represent the most critical and challenging areas for blanket designers, which must be addressed at the early stage of the fusion testing.

2. Boundary conditions and poloidal and toroidal effects are important and should be reproduced to the extent possible.

3. Test data and instrumentation issues
   - limits on the amount of local data and possible accuracy
   - degradation/survival of sensors under irradiation
   - interference of the sensors with the test conditions

4. Support structure
### Operating Conditions for Solid Breeder Test Modules

<table>
<thead>
<tr>
<th>Category</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breeder material</td>
<td>Li₂O</td>
<td>Li₂ZrO₃</td>
</tr>
<tr>
<td>Breeder form</td>
<td>Sintered</td>
<td>Pebble</td>
</tr>
<tr>
<td>Breeder temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>800°C</td>
<td>1000°C</td>
</tr>
<tr>
<td>Minimum</td>
<td>350°C</td>
<td>400°C</td>
</tr>
<tr>
<td>Temperature gradient</td>
<td>~300°C</td>
<td>~400°C</td>
</tr>
<tr>
<td>Breeder density</td>
<td>80%</td>
<td>90%</td>
</tr>
<tr>
<td>(80% packing)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>FS</td>
<td>FS</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water</td>
<td>Helium</td>
</tr>
<tr>
<td>Coolant flow dir.</td>
<td>Toroidal</td>
<td>Poloidal</td>
</tr>
<tr>
<td>Coolant temp. range</td>
<td>280/320°C</td>
<td>300/500°C</td>
</tr>
<tr>
<td>Coolant pressure</td>
<td>15 MPa</td>
<td>5-6 MPa</td>
</tr>
<tr>
<td>Multiplier</td>
<td>Beryllium</td>
<td>Beryllium</td>
</tr>
<tr>
<td>Purge gas</td>
<td>Helium</td>
<td>Helium</td>
</tr>
<tr>
<td>Purge gas pressure</td>
<td>0.1 MPa</td>
<td>0.2 MPa</td>
</tr>
<tr>
<td>Additives</td>
<td>H₂</td>
<td>H₂</td>
</tr>
<tr>
<td>Test article size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toroidal x poloidal x radial</td>
<td>0.2x6x0.6</td>
<td>0.2x6x0.6</td>
</tr>
<tr>
<td>Number of test articles</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Plasma exposure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Test phase</td>
<td>BPP</td>
<td>BPP</td>
</tr>
</tbody>
</table>
Fig. 9.4-1. Reference design configuration for LiA10₂/H₂O/FS/ Be concept-tokamak
Candidate SiC/SiC Composite Solid Breeder
Toroidally-Cooled Blanket/Shield Module

- Coolant Outlet
- Inlet Coolant Manifold
- SiC/SiC Coolant Tube Sheets
- Coolant Flow Path
- First Wall
- Detailed View

UCLA
SS A1 FPC_9404
Candidate SiC/SiC Composite Solid Breeder
Toroidally-Cooled Blanket/Shield Module

- Blanket/Shield SiC/SiC Tube Sheets
- Shield
- Reflector Coolant Manifold
- FW/Blanket Coolant Manifold
- Solid Breeder
- Reflector
- Beryllium
- He-Coolant Channels
- FW SiC/SiC Tube Sheet

Detailed View
ITER Poloidally-Cooled Blanket Test Module

Blanket Test Module

FW/Blanket Collant Pipes

Plasma

Divertor Region
ITER Blanket Test Submodules

ITER Poloidally-Cooled Blanket Test Module

1 of 3 per Test Port
(overall dimensions & cooling pipes only)

1 of 2 Sets per Test Port
(overall dimensions only)
Testing of Liquid Metal Blankets

- **Primary Option**
  - Self-cooled Li/V
  - Poloidal flow

- **Differences from ITER Liquid Metal Option**
  - Operating temperature
  - Flow geometry
  - TBR > 1
  - Advanced structural alloy and insulator coating

- **Important Features of Fusion Test Environment**
  - Bulk heating
  - Large test volume
  - Magnetic field distribution
  - Neutron spectrum

- **Testing Approach**
  - Tests of liquid metal modules can begin at the beginning of the BPP.
  - Initial tests can be done in the absence of the plasma.
    - magnetic field only
  - Tests can be performed during H or D plasma operation.
  - First wall heat flux.
  - Fully integrated tests can be performed during D-T plasma operation.
Role of Test Temperature

- The Li outlet temperature in an electric power producing blanket will be 500-600°C.
  - 300°C for ITER blanket option.

