FUSION NUCLEAR TECHNOLOGY
TESTING REQUIREMENTS FOR ETR

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FUSION NUCLEAR TECHNOLOGY

• Top Level Issues

- Fuel Self-Sufficiency

- Efficient, Reliable and Safe Energy Conversion and Use

- Radiation Protection of Components, Personnel

Suggested ETR Nuclear Mission

Demonstrate the performance of nuclear components and tritium self-sufficiency at reactor-relevant conditions
FNT R&D Framework

• **Non-Fusion Testing** (+ Model Development)

  Non-Neutron Test Stands
  Fission Reactors
  14 MeV Neutron Sources

  - Support Conceptual Design Screening and Evolution

  - Initial Validation of Theory and Models

  - Provide Data for Design, Construction and Operation of Test Elements and Modules in ETR

• **Fusion Testing**

  - Verify Theory/Models, Design Codes

  - Data for Concept Selection

  - Demonstrate Performance Level
    Extrapolatable to Reactor

  - Demonstrate Adequate Level of Reliability
Framework For Fusion Nuclear Technology Development

Non-Neutron Test Stands
- Fission Reactors
- Point Neutron Source

Theory and Analysis

Component Development

ETR
- Design
- Construction
- Physics
- Nuclear Testing

Test Modules

Basic Data, Phenomena Exploration
- Concept Verification
- Reliability Growth

FUSION TEST MATRIX

SPECIMEN

MATERIAL BEHAVIOR, PROPERTIES

ELEMENT

SPECIFIC ISSUES IN THE FUSION ENVIRONMENT (E.G., LIQUID METAL BULK HEATING)
SUB-SCALE INTERACTIVE EFFECTS (SWELLING/CREEP, ETC.)

SUB-MODULE

SEVERAL ELEMENTS
CLASS OF ISSUES
INTERACTION AMONG ELEMENTS

MODULE

INTEGRATED COMPONENT BEHAVIOR
BOUNDARY CONDITIONS MAY NOT BE PROTOTYPIC

SECTOR (ALL MODULES IN A TOROIDAL SEGMENT)

INTERACTIONS AMONG MODULES
PROPER PLOIDAL BOUNDARY CONDITIONS
MORE PROTOTYPIC CONFIGURATION/Maintenance
Table 1.3-6 Examples of Number and Size of Test Articles Required for Fusion Nuclear Technology Testing

