# ITER Technology Mission and Test Program

Presented By

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- Most of the analysis/recommendations presented here are based on the results of many technical studies by many groups, particularly the International Test Group for ITER.
- Input was provided by many experts, special thanks to Mark Tillack, and Richard Mattas for assistance

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# Summary of Recommendations

1. Technology mission should be a key part of ITER objectives and design

2. ITER should have a strong test program, particularly for nuclear components

3. Nuclear testing requirements

   - Fluence
     Desirable: 4-6 MW.y/$m^2$
     Strongly Recommended: 2-3 MW.y/$m^2$
     Minimum: 1 MW.y/$m^2$

   - Neutron Wall Load: $>$ 1 MW/$m^2$

   - Plasma Mode
     Highly Desirable: Steady State
     Highly Recommended: Long burn 1-3 hrs
     Highly Recommended: Short burntime

4. EDA should have a viable organization of the test program activity that takes into account:

   - Strong interaction between designers (e.g. engineering, configuration and maintenance) and test group

   - Test program is a link between ITER organization and R & D base program in the world

# Should We Have Technology Testing In ITER?

## What is Needed?

Technology tests in the integrated fusion environment have to be done sooner or later in order to:

A) Provide the data base for construction of DEMO

B) Show that fusion is viable and has potential attractiveness as ENERGY source

*Options*

1. One (combined) device (like CDA ITER)
   Both physics and technology

2. Two separate parallel devices:
   One for physics: TFCX like
   One for technology: ?

   Key Problem:
   - No credible design was ever found for a separate technology device whose cost and risk are considerably less than the one combined device (Have only Tokamak. Nature of Tokamaks)

3. Two separate sequential devices:
   Physics device followed by technology device

   Key Problems:
   - Expensive: Cost of additional machine
   - Time delays: 15 or 20 years later (2020?)

# Recommendation

Given the Present state-of-the-art of Magnetic Fusion, technology testing in ITER appears to be:

1) The least expensive
2) Nearest-term

Option to accomplishing the objectives of fusion energy R & D

- ITER should continue to have a Technology Mission

- The test program objectives in the terms of reference should be modified:

  *old wording:*
  "ITER should serve as a test facility...and...extract high-grade heat..."

  *suggested change:*
  "The test program should demonstrate that DEMO nuclear components could be built and operated with a high degree of confidence"

# Demonstration of Fusion Potential Through Testing in ITER

- Performance and Economic Attractiveness
  - Demonstrate ability to generate electricity efficiently
  - Demonstrate operation of the entire fuel cycle
  - Demonstrate temperature limits of materials
  - Obtain data crucial to tritium self-sufficiency

- Safety Demonstration
  - Inherent safety
  - Response to transients and off-normal operating modes
  - Effects of afterheat
  - Operating experience with tritium, radioactive materials, hazardous chemicals (e.g., liquid metals, Be)

- Environmental Demonstration
  - Direct measurement of induced radioactivity afterheat
  - Demonstration of low activation options (e.g., Li/V, $Li_20$/SiC)

- Other

  Not yet studied

  - Can ITER environment be sold to other applications? (e.g., burning actinides?, medical-related applications?)

# Testing Strategy to Reduce Risk

The ETR objectives can be achieved most effectively through a test program which utilizes both the basic machine components as well as specialized test ports

1) Basic Machine

Conservative design (including base blanket) maximizes reliability, flexibility and safety of ITER

2) Test Program

Space for test modules allows testing of advanced concepts and partial demonstration of the ultimate potential of fusion

# Specific Objectives of the Test Program for Nuclear Components

Screening of concepts that require a fusion environment

Validation of a select number of DEMO component candidates

Calibration of fusion tests with non-fusion tests to take advantage of the wealth of non-fusion test data

Testing of advanced concepts, e.g.:

low activation
inherent safety

powerful, albeit limited, demonstration of fusion potential

# Engineering Issues That Should Be Addressed in the Test Program

| Issue | Components Involved |
|---|---|
| Fuel self-sufficiency | test modules & ancillary equipment, blanket, entire fuel system, impurity control & exhaust systems |
| Tritium recovery & control | test modules & ancillary equipment, fuel system, all components exposed to tritium |
| Blanket thermomechanical performance | test modules, base blanket, ancillary equipment |
| Impurity control system thermomechanical performance | divertor & ancillary equipment, test modules |
| Safety & environment (radioactivity, decay heat, etc.) | test modules, basic machine components |
| Shielding effectiveness | magnets, entire reactor |
| Materials behavior in the fusion environment | material specimens, PIE of all in-vessel components |
| Reliability and failure modes | all reactor components |

# 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

# DEMO Characteristics

| | |
|---|---|
| Neutron Wall Loading | 2-3 MW/m$^2$ |
| Availability* | > 50% |
| Fluence | 5-10 MW-yr/m$^2$ |
| Fuel Cycle | Self-sufficient, demonstrate doubling time requirements |
| Plasma Mode of Operation | Steady state (or very long burn, short dwell) |

* To achieve machine availability of 50%, means the availability per blanket module needs to be > 99%

# NUCLEAR TESTING REQUIREMENTS

| | Recommendations | | ITER |
|---|---|---|---|
| | Minimum | Highly Desirable | Reference Parameter |
| Neutron Wall Load (MW/m$^2$) | ≥ 1 | 2 | 1.3 |
| Plasma Burn Time | ≥ 1000 s | 1-3 hours to steady state | 2500 S |
| Dwell Time | a | < 20 s | 200 - 400 s |
| Continuous Test Duration (100% availability) | > 1 week | 2 weeks | |
| Average Availability | 10 - 15% | 25 - 30% | 18% |
| Total Neutron Fluence (MW·y/m$^2$) | 1.5 | 4 - 6 | 1.5 |

# Remarks on Fluence Issue

- Fluence received at the test module is about a factor of 2 lower than the device fluence
- Credible concept verification requires attainment of fluence within a factor of 2-3 of DEMO
- Value of testing of nuclear components is strongly dependent on fluence
- Testing of nuclear components and resolving nuclear issues requires a fusion device with "volume" testing. It can <u>not</u> be achieved in a "point" neutron source
- Considerable information is obtained from operating the basic components of the device. Data is crucial to DEMO
- The increment in the cost of the device to go trom 0.1 to 1-3 MW.y/m$^2$ is relatively small compared to the benefits

# FLUENCE GOALS

Device fluence (at first wall) is a factor of 2 larger than fluence received at the test module

Device Fluence (MW•y/m$^2$)

$$I_d = P_{nw} \cdot A \cdot t_d$$

Fluence at the Test Module (MW•y/m$^2$)

$$I_m = P_{nw} \cdot A \cdot t_m \cdot T$$

Why $I_d > I_m$ (typical: factor of 2)

- $t_d > t_m$
  - Sequential tests required for scoping → verification
  - Also, failure and replacement of test modules
- $T < 1$
  - Attenuation through PfC, first wall

# Fluence Requirements for Testing

- Major changes in the mechanical properties occur in the range of 0.1 to 1 MW.y/m$^2$

- Mechanical property changes will affect the response of test components

- The integrated response of test components need to be evaluated to at least the level where property changes saturate (1-3 MW.y/m$^2$)

- Failure mechanisms and damage accumulation continue to be a concern after properties saturate
  - Fatigue damage
  - Crack growth

# Fluence Effects

- **0-0.1 MW-yr/m$^2$** (at test module) Some changes in thermophysical properties of non-metals occur below 0.1 MW-yr/m$^2$

- **0.1-1 MW-yr/m2** (at test module) Several important effects become activated in the range of 0.1-1 MW-yr/m$^2$
  - Major changes in mechanical properties
  - Radiation creep will change stress distribution (integrated response)
  - Solid breeder sintering and cracking
  - Possible onset of breeder/multiplier swelling
  - He embrittlement

  Correlation of materials data with fission reactors and 14 MeV sources can be done with 1 MW-yr/m2

