FUSION NUCLEAR TECHNOLOGY TEST REQUIREMENTS AND ENGINEERING SCALING FOR ETR

M. Abdou
M. Tillack

Presented at the ETR Nuclear Performance Group Meeting
17 December 1986

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

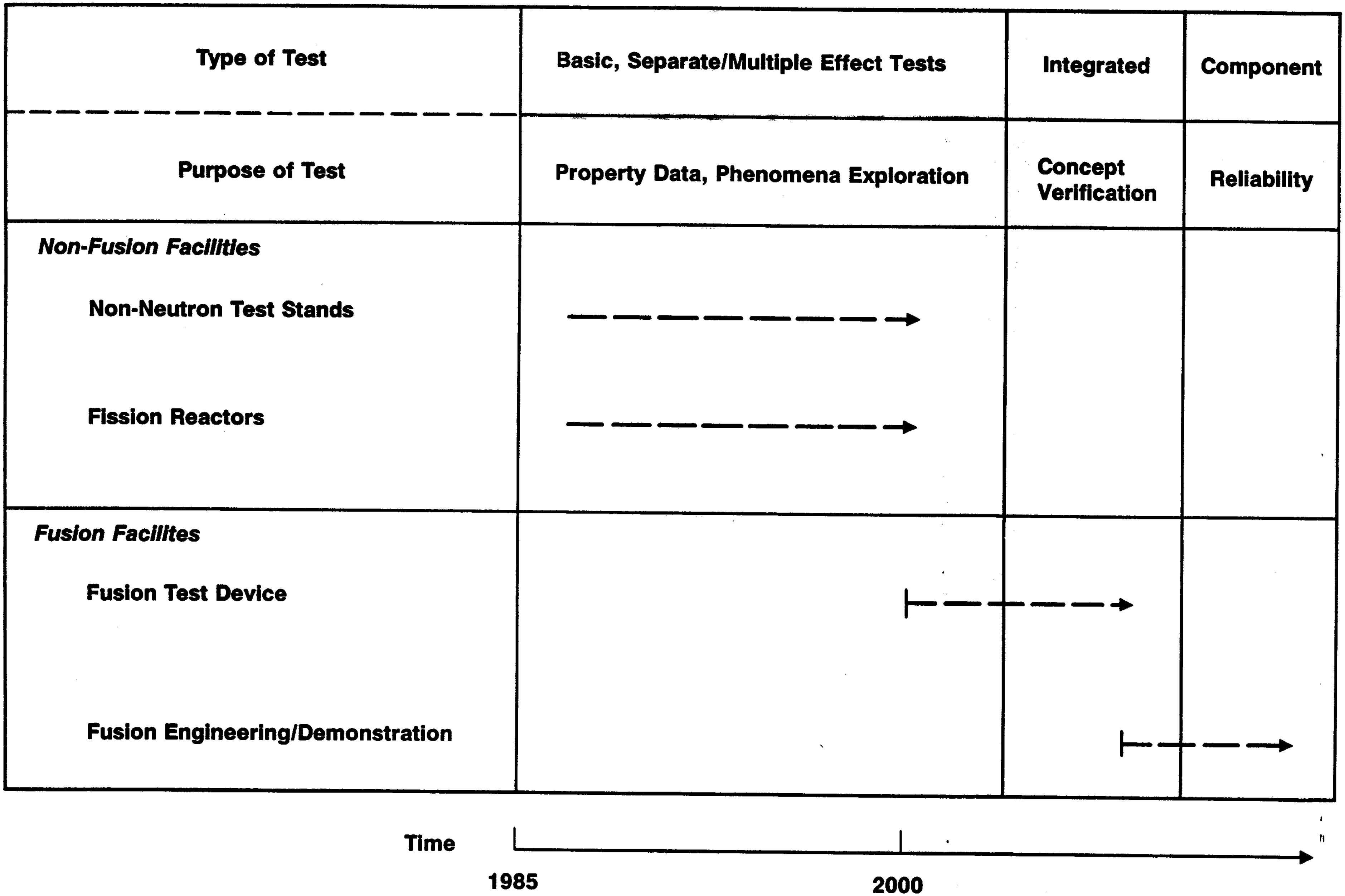
Several Elements
Class of Issues
Interaction Among Elements

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



Type of Test
Basic, Separate/Multiple Effect Tests
Integrated
Component
Purpose of Test
Property Data, Phenomena Exploration
Concept Verification
Reliability
Non-Fusion Facilities
Non-Neutron Test Stands
Fission Reactors
Fusion Facilites
Fusion Test Device
Fusion Engineering/Demonstration
Time
1985
2000

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

MAJOR PARAMETERS

- Neutron Wall Load
- Surface Heat Load
- Plasma Cycle Burn/Dwell Times
- Minimum Continuous Time
- Availability
- Fluence
- Magnetic Field Strength
- Test Area/Size

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 (Quantify?)
  - Demonstrate Adequate Level of Reliability (Quantify?)

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

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 ΔT

- Lower P_N Requires Longer Time to Equilibrium

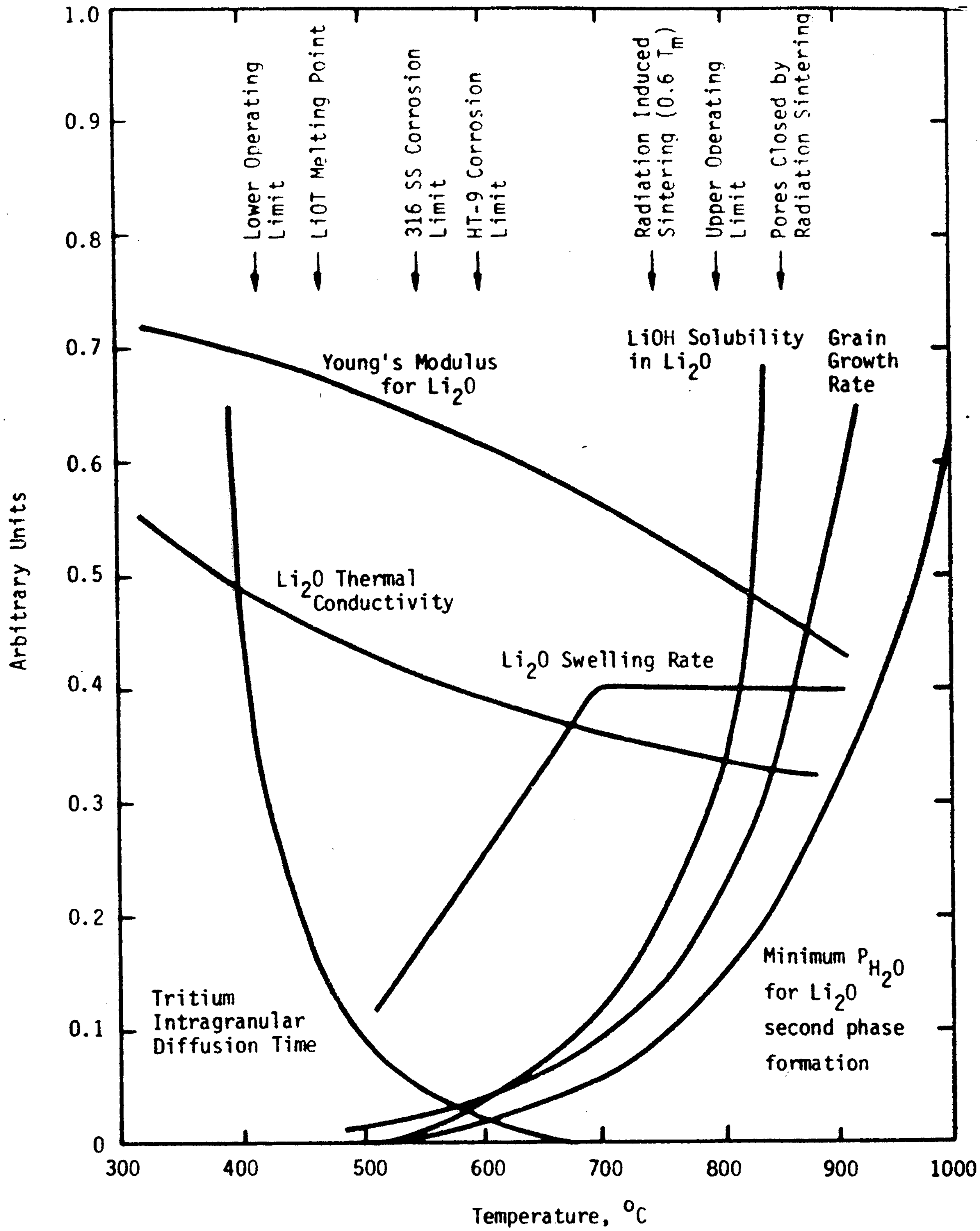
- Lower B Requires Larger Dimensions to Preserve MHD Effects ($Ha \sim aB$)

NEUTRON WALL LOAD REQUIREMENTS

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

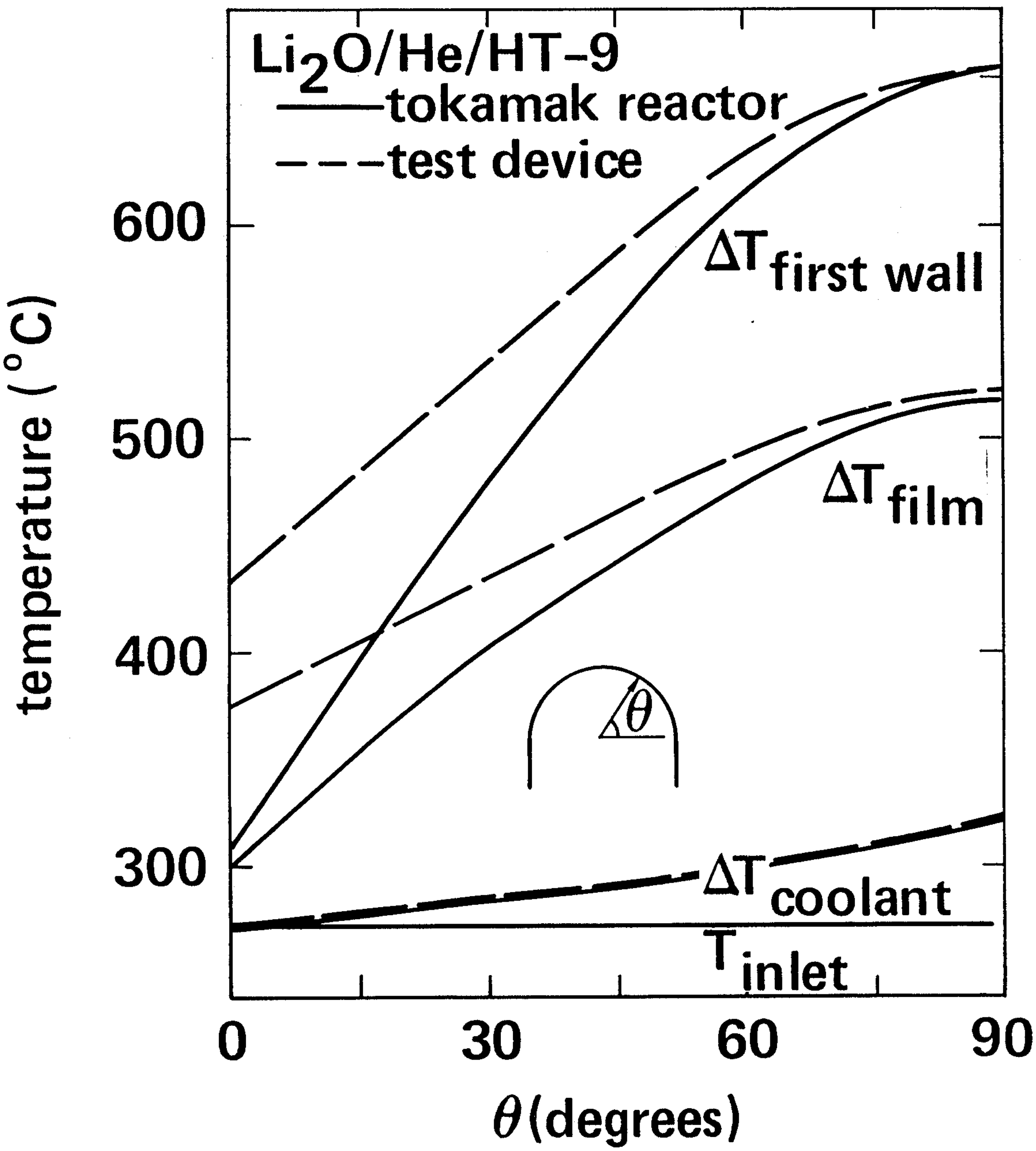
P_N →

- → 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

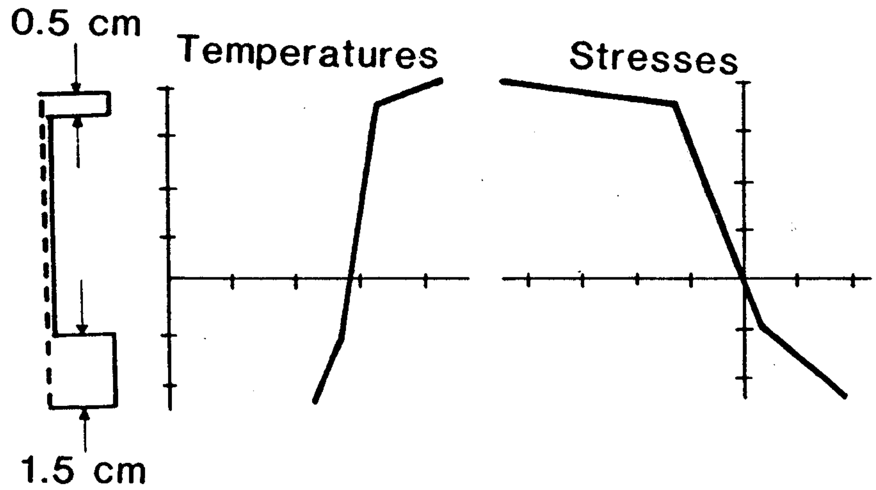
WHILE AVERAGE TEMPERATURES CAN BE COMPENSATED BY CONTROLLING THE COOLANT INLET TEMPERATURE, TEMPERATURE GRADIENTS ARE UNAVOIDABLY CHANGED BY REDUCED HEAT INPUT. ENGINEERING SCALING IS ONLY PARTIALLY SUCCESSFUL AT RECOVERING THE CORRECT PROFILES.



