Role of ITER

and

Testing Requirements on ITER Device

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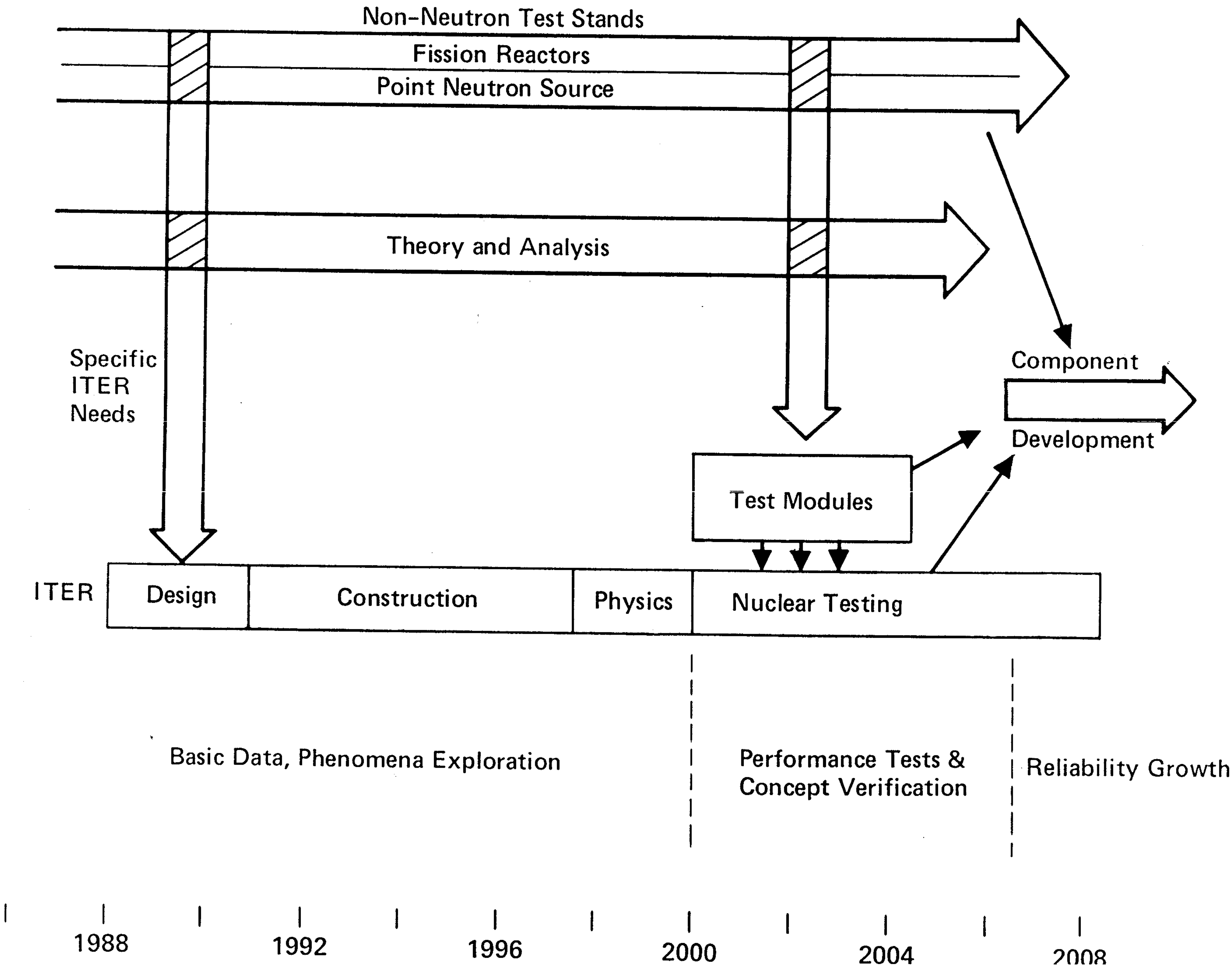
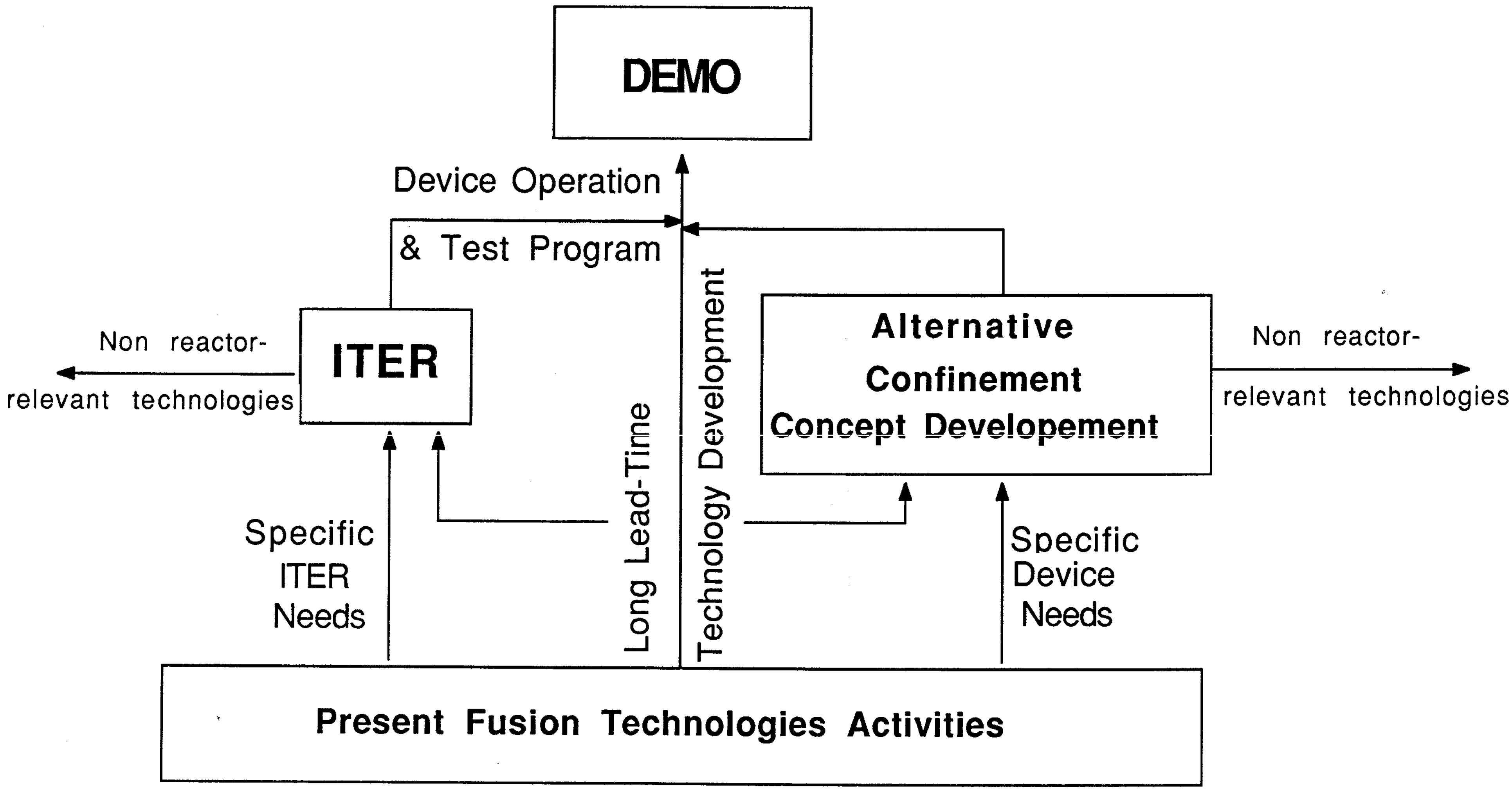
Framework For Fusion Nuclear Technology Development




DEMO
Device Operation
& Test Program
Non reactor-
relevant technologies
ITER
Long Lead-Time
Technology Development
Alternative
Confinement
Concept Developement
Non reactor-
relevant technologies
Specific
ITER
Needs
Specific
Device
Needs
Present Fusion Technologies Activities