- **1-3 MW-yr/m$^2$** (at test module)
  - Property changes begin to saturate
    - * Evaluate integrated response of test component
    - * Begin to observe life-limiting effects
  - Numerous individual effects and component (element) interactions occur here:
    - * Burnup effects in solid breeders
    - * Swelling in solid breeders
    - * Breeder/clad interactions
    - * Changes in DBTT
    - * Changes in fracture toughness
    - * He embrittlement
    - * Creep-swelling interactions

- Unpredictable Events
  - Failure modes
  - Changes in weld properties
  - Changes in braze properties
  - Evolution of solid breeder microstructure and effects on tritium release and inventory

# ITER First Wall Property Changes

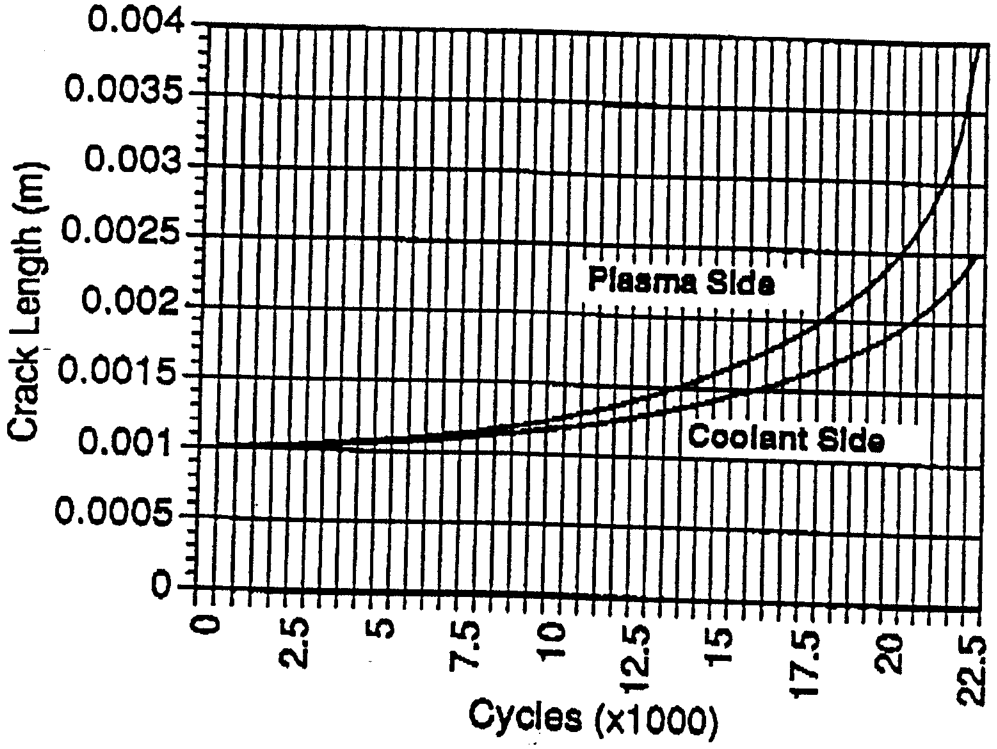
- **Yield Strength Increases Continuously During Technology Phase**
  - Saturation not yet reached.

- **Uniform Elongation Decreases Into Technology Phase**
  - Saturation at 7-10 dpa

- **Radiation Creep Stress Relaxation**
  - Saturates about midway through Technology Phase.
  - Approximately 1/2 of Technology Phase is needed to reach the final stress distribution in first wall.
  - A longer period for stress relaxation is required for material deeper into blanket where flux is lower.

- **Fatigue Damage and Crack Growth**
  - Stress redistribution and property changes will alter the rate of fatigue damage accumulation and crack growth.
  - Important information needs to be obtained after property saturation.

# FW Crack Growth - fw59 - .6MW/m2 - SA 316

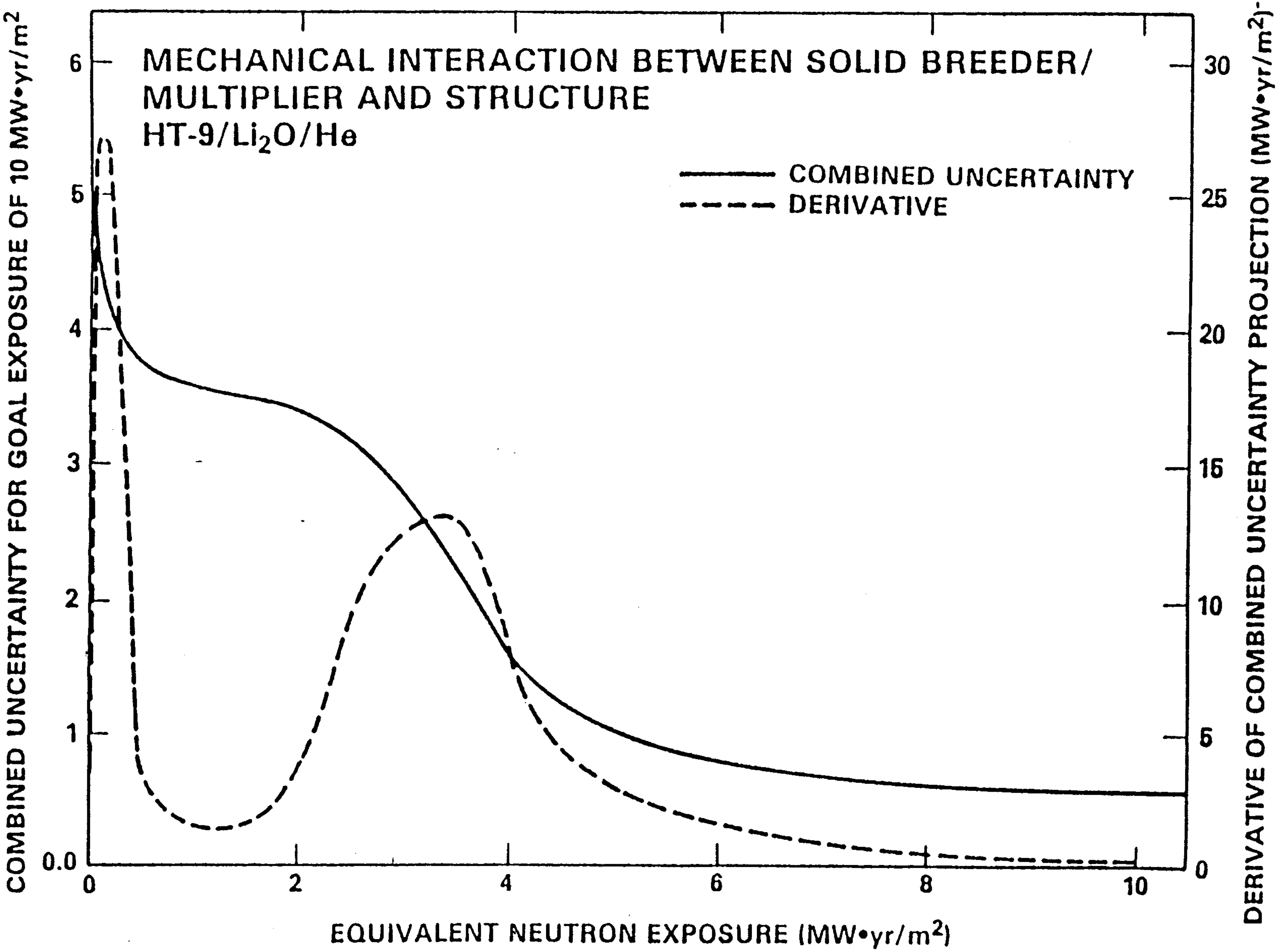


# Total Operating Time and Expected Benefits Associated With Various Fluence Goals

(Assuming 1 $MW/m^2$ wall load)

| Device Fluence $MW\text{-}yr/m^2$ | Full Power Days | Testing Capabilities |
|---|---|---|
| 0.1 | 36.5 | Scoping tests for a limited number of concepts |
| 1 | 365 | Conduct performance-oriented test program, some fluence effects observed |
| 3 | 1095 | Fluence effects, concept verification for DEMO |