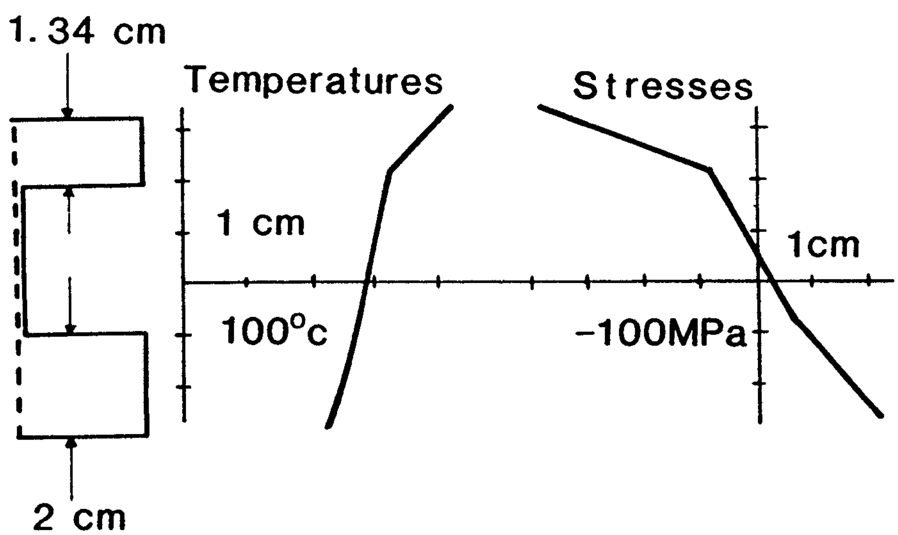
Heat source effect on the BCSS Li_2O/He/HT-9 first wall temperature profile (reactor at 5 MW/m^2 neutron and 1 MW/m^2 surface heat load; scaled test module at 2.5 and 0.1 MW/m^2.

THERMAL STRESSES CAN BE MAINTAINED UNDER REDUCED HEAT LOADS, BUT OTHER ISSUES MAY BE AFFECTED BY CHANGES IN DIMENSIONS

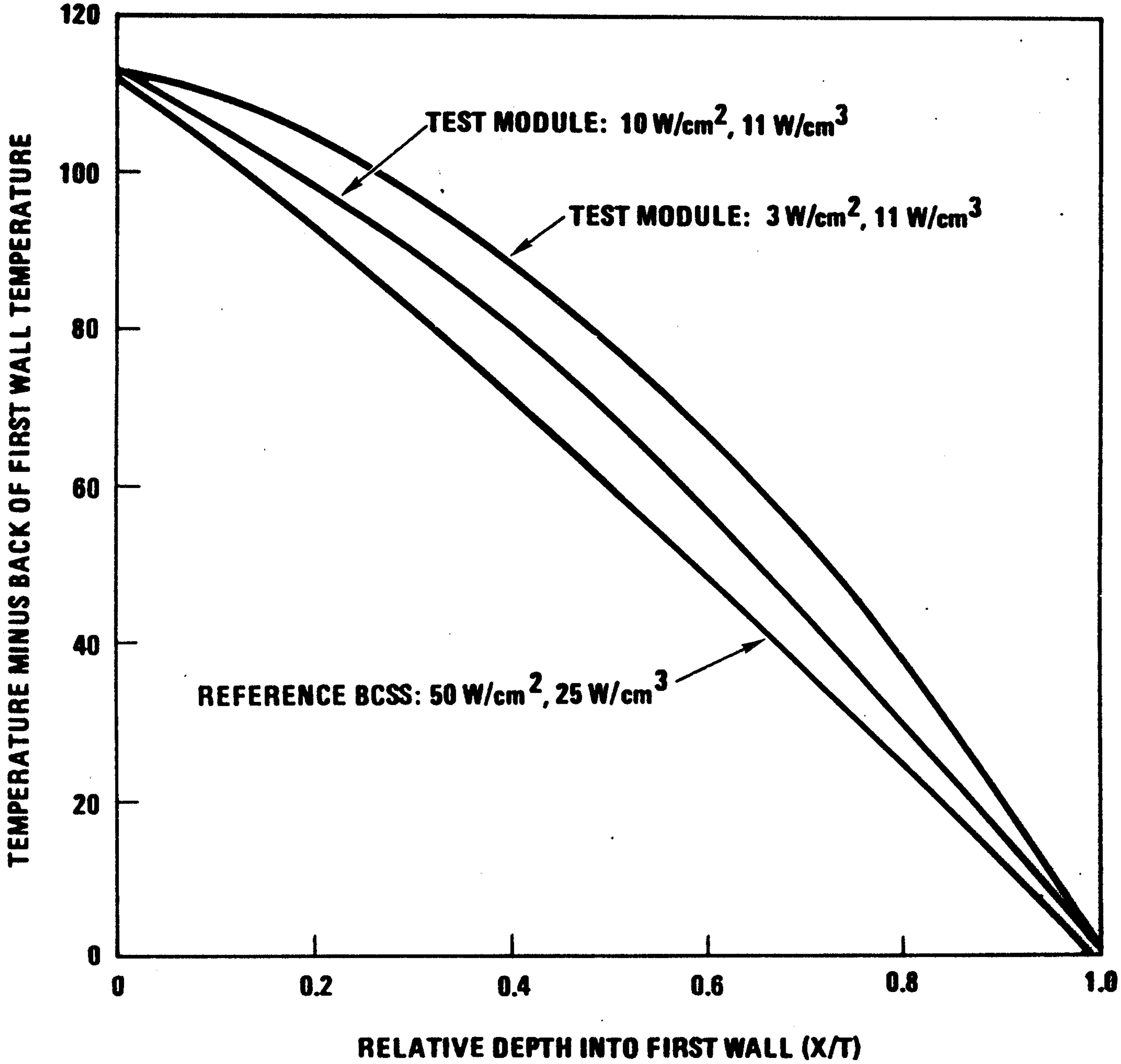
BCSS THERMAL STRESSES



TEST MODULE THERMAL STRESSES

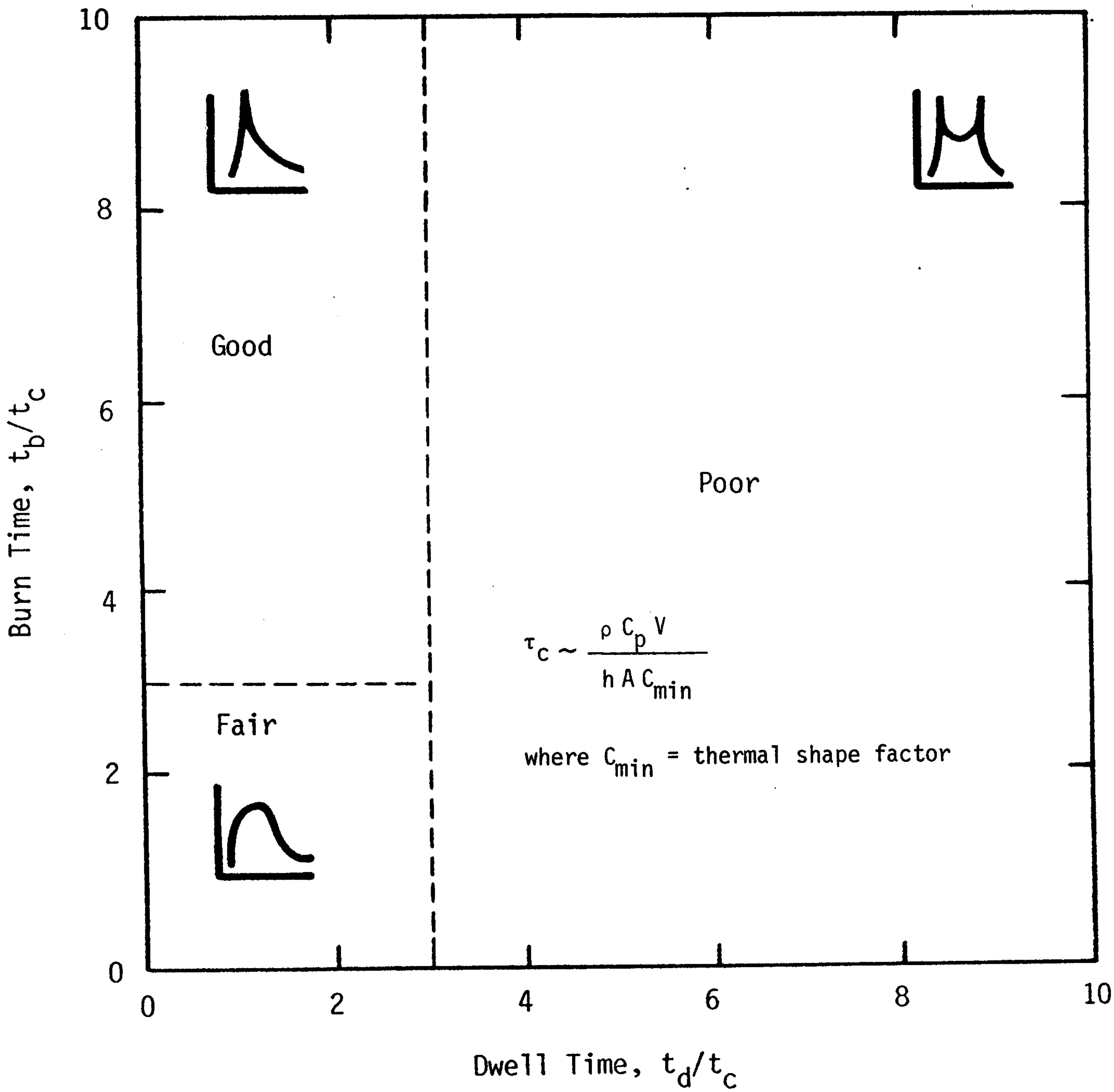


TEMPERATURE PROFILES IN THE FIRST WALL CHANGE AS THE THICKNESS IS CHANGED DUE TO RELATIVE CONTRIBUTIONS OF BULK HEATING AND SURFACE HEATING

