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)

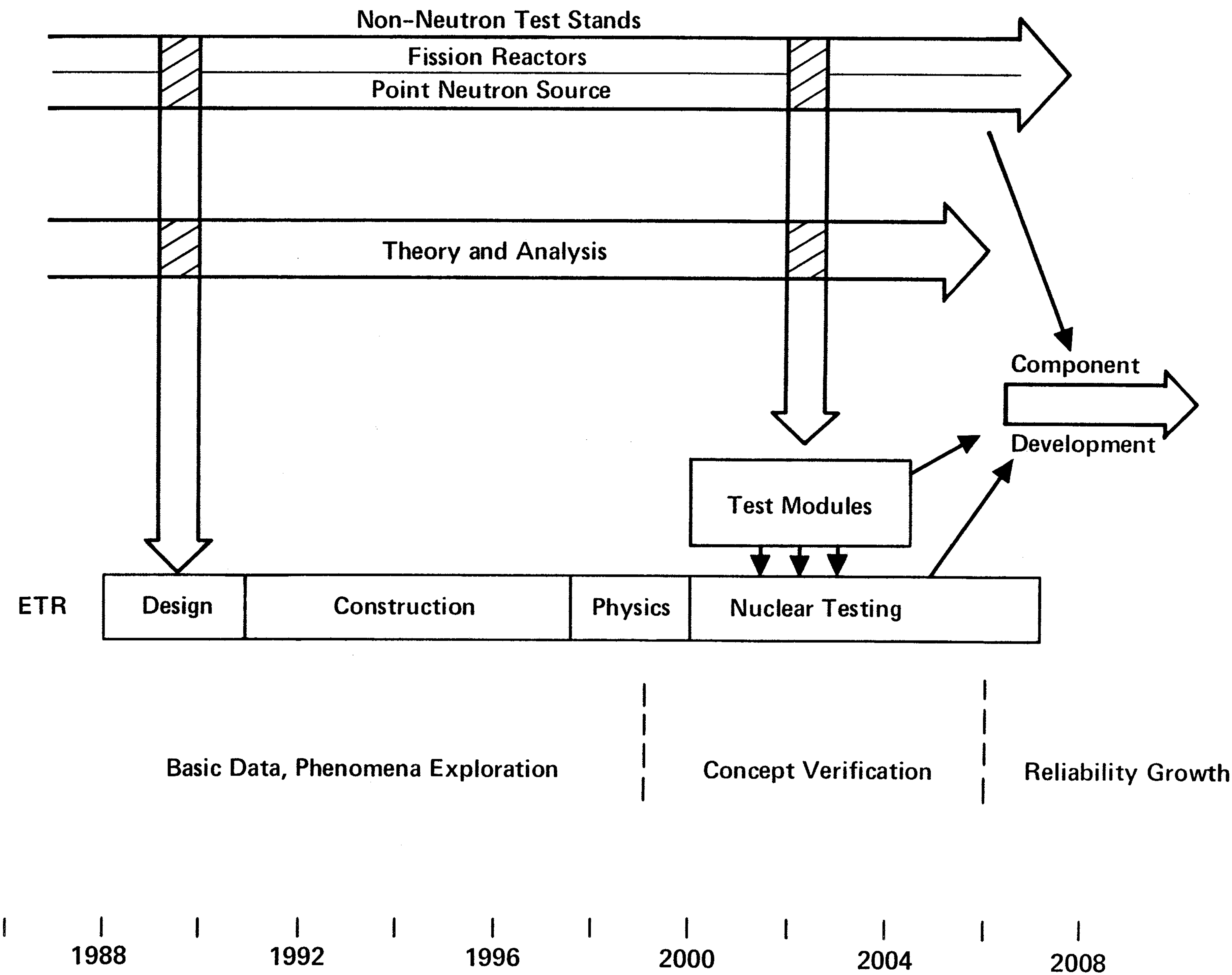
  Non-Neutron Test Stands
  Fission Reactors
  14 MeV Neutron Sources

  - 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



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 1.3-6 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.

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

<u>Scaling of Major Parameters</u>

- Cost Forces Scaled-Down Conditions
- "<u>Look-Alike</u>" Test Modules are Useless
- "<u>Act-Alike</u>" 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 ΔT

- Lower P_N Requires Longer Time to Equilibrium

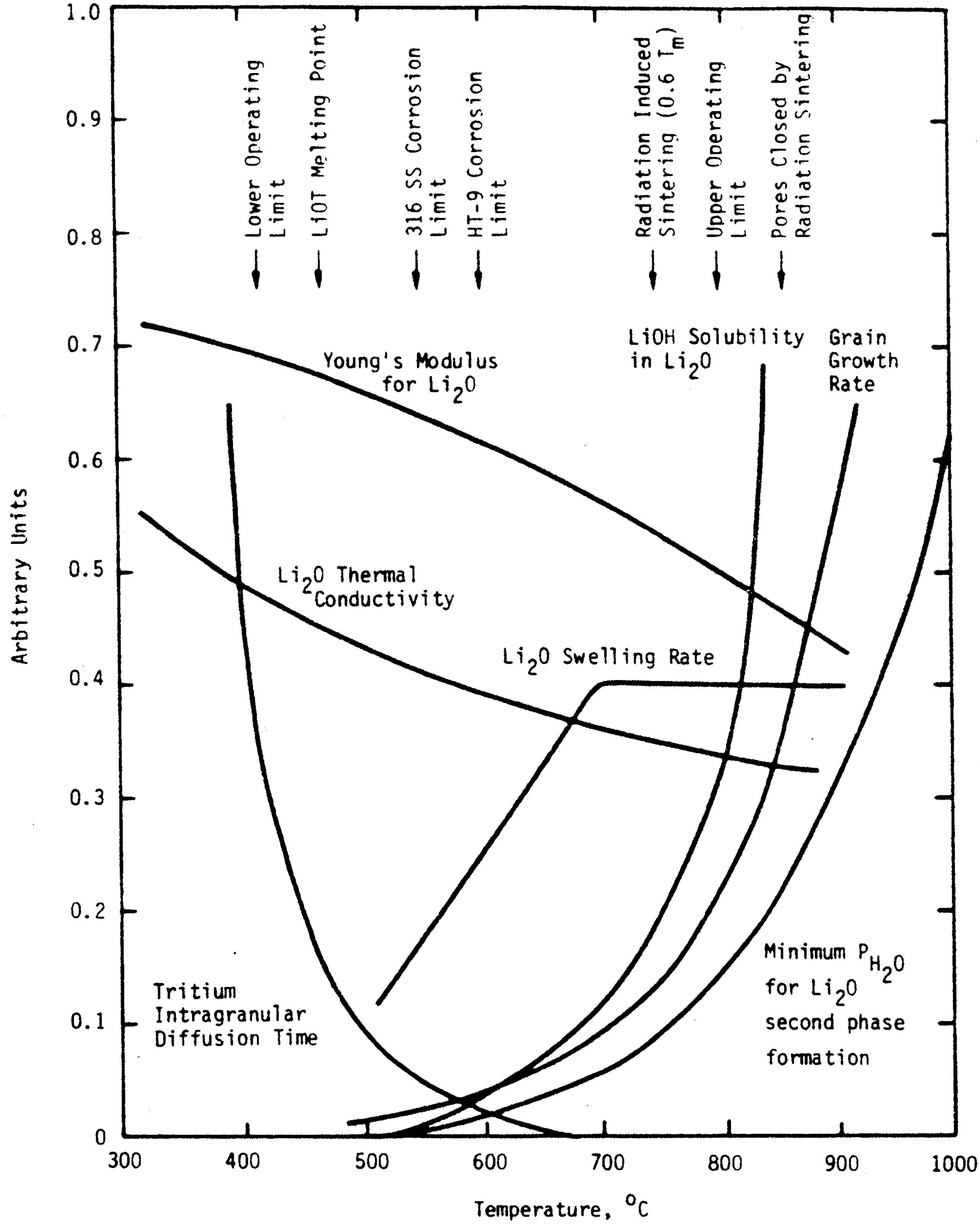
- Lower B Requires Larger Dimensions to Preserve MHD Effects ($Ha \sim aB$)