# EXAMPLE OF BENEFIT Vs. FLUENCE



HEDL 8409-213.38

# Device Availability Issue

Concern

Achieving availability of 20-30% availability in ITER may be too ambitious

Counter Arguments

Valid concern but,

1) Since this is required for reasonable time scale for fusion R & D, option should not be foreclosed at the beginning of EDA

   - Plan EDA with driver blanket and significant fluence and do the best design for availability, then evaluate at end of EDA

2) If we can not presently predict availability to orders of magnitude, then 20% is not significantly less likely than 5%

3) ITER must achieve high availability in its own right as precursor to the DEMO

# Burn Cycle Recommendations

1. Steady state is very desirable for ITER

   - To qualify DEMO components (assuming DEMO is S.S. or very long burn)
   - To prevent irreversible changes due to cycling
   - To prevent difficulty interpretting and extrapolating data

   *If ITER operates in a pulsed mode, substantial additional experiments and model development will be needed to help extrapolate results to DEMO*

2. If steady state can not be achieved, then long burn time (1-3 hours) is **extremely important** to:

   - provide thermal equilibrium during tests
   - provide useful information on tritium behavior
   - reduce high-cycle structural effects

3. Burn time greater than ~1 hour provides most of the test value which can be obtained under cyclic conditions

   - ability to maintain equilibrium conditions for long periods of time
   - ability to complete many tests within a single burn time

4. The dwell time should be kept as short as possible; however, if the dwell time is longer than ~10-50 s, then prototypical conditions are unavoidably lost between burn times

# ITER TEST PROGRAM DESCRIPTION

Physics Phase: 6 years

Machine checkout
Physics testing
Some technology testing

Technology Phase: 8 years

Technology testing

- Test modules
- Information from basic device

## Space Available for Testing

| | |
|---|---|
| Physics phase: | 3 ports |
| Technology phase: | 5 ports |

Each port is 1m x 3m at first wall

# International Aspects of ITER Test Program

- There is neither sufficient space nor time to serve the needs of four independent national programs

- International collaboration is necessary

- A scheme has been developed for sharing space and time on ITER among the four parties

- Such collaboration involves issues that extend beyond collaboration on construction of ITER
  - It involves the world Base Programme
  - This is an additional benefit from ITER as it encourages collaboration on Base Programme