<table>
<thead>
<tr>
<th>Tests</th>
<th>Typical Test Article Size (cm x cm x cm)</th>
<th>Number of Test Articles⁹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Specimen</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural material irradiated properties</td>
<td>1 x 1 x 2</td>
<td>30,000</td>
</tr>
<tr>
<td>Solid breeder and multiplier irradiated properties</td>
<td>1 x 1 x 2</td>
<td>1,200</td>
</tr>
<tr>
<td>Plasma interactive materials irradiated properties</td>
<td>1 x 1 x 5</td>
<td>900</td>
</tr>
<tr>
<td>Radiation damage indicator cross-sections</td>
<td>1 x 1 x 0.5</td>
<td>500</td>
</tr>
<tr>
<td>Long-lived isotope activation cross-sections</td>
<td>1 x 1 x 0.1</td>
<td>200</td>
</tr>
<tr>
<td><strong>Element</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure thermomechanical response</td>
<td>10 x 10 x 10</td>
<td>50</td>
</tr>
<tr>
<td>Effects of bulk heating on heat transfer</td>
<td>10 x 10 x 100</td>
<td>5</td>
</tr>
<tr>
<td>Various element tests for solid breeder blankets</td>
<td>10 x 10 x 5</td>
<td>50</td>
</tr>
<tr>
<td>Weld behavior</td>
<td>10 x 10 x 5</td>
<td>50</td>
</tr>
<tr>
<td>Optical component radiation effects</td>
<td>2 x 2 x 2</td>
<td>20</td>
</tr>
<tr>
<td>Instrumentation transducer lifetime</td>
<td>1 x 1 x 2</td>
<td>70</td>
</tr>
<tr>
<td>Insulator/substrate seal integrity</td>
<td>1 x 1 x 2</td>
<td>20</td>
</tr>
<tr>
<td><strong>Submodule</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit cell thermal and corrosion behavior</td>
<td>LB b: 100 x 50 x 30</td>
<td>5</td>
</tr>
<tr>
<td>Submodule mechanical responses</td>
<td>SB b: 10 x 50 x 30</td>
<td>5</td>
</tr>
<tr>
<td>Tritium behavior (e.g., permeation in coolant, response to thermal and flow transients)</td>
<td>10 x 50 x 10</td>
<td>3</td>
</tr>
<tr>
<td><strong>Module</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verification of neutronic predictions</td>
<td>50 x 50 x 100</td>
<td>4</td>
</tr>
<tr>
<td>- Tritium breeding, nuclear heating during operation, and induced activation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full module verification</td>
<td>LB c: 100 x 100 x 50</td>
<td>5</td>
</tr>
<tr>
<td>- Thermal and corrosion</td>
<td>SB: 100 x 100 x 50</td>
<td>5</td>
</tr>
<tr>
<td>- Module thermomechanical lifetime</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Tritium recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shield effectiveness in complex geometries</td>
<td>50 x 50 x 100</td>
<td>50</td>
</tr>
<tr>
<td>Biological dose rate profile verification</td>
<td>DT device</td>
<td>1</td>
</tr>
<tr>
<td>Afterheat profile verification</td>
<td>DT device</td>
<td>1</td>
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<tr>
<td><strong>Sector</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blanket performance and lifetime verification</td>
<td>LB: 900 x 300 x 80</td>
<td>3</td>
</tr>
<tr>
<td>Radiation effects on electronic components</td>
<td>SB: 300 x 100 x 80</td>
<td>3</td>
</tr>
<tr>
<td>Instrumentation performance and lifetime</td>
<td>1 x 1 x 1</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>5 x 5 x 5</td>
<td>100</td>
</tr>
</tbody>
</table>

⁹Test article defined as one physical entity tested at one set of conditions. Duplication of tests for statistical purposes, off-normal conditions, data at several time intervals, for high fluence tests, etc., are not included in the number of test articles.

bLB = liquid breeder blankets, SB = solid breeder blankets.

cSome designs require larger test volume.
FNT Testing Requirements

- **Major Parameters of Device**
  - Device Cost Drivers
  - Major Impact on Test Usefulness

- **Engineering Design of Device**
  
  E.g.,
  
  - Access to Place, Remove Test Elements
  - Provision for Ancillary Equipment
  - Accommodation of Failures in Test Elements
MAJOR PARAMETERS

• Neutron Wall Load

• Surface Heat Load

• Plasma Cycle Burn/Dwell Times

• Minimum Continuous Time

• Availability

• Fluence

• Magnetic Field Strength

• Test Area/Size
Scaling of Major Parameters

• Cost Forces Scaled-Down Conditions

• "Look-Alike" Test Modules are Useless

• "Act-Alike" Test Modules are Necessary

• Engineering Scaling Laws must be followed
  - To Preserve Important Phenomena
  - To Correctly Determine Test Requirements
ENGINEERING SCALING IN ACT-ALIKE TEST
MODULES HAS LIMITATIONS

• Not all parameters can be scaled down simultaneously
  - Simulation is never perfect
  - Trade-offs among parameters result

• Complex engineering issues are involved
  - Large uncertainties in individual issues
  - Value judgements on relative importance of different issues and environmental conditions
Some Engineering Scaling Trade-offs

- Lower $P_N$ requires larger dimensions to preserve $\Delta T$

- Lower $P_N$ requires longer time to equilibrium

- Lower $B$ requires larger dimensions to preserve MHD effects ($H_A \sim AB$)
NEUTRON WALL LOAD REQUIREMENTS

NEUTRON WALL LOAD IS A PRIMARY SOURCE OF BOTH HEATING AND NUCLEAR REACTIONS IN THE BLANKET

\[ P_N \rightarrow \]

- BULK HEATING
- SURFACE HEATING
- REACTION RATE (E.G., TRITIUM PRODUCTION)
- FLUENCE
The heat source determines temperatures in the blanket, which activates many important engineering processes.
While average temperatures can be compensated by controlling the coolant inlet temperature, temperature gradients are unavoidably changed by reduced heat input. Engineering scaling is only partially successful at recovering the correct profiles.