Neutron Wall Load Requirements

Neutron Wall Load is a Primary Source of Both Heating and Nuclear Reactions in the Blanket

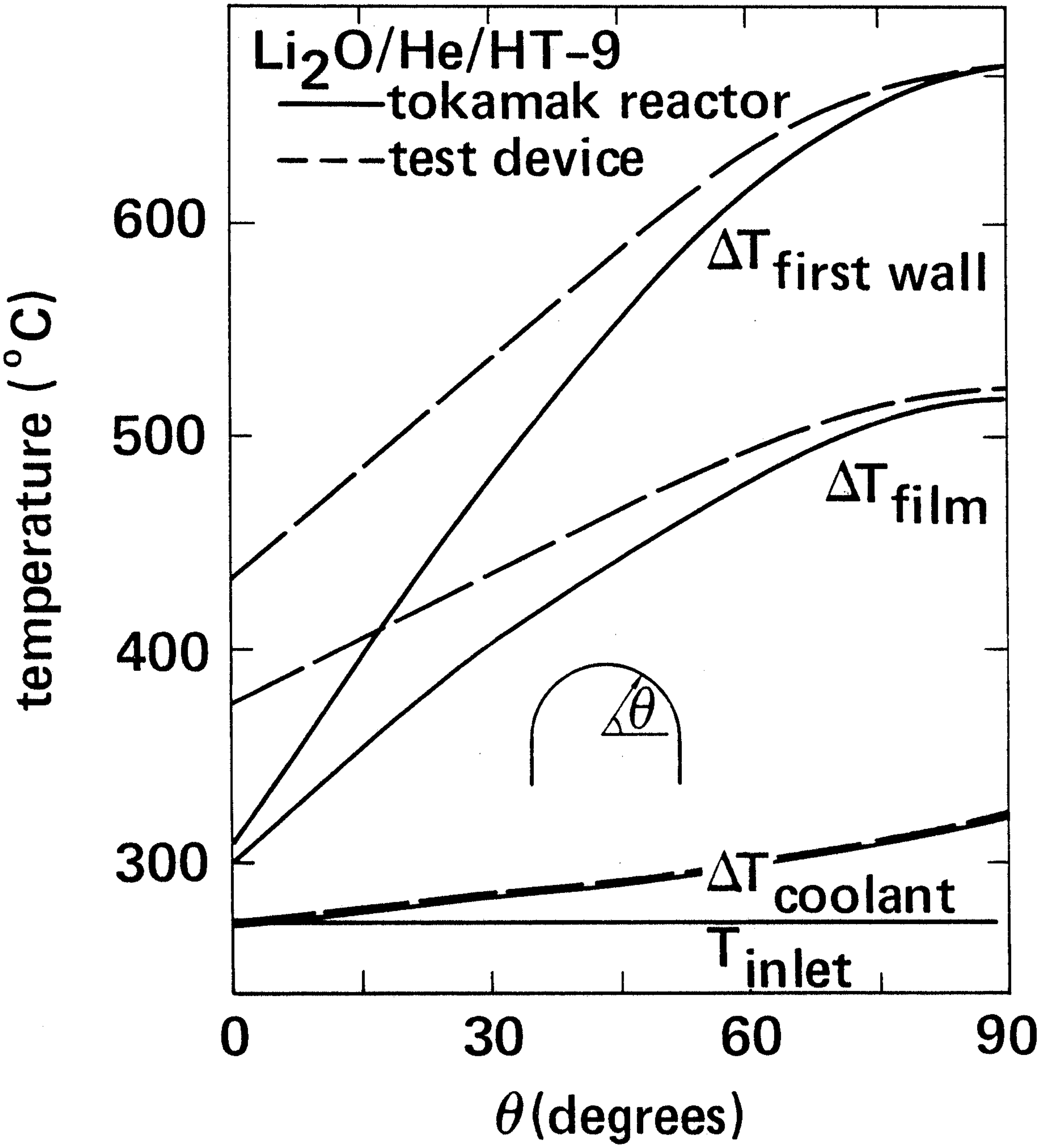
P_N →

- → BULK HEATING
- → SURFACE HEATING
- → REACTION RATE (E.G., TRITIUM PRODUCTION)
- → FLUENCE



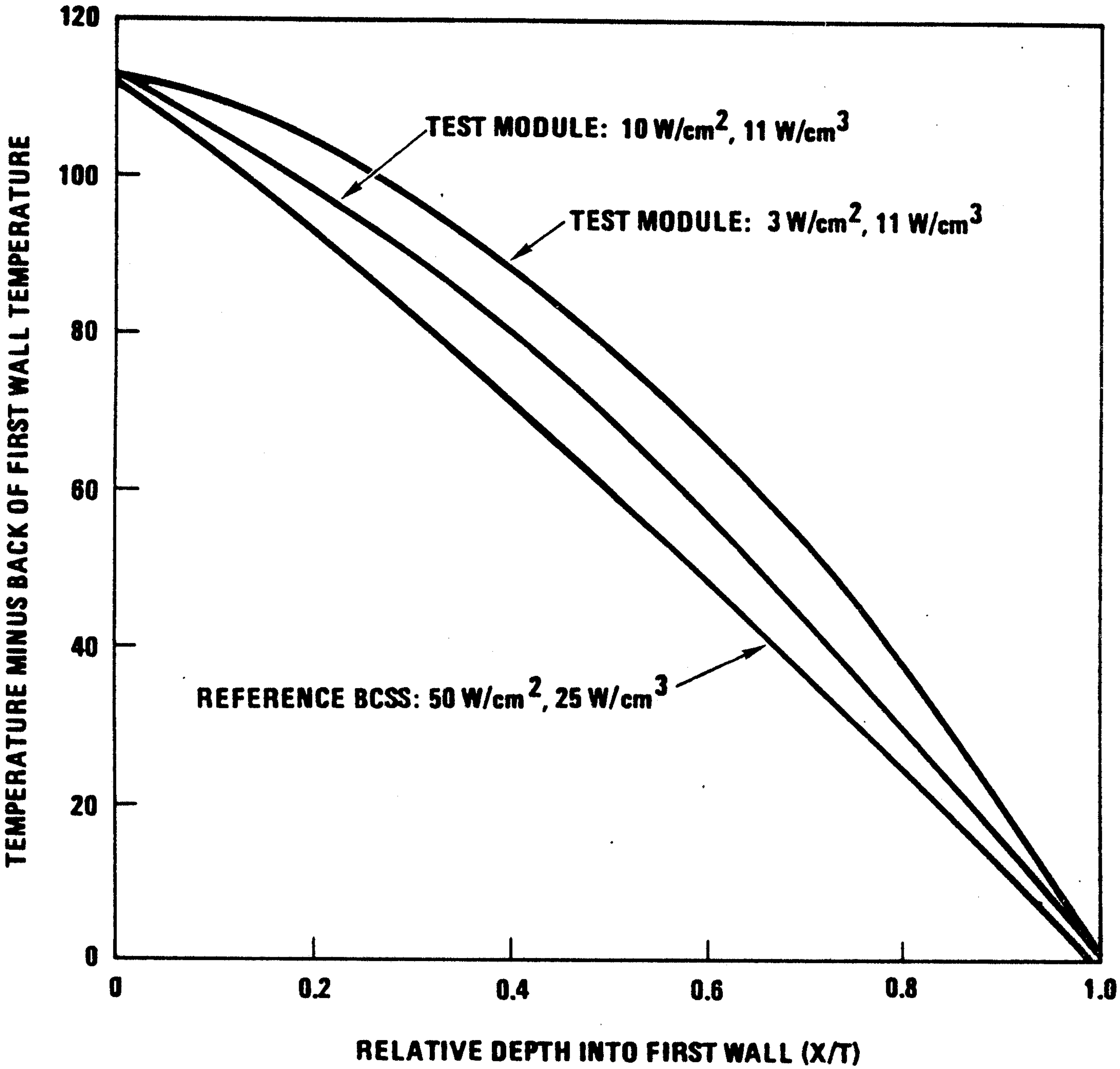
THE HEAT SOURCE DETERMINES TEMPERATURES IN THE BLANKET, WHICH ACTIVATES MANY IMPORTANT ENGINEERING PROCESSES

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 Li_2O/He/HT-9 first wall temperature profile (reactor at 5 MW/m^2 neutron and 1 MW/m^2 surface heat load; scaled test module at 2.5 and 0.1 MW/m^2.