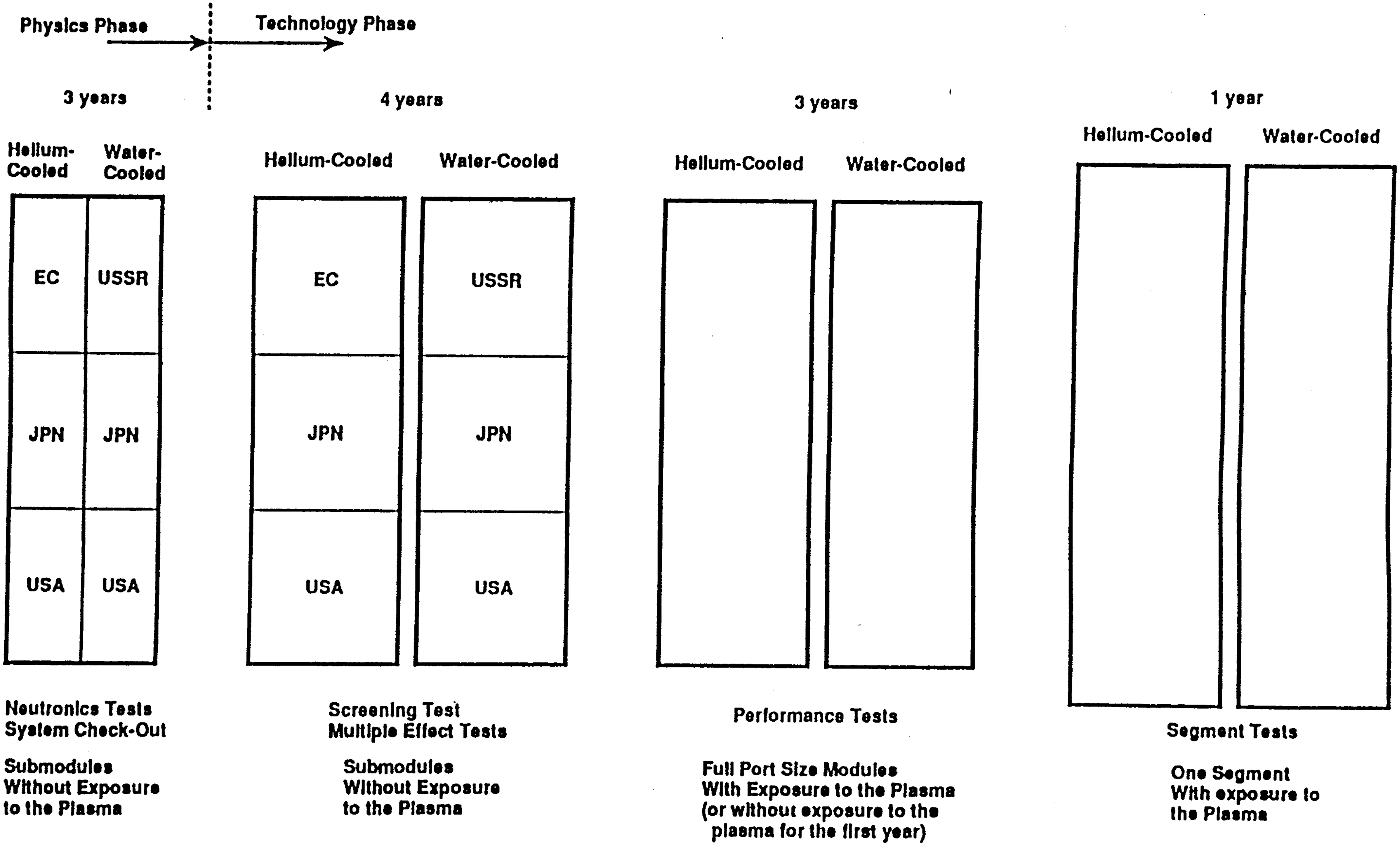


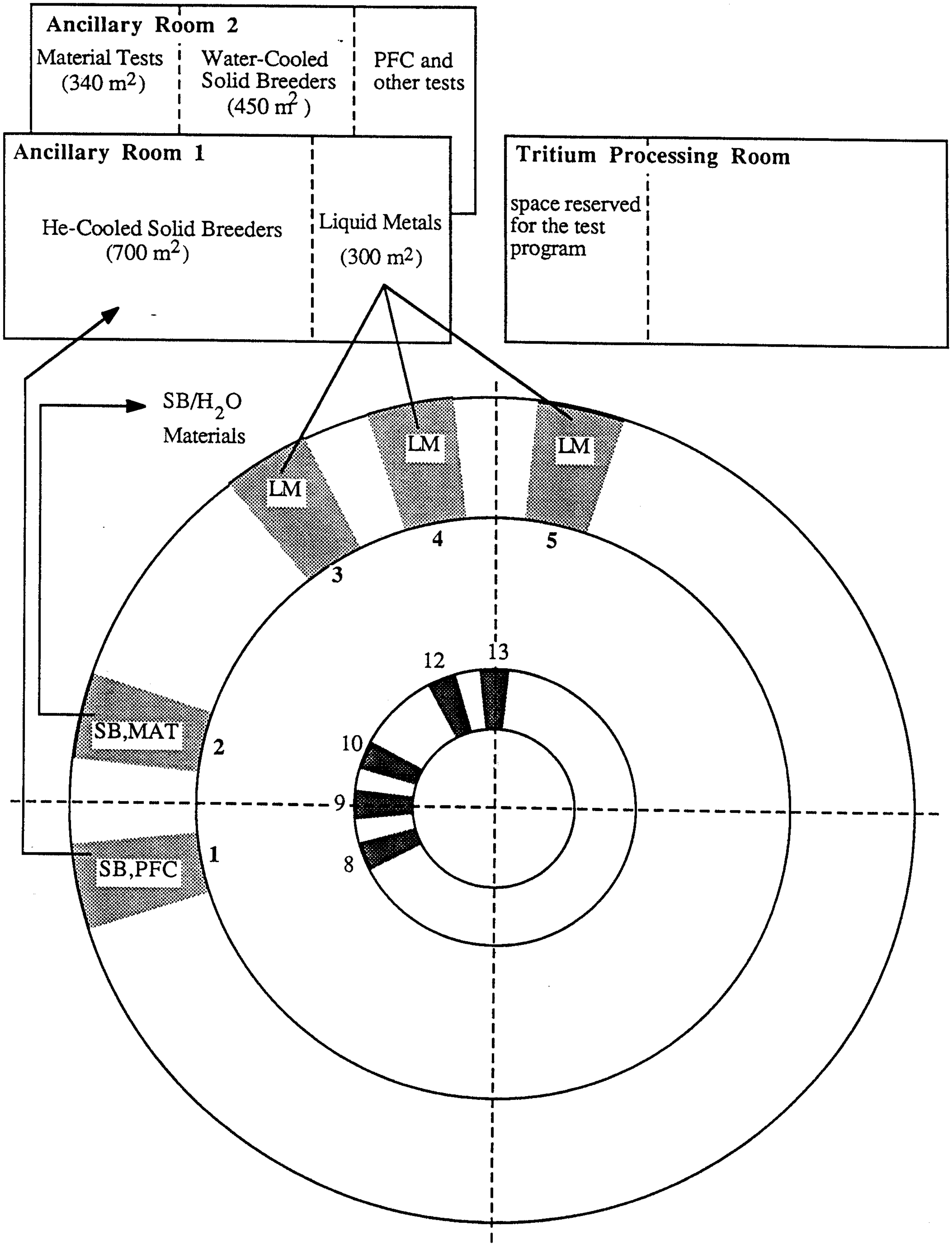
Fig. 2.6.1 Test Port Allocation to Helium- and Water-Cooled Solid Breeder Blankets

# ANCILLARY EQUIPMENT FOR TEST MODULES

e.g.
- Heat rejection system
- Tritium recovery systems
- Coolant and purge fluid storage
- Hot cells and PIE

- Extensive requirements on ITER configuration and maintenance

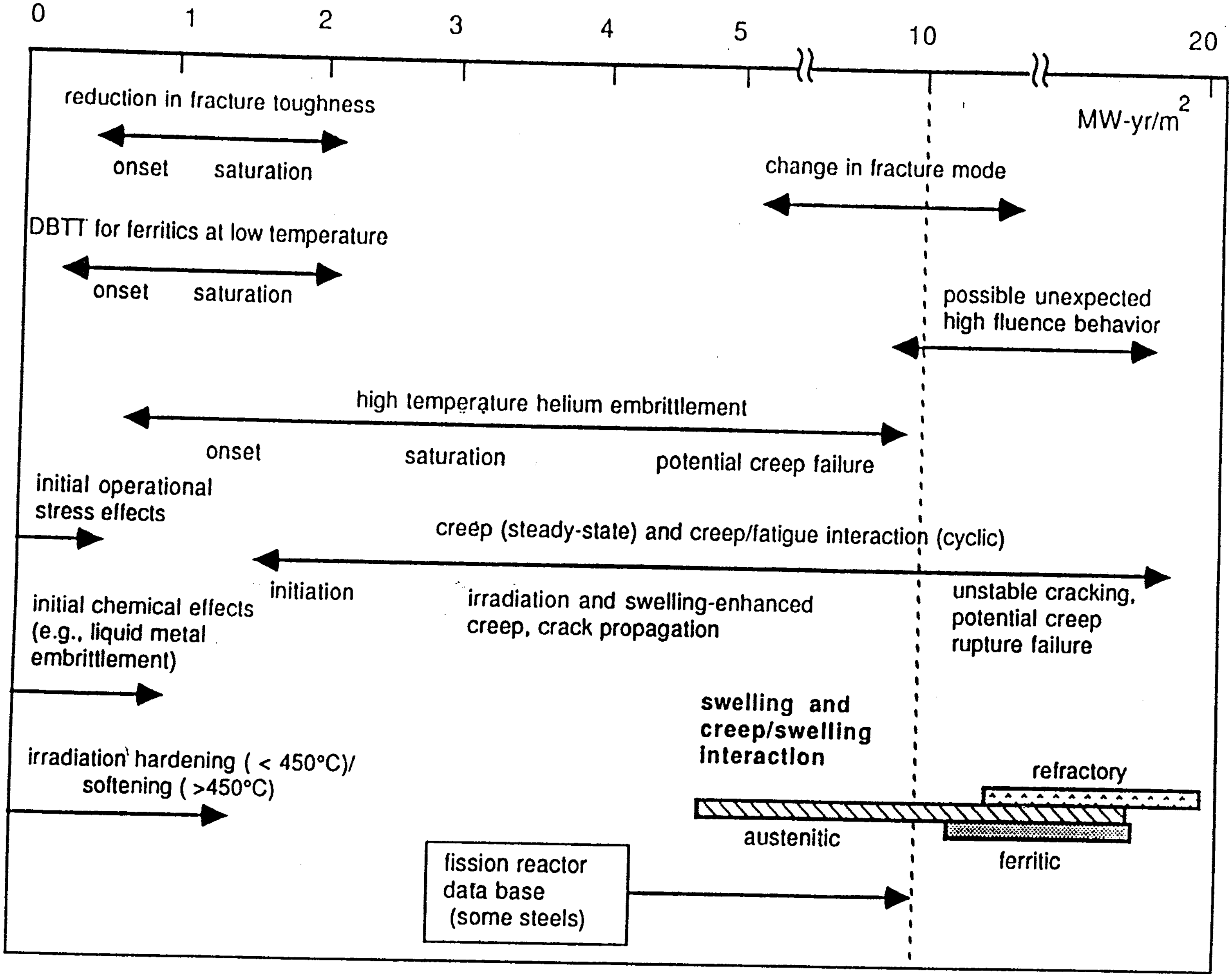
(Ancillary Equipment)
Space allocation during the Technology Phase