- The thermodynamic equilibria and reaction rates between materials will be significantly different.

- At 300°C there is little concern of interstitial transfer in bi-metallic loops, but his could be a concern at 500-600°C.

- The kinetics of insulator coating growth will be faster.
  - Consider other candidate coatings.

- Permeation and solubility levels of H isotopes will be different.

- Alloy strength changes at high temperature.
  - Optimize V-alloys for high temperature strength.
Test Types for Liquid Metal Blankets

• MHD Pressure Drop and Flow Behavior
  - Validate out-of-reactor test predictions.

• Heat Transfer
  - First wall and bulk heating.

• Short-term Integrated Performance
  - Influence of fusion irradiation on insulator coating.
  - Thermal cycling.

• Tritium Permeation and Recovery

• Neutronics
  - TBR.
  - Activation.

• Long-term Integrated Testing
  - Reliability.
  - Corrosion/mass transfer.
Questions/Concerns

- Limit on Li Volume
- Inert Environment
- Interface with Base Blanket
- Space for Auxiliary Equipment
- Exposed First Wall
  - Consequences of a failure.
- Testing Time
  - Burn time
  - Dwell time
  - Fluence
- Number of Simultaneous Test Modules
Neutronics Tests

1. Dedicated Neutronics Tests

Objectives
a.) Verify Codes and Data
b.) Obtain Safety Factors

Test Vehicles: Look-Alike Test Modules

Requirements:

• Reproductible and Stable Neutron Field
• Special Boundary Regions around the test module to preserve prototypicality and allow accurate calculations
• Very low fluence

Special Case: Tritium Self Sufficiency
(discussed later)

2. Supplementary Neutronics Tests

Measurements performed in test modules (or submodules) used for other non-neutronics tests (e.g. solid breeder of liquid metal thermomechanics submodules)

Objectives:

1.) Additional information to support dedicated neutronics tests
2.) Provide the source terms and associated uncertainties (e.g. heat generation and tritium production rate) for non-neutronics tests (e.g. tritium recovery, theromechanics, safety tests)
## Dedicated Neutronics Test Matrix

<table>
<thead>
<tr>
<th>Neutronics Parameters</th>
<th>Source characterization</th>
<th>In-Module Neutronics Parameters</th>
<th>Out-of-Module Neutronics Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neutron Yield</td>
<td>TPR, Heating Rate,</td>
<td>H, He, dpa Rates Breeder Burn-Up</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Neutron Spectrum, Gamma Spectrum</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reaction Rates</td>
<td></td>
</tr>
<tr>
<td>Type of Test</td>
<td>Out-of-Module</td>
<td>In-Module, Integrated</td>
<td>In-Module, Integrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(at a Location)</td>
<td>(at a Location)</td>
</tr>
<tr>
<td>Test Module Conditions: Material, Geometry Test Module Size</td>
<td>N/A</td>
<td>A sub module (0.3 x 0.3 x 1 m) or module (2 x 1 x 1 m) is sufficient to perform these tests as long as the geometrical details surrounding the test module are accurately considered in the calculational model. It is however preferred to apply these tests in modules. Typical materials and configuration of FW/B/S are needed.</td>
<td></td>
</tr>
<tr>
<td>Device Operation Conditions Fluence</td>
<td>≤ 1 W.sec/m² to 1 MW.sec/m² ⇒ Any linear combination of wall load and operating time that results in this range of fluence is suitable to perform the tests. Typically, 20 sec of operation at 5 x 10¹² n/cm².sec is adequate</td>
<td>&lt; 0.1 MW yr/m² This relatively larger fluence is required to accumulate reasonable and detectable level of damage to the FW and burn-up of the breeding material</td>
<td>Same as for in-module parameters but the higher end (1 MW.sec/m²) is preferable</td>
</tr>
<tr>
<td>Operating Scenario</td>
<td>Steady State or pulsed operation is acceptable provided the accumulated required fluence is reached</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Operating Phase**
- Second year of SD&PT phase
- S & CV phases. Could be continued during RG phase
- Second year of SD&PT phase and S phase. Could Be continued during CV phase.
- S & CV phase. Could be continued to first two years of the RG phase.
- Concurrent with in-module neutronics tests