TEMPERATURE PROFILES IN THE FIRST WALL CHANGE AS THE THICKNESS IS CHANGED DUE TO RELATIVE CONTRIBUTIONS OF BULK HEATING AND SURFACE HEATING



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" $(\phi T)_F$

$$(\phi T)_F > 2(\phi T)_M \text{ IN GENERAL}$$

  - 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")

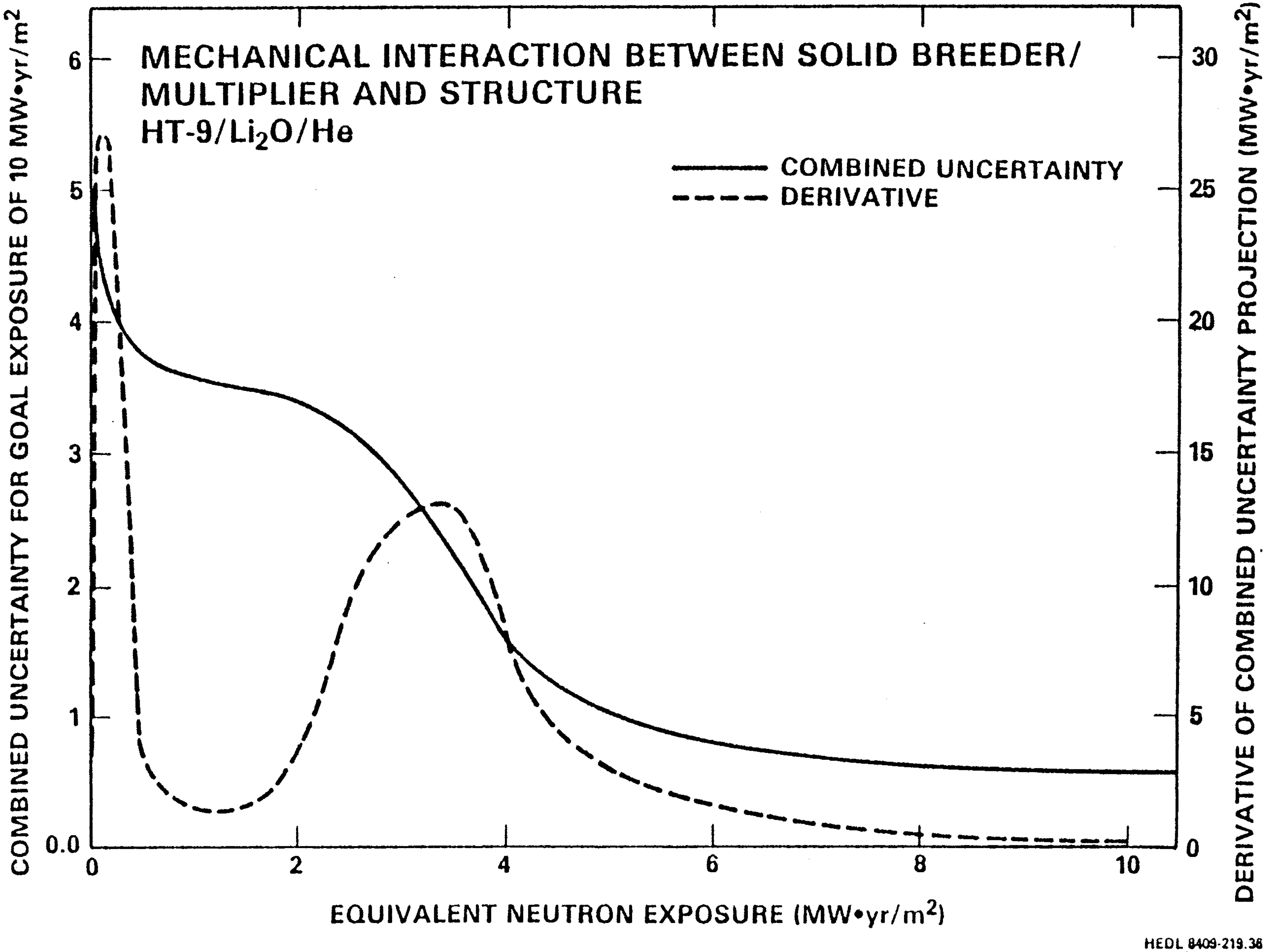
  - THERE IS INEVITABLY A LONG PERIOD OF FAIL/REPLACE/FIX FOR TEST MODULE (REMEMBER: FIRST TIME TO TEST IN FUSION ENVIRONMENT)

Table 1.3-3 Examples of Important Effects as a Function of Exposure

Exposure MW-yr/m^2	Phenomena/Effects
0-0.2	Thermophysical Property Changes (e.g., Thermal Conductivity) Solid Breeder Cracking Liquid Metal Embrittlement of Structure Onset of Li_2O 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	Li_2O 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 Unforseen High-Fluence Material Behavior (e.g., Solid Transmutations)