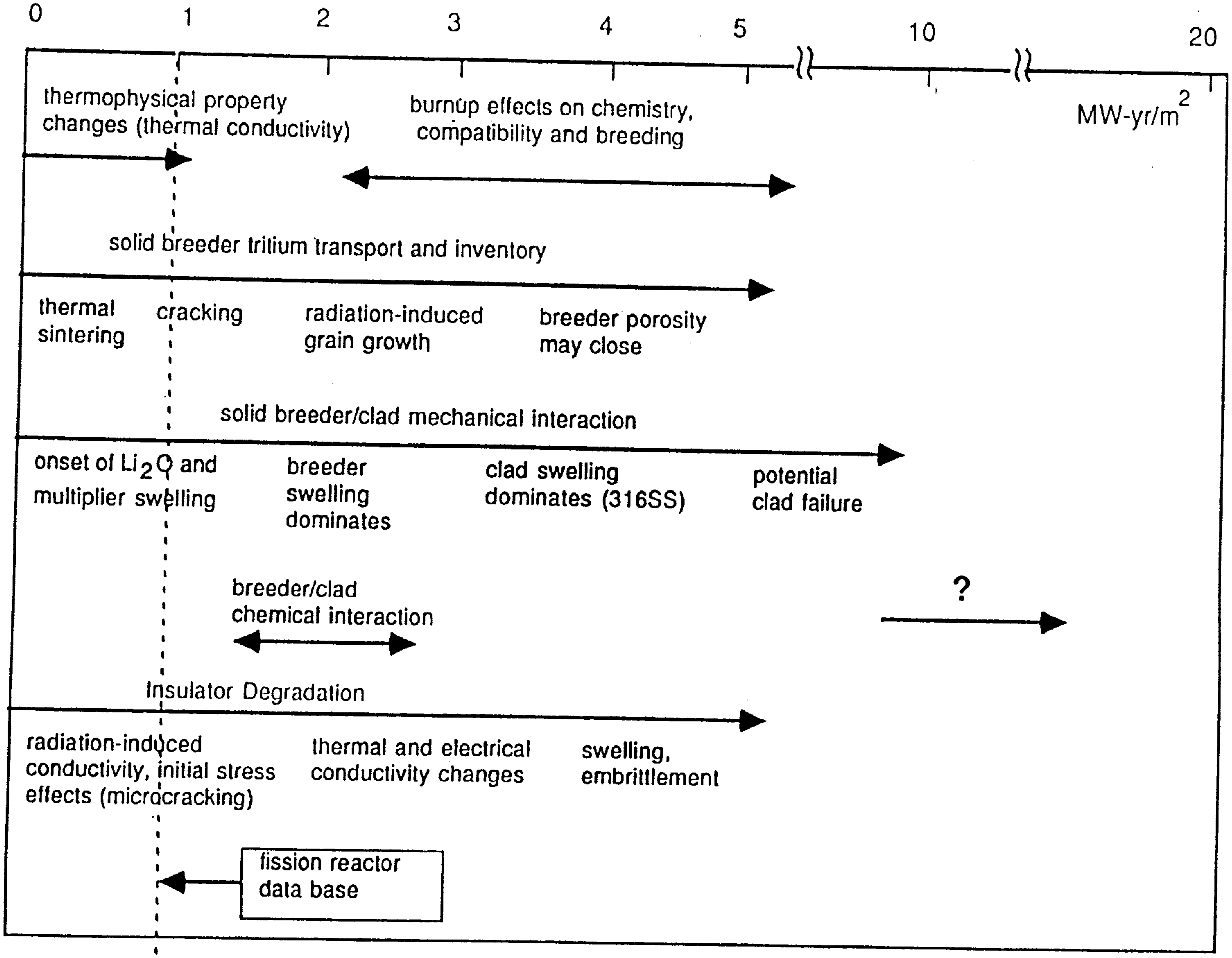
# Suggestions for EDA Phase Test Program Activities

- Well-identified activity with sufficient resources
- Strong interaction with machine design as well as the base program in the fusion community
- Should cover all key components:
  - Blanket
  - Impurity control
  - Auxilliary heating system interface to plasma
  - Others
- Information to be obtained from the base machine should be emphasized
- Issues related to diagnostics and instrumentation should be addressed
- Characteristics of international test program should be clarified

