NUCLEAR TESTING REQUIREMENTS FOR FUSION ENGINEERING TESTING FACILITY:

TIME-RELATED PARAMETERS

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Role of Non-Fusion Testing (+ Model Development) in FNT Development

Non-Neutron Test Stands
Fission Reactors
14 MeV Neutron Sources

- Support Conceptual Design Screening

- Initial Validation of Theory and Models

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

- Demonstrate Adequate Level of Reliability

Role of Next Fusion Facility in Nuclear Technology Development

- Data to Verify Theory/Models, Design Codes

- Data for Concept Selection, Verification

- Demonstrate Performance level Extrapolatable to Reactor Conditions

- Demonstrate Adequate Level of Reliability of FNT Components

<u>FUSION TEST MATRIX</u>

<u>Specimen</u>

Material Behavior, Properties

<u>Element</u>

Specific Issues in the Fusion Environment
(e.g., liquid metal bulk heating)
Sub-Scale Interactive Effects (swelling/creep, etc.)

<u>Sub-Module</u>

Several Elements
Class of Issues
Interaction Among Elements

<u>Module</u>

Integrated Component Behavior
Boundary Conditions May Not Be Prototypic

<u>Sector</u> (all modules in a toroidal segment)

Interactions Among Modules
Proper Poloidal Boundary Conditions
More Prototypic Configuration/Maintenance

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

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]
<u>Specimen</u>		
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
<u>Element</u>		
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
<u>Submodule</u>		
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
<u>Module</u>		
Verification of neutronic predictions	50 x 50 x 100	4
- Tritium breeding, nuclear heating during operation, and induced activation		
Full module verification	LB[c]: 100 x 100 x 50	5
- Thermal and corrosion	SB: 100 x 100 x 50	5
- Module thermomechanical lifetime		
- Tritium recovery		
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
<u>Sector</u>		
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 <u>not</u> included in the number of test articles.

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

[c]Some designs require larger test volume.

MAJOR PARAMETERS

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

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"

Time-Related Parameters

- Fluence

- Plasma Burn Time, Dwell Time (Duty Cycle)

  Steady State?

- Minimum Continuous Operating Time

  (100% availability)

Note

- Time-related parameters have large impact on the device design, cost, required R&D and usefulness of testing information

- Area of largest difference among NET, FER and TIBER

Neutron Fluence

- Higher Fluence is Costly
  - Device Availability (Reliability)
  - Tritium Supply

- Higher Fluence is Very Beneficial
  - Many interactive effects will occur at higher fluence
  - True concept verification for components requires fusion testing data on these interactive effects
  - (Note: While "end-of-life" material irradiation is very useful, it is assumed to be beyond the capability of ETR)