Heat source effect on the BCSS Li₂O/He/HT-9 first wall temperature profile (reactor at 5 MW/m² neutron and 1 MW/m² surface heat load; scaled test module at 2.5 and 0.1 MW/m²).
Temperature profiles through the first wall under various operating conditions.
Neutron Fluence

- Benefits to FNT testing as a function of neutron fluence have been identified
  - Many issues show continuous increase in benefits at higher fluences
  - Some issues show distinct fluence regions of highest benefit

- Higher fluences are costly
  - Device availability (reliability)
  - Tritium supply

- Must make a distinction between:
  - Fluence achievable at test module \((\phi T)_M\)
  - Test facility "lifetime fluence" \((\phi T)_F\)

\[(\phi T)_F > 2(\phi T)_M\] in general

- Attenuation in device first wall and other in-vessel components reduces flux at test modules (Most test modules must be isolated from the device "vacuum")

- There is inevitably a long period of fail/replace/fix for test module (Remember: first time to test in fusion environment)
<table>
<thead>
<tr>
<th>Exposure MW-yr/m²</th>
<th>Phenomena/Effects</th>
</tr>
</thead>
</table>
| 0-0.2            | Thermophysical Property Changes (e.g., Thermal Conductivity)  
Solid Breeder Cracking  
Liquid Metal Embrittlement of Structure  
Onset of Li₂O and Multiplier Swelling  
Insulator Embrittlement and Conductivity Changes  
First Wall Erosion  
Initial Operational Stress Effects  
Tritium Permeation through First Wall and Clad  
Hydride Formation and Hydrogen Embrittlement in Structure  
Porosity in Breeder May Close Off  
Radiation-Induced Sintering and Grain Growth |
| 0.2-1            | Li₂O Swelling Dominates Breeder/Clad Mechanical Interaction  
Ductility Changes (HT-9, 316 SS)  
Initiation of Fatigue and Creep/Fatigue  
First Wall Erosion/Redeposition and Surface Cracking  
Relaxation of Thermal Stress  
Radiation-Induced Trapping in Structure (Defect Saturation)  
Reduction in Fracture Toughness (Structure)  
Early Transmutation Effects (e.g., Drop in Conductivity of Copper Due to Ni Production)  
Measurable Radioisotope Concentration |
| 1-3              | Changes in Ductility Start to Saturate (HT-9, 316)  
Fracture Toughness, Δ-DBTT Saturates  
Thermal Stress Relaxation Complete  
Burnup Effects on Chemistry, Compatibility, Breeding  
Breeder/Clad Corrosion  
Irradiation Hardening (<450°C)/Softening (>450°C) Saturates |
| 3-5              | Possible Fatigue Crack Propagation  
Onset of Irradiation Creep/Swelling Interaction of Austenitic Alloy  
Clad Swelling (316) Dominates Breeder/Clad Interaction  
Possible Fracture Toughness Degradation (HT-9) |
| 5-10             | Potential Onset of Irradiation Creep/Swelling Interaction of HT-9  
Possible Fatigue Failure  
Change in Fracture Mode  
Changes in Toughness/Strength/Ductility and Tearing Modulus |
| 10-20            | End-of-Life Phenomena:  
Operational Stress Effects  
- First Wall Thinning - Unstable Deformation  
- Fatigue, Creep Fatigue - Unstable Cracking  
Unforeseen High-Fluence Material Behavior (e.g., Solid Transmutations) |
EXAMPLE OF BENEFIT Vs. FLUENCE

MECHANICAL INTERACTION BETWEEN SOLID BREEDER/MULTIPLIER AND STRUCTURE
HT-9/Li2O/He

- COMBINED UNCERTAINTY
- DERIVATIVE

COMBINED UNCERTAINTY FOR GOAL EXPOSURE OF 10 MW•yr/m²

DERIVATIVE OF COMBINED UNCERTAINTY PROJECTION (MW•yr/m²)
Fluence-Related Effects in Blanket Structural Materials