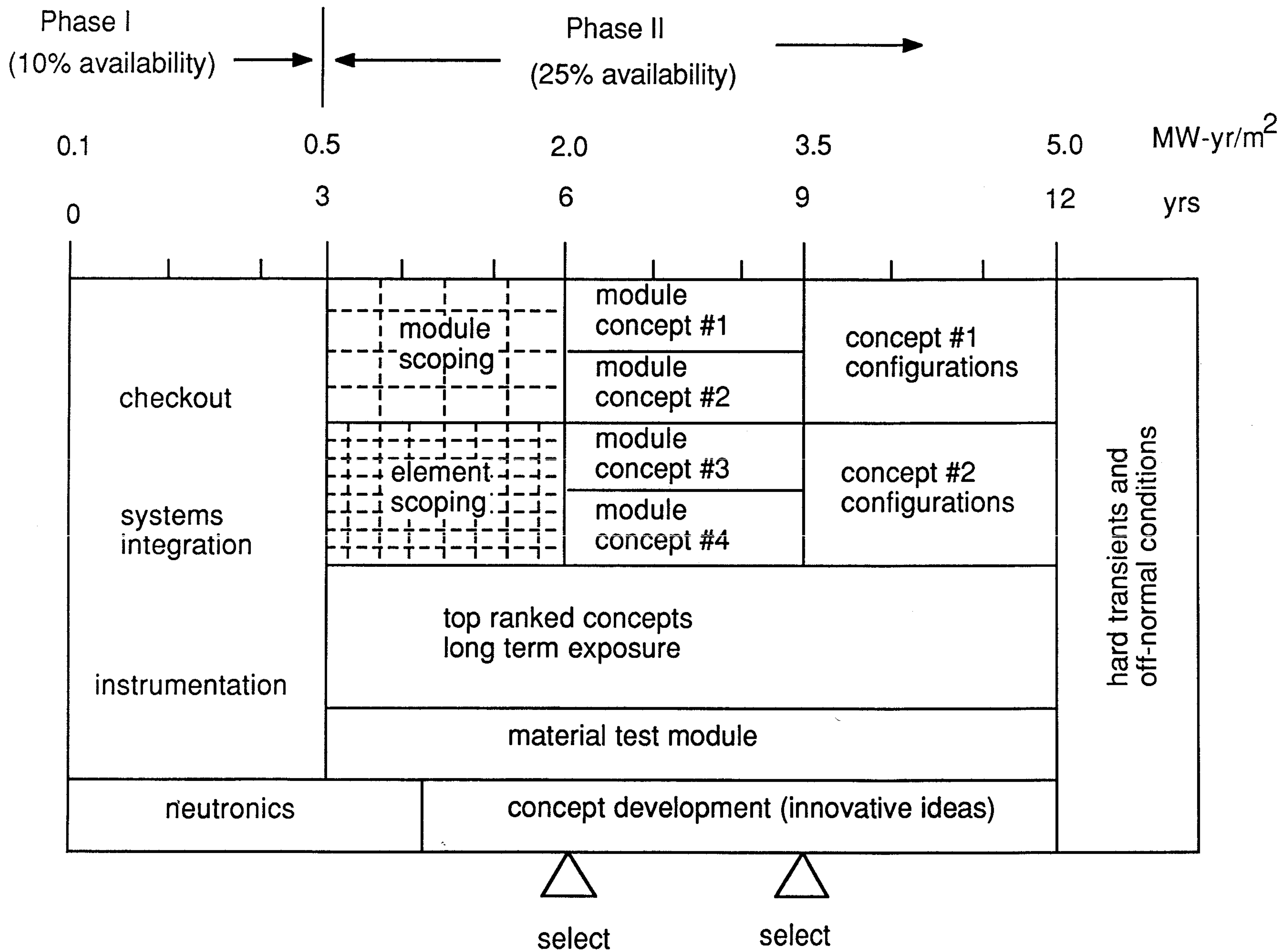
Role of ITER in Fusion Nuclear Technology Development

Minimum Technical Goal for ITER Testing

Provide definitive data to select with confidence concepts (particularly for blanket) which can operate with good performance and reasonable reliability in DEMO (device following ITER)

"Outline" of Role

- Provide Fusion Integrated Testing Data to Calibrate Results from Non-Fusion Facilities
  - Verify/theory models, design codes
- Provide Data for Concept Comparison, Selection
- Demonstrate Performance Level Extrapolatable to Reactor Conditions
- Demonstrate Adequate Level of Reliability of FNT Components
- Demonstrate Tritium Self-Sufficiency



Space-Time Utilization Logic for ITER Tests

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 Poloidal Boundary Conditions
More Prototypic Configuration/Maintenance

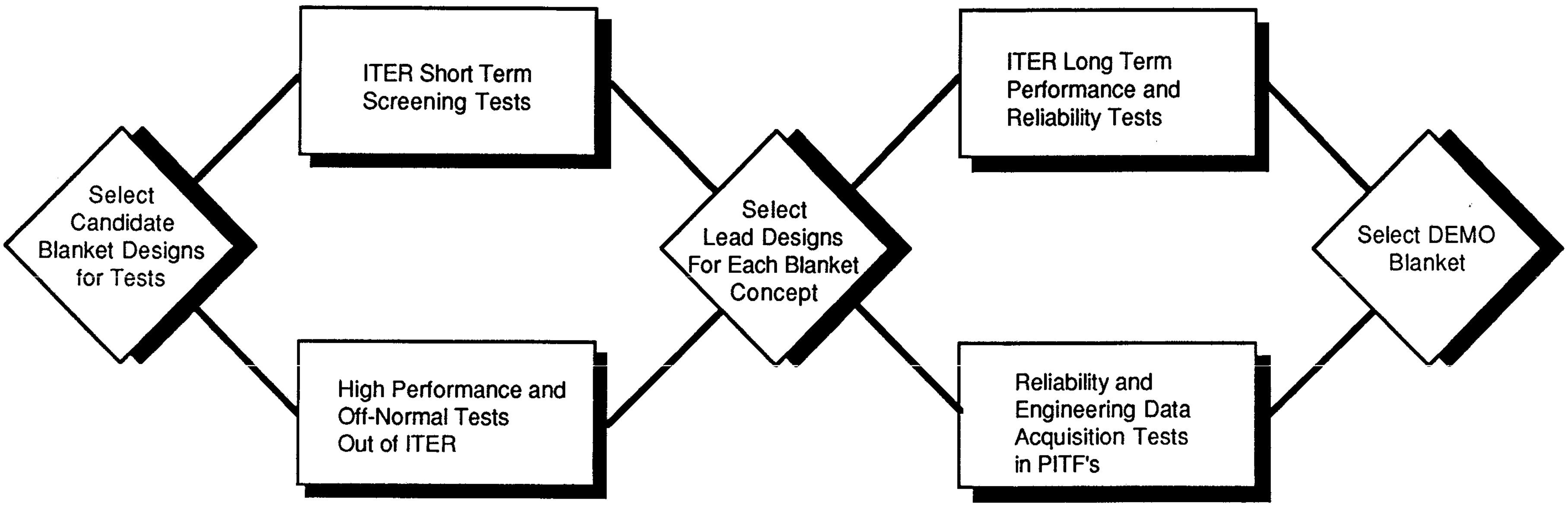
Table 3-6 Examples of Number and Size of Test Articles Required for Fusion Nuclear Technology Testing

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

[a]Test 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.

[b]LB = liquid breeder blankets, SB = solid breeder blankets.

[c]Some designs require larger test volume.



TEST SCENARIO FOR BLANKET TESTING AND SELECTION

Test Program
Key Issues of Immediate Concern

- Recommendation on List of Parameters for ITER (wall load, fluence, steady state/pulsing, etc.) to Satisfy Test Requirements

- Blanket Module Versus Sector Testing

- Divertor Testing
  - Can the divertor for the basic device be used for testing?
  - If no, how else can testing be done?
  - If yes, can we replace a module, or do we need to replace all of the divertor?

- How Do the Test Modules Interface With the Rest of the Machine?

  e.g.,
  - temperature compatibility
  - magnetic compatibility

- How Do All the Ancillary Equipment for the Test Modules Fit Outside the Device?

Test Program
Key Issues of Immediate Concern (cont'd.)

- Reliability/Availability Considerations
  - Can test modules be designed to accommodate failure/damage?
  - What is the impact of scheduled and forced replacement of test modules on machine availability?
  - What are the targets for test module reliability/availability in order to be consistent with overall ITER availability goals?

- Safety Related Issues
  - How do we handle liquid metals? Volume?
  - Validation of plasma shutdown and control?
  - Can Vanadium-type ("unqualified") materials be tested in ITER?