* SD&PT Phase = Shakedown and Physics Testing Phase
* S Phase = Scoping Phase, CV Phase = Concept Validation Phase, RG Phase = Reliability Growth Phase
## Supplementary Neutronics Measurements For Non-Neutronics Tests

<table>
<thead>
<tr>
<th>Neutronics Parameters</th>
<th>In-Module Neutronics Parameters</th>
<th>Out-of-Module Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local TPR</td>
<td>Local Heating Rate</td>
<td>FW damage parameters</td>
</tr>
<tr>
<td>Zonal TPR</td>
<td>Zonal Heating Rate</td>
<td>Breeder damage parameters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Σ Neutron and Gamma</td>
</tr>
<tr>
<td></td>
<td></td>
<td>leakage behind shield</td>
</tr>
<tr>
<td></td>
<td></td>
<td>to I/B and O/B at test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>module</td>
</tr>
</tbody>
</table>

| Related Issues        | Thermomechanical response       | Component lifetime         |
|                       | Tritium permeation and recovery | Material properties        |
|                       | Power generation                | under irradiation          |
|                       |                                 |                           |

| Type of Test          | In-Module, Integrated           | Out-of-Module, integrated  |
|                       |                                 |                           |

### Test Module Conditions:
- Material, Geometry,
  Test Module Size

The size required is determined from the test matrix size requirement for other tests. This could be a full test module (2 x 1 x 1 m) or smaller test sub modules. Material selection is also dictated by the other tests.

### Device Operating Conditions:
- Fluence
- Operating Scenario

Fluence requirements could be governed by other non-neutronics tests performed in or out-of-test module. The neutronics test themselves require very low to low fluences (1 W.sec/m2 up to 1 MW/sec/m2) except for damage parameters and burn-up tests which require longer fluences (0.5 to 1 MW.yr/m2). Steady state or pulsed operation are acceptable as long as fluence requirements are met.

### Operating Phase

- First year of Concept Validation (CV) Phase. Could be extended or repeated during the remaining years of CV* Phase
- Last year of Scoping (S*) Phase and first two years of CV* Phase. Could be extended for another year
- Same as local and Zonal TPR and heating rates in the test modules

* S Phase = Scoping Phase, CV Phase = Concept Validation Phase
Materials Test Program

Role of Material Tests:

- Support ITER Component tests

- Obtain Fission / Fusion Correlations
  (at low to moderate fluence)

- Surveillance Program - ITER Materials

- Engineering Data
  (at low to moderate fluence)

Types of Material Tests:

- Advanced Structural Materials

- Surveillance Structural Materials

- Solid Breeder Materials

- Neutron Multiplier (Be)

- Insulators for Liquid Metals

- Special Purpose Materials
  - PFC Materials
  - Magnet Materials
Materials Tests (cont'd)

Operating Temperature Range:

- Cryogenic Temperature for Magnet Materials
- 100 - 400 °C for Surveillance
- Up to 800 - 1000 °C for Advanced Materials

Types of Tests:

- Passive

  -Control of irradiation condition is minimal. It may include at most the irradiation temperature.

- Active

  -Test conditions are varied continuously during the irradiation and in-situ material behavior is collected during irradiation.