- Initial operational stress effects
- Initial degradation of thermal stress factor
- Thermal stress relaxation complete
- Reduction in fracture toughness
  - Onset saturation
- Irradiation hardening (< 450°C)/softening (> 450°C)
  - Onset saturation
- High temperature helium embrittlement
  - Onset saturation potential creep failure
- Liquid metal embrittlement
- Fatigue and creep/fatigue (cyclic failure mechanisms)
  - Initiation crack propagation
  - Unstable cracking, potential failure
- DBTT for ferritics at low temperature
  - Onset saturation
- Tritium permeation, hydride formation and hydrogen embrittlement
- Swelling and creep/swelling interaction
  - Radioisotope concentration
- Austenitic
- Ferritic
- Refractory
- Fission reactor data base
Fluence-Related Effects in Solid Breeders, Ceramics, and Special Materials

- 0  0.2  1  3  5  10  20
  - thermophysical property changes
  - breeder porosity may close
  - radiation-induced sintering and grain growth
  - solid breeder cracking
  - solid breeder/clad mechanical interaction
  - onset of \( \text{Li}_2\text{O} \) and multiplier swelling
  - breeder swelling dominates
  - clad swelling dominates (\(316\text{SS}\))
  - potential clad failure
  - insulator embrittlement and conductivity changes
  - breeder/clad corrosion
  - burnup effects on chemistry, compatibility and breeding

MW-yr/m\(^2\)

fission reactor data base
Fluence-Related Effects in Plasma-Facing Materials

0 0.2 1 3 5 10 20 MW-yr/m²

- erosion
- surface cracking
- thermal
- swelling-induced
- erosion/redemption
- thermal stress & effects of creep or fatigue (thin structures)

Coating Stability

- hardening, embrittlement
- DBTT at low temperature (ferritics)

- tritium permeation, hydride formation and hydrogen embrittlement
- surface damage effects on tritium recovery

- swelling and creep/swelling interaction
- refractory
- austenitic
- ferritic

fission reactor data base
TIME-RELATED PARAMETERS

- Plasma Burn Time, Dwell Time
  (Duty Cycle)

- Minimum Continuous Operating Time
  (100% Availability)
Effects of Pulsing/Steady State Operation on Nuclear Technology Testing

- Plasma cycling means 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 mechanics
  - Time to reach equilibrium
<table>
<thead>
<tr>
<th><strong>Flow</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Breeder Purge Residence</td>
<td>6 s</td>
</tr>
<tr>
<td>Liquid Breeder Coolant Residence</td>
<td>30 s</td>
</tr>
<tr>
<td>Liquid Breeder Cooling Circuit Transit</td>
<td>60 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Thermal</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure Conduction</td>
<td>4 s</td>
</tr>
<tr>
<td>Structure Bulk Temperature Rise</td>
<td>20 s</td>
</tr>
<tr>
<td>Liquid Breeder Conduction (Li)</td>
<td>30 s</td>
</tr>
<tr>
<td>Solid Breeder Conduction (1/2-cm plate)</td>
<td>50-100 s</td>
</tr>
<tr>
<td></td>
<td>(1-cm plate)</td>
</tr>
<tr>
<td>Coolant Bulk Temperature Rise (200 K at 4000 MW&lt;sub&gt;e&lt;/sub&gt;)</td>
<td></td>
</tr>
<tr>
<td>Li</td>
<td>100 s</td>
</tr>
<tr>
<td>LiPb</td>
<td>1500 s</td>
</tr>
<tr>
<td>Solid Breeder Bulk Temperature Rise (LiAlO&lt;sub&gt;2&lt;/sub&gt;, 300-1000°C)</td>
<td></td>
</tr>
<tr>
<td>Front (Near Plasma)</td>
<td>120 s</td>
</tr>
<tr>
<td>Back (Away from Plasma)</td>
<td>1800 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Material Interactions</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolution of Fe in Li (500°C)</td>
<td>40 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Tritium</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion Through Solid Breeder (LiAlO&lt;sub&gt;2&lt;/sub&gt;, 0.2 µm grains)</td>
<td></td>
</tr>
<tr>
<td>1250 K</td>
<td>8-200 s</td>
</tr>
<tr>
<td>750 K</td>
<td>13-300 hours</td>
</tr>
<tr>
<td>Surface Adsorption (LiAlO&lt;sub&gt;2&lt;/sub&gt;)</td>
<td></td>
</tr>
<tr>
<td>Diffusion Through SS316</td>
<td></td>
</tr>
<tr>
<td>800 K</td>
<td>10 days</td>
</tr>
<tr>
<td>600 K</td>
<td>150 days</td>
</tr>
</tbody>
</table>