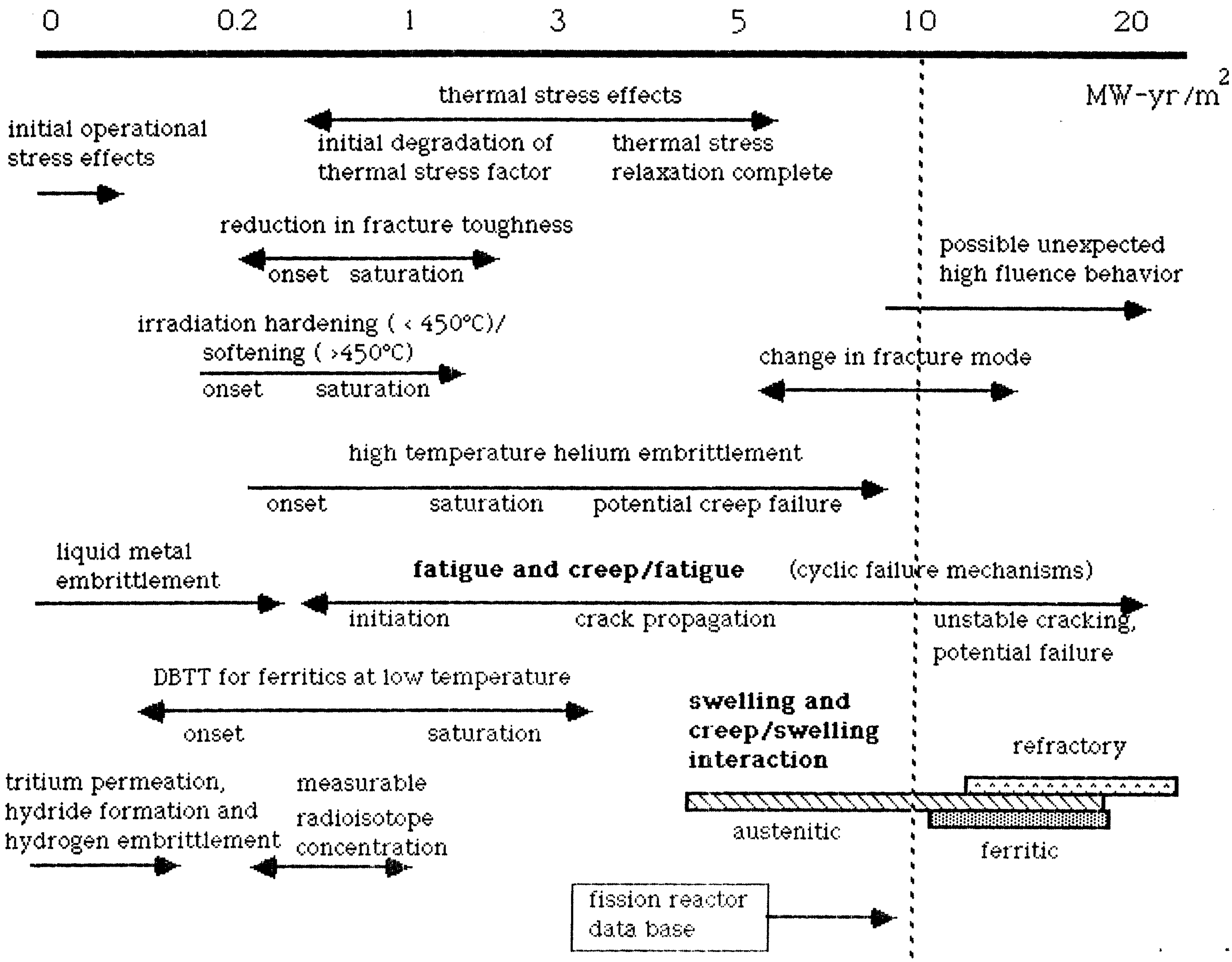
17

EXAMPLE OF BENEFIT Vs. FLUENCE

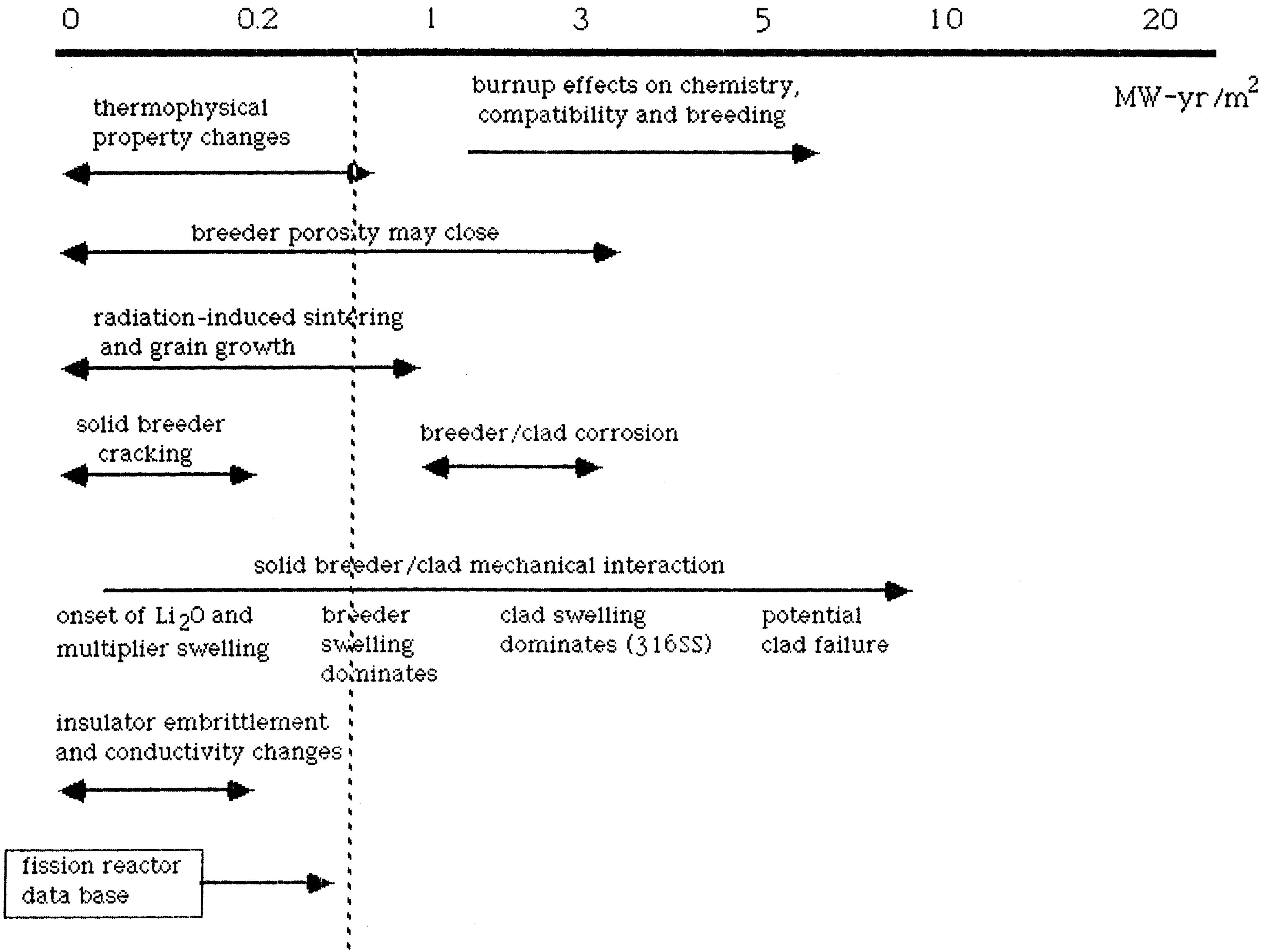


21

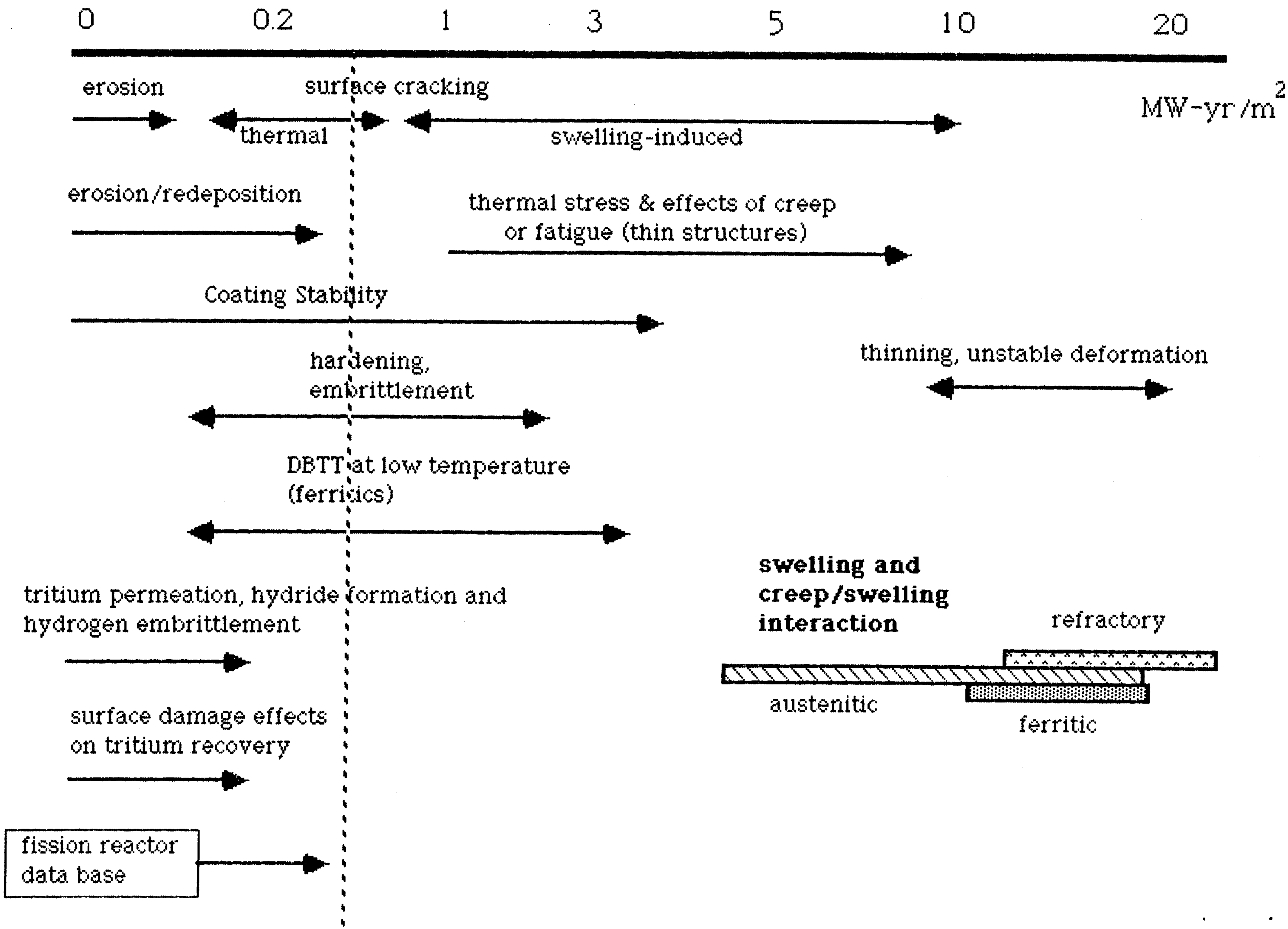
Fluence-Related Effects in Blanket Structural Materials



Fluence-Related Effects in Solid Breeders, Ceramics, and Special Materials



Fluence-Related Effects in Plasma-Facing Materials



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 1.3-5 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

MANY KEY ISSUES REQUIRE LONG BURN TIME

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