- Benefits and Impact of Testing in Basic ITER Blanket in the Context of Overall Fusion Technology Development (testing before and after ITER)

- How Can Tritium Self-Sufficiency Potential for Fusion Reactors be Demonstrated in ITER?

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

Selection of Major Parameters

- Engineering Scaling

  To preserve important phenomena so that data from tests at "scaled-down" conditions can be extrapolated to reactor conditions

- Benefit/Cost/Risk Trade-offs

- "Expert Judgement"

TABLE 1 Fusion Nuclear Technology Recommended Parameters for ITER

Parameters	ITER Minimum	ITER Recommended	Reference Reactor
neutron wall load (MW/m^2)	1	2-3	5
surface heat load (MW/m^2)	0.2	0.5	1
plasma burn time (s)	>500	steady state [a]	steady state
magnetic field (T) [b]	3	5	7 [c]
continuous operating time	days	weeks	months
availability (%)	20	30-50	70
fluence ($MW\text{-}yr/m^2$)			
at test module [b,d]	1-2	3-4	15-20
(device fluence, $MW{\bullet}yr/m^2$)		(6)	
test port size (m^2 x m) [e]			
module	0.5 x 0.3	1 x 0.5	
outboard sector	2.0 x 0.5	4.0 x 0.8	
total test area (m^2) [e]			
modules only	5	10-20	
including outboard sectors	7	20-30	

[a] see text

[b] at the test article

[c] at the inboard blanket

[d] device lifetime fluence is larger, see text

[e] some blanket concepts may require full sector testing

Neutron Wall Load

Desired Value Determined by

1) Engineering Scaling Requirements

2) Fluence Requirements

Device Availability (%)	Neutron Wall Load (MW/m^2) for 6 $MW{\cdot}y/m^2$ Fluence
60	1
40	1.5
30	2
24	2.5

Fluence Goals

Device Fluence (MW·y/m^2)

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

Model Fluence (MW·y/m^2)

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

P_{nw} = wall load

A = device availability

t_d = device lifetime

t_m = module test time

T = Transmission Factor (< 1)

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

- $T < 1$

Fig. 1 Schematic illustration of fluence (MW· y/m^2) accumulated at the test module and corresponding accumulation at the device first wall

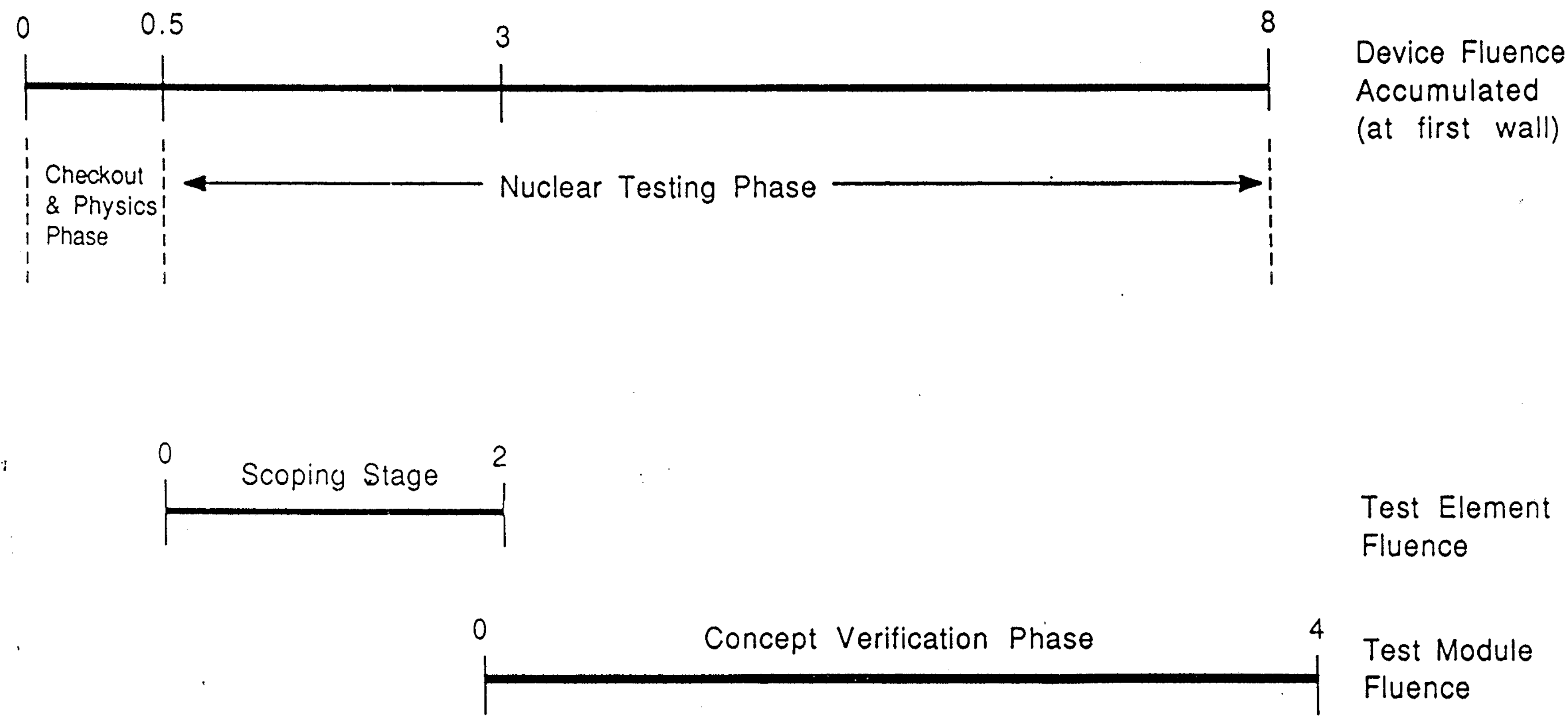
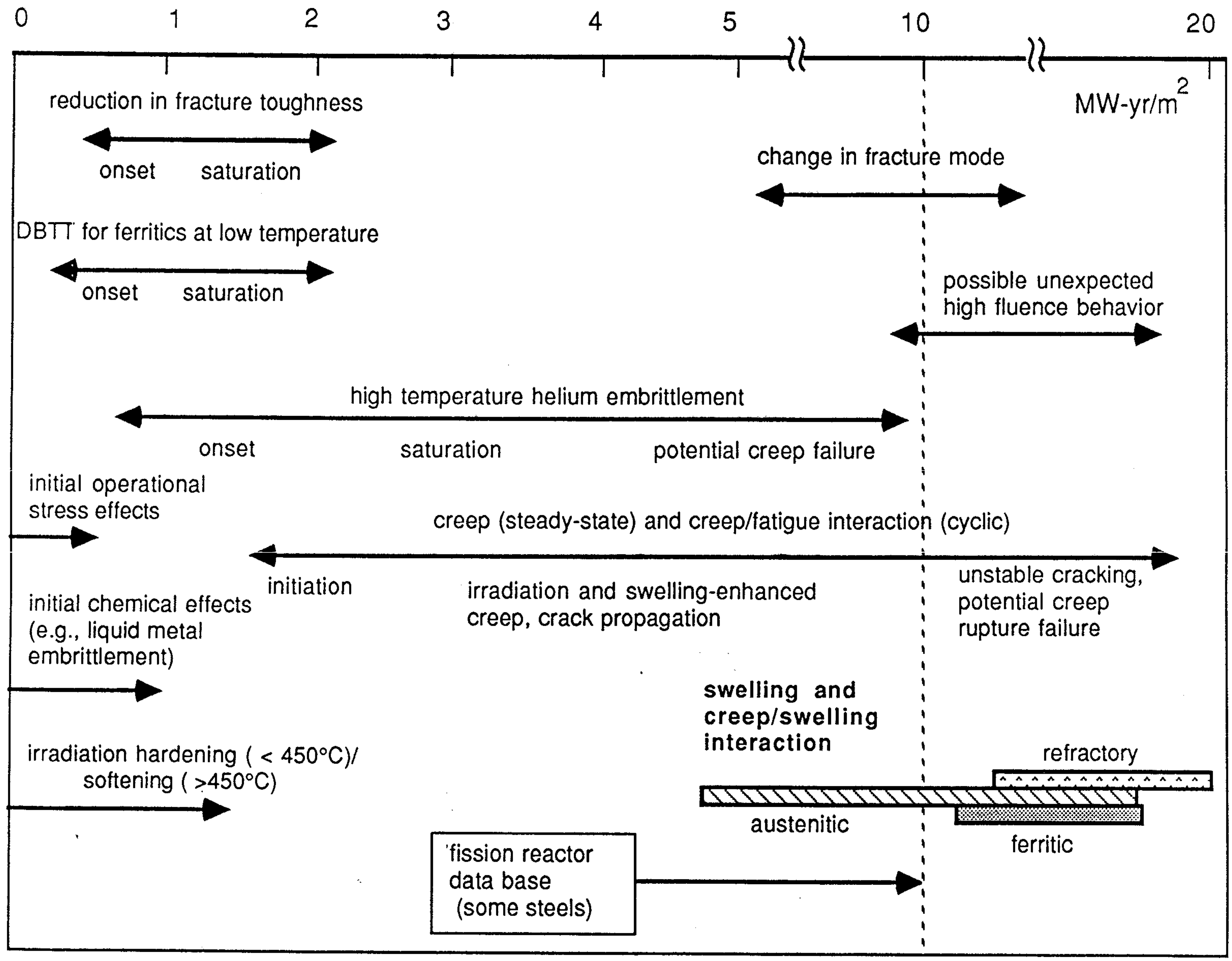
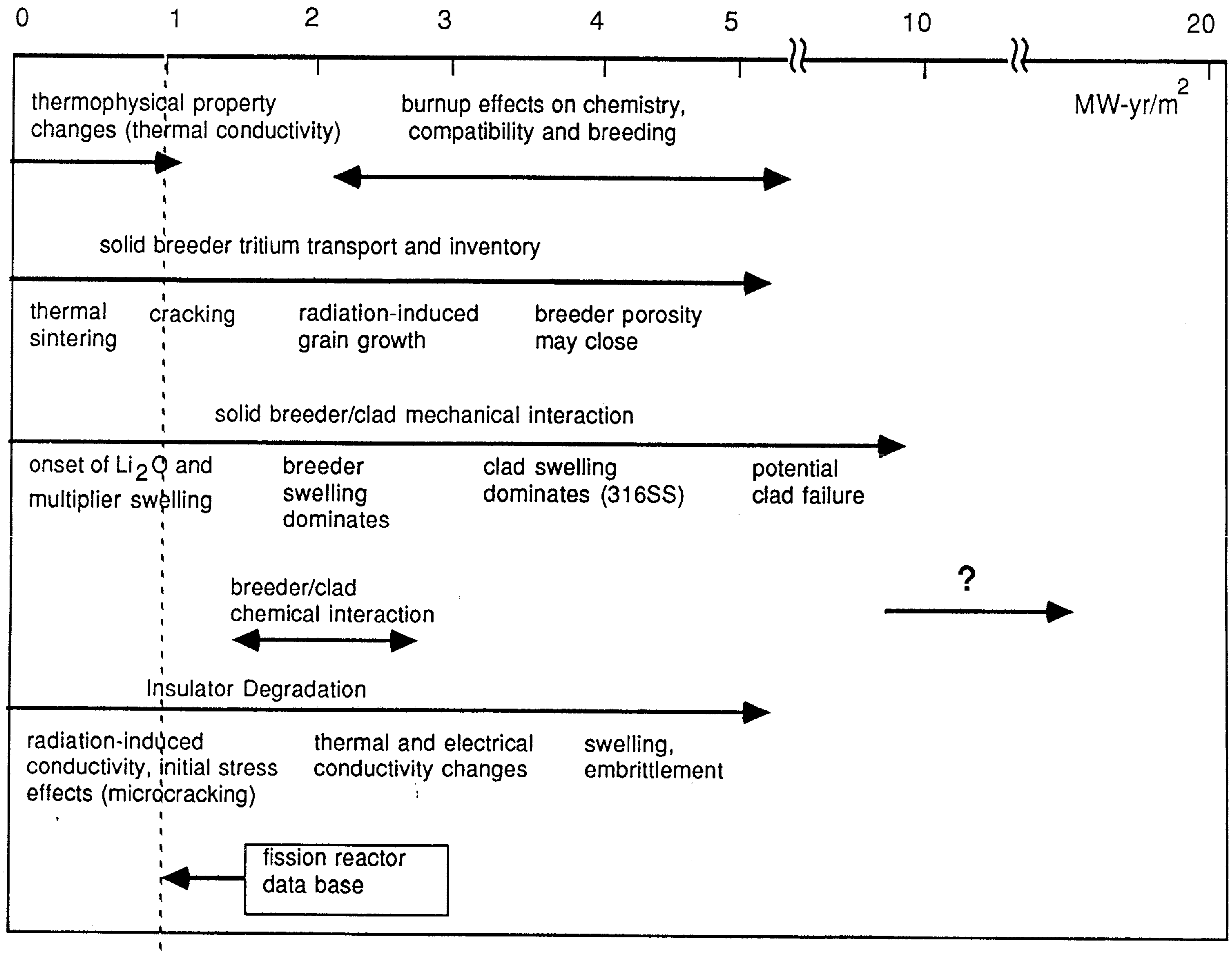