| **Inventory in Solid Breeder** (Water-Cooled LiAlO<sub>2</sub>, 0.2 µm grains) |       |
| 67% of equilibrium | 6 months |
| 99% of equilibrium | 4 years  |

| **Inventory in Liquid Breeder** |       |
| LiPb                           | 30 minutes |
| Li                             | 30 days    |
MANY KEY ISSUES REQUIRE LONG BURN TIME

\[ F = F_0 \left(1 - e^{-T/\tau}\right) \]

PLASMA BURN TIME > 3 \( \tau \) (95%)

<table>
<thead>
<tr>
<th>Time Constants</th>
<th>Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seconds</td>
</tr>
<tr>
<td>Heat Conduction</td>
<td>Minutes</td>
</tr>
<tr>
<td>Flow Processes</td>
<td>Hours</td>
</tr>
<tr>
<td>Thermal Processes</td>
<td></td>
</tr>
<tr>
<td>Tritium Processes</td>
<td></td>
</tr>
<tr>
<td>Material Interactions</td>
<td></td>
</tr>
<tr>
<td>Other Important Processes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slow</td>
</tr>
</tbody>
</table>

NUCLEAR EFFECTS WITH LONG TIME CONSTANTS ARE THE MOST CRITICAL ISSUES FOR TESTING IN THE FUSION ENVIRONMENT
SIGNIFICANT PLASMA DWELL TIME
IMPACTS MANY CRITICAL NUCLEAR TESTS

\[ F = F_0 \frac{t}{e^{\tau}} \]

PLASMA DWELL TIME < 0.1 \( \tau \)

- CRITICAL PROCESSES WITH LONG \( \tau \) WILL BE TREMENDOUSLY COMPLICATED BY SIGNIFICANT DWELL TIME

- THEY DEPEND ON MANY OTHER PROCESSES WITH VERY SHORT TIME CONSTANTS

EXAMPLES

- TRITIUM PROCESSES
  SLOW PROCESS; BUT STRONG DEPENDENCE ON TEMPERATURE AND FLUID FLOW

- CORROSION PROCESSES
  SLOW PROCESS; BUT STRONG DEPENDENCE ON TEMPERATURE AND FLUID FLOW

- FERRITIC DBTT

PLASMA DWELL TIME SHOULD BE NEAR ZERO
Pulsing strongly affects the solid breeder temperature distribution.

- $T_{ss\ max}$
- $T_{ss\ min}$
- $T_{max}$
- $T_{min}$

**Graphs:**
- **Left:**
  - Temperature (°C) vs. Time
  - Marked points: $T_{ss\ max}$, $T_{ss\ min}$, $T_{max}$, $T_{min}$

- **Right:**
  - Breeder fraction per unit temperature (1/K) vs. Temperature (°C)
  - Marked areas: pulse averaged, steady state

**Materials:**
- Li$_2$O/He/HT-9
$\gamma$-LiAlO$_2$

Tritium Diffusion Time Constant Uncertainty Band for Grain of Radius 0.1 $\mu$m.

Thermal Diffusion Time Constant for a Diffusion Length of 0.5 cm.
Tritium Generated in One 0.2 μm dia. LiAlO₂ Grain

Tritium Release to Purge Flow

TRITIUM RELEASE RATE (10⁻²⁵ g/s)

TIME (s)

0  200  400  600  800  1000
TIME-DEPENDENT TRITIUM CONCENTRATION (DIFFUSIVE) PROFILES
IN GRAIN, GRAIN BOUNDARY AND PORE
MANY OF THE CRITICAL NUCLEAR ISSUES THAT REQUIRE TESTING IN THE FUSION ENVIRONMENT NEED LONG PLASMA BURNTIME