Device Life Vs. Test Module Fluence

- Fluence achievable at test module $(\phi t)_m$

- Test facility "lifetime fluence" $(\phi t)_f$

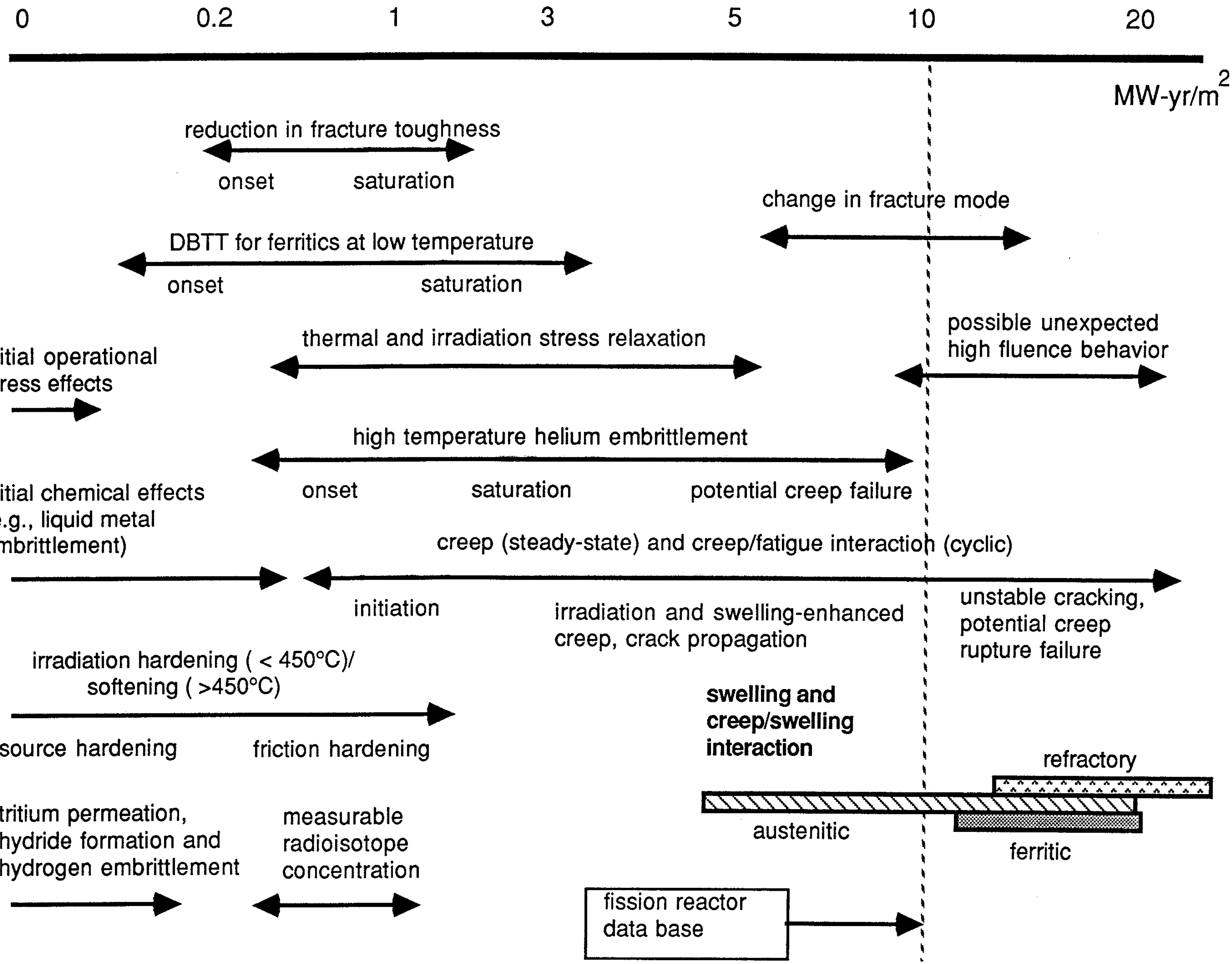
$(\phi t)_f > 2(\phi t)_m$ in general

- 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")

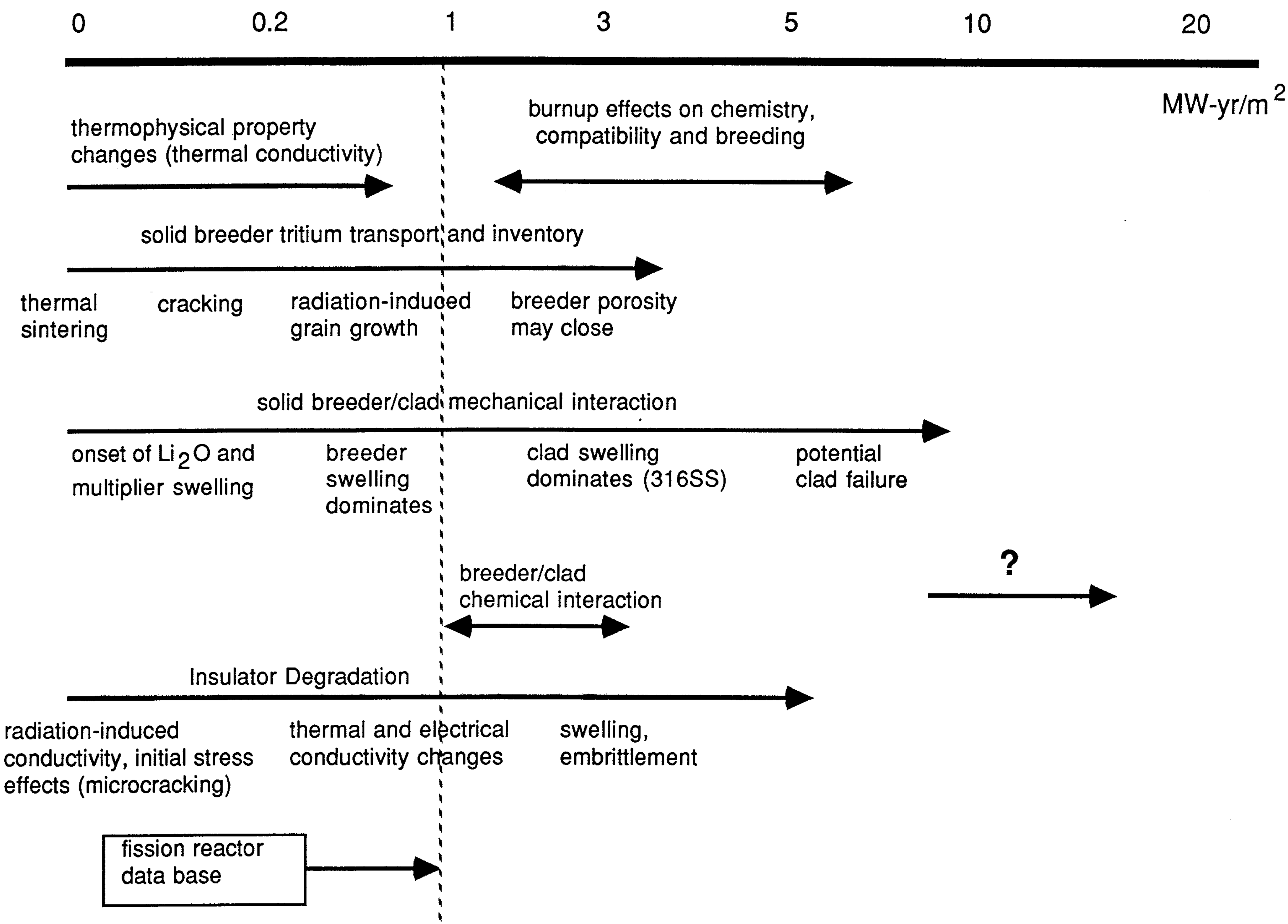
- There is inevitably a long period of fail/replace/fix for test module (remember: first time to test in fusion environment)