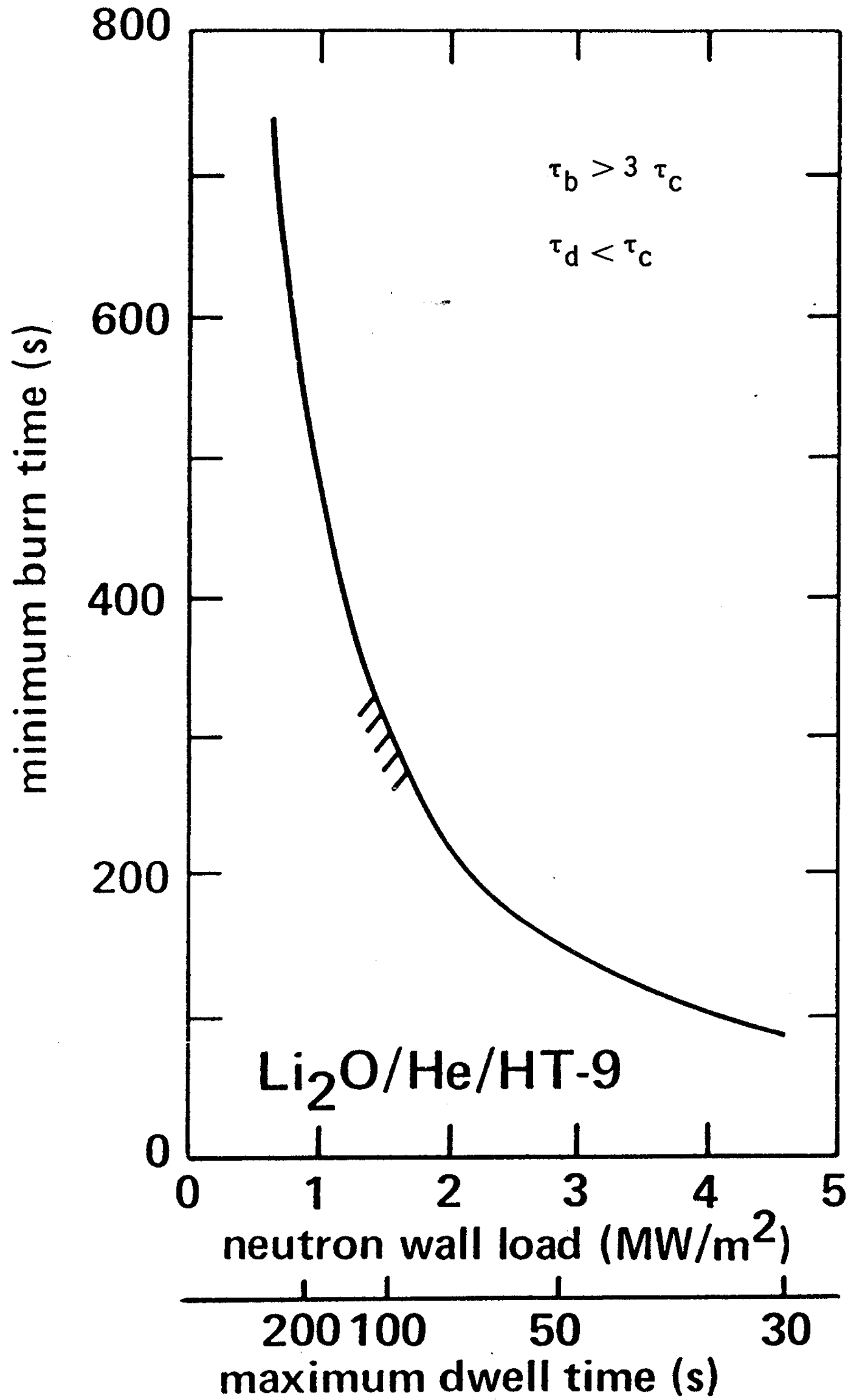


Temperature profiles through the first wall under various operating conditions.

Act-Alike Temperature Density Regions versus Burn and Dwell Times



Burn and dwell time requirements for maintaining solid breeder temperature distribution



NEUTRON FLUENCE

- SHOULD BE DRIVEN BY THE VALUE OF WHAT WE LEARN FROM COMPONENT TESTS

- LOW FLUENCES WILL NOT PERMIT TESTING OF MANY CRITICAL ISSUES

- HIGHER FLUENCES ARE DESIRABLE BUT COSTLY
  - DEVICE AVAILABILITY
  - TRITIUM SUPPLY

- MODEST FLUENCES ARE STILL EXTREMELY VALUABLE

CRITICAL:	1-2 $MW{\cdot}y/m^2$
VERY IMPORTANT:	2-4 $MW{\cdot}y/m^2$
IMPORTANT:	4-6 $MW{\cdot}y/m^2$

OBSERVATION:

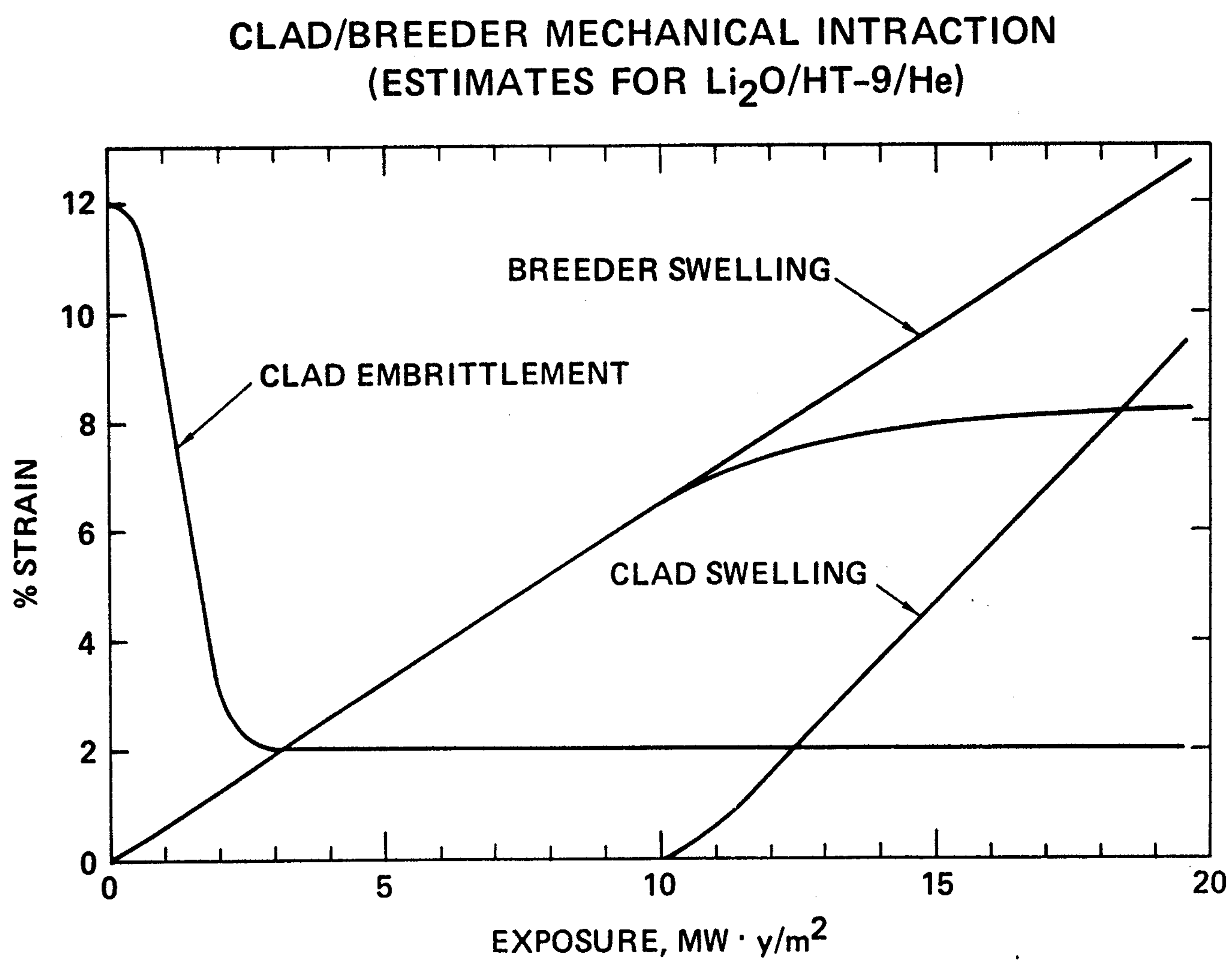
- FLUENCE ACHIEVABLE IN TEST MODULE IS CONSIDERABLY LESS (FACTOR OF 2 OR MORE) THAN THE TEST DEVICE "LIFETIME FLUENCE"

  - 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")

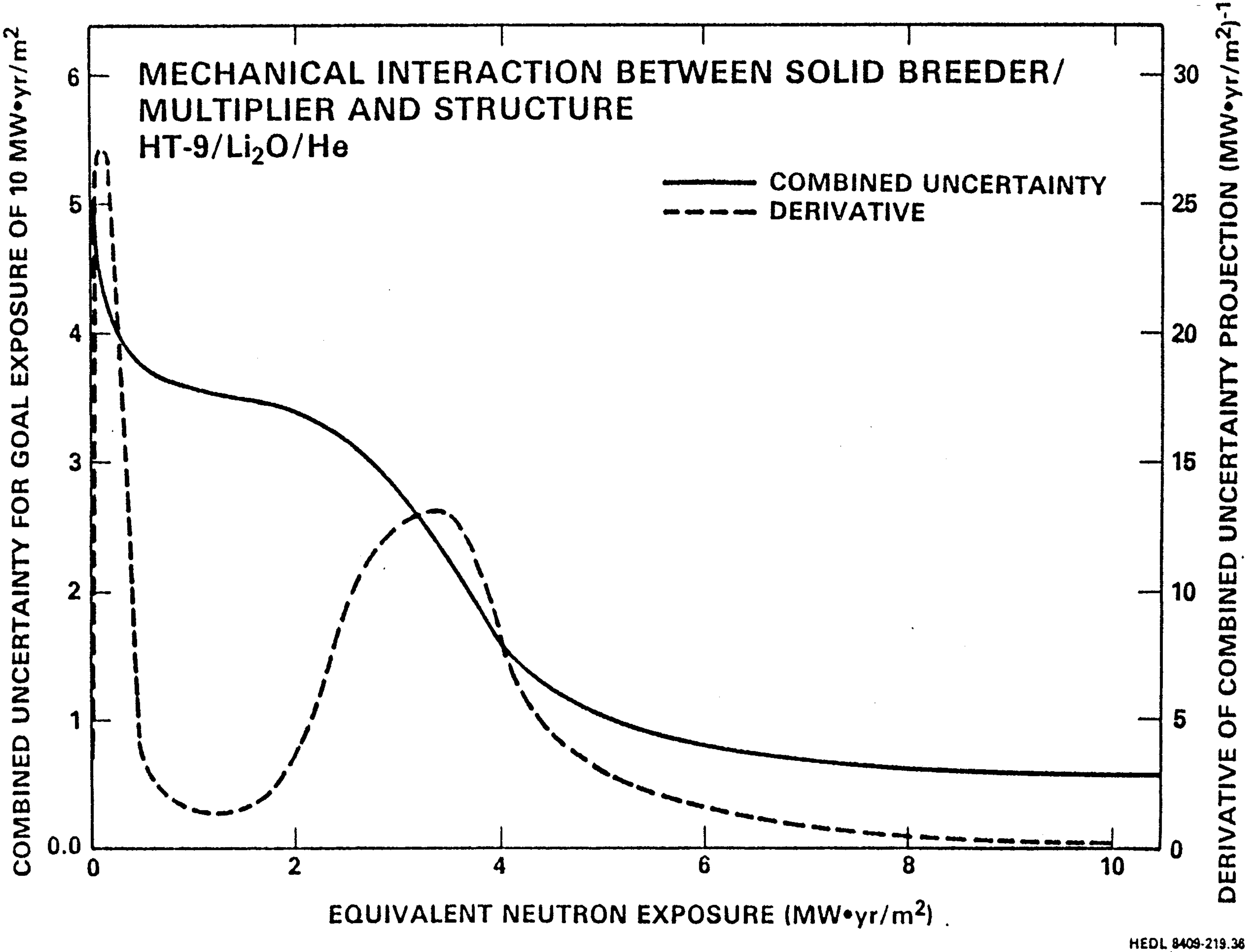
  - THERE IS INEVITABLY A LONG PERIOD OF FAIL/REPLACE/FIX FOR TEST MODULE (REMEMBER: FIRST TIME TO TEST IN FUSION ENVIRONMENT)