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

	TIME CONSTANTS
	FAST
	SECONDS
HEAT CONDUCTION	
FLOW PROCESSES	
	MINUTES
THERMAL PROCESSES	
	HOURS
TRITIUM PROCESSES	
MATERIAL INTERACTIONS	
OTHER IMPORTANT PROCESSES	
	DAYS
	SLOW

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

$$F = F_0 \, e^{-\frac{t}{\tau}}$$

PLASMA DWELL TIME $<0.1\tau$

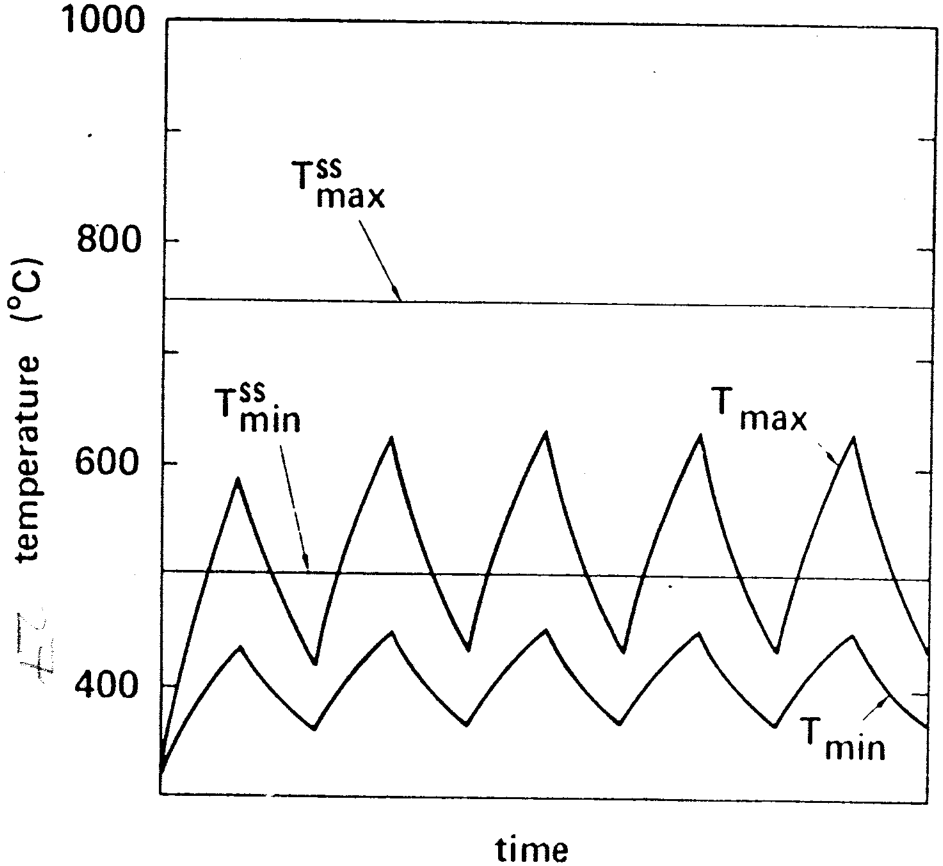
- o CRITICAL PROCESSES WITH LONG τ WILL BE TREMENDOUSLY COMPLICATED BY SIGNIFICANT DWELL TIME
- o THEY DEPEND ON MANY OTHER PROCESSES WITH VERY SHORT TIME CONSTANTS