- Time for concept selection testing prior to concept verification testing

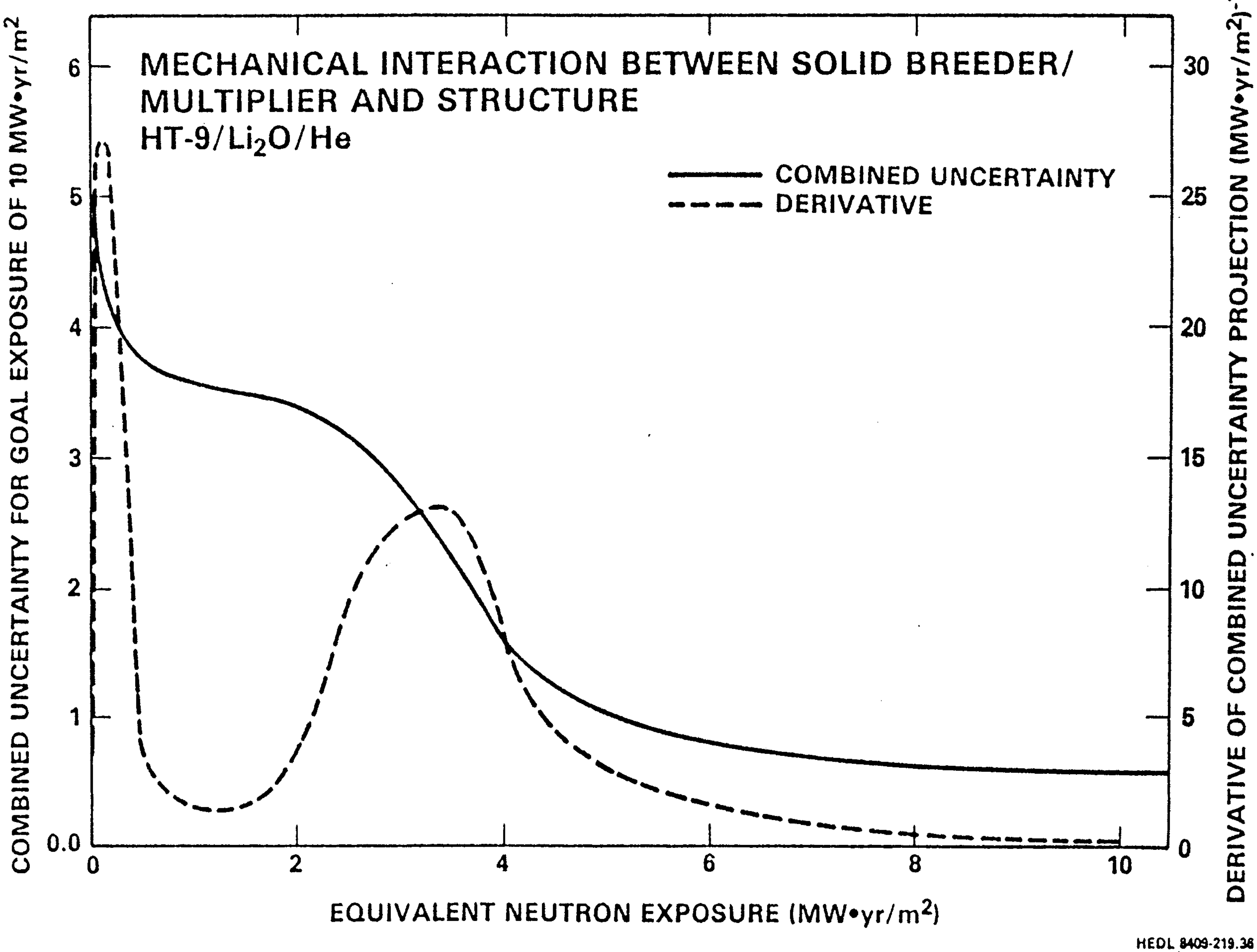
Fluence-Related Effects in Blanket Structural Materials



Fluence-Related Effects in Solid Breeders and Other Ceramics



EXAMPLE OF BENEFIT Vs. FLUENCE



Fluence Recommendations

Concept Verification Requires "Moderately High" Fluence

At Test Module > 3 MW · y/m^2

(Device life: ~ 6 MW · y/m^2)

Examples of Key FNT Issues

- Mechanical Interactions
  e.g., Solid Breeder/Clad Interactions
- Tritium Inventory in Solid Breeders
- Burnup Effects on Chemistry, Compatibility and Breeding
- Corrosion/Redeposition
- Failure Modes, Rates

(Can not wait for DEMO: DEMO needs to operate reliably and safely. Reliability growth is the key in DEMO)

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

Effects of Pulsed Plasma Operation on Nuclear Technology Testing

- 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

Length of Burn Time?