Examples of Important Effects as a Function of Exposure

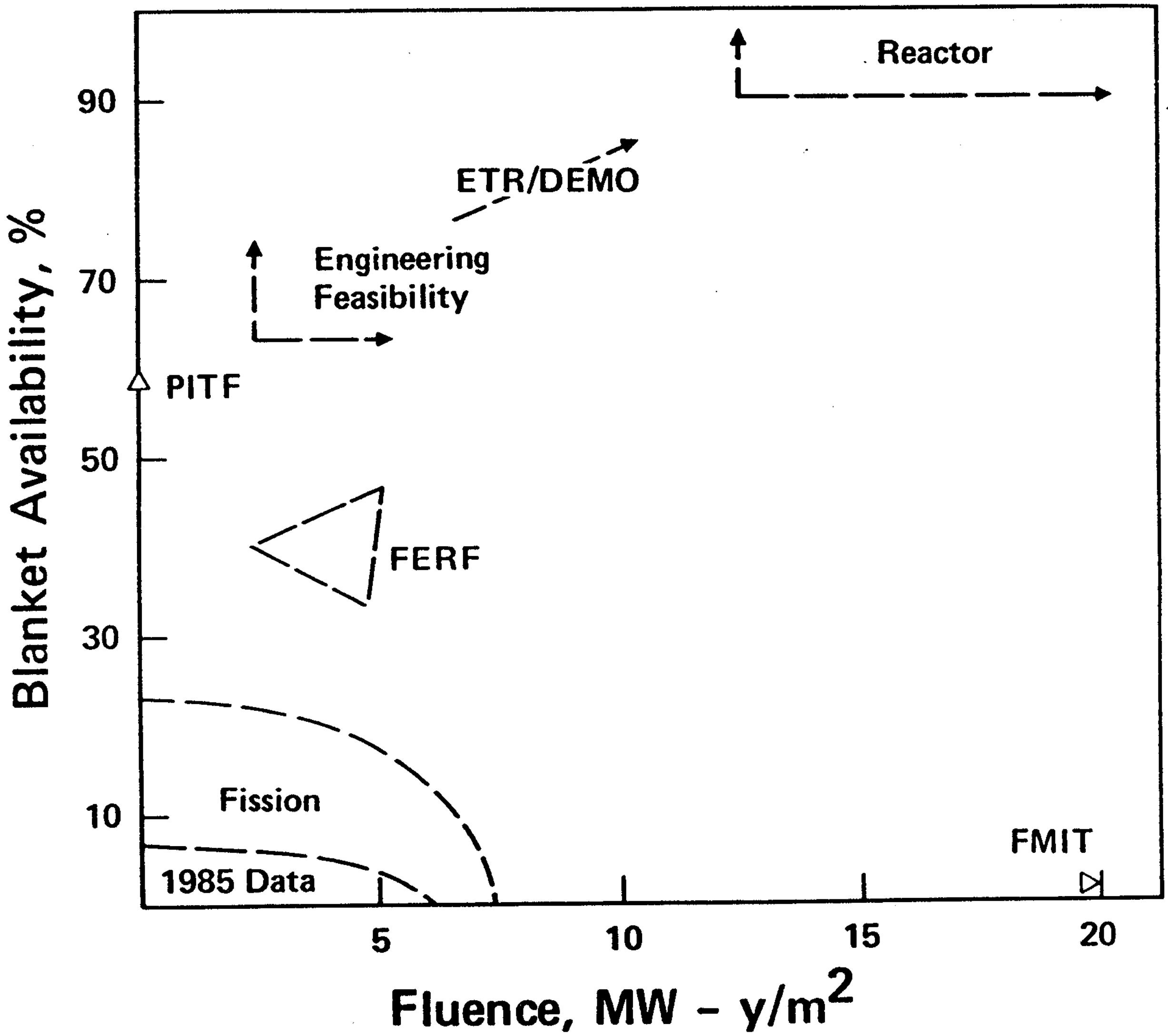
Exposure $MW\text{-}yr/m^2$	Phenomena/Effects
0-0.2	Thermophysical Property Changes (particularly in Thermal Conductivity) Solid Breeder Cracking Liquid Metal Embrittlement of Structure Onset of Li_2O and Multiplier Swelling First Wall Erosion Initial Operational Stress Effects Surface Damage Effects on Tritium Desorption Purge Gas Composition Effects on Tritium Recovery Tritium Permeation through First Wall and Clad
0.2-1	Li_2O Swelling Dominates Breeder/Clad Mechanical Interaction Onset of Tensile Property Changes (HT-9, 316 SS) Fatigue and Creep/Fatigue Initiation First Wall Erosion and Surface Cracking Relaxation of Thermal Stresses Radiation-Induced Trapping (Defect Saturation) Fracture Toughness Reduction Initiated (Structure)
1-3	Tensile Properties Start to Saturate (HT-9, 316) Thermal Stress Relaxation Complete Porosity in Breeder May Close Off Radiation-Induced Sintering Grain Growth Burnup Effects on Chemistry Activated Corrosion Product Transport Breeder/Clad Corrosion Fracture Toughness, Δ-DBTT Saturates
3-5	Irradiation Hardening (<450°C)/Softening (>450°C) Saturates Fatigue Crack Propagation Onset of Irradiation Creep/Swelling of Austenitic Alloy Clad Swelling (316) Dominates Breeder/Clad Interaction
5-10	Potential Onset of Irradiation Creep/Swelling of HT-9 Fatigue Failure
10-20	End-of-Life Phenomena: Operational Stress Effects - First Wall Thinning - Unstable Deformation - Fatigue, Creep Fatigue - Unstable Cracking Unforseen High-Fluence Material Behavior


CLAD/BREEDER MECHANICAL INTRACTION
(ESTIMATES FOR Li_2O/HT-9/He)
BREEDER SWELLING
CLAD EMBRITTLEMENT
CLAD SWELLING
% STRAIN
EXPOSURE, MW · y/m²
0
2
4
6
8
10
12
0
5
10
15
20

EXAMPLE OF BENEFIT Vs. FLUENCE



Obtaining Availability and Fluence Data For Blanket Is Most Difficult



TIME-RELATED PARAMETERS

- PLASMA BURN TIME, DWELL TIME
  (DUTY CYCLE)

- MINIMUM CONTINUOUS OPERATING TIME
  (100% AVAILABILITY)

PULSING/STEADY-STATE OPERATION

- PLASMA CYCLING MEANS TIME-DEPENDENT CHANGES IN ENVIRONMENTAL CONDITIONS FOR TESTING

  - NUCLEAR (VOLUMETRIC) HEATING
  - SURFACE HEATING
  - POLOIDAL MAGNETIC FIELD
  - TRITIUM PRODUCTION RATE

- RESULTS IN TIME-DEPENDENT CHANGES IN RESPONSE OF TEST ELEMENTS

  - EFFECTS CAN BE, IN SOME CASES, MORE DOMINANT THAN THE STEADY-STATE EFFECTS FOR WHICH TESTING IS DESIRED
  - EFFECTS CAN COMPLICATE TESTS AND MAKE RESULTS DIFFICULT TO MODEL AND UNDERSTAND

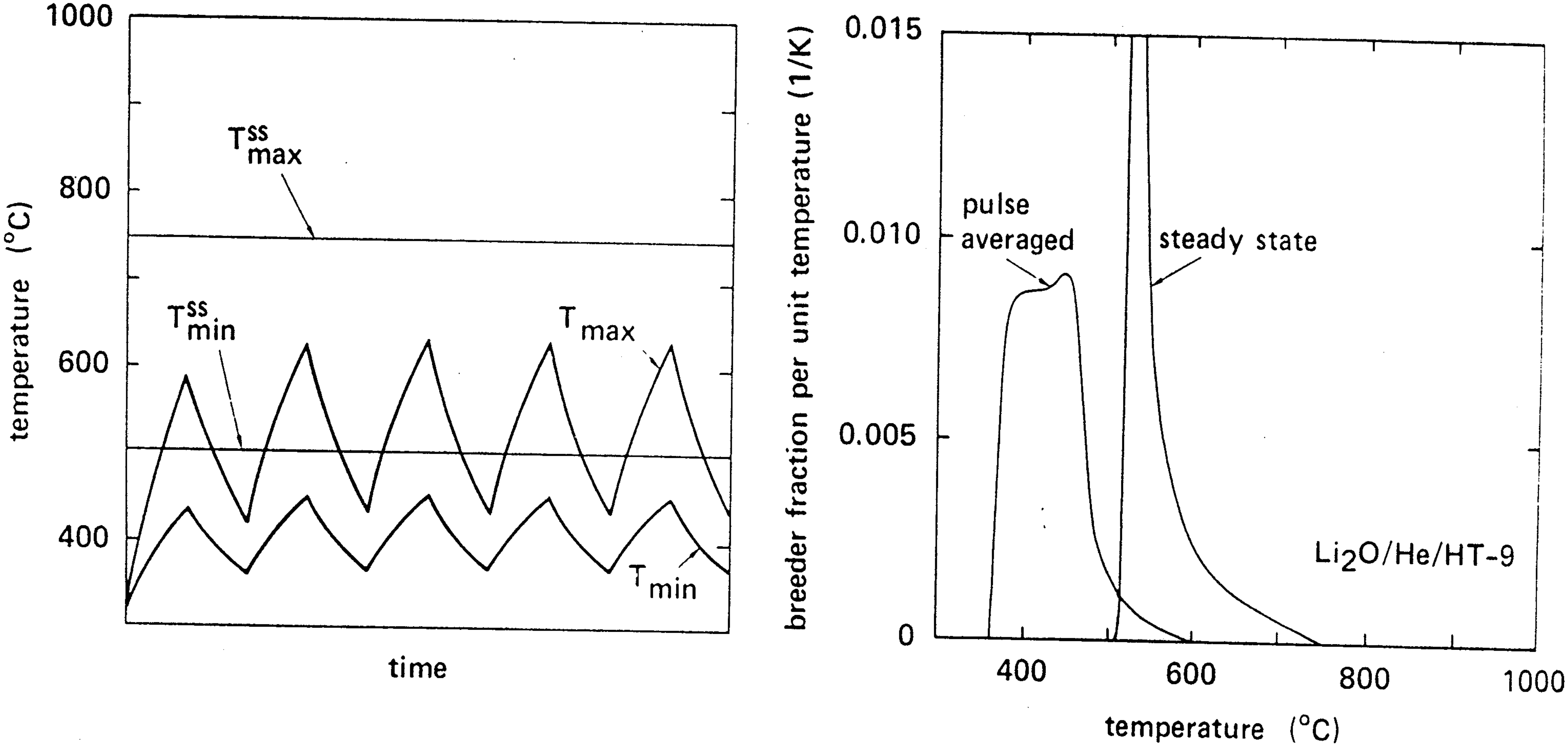
- EXAMPLES OF EFFECTS

  - THERMAL CONDITIONS
  - TRITIUM CONCENTRATION PROFILES
  - FAILURE MODES/FRACTURE METHODS
  - 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	30 s
Solid Breeder Conduction (½-cm plate)	50-100 s
(1-cm plate)	200-400 s
Coolant Bulk Temperature Rise	
Li	100 s
LiPb	1500 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
Diffusion Through SS316	
800 K	10 days
600 K	150 days
Inventory in Solid Breeder ($LiAlO_2$, 0.2 μm grains)	
67% (1 τ)	2 months
99% (3 τ)	6 months
Inventory in Liquid Breeder	
LiPb	30 minutes
Li	30 days

Pulsing strongly affects the solid breeder temperature distribution.