  -Much more complex than passive tests; should be limited to critical areas.
Summary of Number of Specimens for Material Tests

• Structural Materials 25000
  Four Different Alloys
  (SiC, Valloy, Ferritic, developmental)

• Surveillance Structural Materials 1500
  (Assume three different heats of ITER Structural Materials)

• Solid Breeder Materials 1500
  Three materials with 3 different product form / conditions

• Surveillance and Advanced Special Purpose Materials 4000

Total 32000
Representative Materials Test matrix for ITER

<table>
<thead>
<tr>
<th>Program Element</th>
<th>Test Description</th>
<th>Specimen Configuration</th>
<th>Size (mm)</th>
<th>Material Variables</th>
<th>Irradiation Environment</th>
<th>Multi-Total</th>
<th>Total Vol. (cm³)</th>
<th>Vol./Spec. (cm³)</th>
<th>Total Vol. (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Structural Alloys</td>
<td>Charpy-v</td>
<td>1/3 CVN (3.3 x 3.3 x 23.6)</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>896</td>
</tr>
<tr>
<td></td>
<td>Tensile</td>
<td>Flat (0.76 x 25.4 x 5.0)</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>15</td>
<td>1680</td>
</tr>
<tr>
<td></td>
<td>Creep</td>
<td>Tube (4.57 dia. x 23.0)</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>Swelling</td>
<td>Disc (3.18 dia. x 5.0)</td>
<td>144</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>6</td>
<td>24192</td>
</tr>
<tr>
<td></td>
<td>Fracture Toughness</td>
<td>Compact Tension (160 dia. x 2.5)</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>16</td>
<td>1792</td>
</tr>
<tr>
<td></td>
<td>Stress Corrosion Cracking</td>
<td>CERT SS-3 (0.76 x 25.4 x 5.0)</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>24</td>
<td>2688</td>
</tr>
<tr>
<td></td>
<td>Fatigue</td>
<td>Constant Amplitude/High Cycle (6.35 dia. x 38)</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>336</td>
</tr>
<tr>
<td>Surveillance Structural Alloys</td>
<td>Charpy</td>
<td>CVN (9.9 x 9.9 x 24.4)</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>7</td>
<td>504</td>
</tr>
<tr>
<td></td>
<td>Tensile</td>
<td>Round (12.5 dia. x 48)</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>288</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tube (6.35 dia. x 50.8)</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>288</td>
</tr>
<tr>
<td></td>
<td>Creep</td>
<td>Tube (6.35 dia. x 28.2)</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>108</td>
</tr>
<tr>
<td></td>
<td>Fracture Toughness</td>
<td>Compact Tension (30.4 x 31.8 x 12.7)</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>144</td>
</tr>
</tbody>
</table>
Representative Materials Test matrix for ITER, cont'd

<table>
<thead>
<tr>
<th>Solid Breeder Materials</th>
<th>Breed Material Performance (PIE)</th>
<th>Breeder Cylinders ( (6.35 \text{ dia.} \times 50.8) )</th>
<th>5</th>
<th>4</th>
<th>2</th>
<th>480</th>
<th>1.61</th>
<th>772</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surveillance and Advanced Special Purpose Materials</td>
<td>Ceramic: Mechanical</td>
<td>Cylinders ( (12.7 \text{ dia.} \times 50.8) )</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>672</td>
</tr>
<tr>
<td></td>
<td>Ceramic: Thermal/Electrical</td>
<td>Plates ( (25.4 \times 25.4 \times 25.4) )</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>896</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plates ( (25 \times 25 \times 6.35) )</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flat ( (0.76 \times 25.4 \times 5.0) )</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disc ( (3.18 \text{ dia.} \times 0.25) )</td>
<td>16</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tube ( (4.57 \text{ dia.} \times 23.0) )</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Magnets</td>
<td>Plates ( (25 \times 25 \times 6.35) )</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Magnet Material</td>
<td>Plates ( (25 \times 25 \times 6.35) )</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>
Materials Test Program (cont'd)

**Interface With the Machine**

- Temperature Control is Crucial
  Need constant temperature for a given period
  - Dwell Time and COT issues
  - Providing controlled environment (coolant streams, etc.)