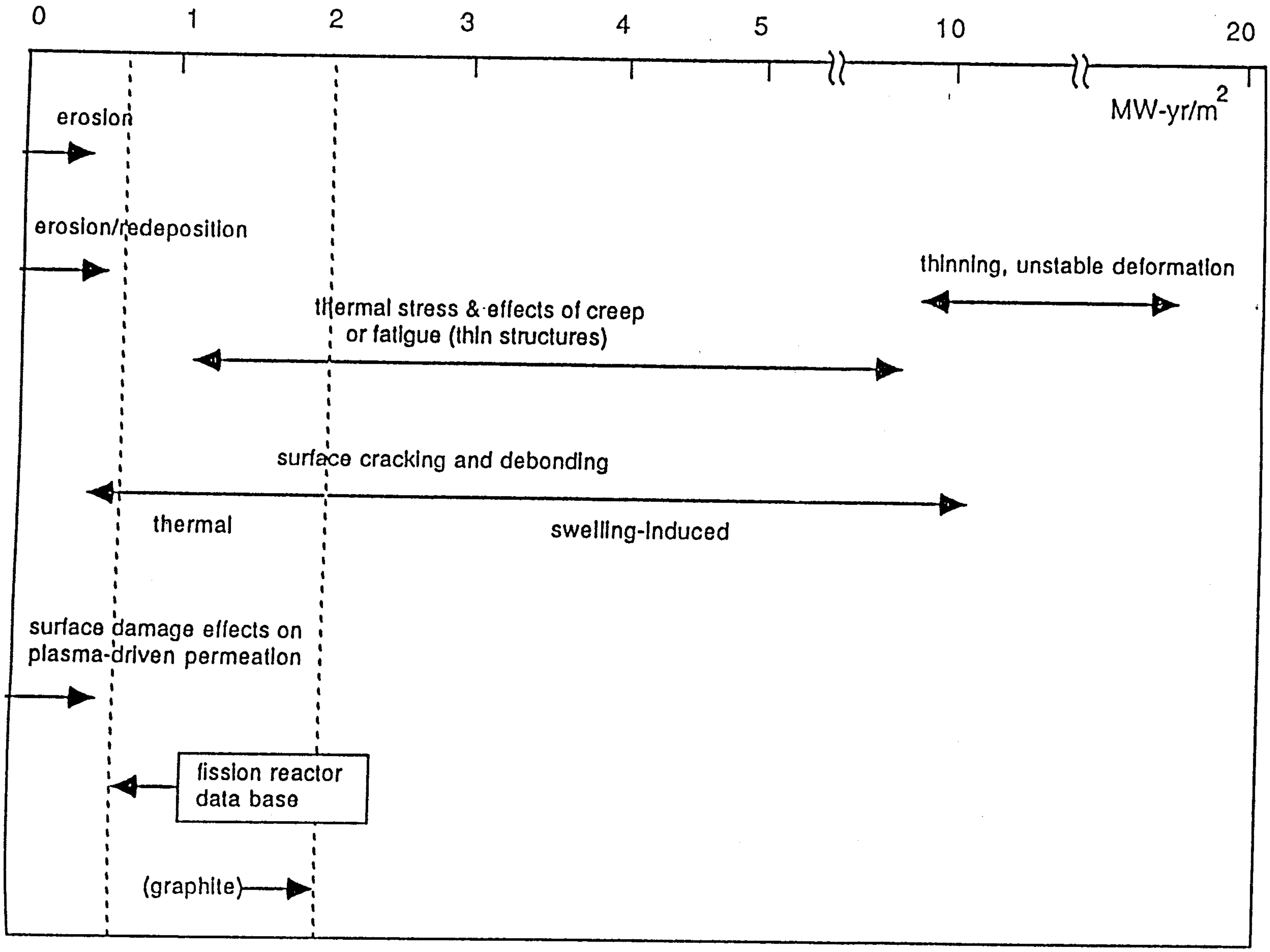
# APPENDIX



A1: Fluence-Related Effects in Blanket Structural Materials



A2: Fluence-Related Effects in Solid Breeders and Insulators



Fluence-related effects in plasma-facing materials

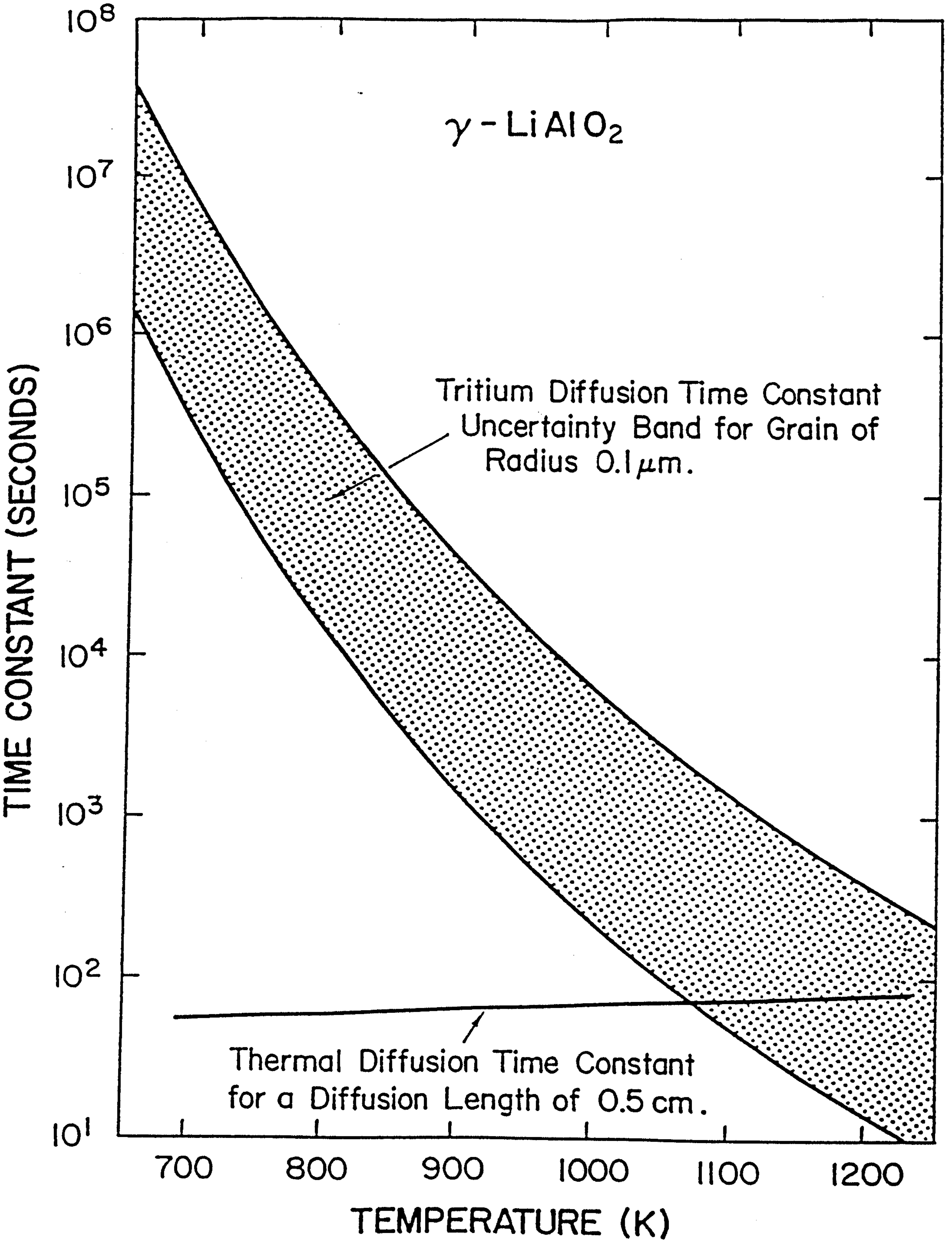
# Characteristic Times for Key Nuclear Processes Range from Very Fast to Very Slow

| **Physical Process** | **Time Constant** |
|---|---|
| Neutronics | Seconds |
| Flow Fields | |
| Thermal Fields and Power Conversion | Minutes |
| Tritium Transport and Recovery | Hours |
| Mechanical Interactions | Days |
| Fluence Effects & Thermophys. Properties Changes in Ceramics | |
| Material Interactions and Corrosion | Months |
| Fluence Effects in Structural Materials | Years |

Most critical nuclear issues for testing in the fusion environment have *Two* characteristics:

processes with long time constants
crucial dependence on other processes with short time constants

I.e., it takes a long time to establish equilibrium but a short time to ruin it.


γ - LiAlO₂
Tritium Diffusion Time Constant Uncertainty Band for Grain of Radius 0.1 μm.
Thermal Diffusion Time Constant for a Diffusion Length of 0.5 cm.
TIME CONSTANT (SECONDS)
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
700
800
900
1000
1100
1200
TEMPERATURE (K)