TRITIUM TRANSPORT MECHANISMS IN SOLID BREEDERS

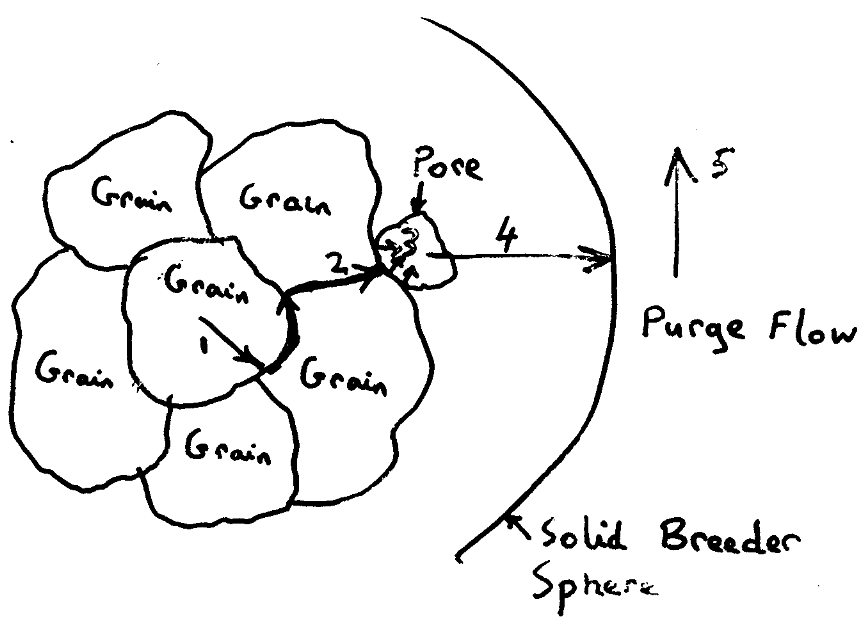
1. INTRA-GRANULAR DIFFUSION

2. GRAIN BOUNDARY DIFFUSION

3. DESORPTION TO FINE PORES

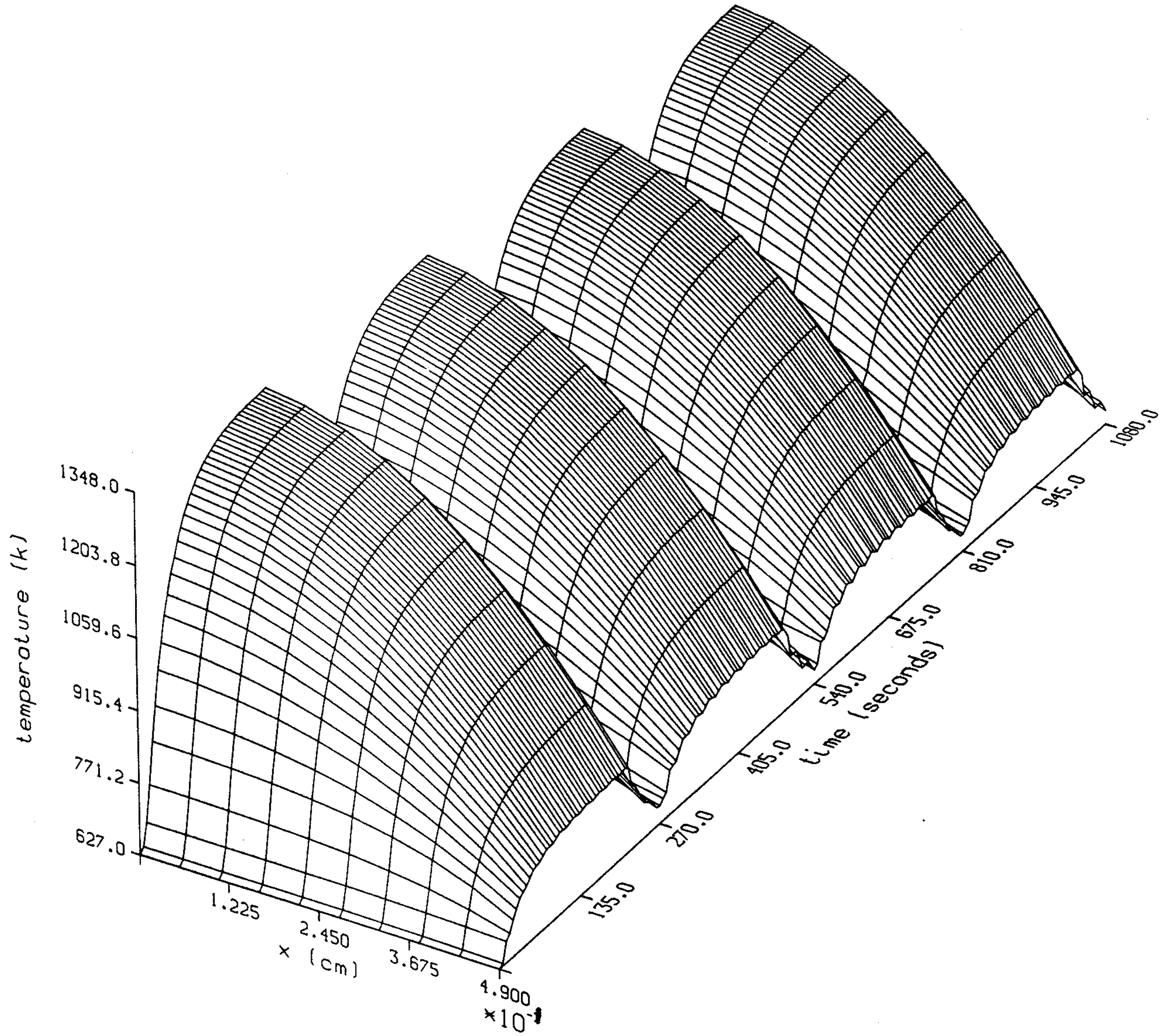
4. PORE DIFFUSION TO PURGE FLOW

5. PURGE FLOW CONVECTION

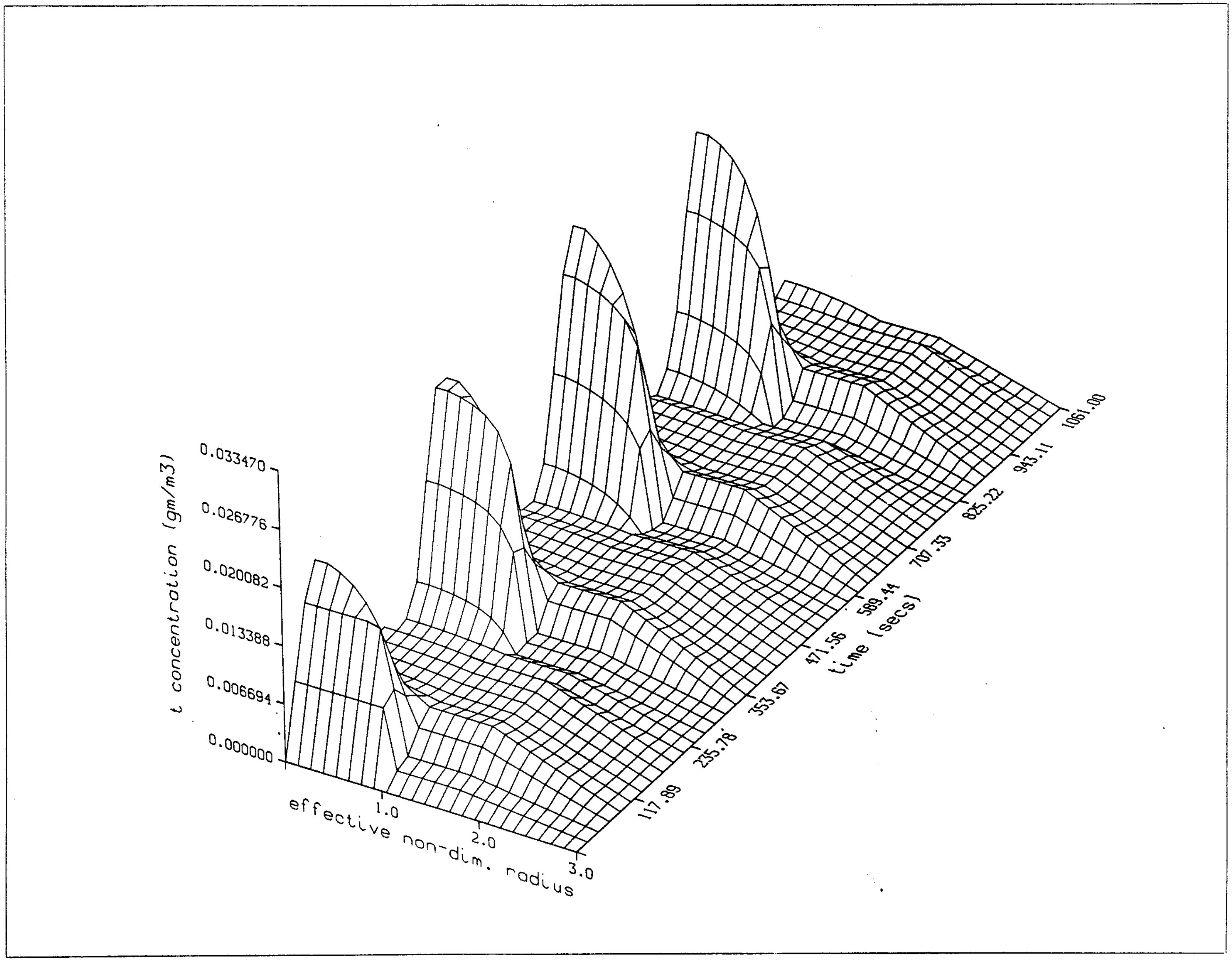


TIME-DEPENDENT TEMPERATURE DISTRIBUTION IN SOLID BREEDER PLATE

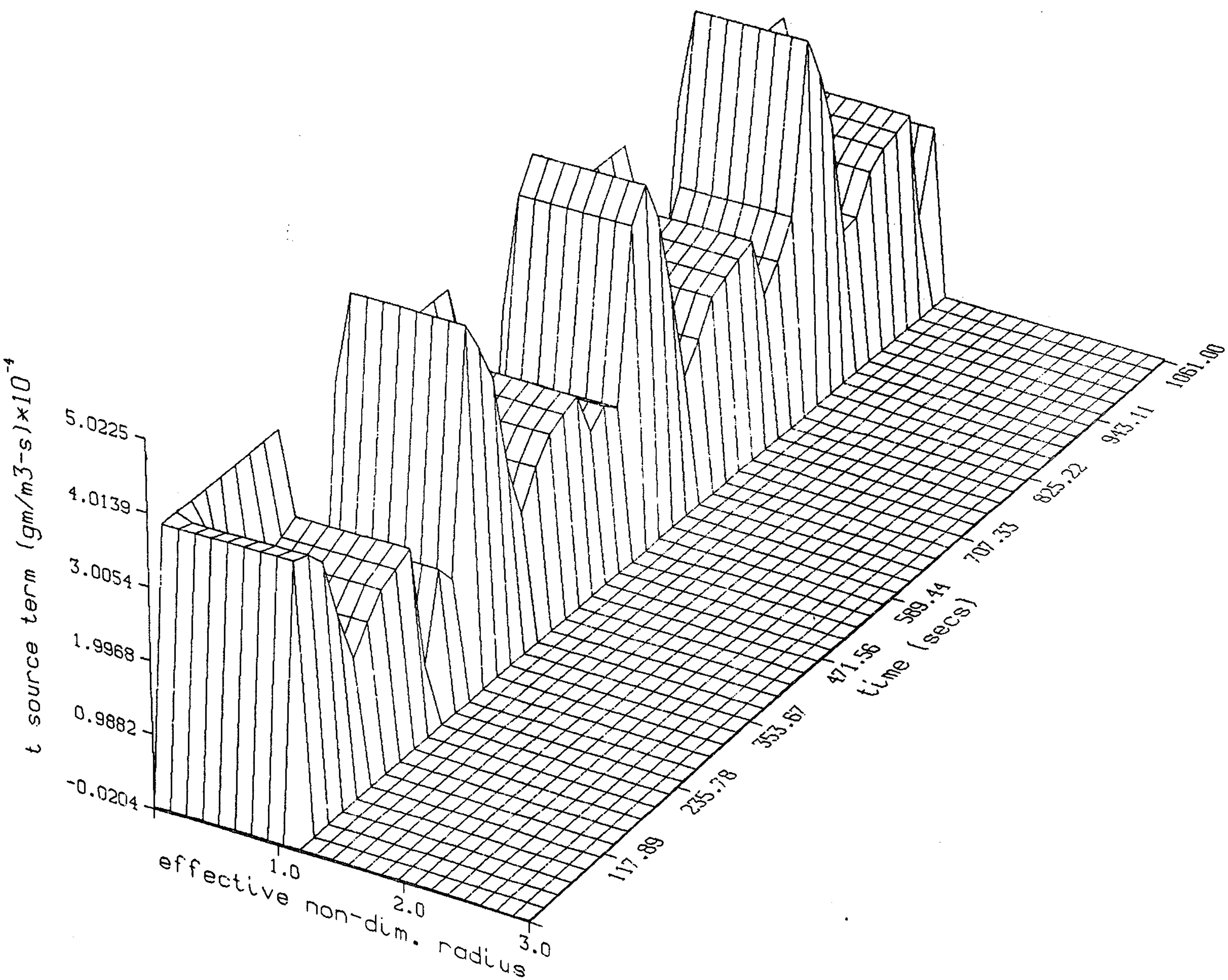
BURN TIME = 200 s; DWELL TIME = 50 s

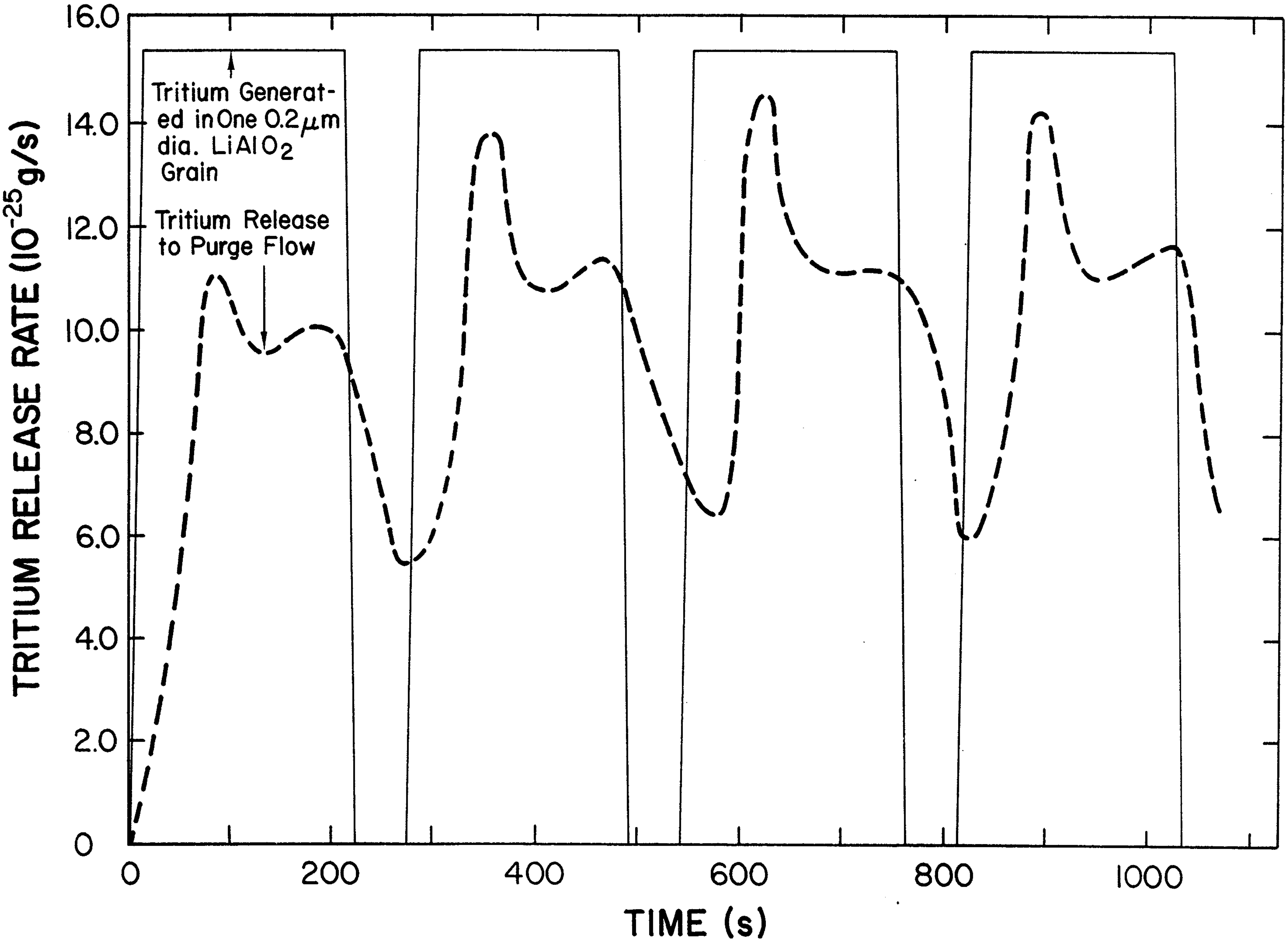