Length of Dwell Time?

<u>Response (e.g., Temperature)</u>:

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

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

τ = characteristic Time Constant

<u>Allowable Variation</u> (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

<u>**Guidelines**</u>
burn time $> 3\ \tau$
dwell time $< 0.05\ \tau$

Note: Doubling or tripling the allowable variation will <u>not</u> 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 (1/2-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

	Time Constants
	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

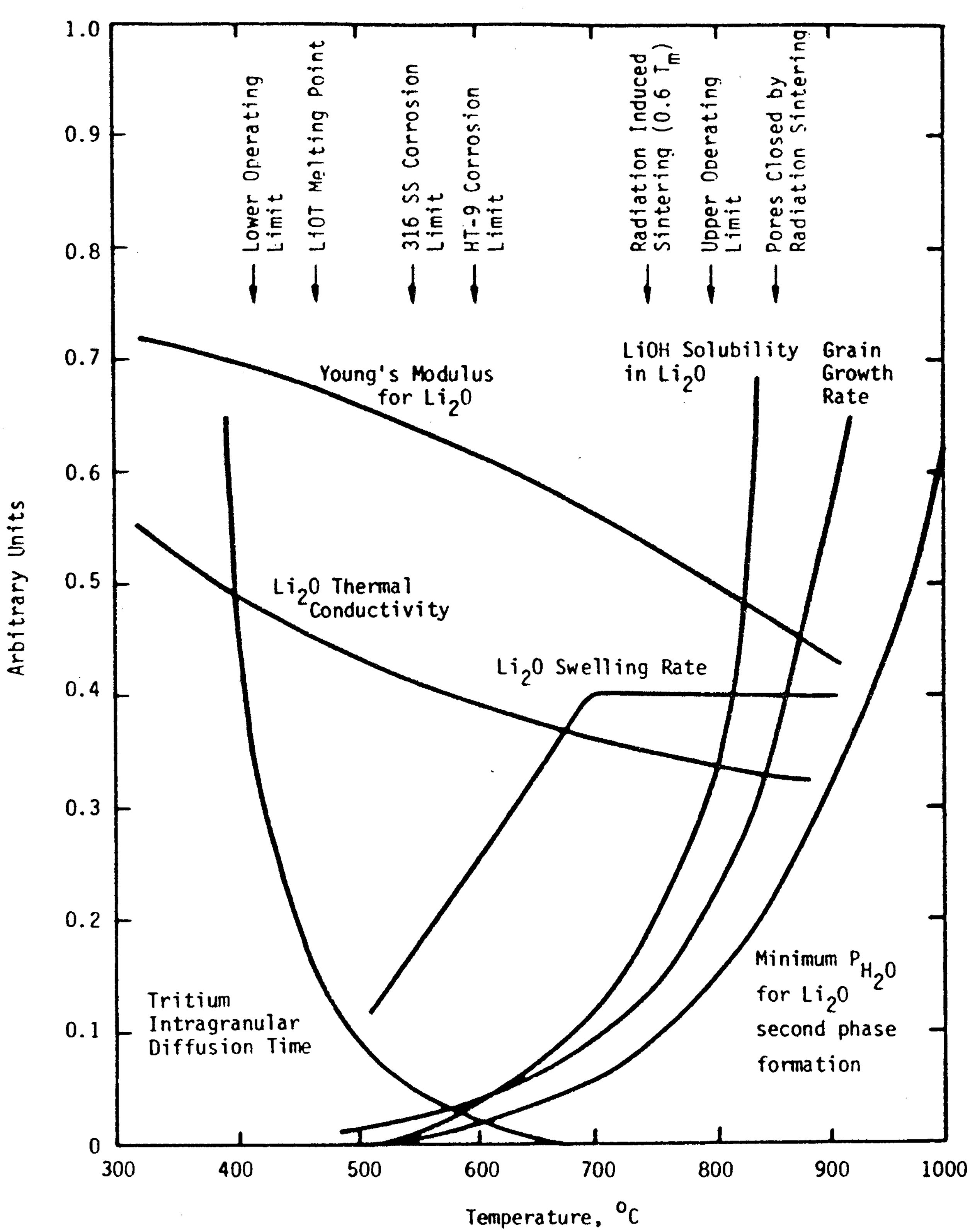
Fast Changes (e.g.)