Table 2 Contributors to the Required Fluence Lifetime of ITER

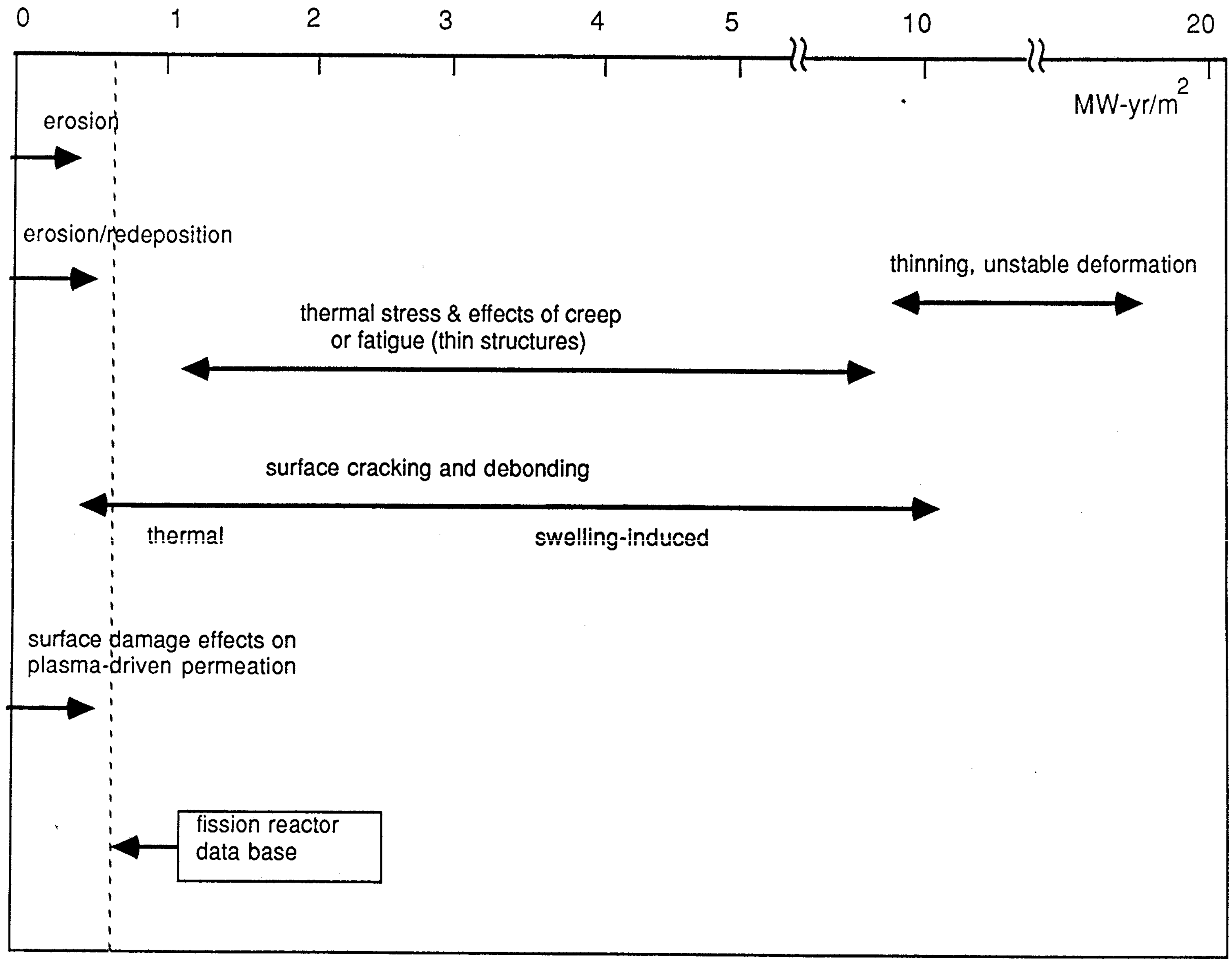
Contributor	Approximate Fluence ($MW \cdot yr/m^2$)
Checkout and physics testing	0.5
Nuclear Stage 1: scoping	1 - 2
Nuclear Stage 2: concept verification	3 - 4
Allowance for enclosure attenuation and test module replacement (25%)	1.0-1.5