TIME-DEPENDENT TRITIUM CONCENTRATION (DIFFUSIVE) PROFILES IN GRAIN, GRAIN BOUNDARY AND PORE



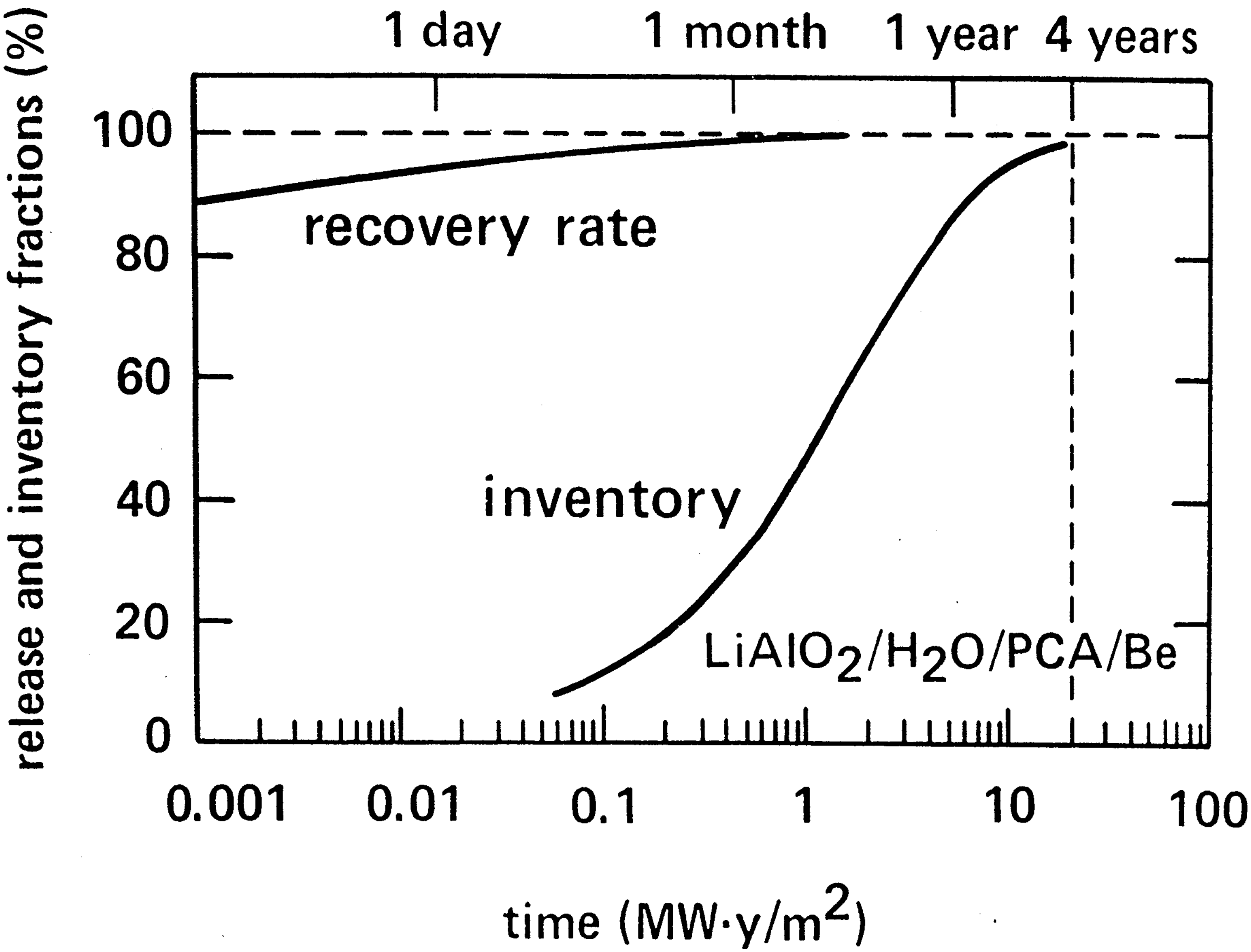
TRITIUM EFFECTIVE SOURCE TERM IN GRAIN





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

Reaching tritium inventory and recovery equilibrium may require long test times



Device Geometry and Test Volume Requirements

Several Aspects of the Device Geometry Impact Nuclear Testing:

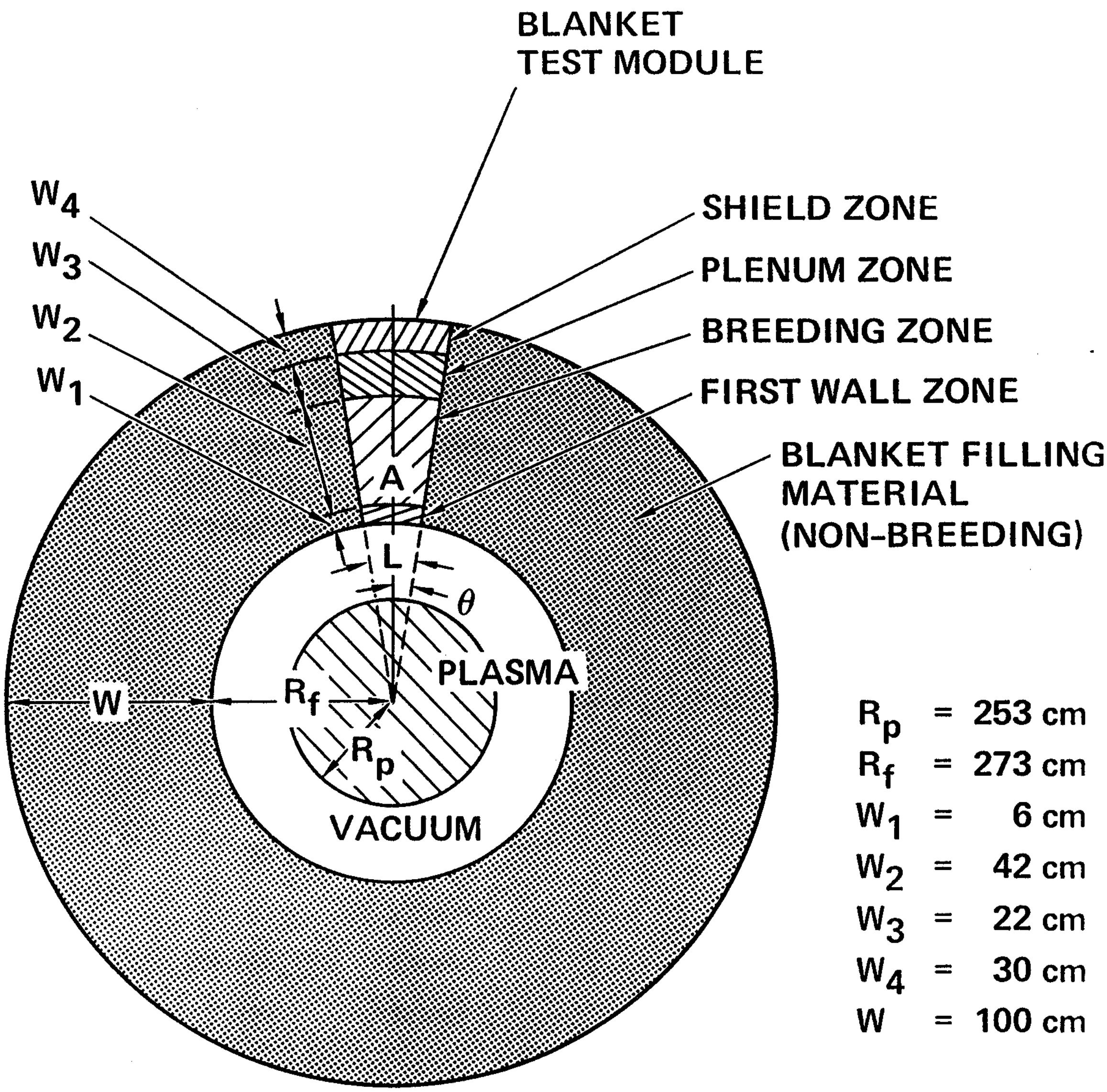
- Test Port Shape, Volume, and Surface Area Exposed to the Plasma
- Position of Test Port Relative to the Device