- Isolation from First Wall is acceptable
  - However, dose drops rapidly with depth behind first wall.

- Material Examination Intervals
  - 100 days to 1 year

- Turnaround time for specimens
  (reconstituting the material test module)
  - ~2 weeks

- Other requirements on maintenance and test vehicle design
Observations on HHFC Testing in ITER

Base Machine Operation

Observation of basic divertor and HHFC operation is an important part of the test program.

Testing in the Divertor Region

Divertor ports (similar to blanket ports) should be considered.

Test articles with the same plasma-facing material as the basic divertor should be allowed.

The conditions available in the divertor "throat" region may allow for high-heat-flux testing of first wall test modules.

Testing in the FW/Blanket Test Ports

Non-PMI issues for PFC materials (e.g., radiation effects) can be tested in a "blanket test port" with plasma exposure.
Testing Issues for Plasma Interactive Components

1. Particle exhaust, erosion and recycling

2. High heat flux removal and thermomechanical response
   - heat transfer limits
   - flow distribution and stability (especially for liquid metals)
   - corrosion and chemistry (including coatings)
   - thermal fatigue
   - bond integrity
   - heat source characterization

3. Disruptions (thermal and electromagnetic effects)

4. Tritium permeation and retention

5. Irradiation effects on component behavior
   - short-term (e.g., thermal conductivity)
   - long-term (swelling, embrittlement, etc.)
Example Test Program for Divertors

Checkout

Concept Screening

Performance Verification and Improvement

Reliability Growth (EPP)

Basic Machine Divertor
- plasma optimization
- performance assessment
- performance ranges

Submodules (non-PMI issues in "blanket test ports")
- design options
- test design options

Full Divertor Panels (substitute for parts of basic divertor)
- replace basic divertor

Divertor Sector
- replace basic divertor
- observe long-term operation (PIE)
- reliability growth
- full sector changeout
Heating and Current Drive Systems Test Program

- Many engineering/nuclear issues need to be tested.
- An example is the launcher array for lower hybrid current drive

Key features:
- very close to plasma
- complex, actively-cooled structures (this is a high-heat-flux component)
- electrical insulators at the vacuum vessel with simple streaming paths
- Be cover and protective limiters needed
- open paths for particle and radiation transport

Changes in performance are likely due to nuclear effects:
- electromagnetic spectrum degradation
- reduced coupling to the plasma
- thermomechanical issues
- shielding effectiveness
Ancillary Equipment
for ITER Test Program
Large Amount of Complex Ancillary Equipment Intimately Tied into the Testing Program

Needed Ancillary Equipment:

- Heat Rejection
- Tritium Recovery Systems and Test-Specific Intermediate Tritium Processing
- Chemical (Impurity) Control Systems
- Coolant and Purge Fluid Storage, Start-up, and Volume Control Systems
- Emergency and Safety Systems
- Remote Handling Equipment
- Test Rooms and Hot Cells for Examinations
- Control and Data Acquisition Systems

The ancillary equipment requirement has several serious issues:

- Space requirement
- Access lines
- Maintenance/removal requirements
- Cost
- R&D
Example Cooling System for a Single Water-Cooled Solid Breeder Blanket Test Module
Tritium Recovery System for Solid Breeder Blanket Test Module

- A tritium recovery process for solid breeder test modules involves: measure, merge and process

Tritium Analysis
IC: Ionization chamber
M: Hygrometers
S: Gas sampling lines
CEC: Ceramic electrolysis cell
FM: Flow meter
FC: Flow controller
P: Pressure gauge
T: Thermometer

Tritium Recovery
MS: Molecular sieve Beds
CT: Cold trap
OX: Catalytic oxidizer
In Order to Ensure That the ITER Design can Accommodate the Test Program

Need to Discuss Ancillary Equipment Arrangements for EDA with JCT and Parties Involved in Testing

FIG. 4.2.4 - Space Allocation During the Technology Phase
TABLE 4.2.4. ESTIMATE OF ANCILLARY EQUIPMENT SPACE REQUIREMENTS