A1: Fluence-Related Effects in Blanket Structural Materials



A2: Fluence-Related Effects in Solid Breeders and Insulators



A3: Fluence-Related Effects in Plasma-Facing Materials

Motivation for Steady State Operation as Design Basis for ITER

1. To Explore Long Term Reactor Potential

2. To Reduce the Failure Rate and Improve the Reliability of Many of the Basic ITER Components

3. To Substantially Increase the Capability for Nuclear Technology Testing

<u>Effects of Pulsed Plasma Operation on Nuclear Technology Testing</u>

- Time-Dependent Changes in *<u>Environmental Conditions</u>* for Testing:

  - Nuclear (volumetric) heating
  - Surface heating
  - Poloidal magnetic field
  - Tritium production rate

- Result in Time-Dependent Changes and Effects in *<u>Response</u>* 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

Length of Burn Time?

Length of Dwell Time?

Response (e.g., Temperature):

Burn: $F = F_o (1 - e^{-t/\tau})$

Dwell: $F = F_o e^{-t/\tau}$

τ = characteristic Time Constant

Allowable Variation (During a Specific Test)

- The goal is not just reaching equilibrium. It is to stay at equilibrium during test
- Small changes in some fundamental quantities result in large changes in key parameters

  e.g., 5% change in SB temperature results in a factor of 5 change in Tritium Diffusion Time Constant

Guidelines (95% Level)
burn time > 3 τ
dwell time < 0.05 τ

Note: Doubling or tripling the allowable variation will not significantly alter conclusions

Table 3-5 Approximate Characteristic Time Constants in Representative Blankets

Flow	
Solid Breeder Purge Residence	6 s
Liquid Breeder Coolant Residence	30 s
Liquid Breeder Cooling Circuit Transit	60 s
Thermal	
Structure Conduction	4 s
Structure Bulk Temperature Rise	20 s
Liquid Breeder Conduction (Li)	30 s
Solid Breeder Conduction (½-cm plate)	50–100 s
(1-cm plate)	200–400 s
Coolant Bulk Temperature Rise (200 K at 4000 MW_t)	
Li	100 s
LiPb	1500 s
Solid Breeder Bulk Temperature Rise ($LiAlO_2$, 300–1000°C)	
Front (Near Plasma)	120 s
Back (Away from Plasma)	1800 s
Material Interactions	
Dissolution of Fe in Li (500°C)	40 days
Tritium	
Diffusion Through Solid Breeder ($LiAlO_2$, 0.2 μm grains)	
1250 K	8–200 s
750 K	13–300 hours
Surface Adsorption ($LiAlO_2$)	3–10 hours
Diffusion Through SS316	
800 K	10 days
600 K	150 days
Inventory in Solid Breeder (Water-Cooled $LiAlO_2$, 0.2 μm grains)	
67% of equilibrium	6 months
99% of equilibrium	4 years
Inventory in Liquid Breeder	
LiPb	30 minutes
Li	30 days

TIME CONSTANTS FOR KEY NUCLEAR PROCESSES RANGE FROM VERY FAST TO VERY SLOW

<u>Time Constants</u>

Fast ↓

Seconds

Heat Conduction

Flow Processes

Minutes

Thermal Processes

Hours

Tritium Processes
Material Interactions
Other Important Processes

Days

Tritium Inventory

Slow

Most Critical Nuclear Issues for Testing in the Fusion Environment Have *Two* Characteristics:

1) Processes with long time constants
2) Crucial dependence on other processes with short time constants

(It takes a long time to establish equilibrium; a short time to ruin it)

Significant Plasma Dwell Time Impacts Many Critical Nuclear Tests

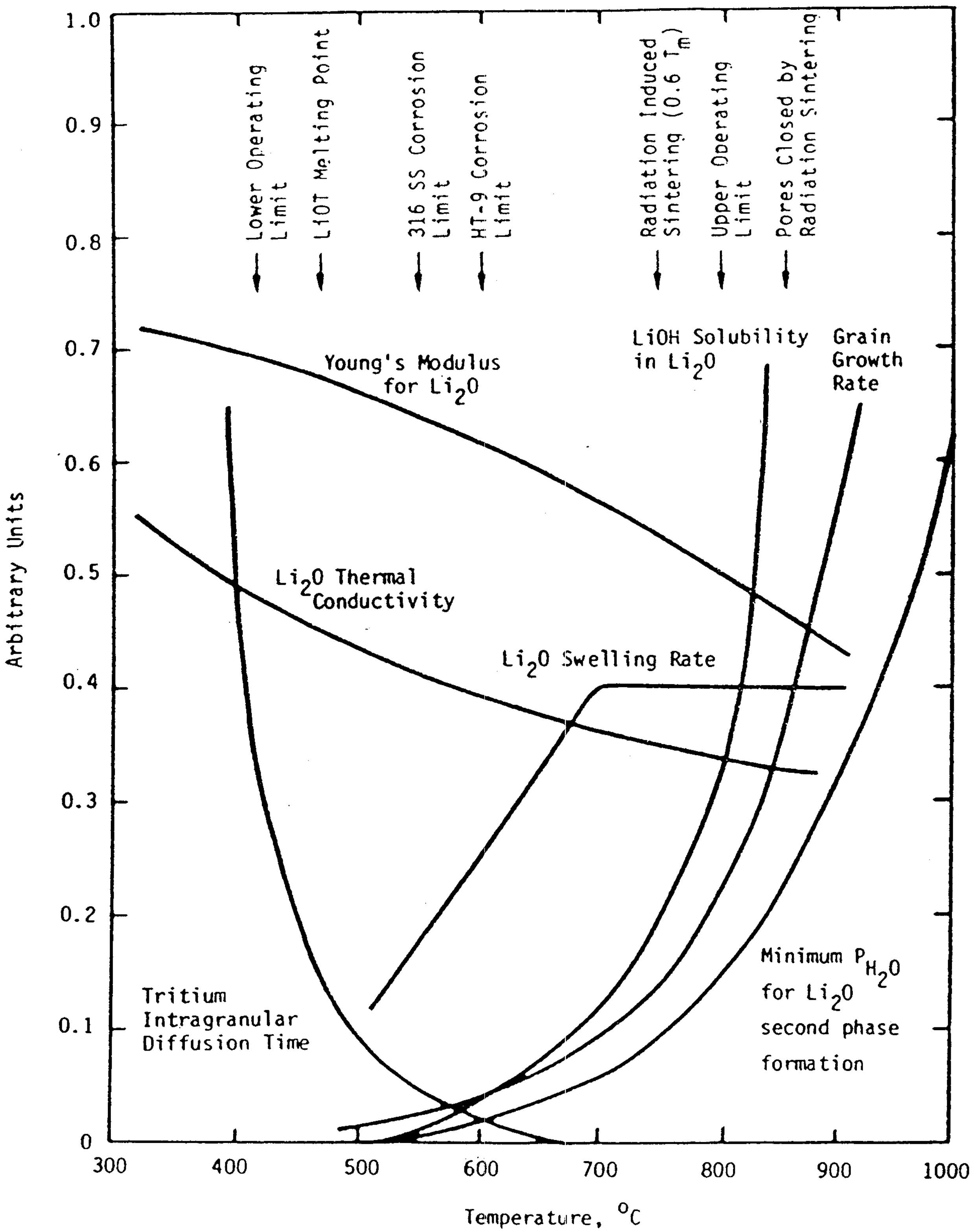
Fast Changes (e.g.)