# VARIATION OF TEMPERATURE WITH TIME FOR DIFFERENT DWELL TIMES (LIALO2 BREEDER)

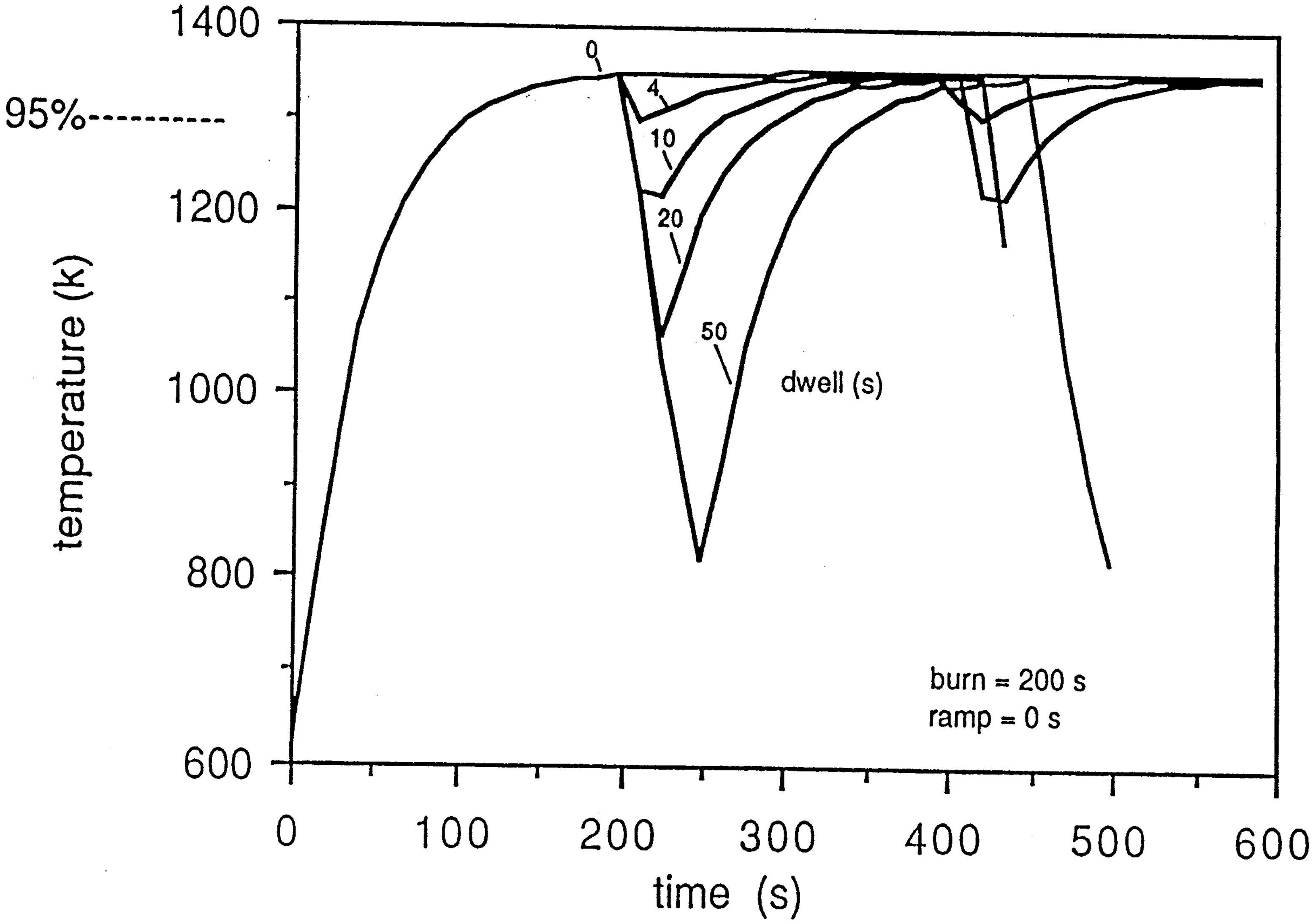
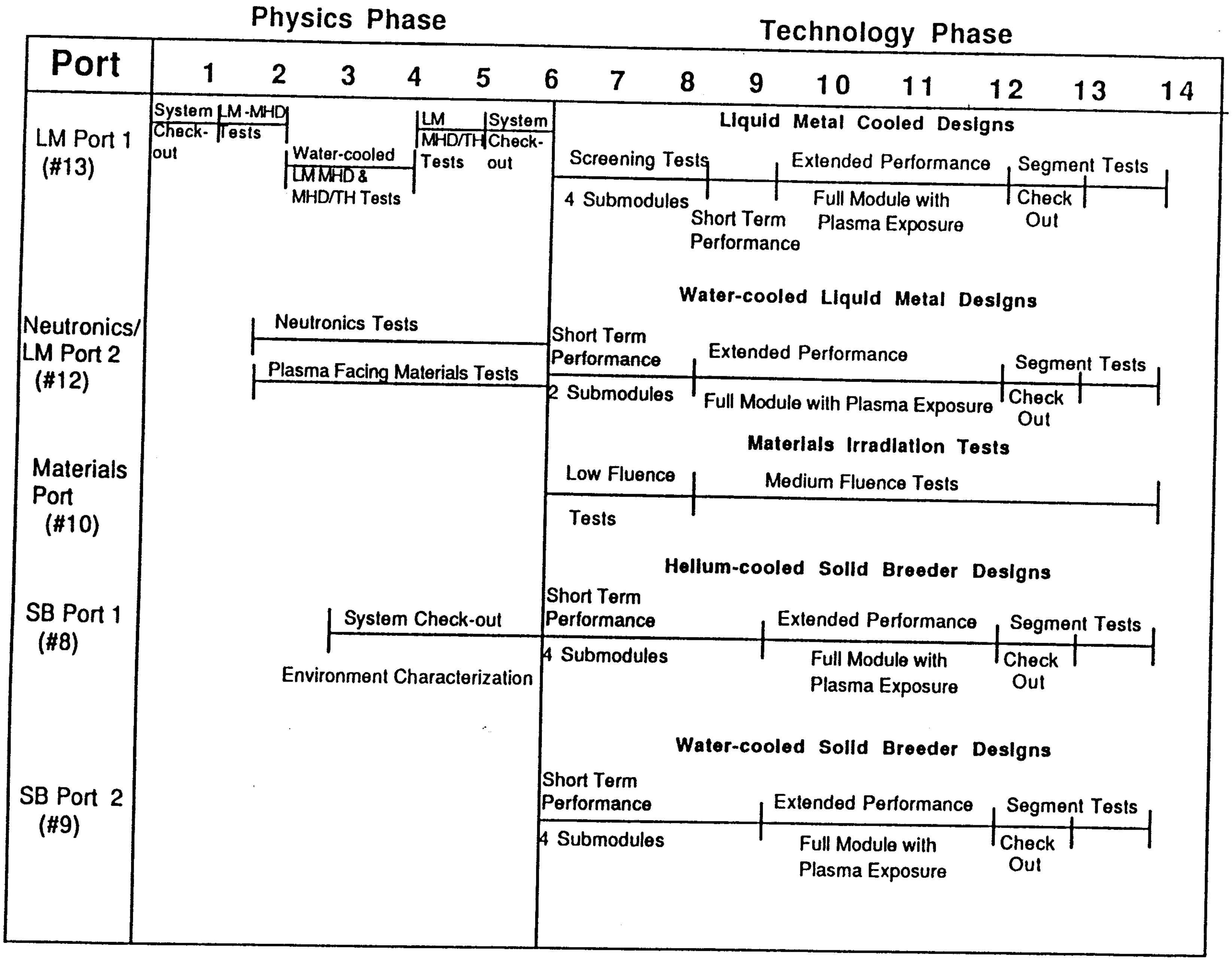
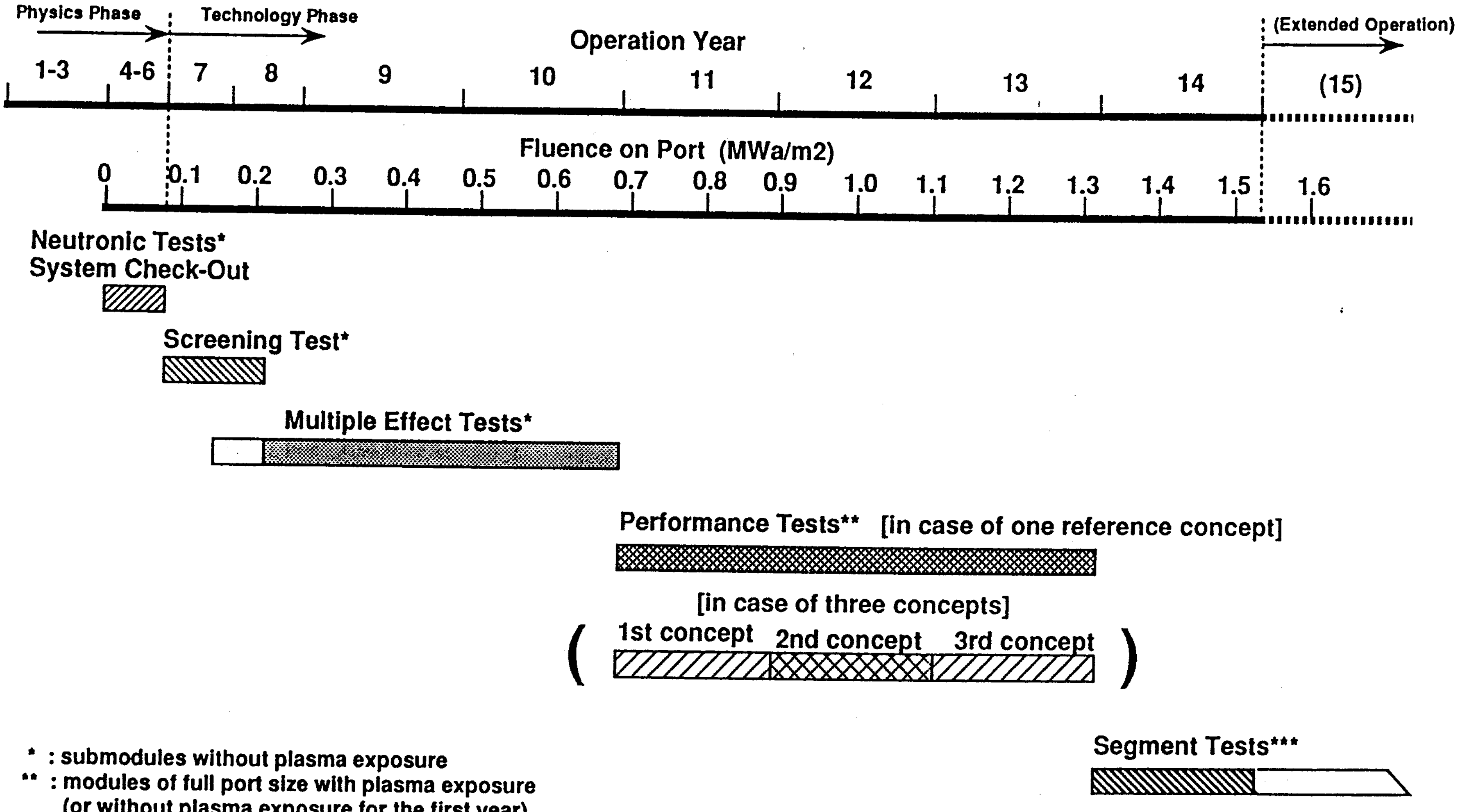