  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

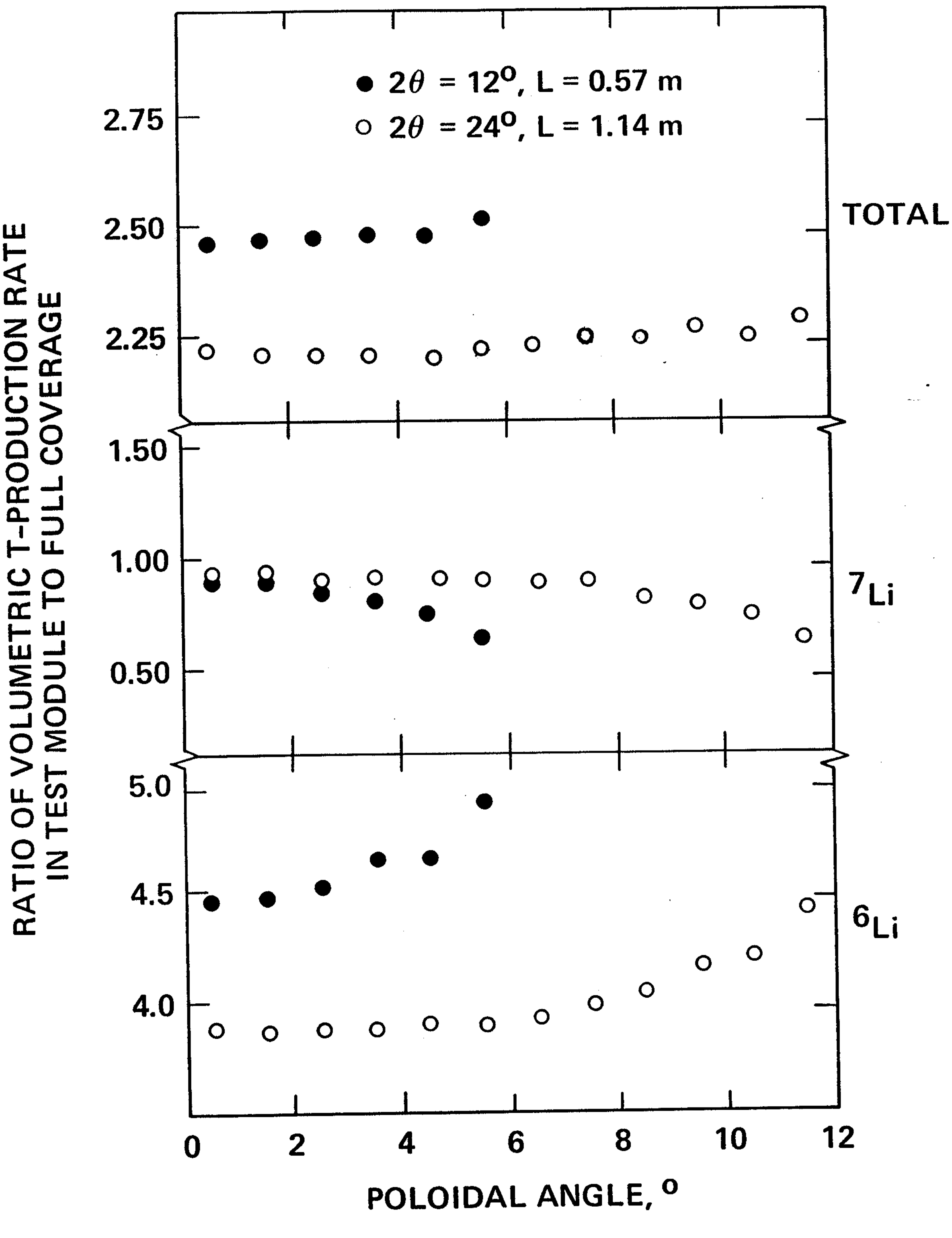
BLANKET TEST MODULE TRITIUM PRODUCTION

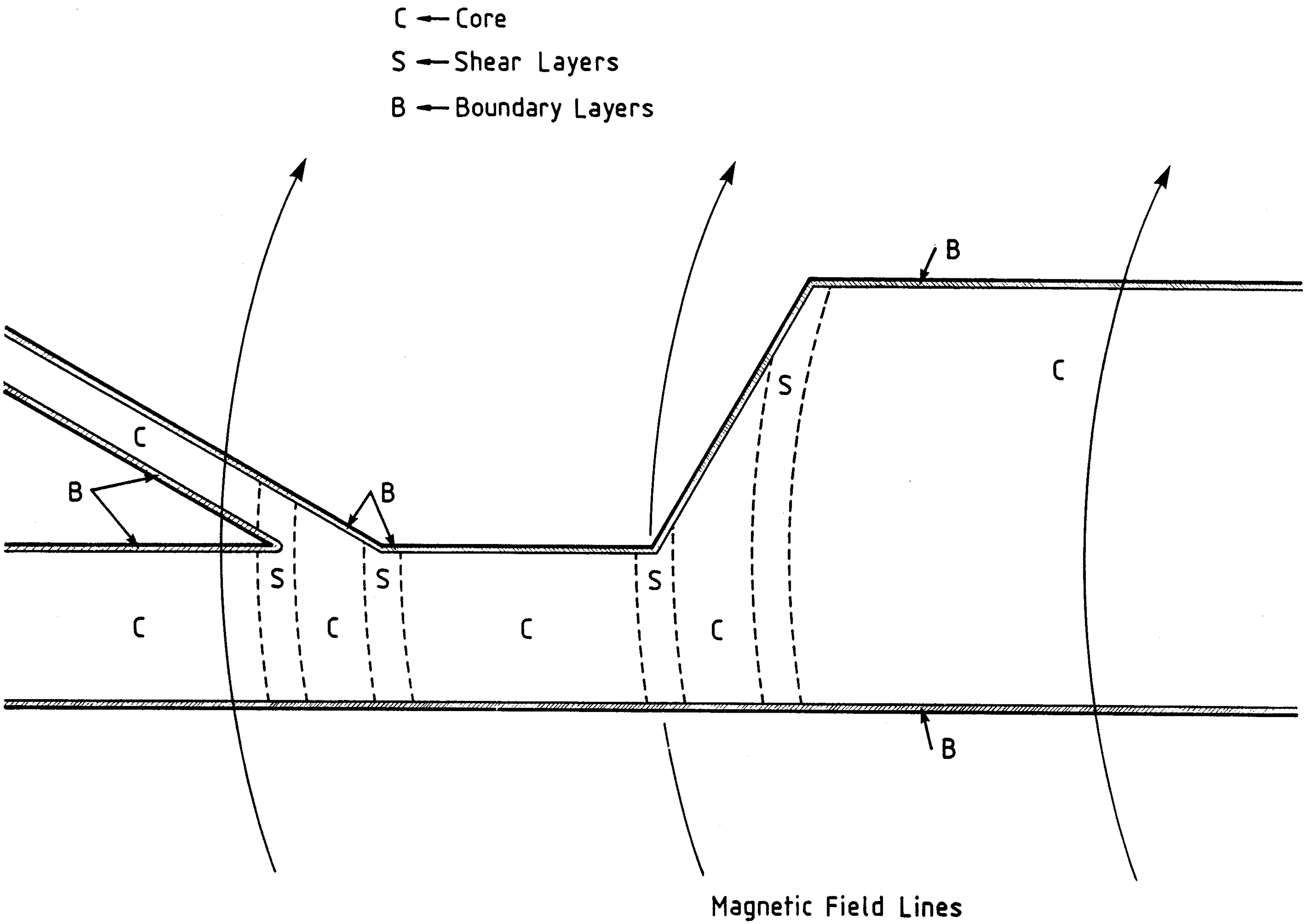


$$L = \frac{2\pi R \cdot 2\theta}{360}$$

FIRST WALL ZONE:	PCA, 6.6% DENSE, BALANCE HELIUM
BREEDING ZONE:	6% PCA, 85% Li_2O (DENSITY FACTOR 0.8) BALANCE HELIUM
PLENUM ZONE:	PCA, 10% DENSE, BALANCE HELIUM
SHIELD ZONE:	100% STAINLESS STEEL

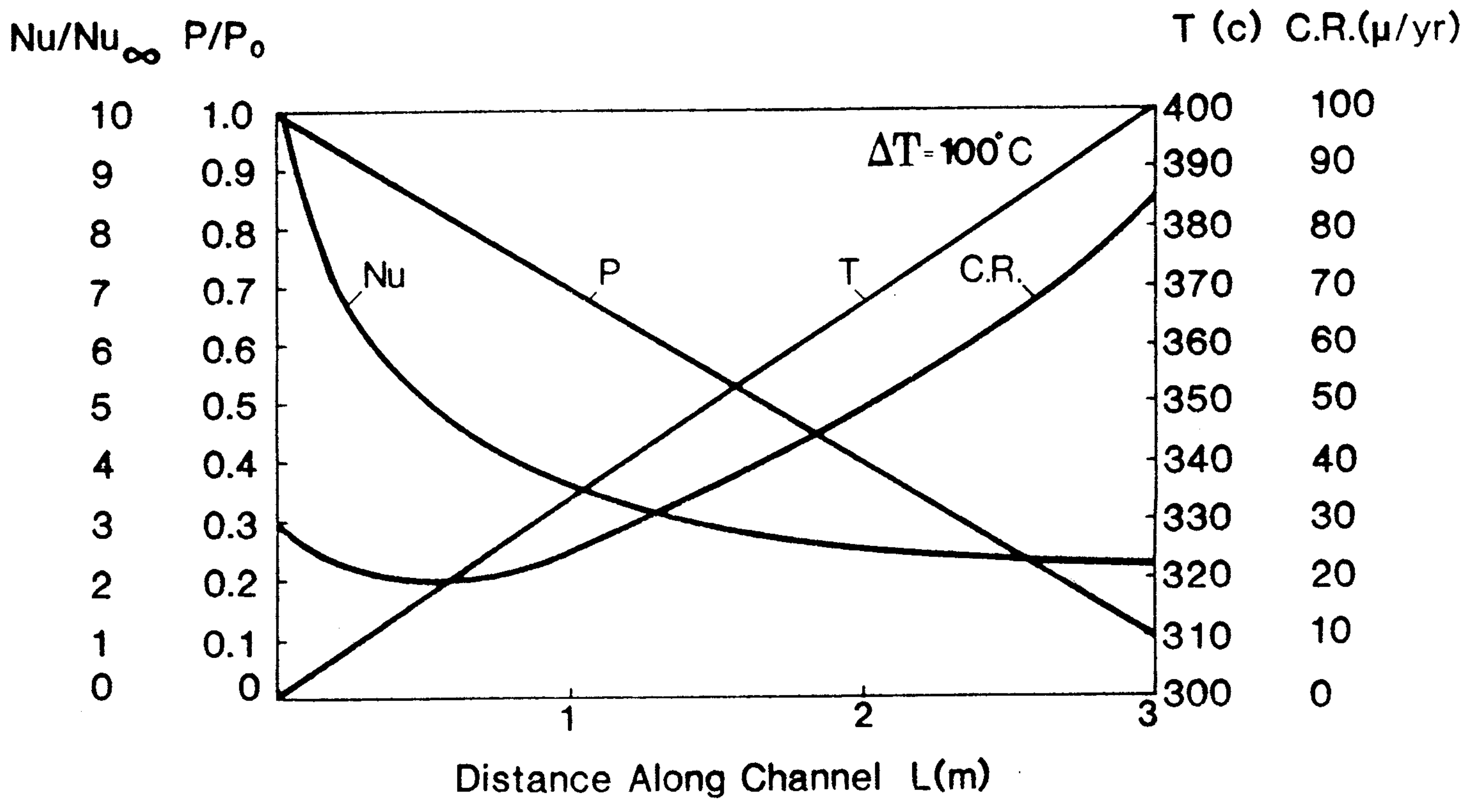
LIMITING BLANKET TEST MODULE SIZE SUBSTANTIALLY CHANGES TRITIUM PRODUCTION PROFILES





MHD EFFECTS ARE INTIMATELY CONNECTED TO GEOMETRIC DETAILS, AND REQUIRE SIMULATION OF THE FULL COMPONENT

Heat Transfer (Nu), Corrosion (C.R.) and Pressure Stresses Are Strongly Dependent on Location in Liquid Metal Blankets



Fundamental Scaling Relationships for MHD Effects

Parameter	Definition	Typical Reactor Values	
		Li	$Li_{17}Pb_{83}$
Hartmann Number	$Ha = aB\sqrt{\frac{\sigma}{\mu}}$	$6.3x10^4$	$1.6x10^4$
Reynolds Number	$Re = va\frac{\rho}{\mu}$	$6.6x10^4$	$3.1x10^5$
Interaction Parameter	$N = \frac{aB^2}{v}\frac{\sigma}{\rho}$	$6.0x10^4$	825
Magnetic Reynolds Number	$Re_m = av\ \mu_o\sigma$	0.19	0.090
Wall Conductance Ratio	$C = \frac{\sigma_w t}{\sigma a}$	0.025	0.025
Value of Parameters:	$\sigma = 3x10^6$	$0.83x10^6$	
	$\mu = 0.38x10^{-3}$	$1.5x10^{-3}$	
	$\rho = 495$	9200	

$a = 0.1$

$B = 7$

$v = 0.5$

$\sigma_w = 1.5x10^6$

$t = 0.005$

$\mu_o = 4\pi x10^{-7}$

all units mks

FNT Recommended Parameters

Parameters	ETR Minimum	ETR Desirable	Reference Reactor
Neutron Wall Load, MW/m^2 Surface Heat Load, MW/m^2	1 0.2	2 - 3 0.5	5 1
Plasma Burn Time, s	500	> 1000[A]	Steady
Magnetic Field,[B] T	3	5	7
Continuous Operating Time Availability, % Fluence,[B] $MW \cdot y/m^2$	Days 20 1 - 2	Weeks 30 - 50 3 - 6	Months 70 15 - 20
Test Port Size, $m^2 \times m$ Total Test Area, m^2	0.5 x 0.3 5	1 x 0.5 10 - 20	

[A]Steady-state preferred

[B]At test article

How Good Are Present Designs?