- Nuclear Heating
- Temperature
- Temperature Gradients
- Stresses
- Tritium Production
- Tritium Concentration Profiles

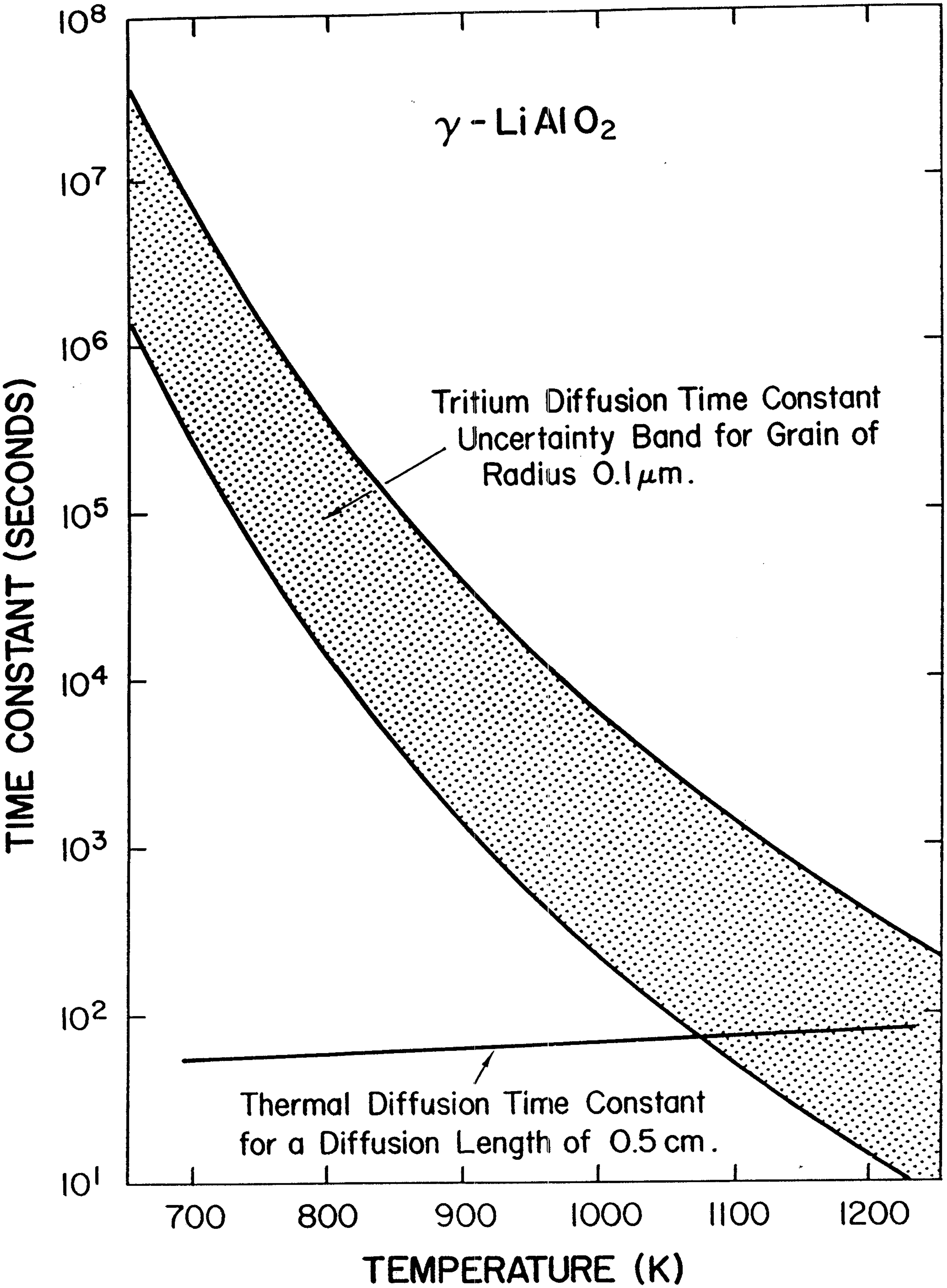
Impact on Processes with Long Time Constants (e.g.)

- Tritium Processes
  - Slow
  - Strong Dependence on Temperature, Fluid Flow and Tritium Production
- Corrosion and Redeposition Processes
  - Slow
  - Strong Dependence on Temperature and Fluid Flow
- Ferritic DBTT

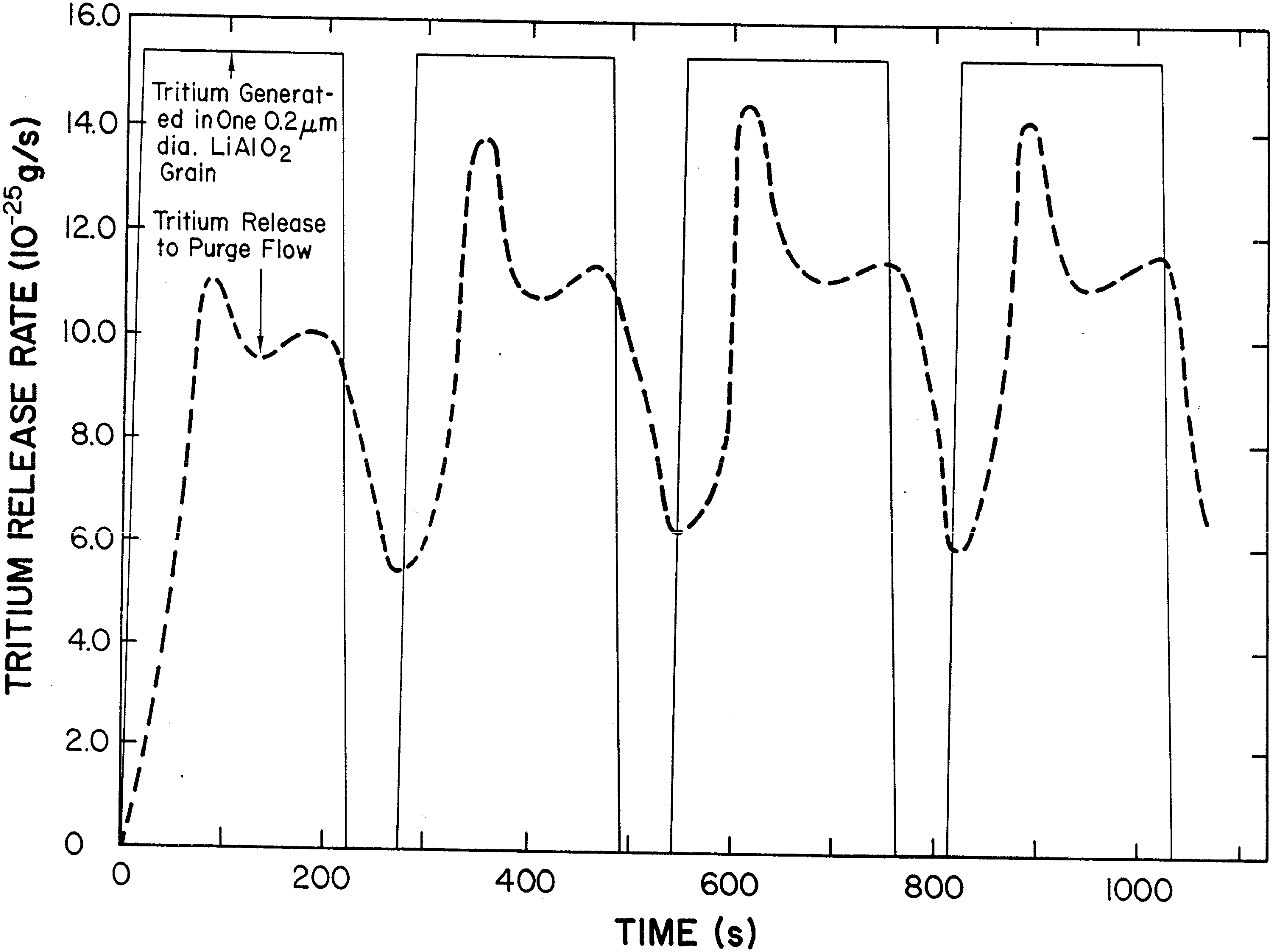
- Plasma Dwell Time Should be Near Zero
- Dwell Time of 5 s Results in Too Large Changes in Temperature-Dependent Processes



THE HEAT SOURCE (MAGNITUDE AND TIME DEPENDENCE) DETERMINES TEMPERATURES IN THE BLANKET, WHICH ACTIVATES MANY IMPORTANT ENGINEERING PROCESSES