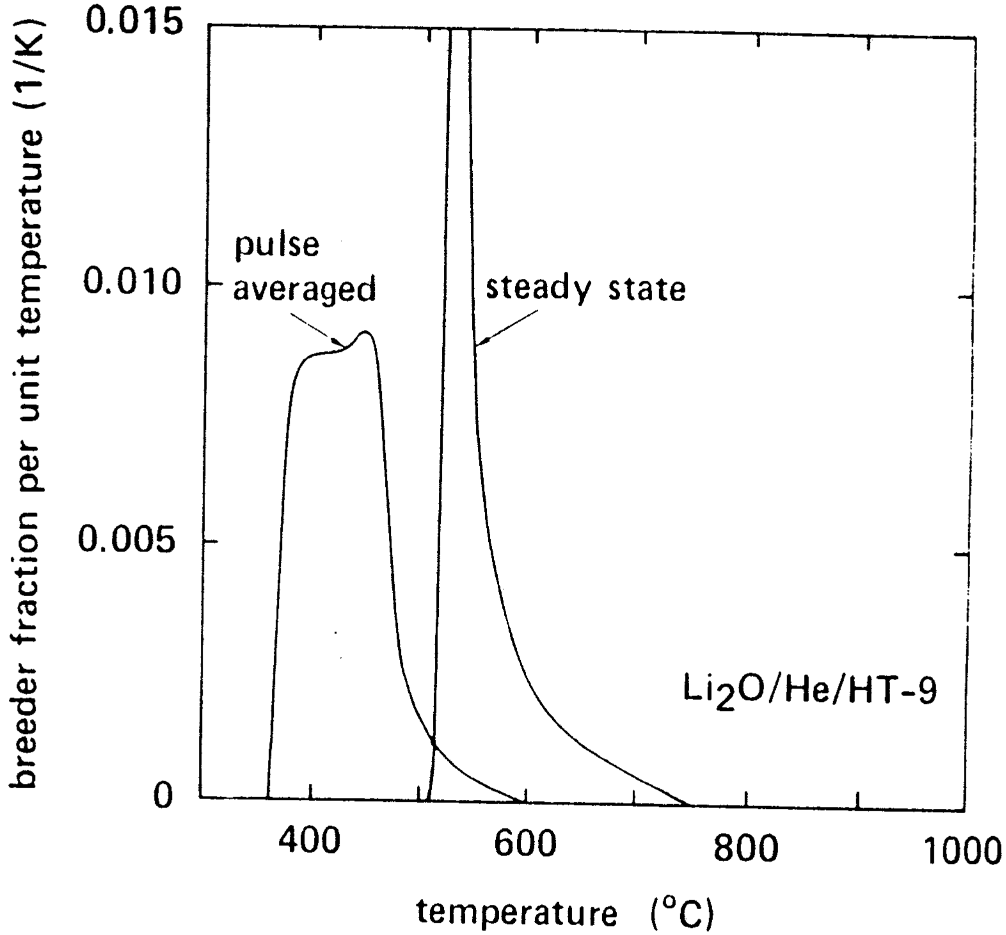
EXAMPLES

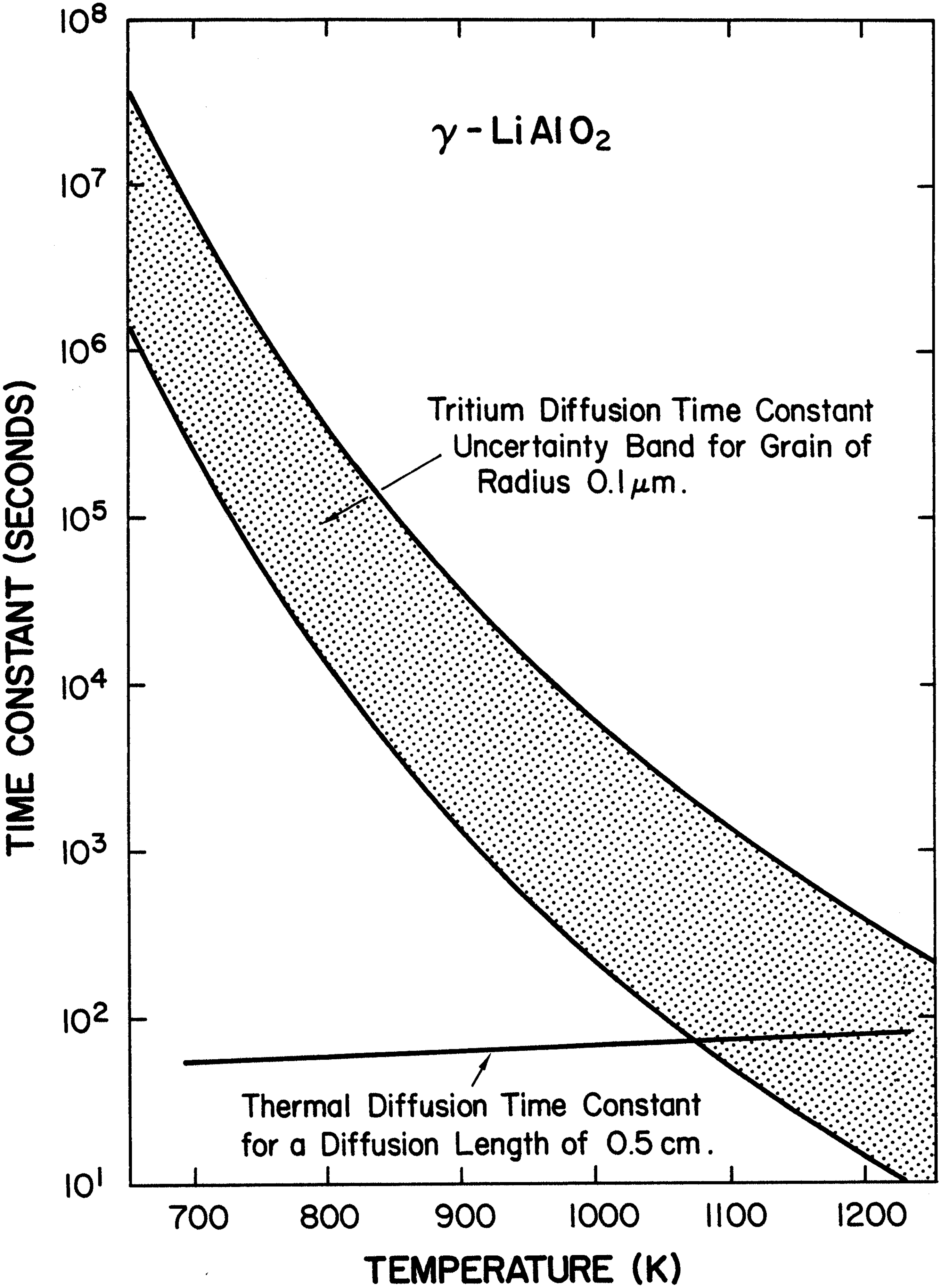
- TRITIUM PROCESSES
  SLOW PROCESS; BUT STRONG DEPENDENCE ON TEMPERATURE AND FLUID FLOW
- CORROSION PROCESSES
  SLOW PROCESS; BUT STRONG DEPENDENCE ON TEMPERATURE AND FLUID FLOW
- FERRITIC DBTT