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

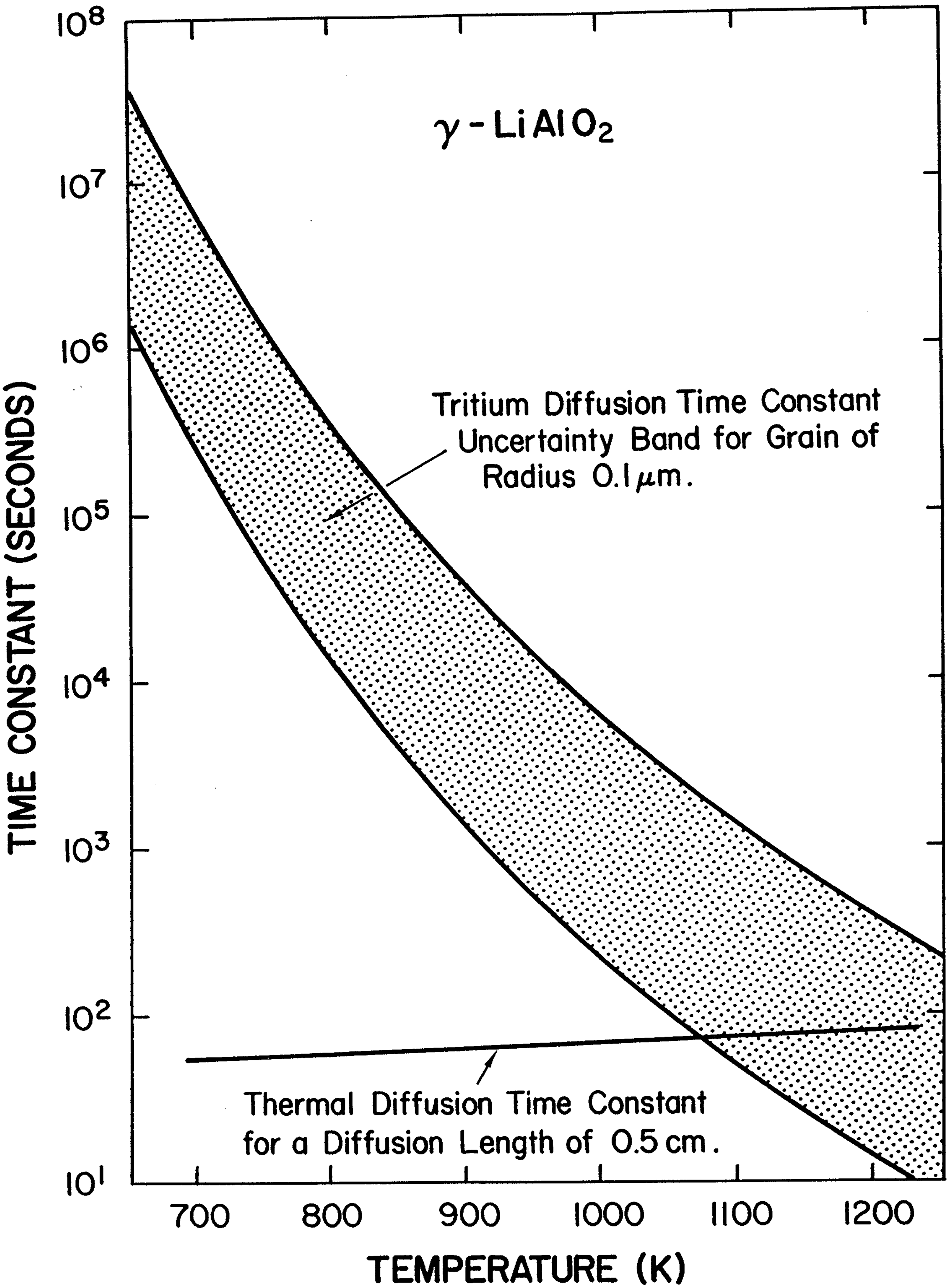
Impact on Processes with Long Time Constants (e.g.)