	Recommended			
	Minimum	Desirable	TIBER-II	NET
Neutron Wall Load, MW/m^2	1	2 - 3	2/1.3	1
Plasma Burn Time, s	500	> 1000*	Steady	600
Magnetic Field,[A] T	3	5	4.5	3.9
Availability, %	20	30 - 50	30	25
Fluence, $MW \cdot y/m^2$	1 - 2[B]	3 - 6[B]	3[C]	0.8[C]
Fusion Power, MW	< 50		300	600

[A] At outboard region
[B] At test module
[C] Device lifetime

*Steady-state preferred

Observations

- Present TIBER-II Design Reasonably Satisfies Most of the Presently Recommended FNT Values for Device Major Parameters

- From FNT Standpoint, TIBER-II is Preferable to NET in the Following Areas:

  Burn time

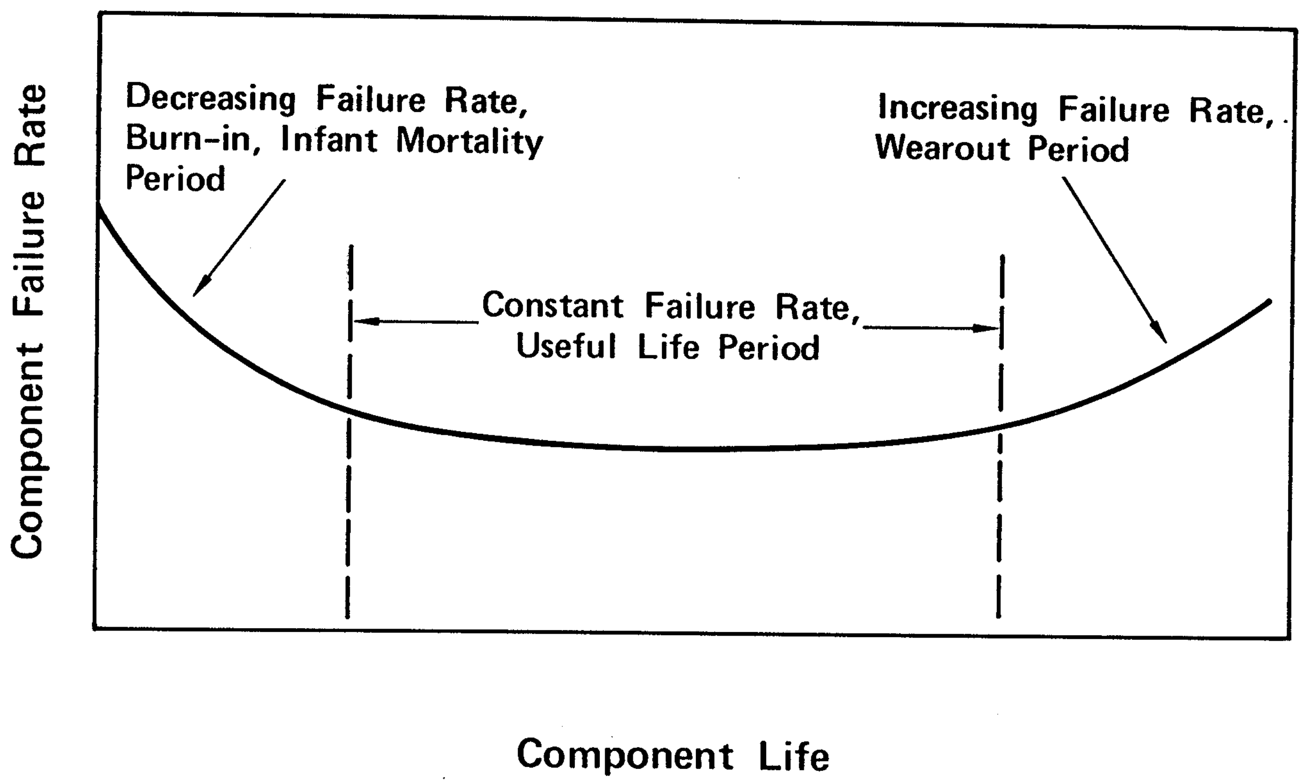
  Fluence

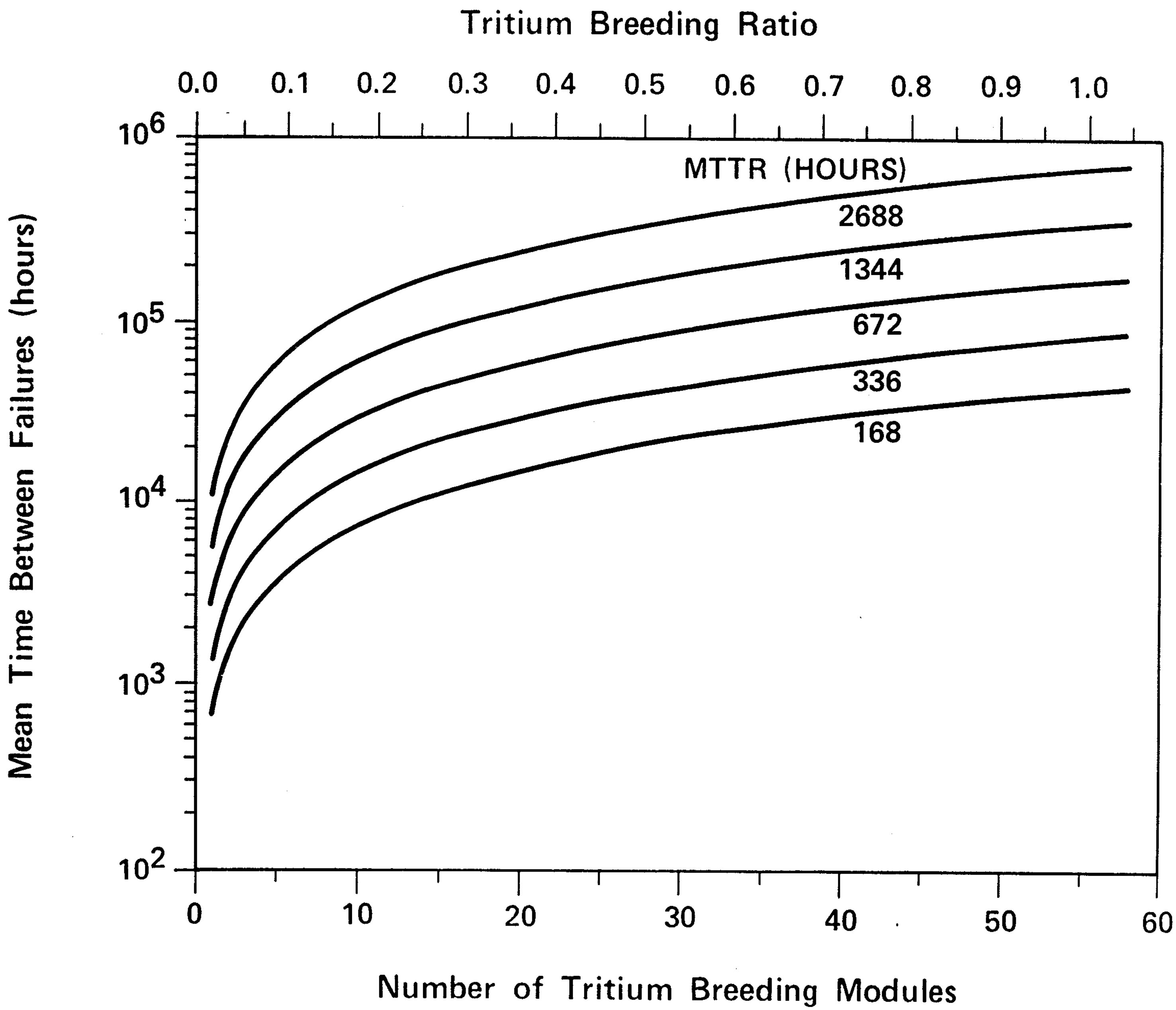
  Wall Load

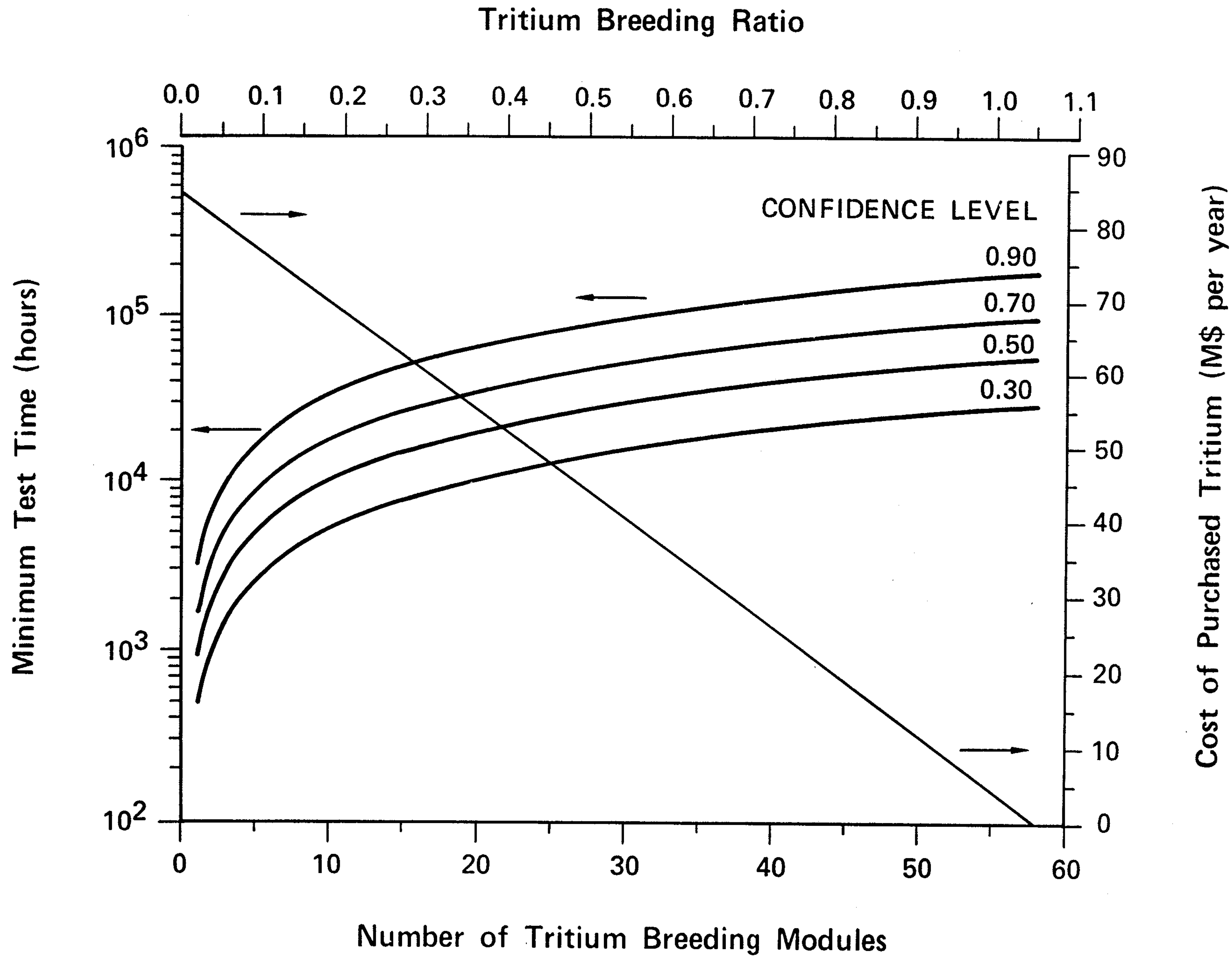
- Areas Requiring Analysis/Review and Possible Change (if necessary) in TIBER:

  - Space available for testing (area at first wall adequate) depth; accommodation of manifolds, feed lines, etc.

  - Ease of insertion, replacement


Component Failure Rate
Decreasing Failure Rate,
Burn-in, Infant Mortality
Period
Increasing Failure Rate,
Wearout Period
Constant Failure Rate,
Useful Life Period
Component Life


Tritium Breeding Ratio
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
MTTR (HOURS)
2688
1344
672
336
168
Mean Time Between Failures (hours)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
Number of Tritium Breeding Modules



Tritium Breeding Ratio
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
CONFIDENCE LEVEL
0.90
0.70
0.50
0.30
Minimum Test Time (hours)
10^6
10^5
10^4
10^3
10^2
Cost of Purchased Tritium (M$ per year)
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Number of Tritium Breeding Modules