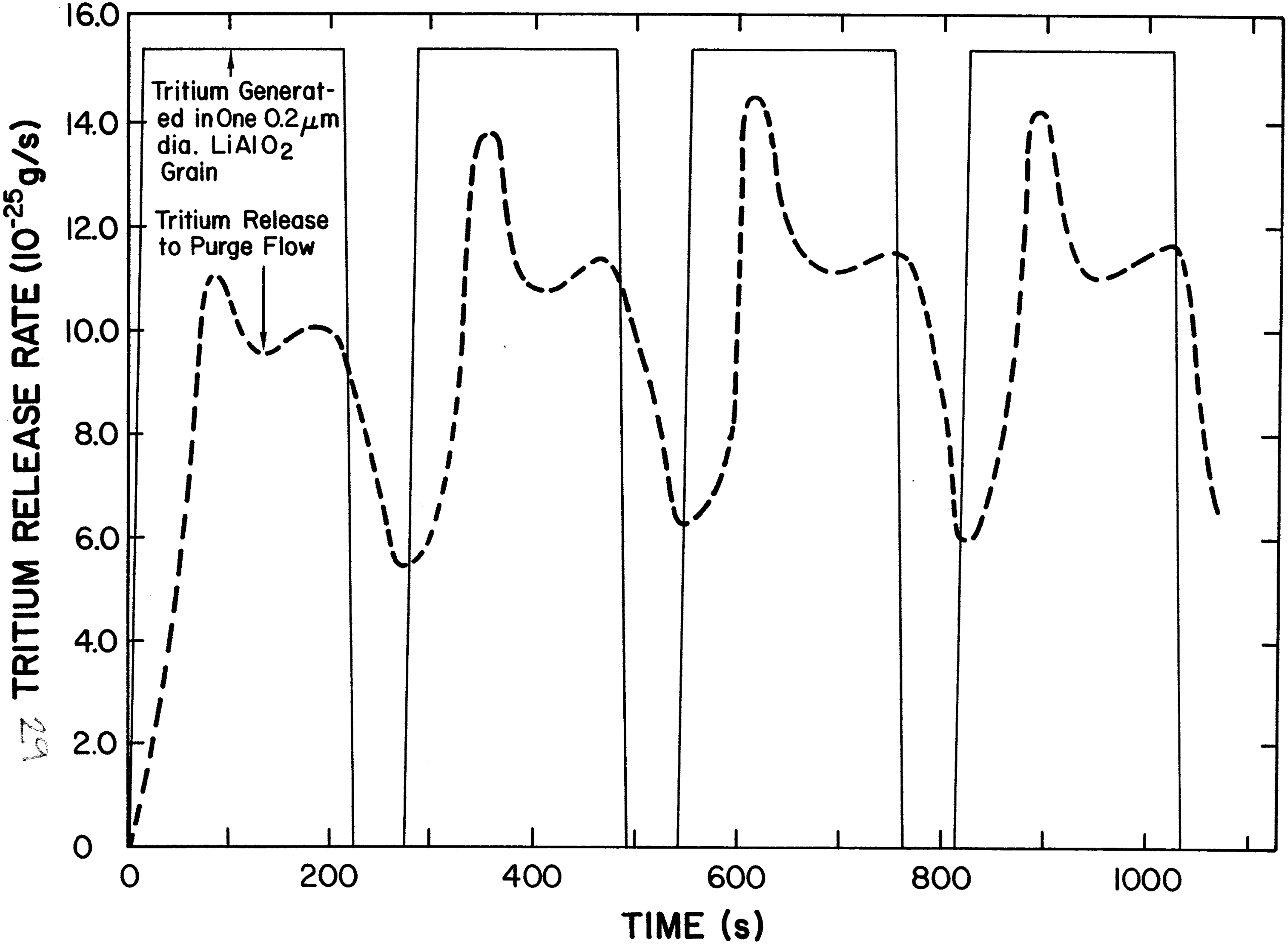
PLASMA DWELL TIME SHOULD BE NEAR ZERO

Pulsing strongly affects the solid breeder temperature distribution.





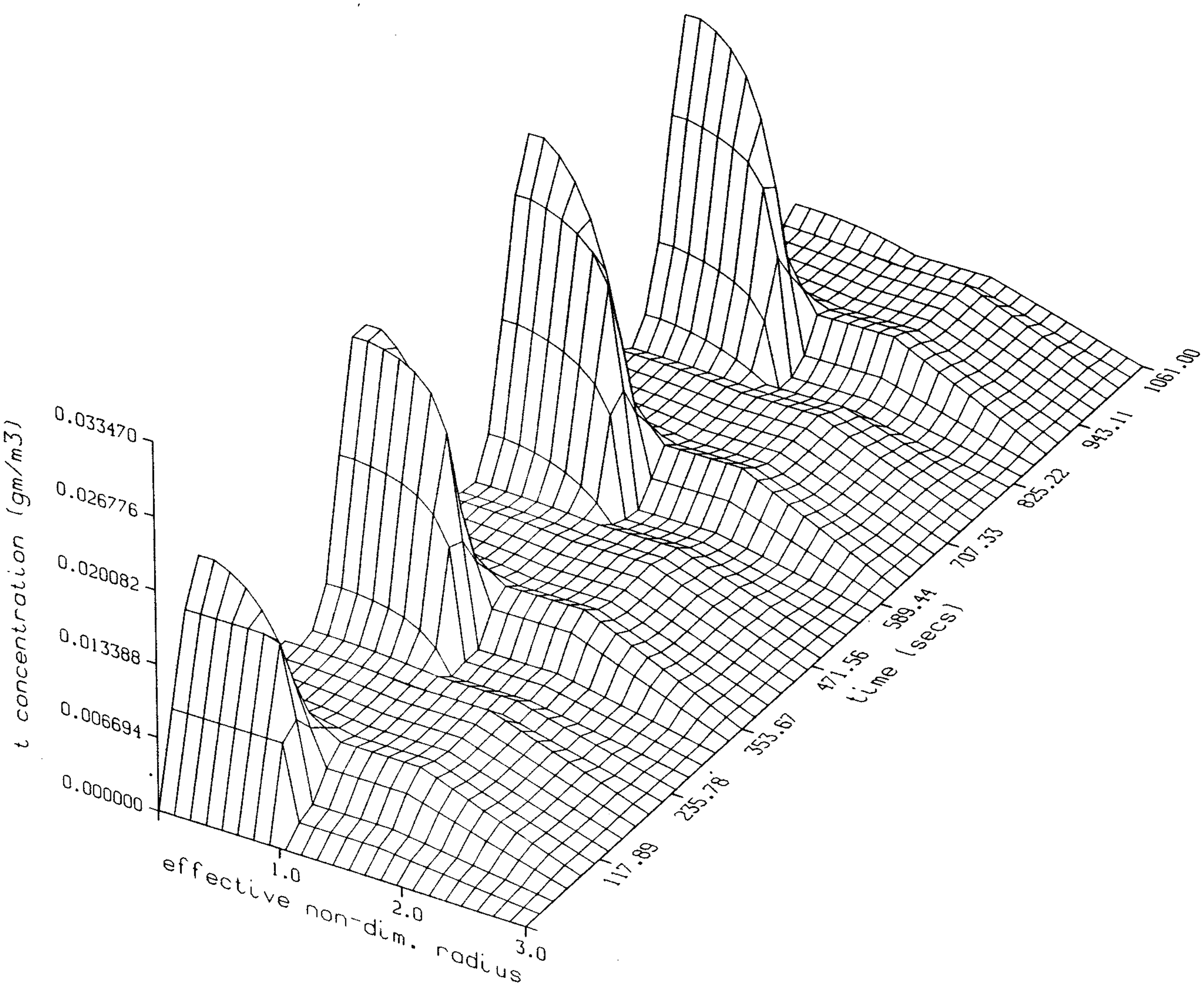

γ - LiAlO2
TIME CONSTANT (SECONDS)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
Tritium Diffusion Time Constant Uncertainty Band for Grain of Radius 0.1 μm.
Thermal Diffusion Time Constant for a Diffusion Length of 0.5 cm.
700
800
900
1000
1100
1200
TEMPERATURE (K)



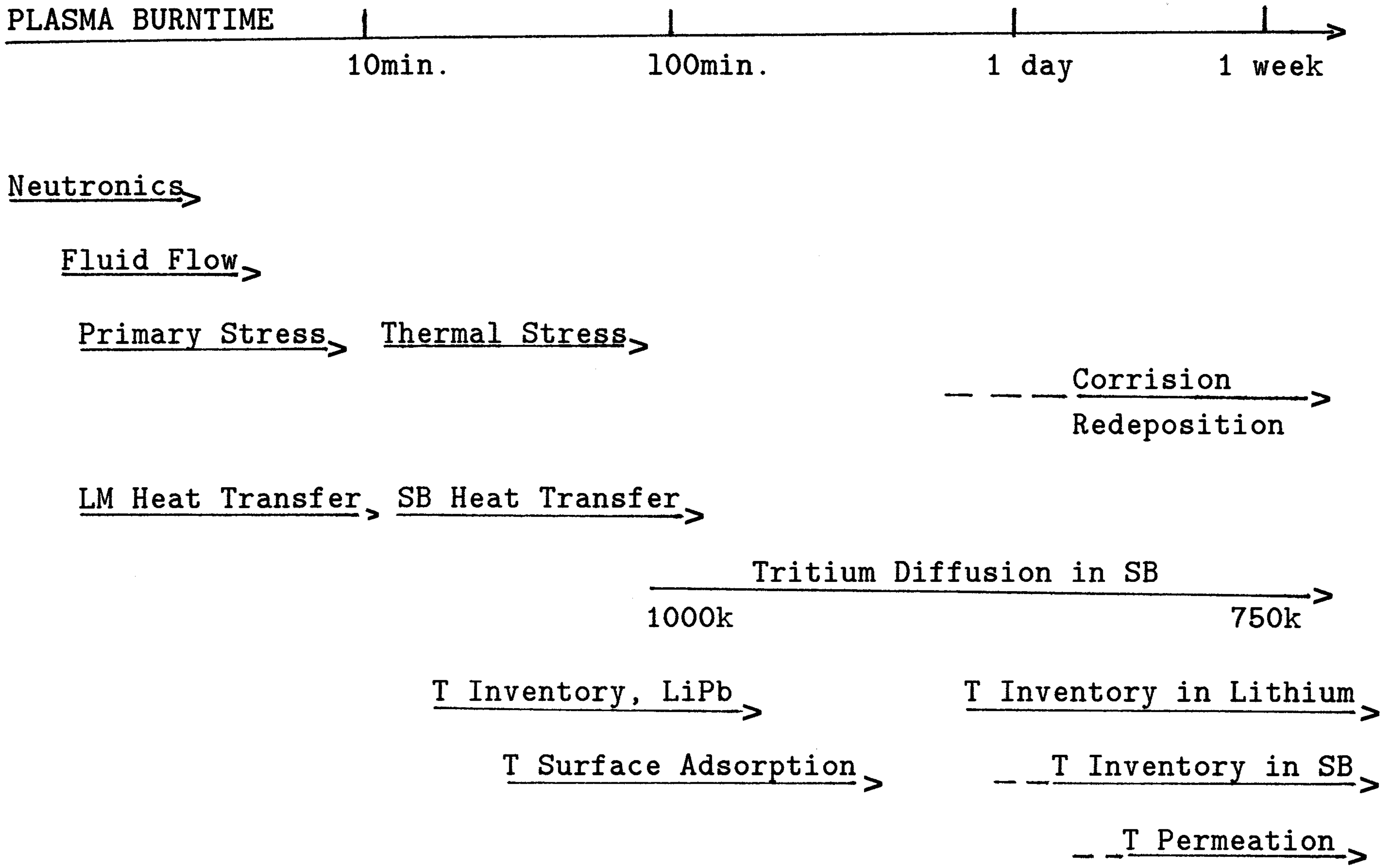
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
TRITIUM RELEASE RATE (10^{-25} g/s)
Tritium Generated in One 0.2 μm dia. $LiAlO_2$ Grain
Tritium Release to Purge Flow
0
200
400
600
800
1000
TIME (s)