Fig. 2.3.-1 Blanket Test Schedule

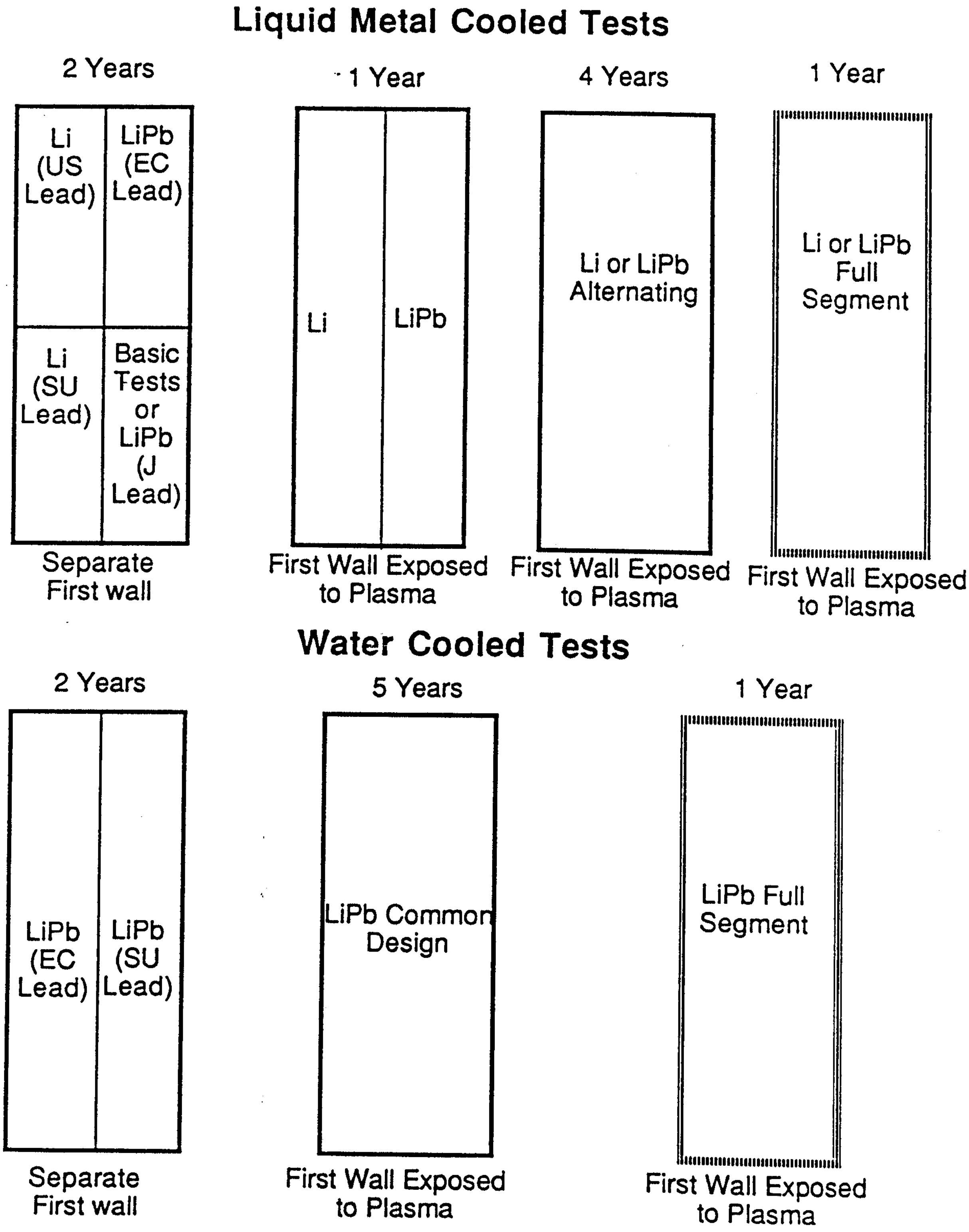


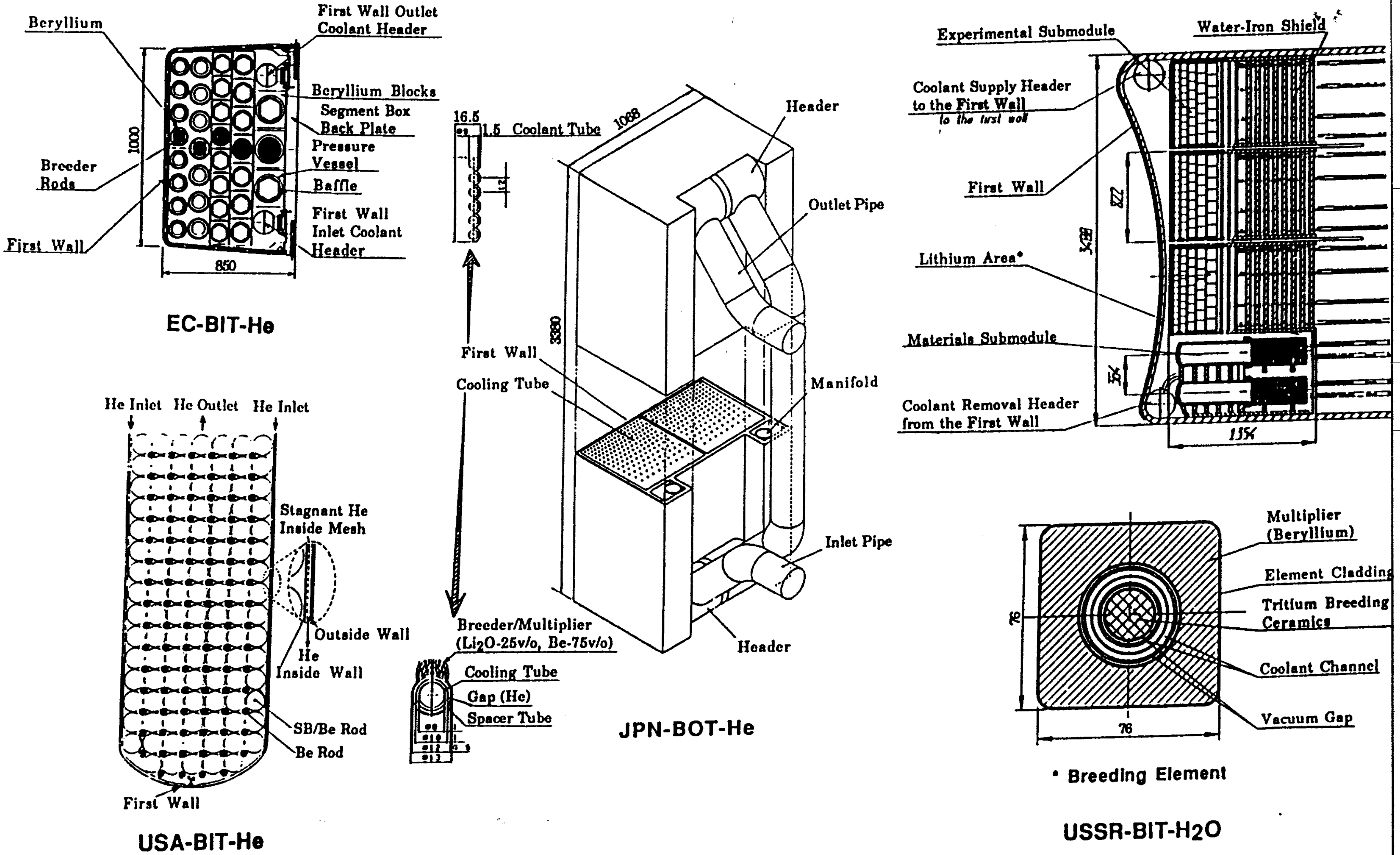


* : submodules without plasma exposure
** : modules of full port size with plasma exposure
(or without plasma exposure for the first year)
*** : segment size modules with plasma exposure

Fig. II.6.37 Testing Schedule for Helium- and Water-Cooled Solid Breeder Blankets

Fig 2.5-1 Test Sequence for Liquid Metal Blankets





EC-BIT-He

JPN-BOT-He

USA-BIT-He

USSR-BIT-$H_2O$

Fig. II.6.39 Examples of Test Module Design