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

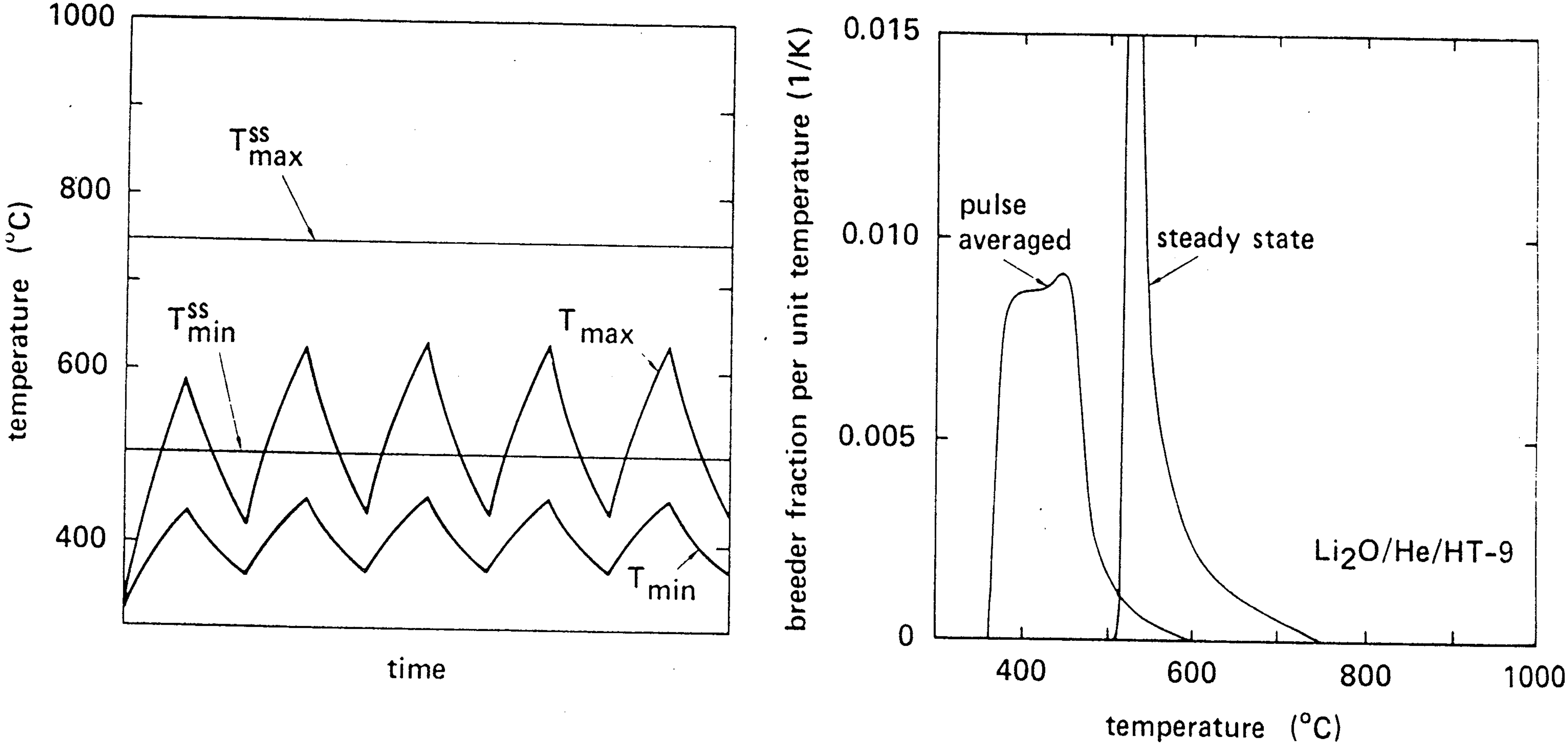
- Plasma Dwell Time Should be Near Zero
- Dwell Time of 5 s Results in Too Large Changes in Temperature-Dependent Processes



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


γ - 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)
TEMPERATURE (K)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
700
800
900
1000
1100
1200

Pulsing strongly affects the solid breeder temperature distribution.