PLASMA BURNTIME

10min. 100min. 1 day 1 week

Neutronics

Fluid Flow

Primary Stress Thermal Stress

Corrosion Redeposition

LM Heat Transfer SB Heat Transfer

Tritium Diffusion in SB

1000k 750k

T Inventory, LiPb T Inventory in Lithium

T Surface Adsorption

T Inventory in SB T Permeation
Reaching tritium inventory and recovery equilibrium may require long test times.
RECOMMENDATIONS

- Adopt Steady State as Design Basis for the Nuclear Testing Phase in ETR

- Plan on Many Periods with Continuous Device Operation (100% Availability)

Each Period: Weeks
DEVICE GEOMETRY AND TEST VOLUME REQUIREMENTS

SEVERAL ASPECTS OF THE DEVICE GEOMETRY IMPACT NUCLEAR TESTING:

- **Test Port Shape, Volume, and Surface Area Exposed to the Plasma**

- **Position of Test Port Relative to the Device**
  - E.g., inboard vs. outboard proximity of other components

- **Overall Device Geometry**
  - Plasma
  - Magnetic Field
  - Structure

---

LARGEST INFLUENCE OF GEOMETRY IS ON:

- Neutronics
- Liquid Metal MHD
- Structural Responses
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Typical Reactor Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hartmann Number</td>
<td>$Ha = aB \sqrt{\frac{\sigma}{\mu}}$</td>
<td>6.3x10$^4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.6x10$^4$</td>
</tr>
<tr>
<td>Reynolds Number</td>
<td>$Re = av \frac{\rho}{\mu}$</td>
<td>6.6x10$^4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.1x10$^5$</td>
</tr>
<tr>
<td>Interaction Parameter</td>
<td>$N = \frac{aB^2}{v} \frac{\sigma}{\rho}$</td>
<td>6.0x10$^4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>825</td>
</tr>
<tr>
<td>Magnetic Reynolds Number</td>
<td>$Re_m = av \mu_o \sigma$</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.052</td>
</tr>
<tr>
<td>Wall Conductance Ratio</td>
<td>$C = \frac{\sigma_w t}{\sigma a}$</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.090</td>
</tr>
<tr>
<td>Property Values:</td>
<td></td>
<td>3x10$^6$</td>
</tr>
<tr>
<td>(all units mks)</td>
<td></td>
<td>0.83x10$^6$</td>
</tr>
<tr>
<td></td>
<td>$\sigma = 3x10^6$</td>
<td>0.38x10$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$\mu = 0.38x10^{-3}$</td>
<td>1.5x10$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$\rho = 495$</td>
<td>9200</td>
</tr>
<tr>
<td>Reactor Conditions</td>
<td></td>
<td>1.5x10$^6$</td>
</tr>
<tr>
<td>Assumed:</td>
<td>$a = 0.1$</td>
<td></td>
</tr>
<tr>
<td>(all units mks)</td>
<td>$\sigma_w = 1.5x10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B = 7$ (at inboard)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$t = 0.005$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\nu = 0.5$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\mu_o = 4\pi x10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>Parameters</td>
<td>ETR</td>
<td>Reference Reactor</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Neutron Wall Load, MW/m²</td>
<td>Minimum 1</td>
<td>Recommended 2-3</td>
</tr>
<tr>
<td>Surface Heat Load, MW/m²</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Plasma Burn Time, s</td>
<td>500</td>
<td>&gt;1000&lt;sup&gt;A&lt;/sup&gt;</td>
</tr>
<tr>
<td>Magnetic Field&lt;sup&gt;B&lt;/sup&gt;, T</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Continuous Operating Time</td>
<td>Days</td>
<td>Weeks</td>
</tr>
<tr>
<td>Availability, %</td>
<td>20</td>
<td>30-50</td>
</tr>
<tr>
<td>Fluence&lt;sup&gt;B&lt;/sup&gt;, MW·y/m²</td>
<td>1-2</td>
<td>3-6</td>
</tr>
<tr>
<td>Test Port Size, m² x m</td>
<td>0.5 x 0.3</td>
<td>1 x 0.5</td>
</tr>
<tr>
<td>Total Test Area, m²</td>
<td>5</td>
<td>10-20</td>
</tr>
</tbody>
</table>

<sup>A</sup> Steady-state strongly preferred
<sup>B</sup> At test article (device lifetime fluence is larger)