29

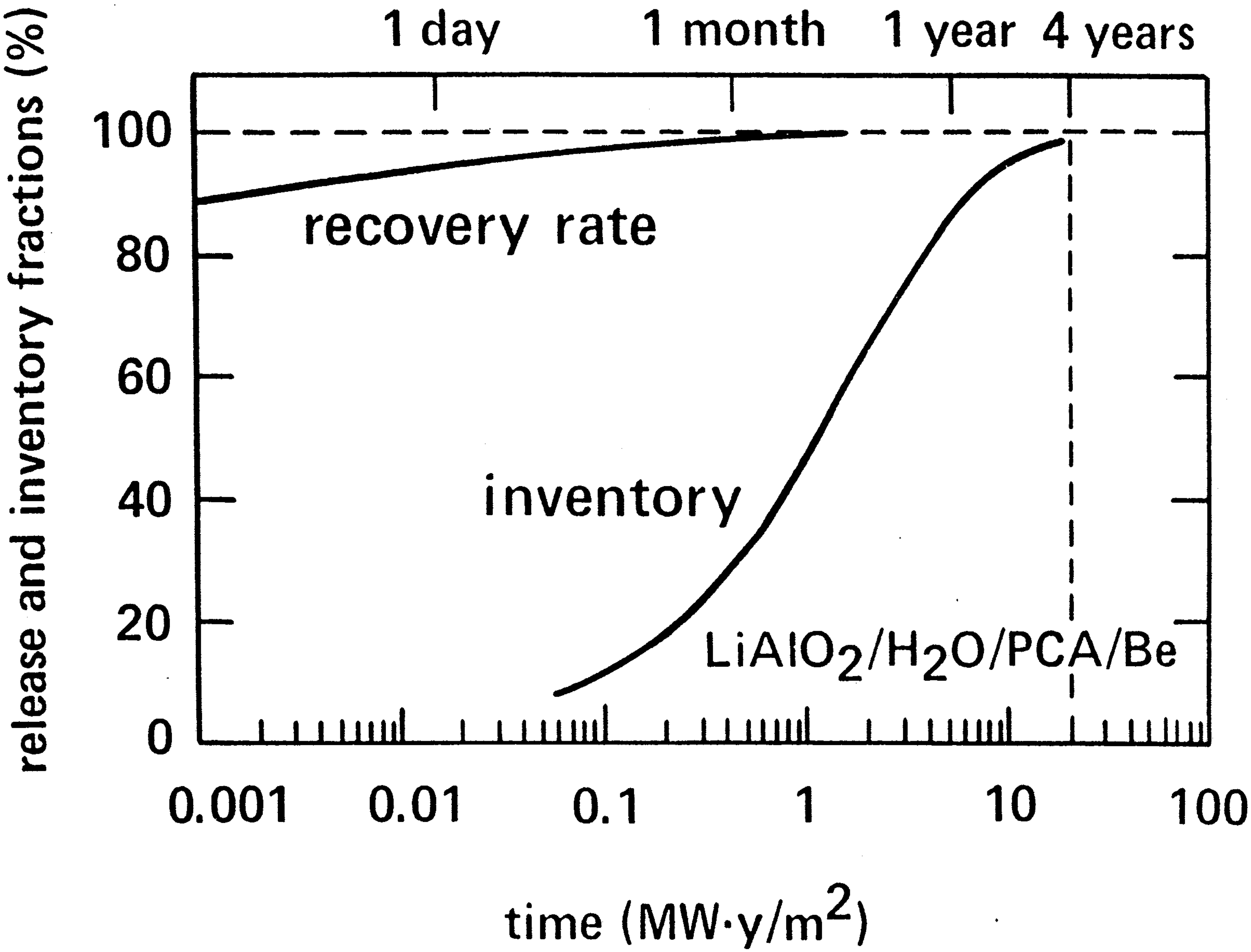
Time-Dependent Tritium Concentration (Diffusive) Profiles in Grain, Grain Boundary and Pore



MANY OF THE CRITICAL NUCLEAR ISSUES THAT REQUIRE TESTING IN THE FUSION ENVIRONMENT NEED LONG PLASMA BURNTIME



Reaching tritium inventory and recovery equilibrium may require long test times



31

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 1.3-7 Definitions and Evaluation of MHD Parameters

Parameter	Definition	Typical Reactor Values	
		Li	17Li-83Pb
Hartmann Number	$Ha = aB\sqrt{\frac{\sigma}{\mu}}$	6.3×10^4	1.6×10^4
Reynolds Number	$Re = av\frac{\rho}{\mu}$	6.6×10^4	3.1×10^5
Interaction Parameter	$N = \frac{aB^2}{v}\frac{\sigma}{\rho}$	6.0×10^4	825
Magnetic Reynolds Number	$Re_m = av\mu_o\sigma$	0.19	0.052
Wall Conductance Ratio	$C = \frac{\sigma_w t}{\sigma a}$	0.025	0.090
Property Values: (all units mks)		$\sigma = 3\times10^6$ $\mu = 0.38\times10^{-3}$ $\rho = 495$	0.83×10^6 1.5×10^{-3} 9200
Reactor Conditions Assumed: (all units mks)	$a = 0.1$ $B = 7$ (at inboard) $v = 0.5$	$\sigma_w = 1.5\times10^6$ $t = 0.005$ $\mu_o = 4\pi\times10^{-7}$	

FNT RECOMMENDED PARAMETERS

Parameters	ETR Minimum	ETR 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	>1000[A]	Steady
Magnetic Field[B], T	3	5	7
Continuous Operating Time	Days	Weeks	Months
Availability, %	20	30-50	70
Fluence[B], $MW \cdot y/m^2$	1-2	3-6	15-20
Test Port Size, $m^2 \times m$	0.5 x 0.3	1 x 0.5	
Total Test Area, m^2	5	10-20	

[A] Steady-state strongly preferred

[B] At test article (device lifetime fluence is larger)