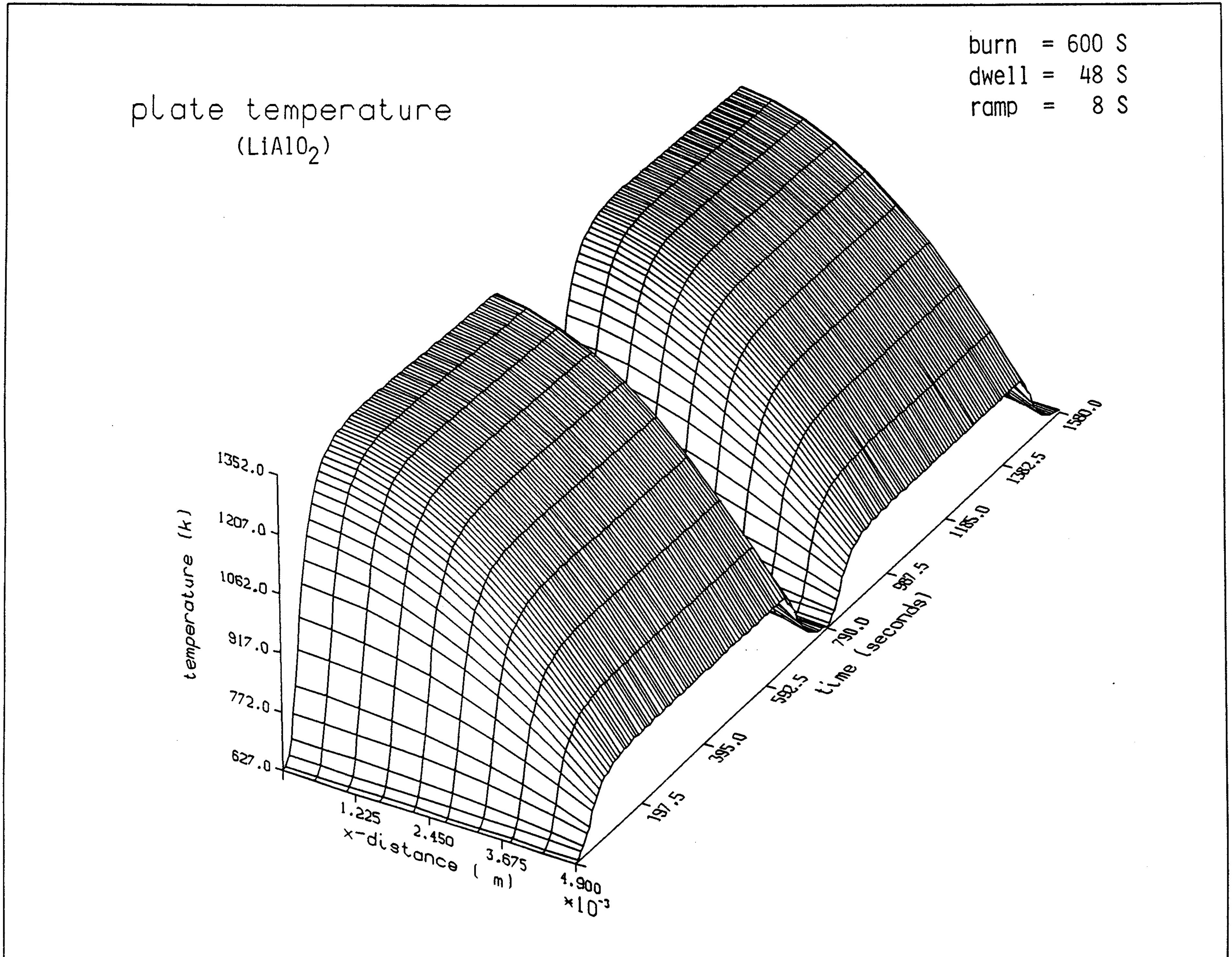


plate temperature
(LiAlO2)
burn = 600 S
dwell = 48 S
ramp = 8 S
temperature (k)
1352.0
1207.0
1062.0
917.0
772.0
627.0
1.225
2.450
3.675
4.900
x-distance (m)
×10⁻³
197.5
395.0
592.5
790.0
987.5
1185.0
1382.5
1580.0
time (seconds)