<table>
<thead>
<tr>
<th>Port</th>
<th>Test Article Type</th>
<th>Space Requirements (Area x Height, m² x m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>behind test port</td>
</tr>
<tr>
<td>SB/gas</td>
<td>3 submodules</td>
<td>730 x 11</td>
</tr>
<tr>
<td></td>
<td>full module or segment</td>
<td>370 x 11</td>
</tr>
<tr>
<td>SB/H2O</td>
<td>3 submodules</td>
<td>450 x 11</td>
</tr>
<tr>
<td></td>
<td>full module or segment</td>
<td>150 x 11</td>
</tr>
<tr>
<td>LM/self</td>
<td>4 submodules</td>
<td>300 x 11</td>
</tr>
<tr>
<td></td>
<td>full module or segment</td>
<td>300 x 11</td>
</tr>
<tr>
<td>LM/H2O</td>
<td>2 submodule</td>
<td>50 x 11</td>
</tr>
<tr>
<td></td>
<td>full module</td>
<td>100 x 11</td>
</tr>
<tr>
<td></td>
<td>segment</td>
<td>100 x 11</td>
</tr>
<tr>
<td>Materials</td>
<td>Test assembly</td>
<td>120 x 5 **</td>
</tr>
</tbody>
</table>

TOTAL FLOOR AREA

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>400-500 m²</td>
<td>1600 m²</td>
</tr>
</tbody>
</table>

* plant services include space allocated in the main tritium processing hall and post-irradiation examination rooms (hot cells)

** pneumatic system for test specimen insertion/extraction, may be located in ancillary room
International Aspects
of ITER Test Program
Collaboration in the ITER Test Program

Collaboration on the test program is fundamentally different from collaboration on the basic device:

- R&D for ITER construction is specific to ITER and of common interest to parties

- The test program is tightly coupled to and plays a key role in R&D programs for DEMO and commercial reactor development

Difficulties may arise due to:

- differences in design choices
- differences in the overall strategies for fusion development
- differences in the approaches to testing

At present, there is no formal framework or agreement on collaboration on the test program

Need a mechanism to address parties’ interests and collaboration on the test program

- (R&D)
- design and construction of test modules
- operation and sharing of information from the test program
(CDA Choice)
Fig 2 Test Sequence for Liquid Metal Blankets

Liquid Metal Cooled Tests (CDA Choice)

<table>
<thead>
<tr>
<th>2 Years</th>
<th>1 Year</th>
<th>4 Years</th>
<th>1 Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li (US Lead)</td>
<td>LiPb (EC Lead)</td>
<td>LiPb Alternating</td>
<td>Li or LiPb Full Segment</td>
</tr>
<tr>
<td>Li (SU Lead)</td>
<td>Basic Tests or LiPb (J Lead)</td>
<td>First Wall Exposed to Plasma</td>
<td>First Wall Exposed to Plasma</td>
</tr>
<tr>
<td>Separate First wall</td>
<td>First Wall Exposed to Plasma</td>
<td>First Wall Exposed to Plasma</td>
<td></td>
</tr>
</tbody>
</table>

Water Cooled Tests

<table>
<thead>
<tr>
<th>2 Years</th>
<th>5 Years</th>
<th>1 Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiPb (EC Lead)</td>
<td>LiPb (SU Lead)</td>
<td>LiPb Full Segment</td>
</tr>
<tr>
<td>Separate First wall</td>
<td>First Wall Exposed to Plasma</td>
<td>First Wall Exposed to Plasma</td>
</tr>
</tbody>
</table>
Options for the International Test Program

<table>
<thead>
<tr>
<th>CDA choice</th>
<th>EDA choice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

1. Allocation of available testing spaces to parties
   - fully independent
   - lead role given to individual parties
   - spaces assigned to international groups
   - fully common test program

2. Design of testing spaces and ancillary equipment
   - generic test spaces capable of testing any concept
   - single-coolant test spaces
   - custom-designed test spaces

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