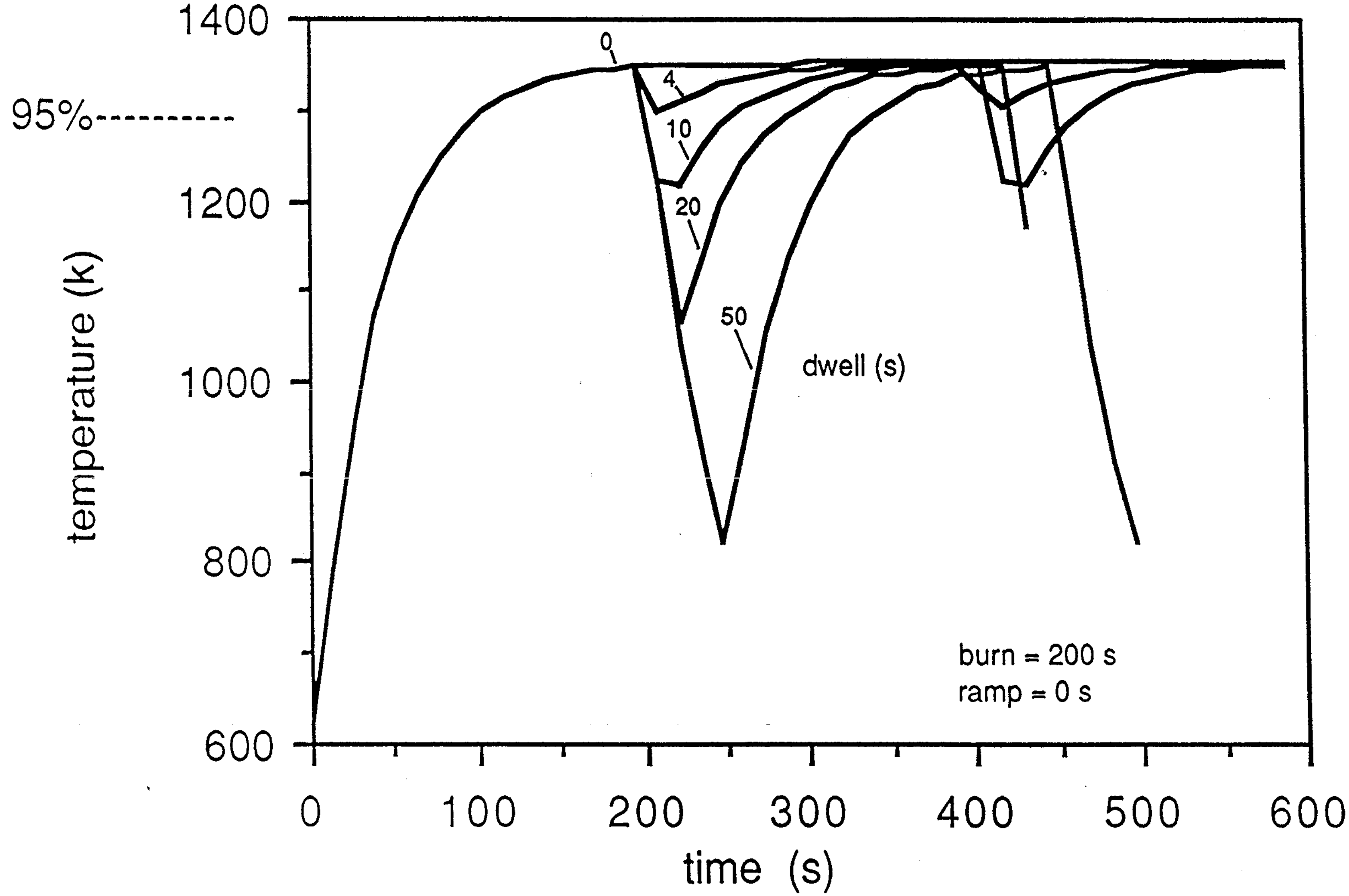


γ-LiAlO$_2$
Tritium Diffusion Time Constant Uncertainty Band for Grain of Radius 0.1 μm.
Thermal Diffusion Time Constant for a Diffusion Length of 0.5 cm.
TIME CONSTANT (SECONDS)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
700
800
900
1000
1100
1200
TEMPERATURE (K)



16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
TRITIUM RELEASE RATE (10^{-25} g/s)
Tritium Generated in One 0.2 μm dia. $LiAlO_2$ Grain
Tritium Release to Purge Flow
0
200
400
600
800
1000
TIME (s)

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



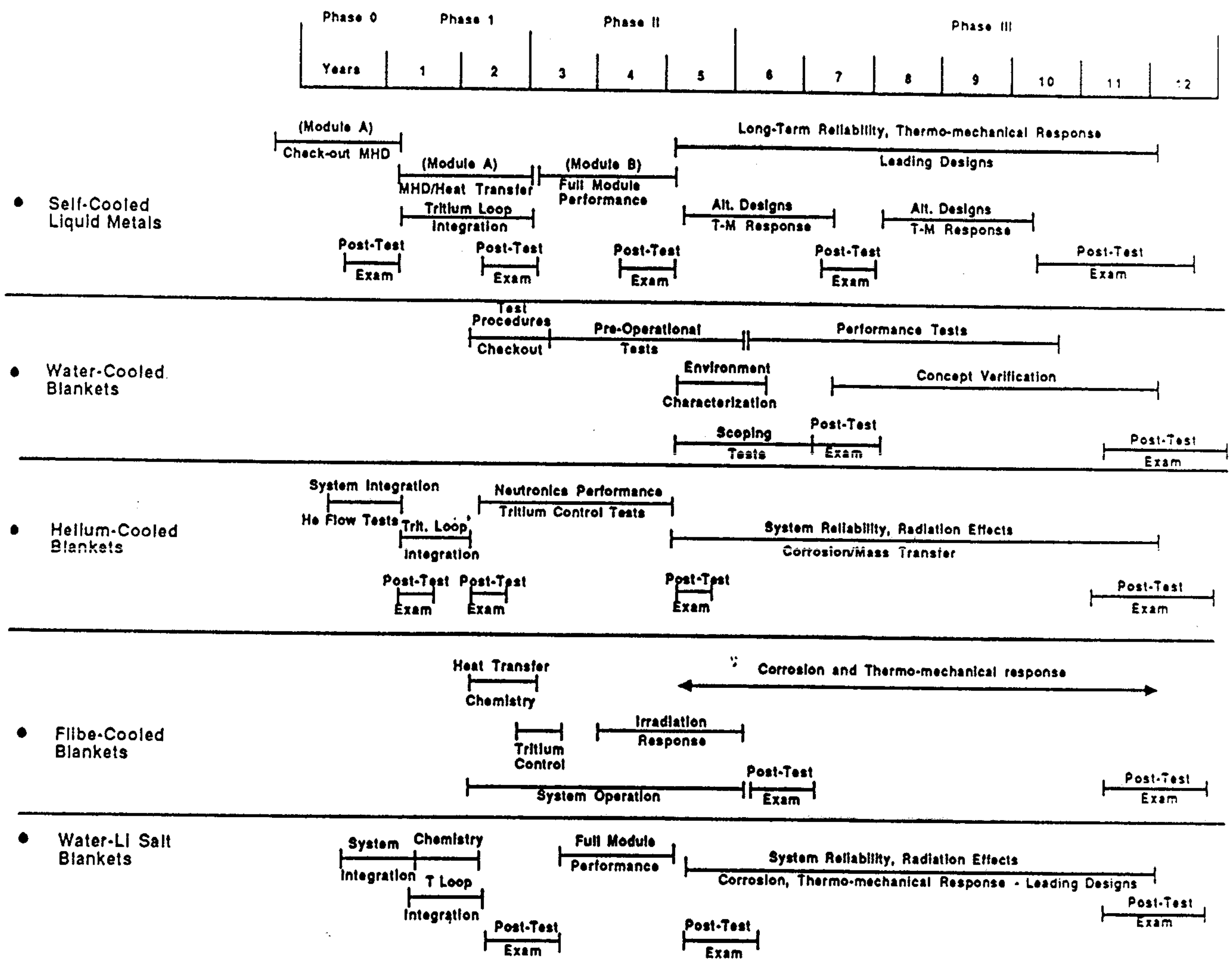


Figure B-3. Blanket module tests for ITER/TIBER.

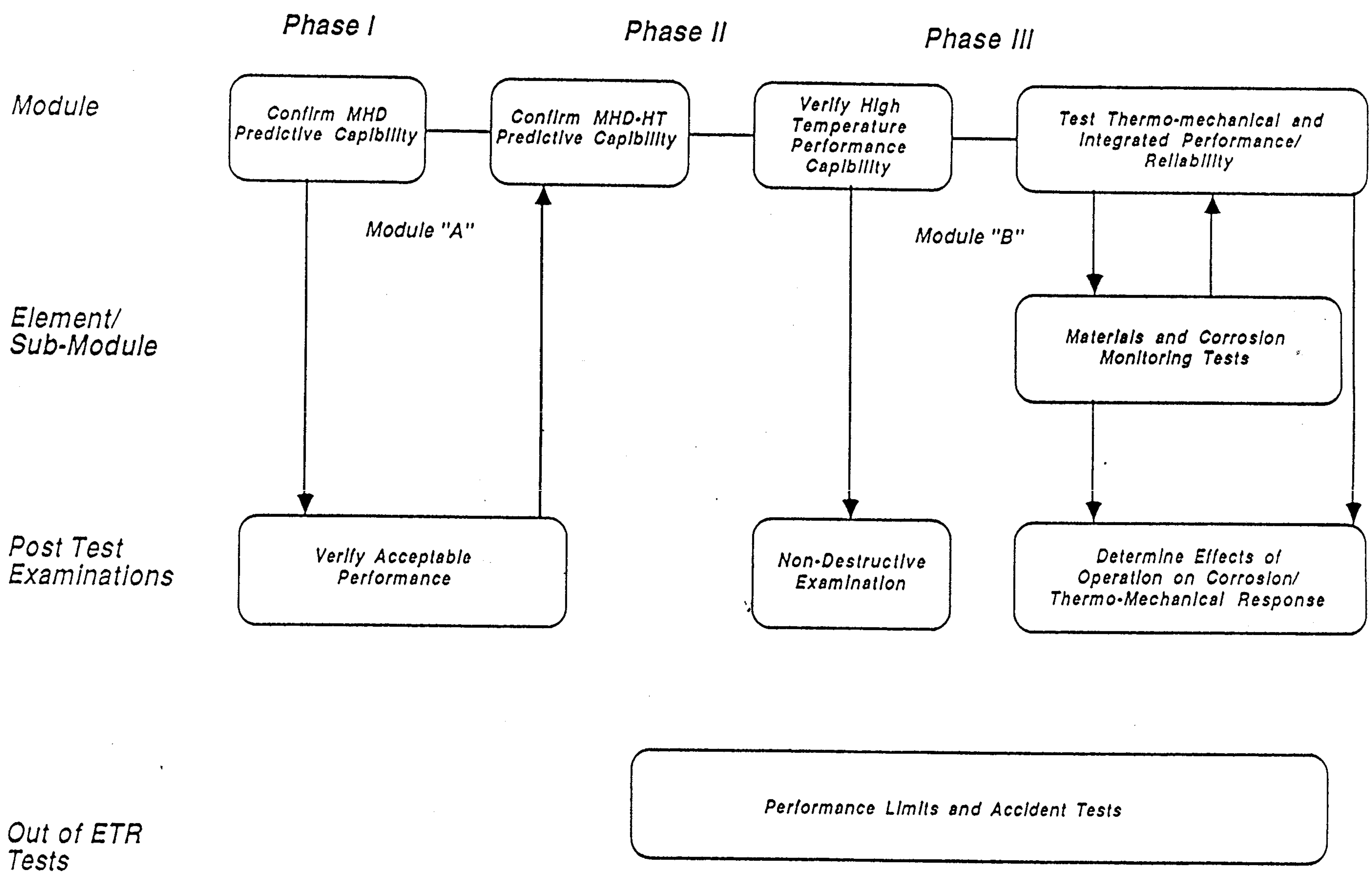
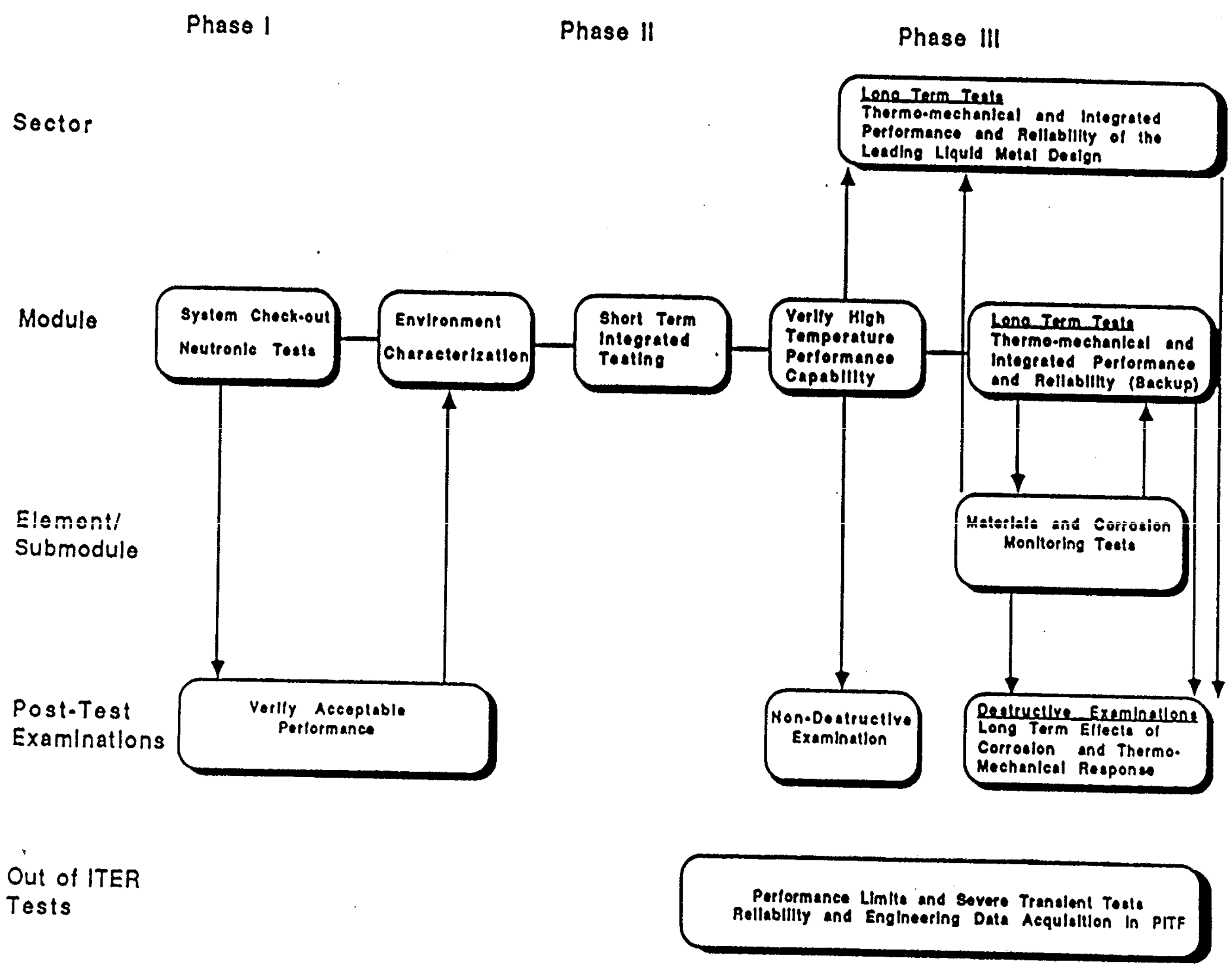


Figure B-4. Liquid metal tests plan.

Example of Blanket Test Schedule with Sectors



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Some Conclusions on Blanket Testing in ITER
(Based on USA Study)

- In addition to blanket submodule and module tests, some SECTOR Tests will be necessary for

  - Verification of tritium self-sufficiency (e.g., solid breeders)

  - Blanket concepts whose unit size is large (e.g., some self-cooled liquid metals)

- Water Cooling of the Basic Machine (blanket and/or divertor) Hampers Testing of Hot Surfaces and Lithium Blanket

- Safety Guidelines

  - Limit lithium volume to ~1 m^3

  - Double-wall test module except at first wall

  - For large volume lithium, double wall at the first wall is also necessary