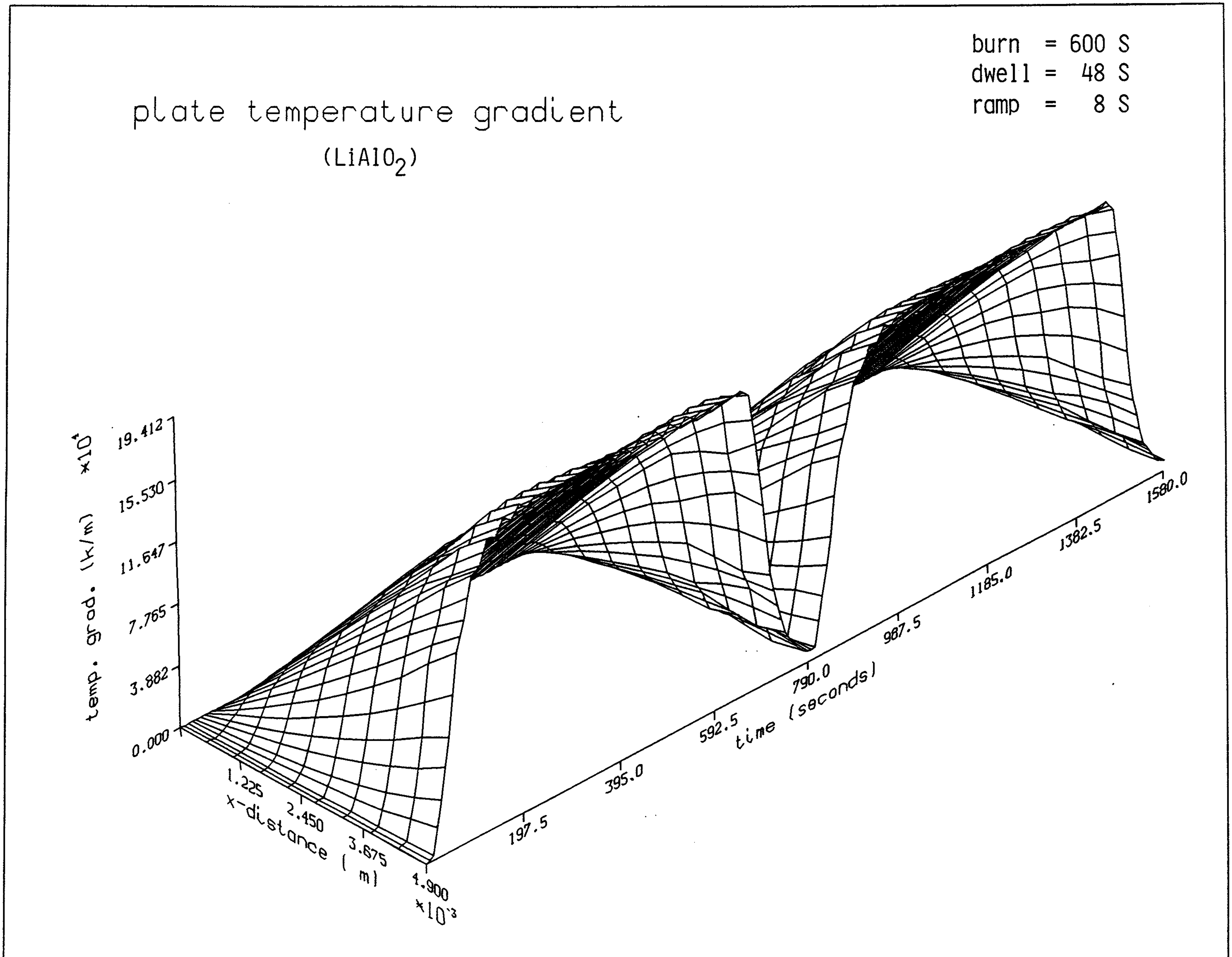
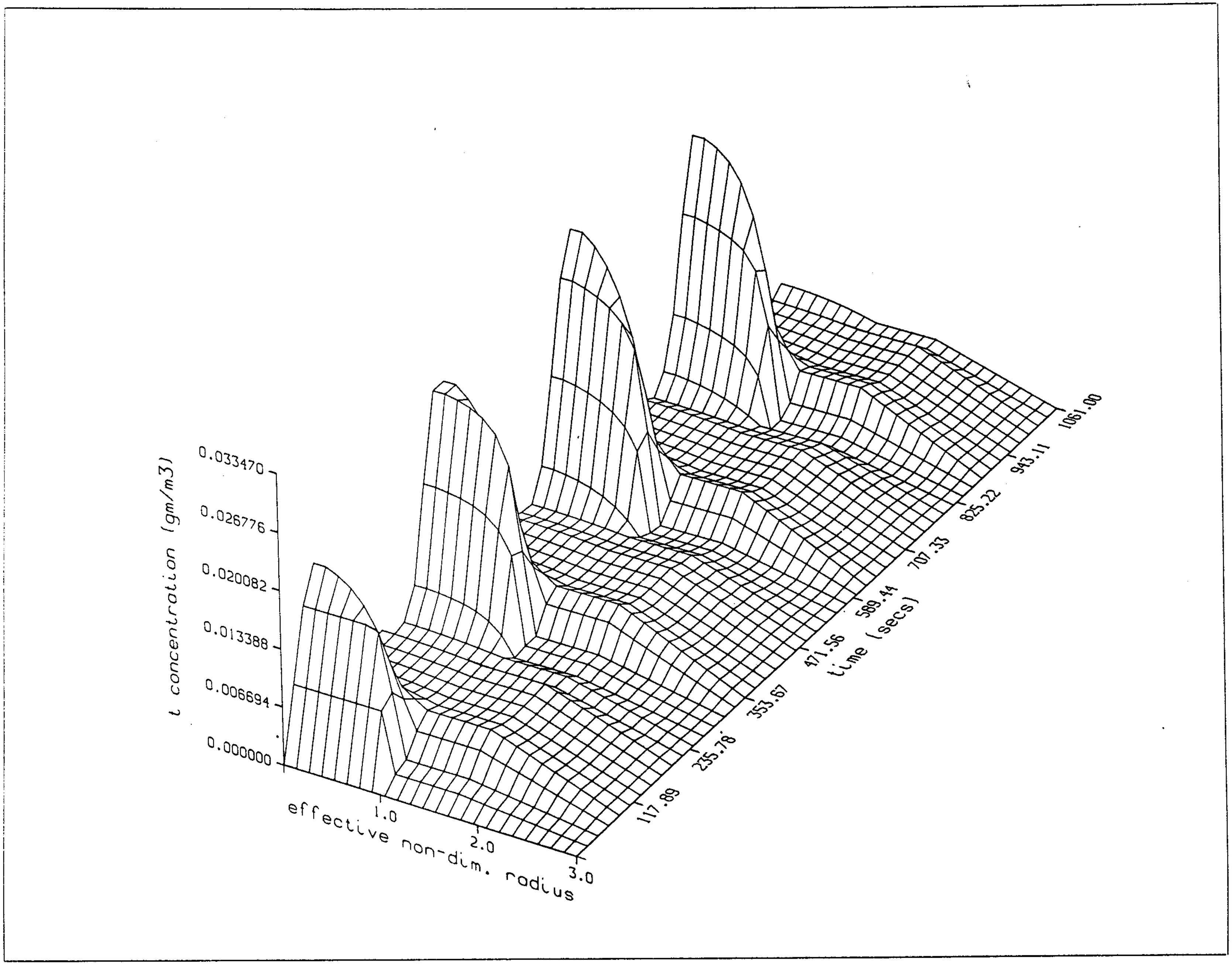
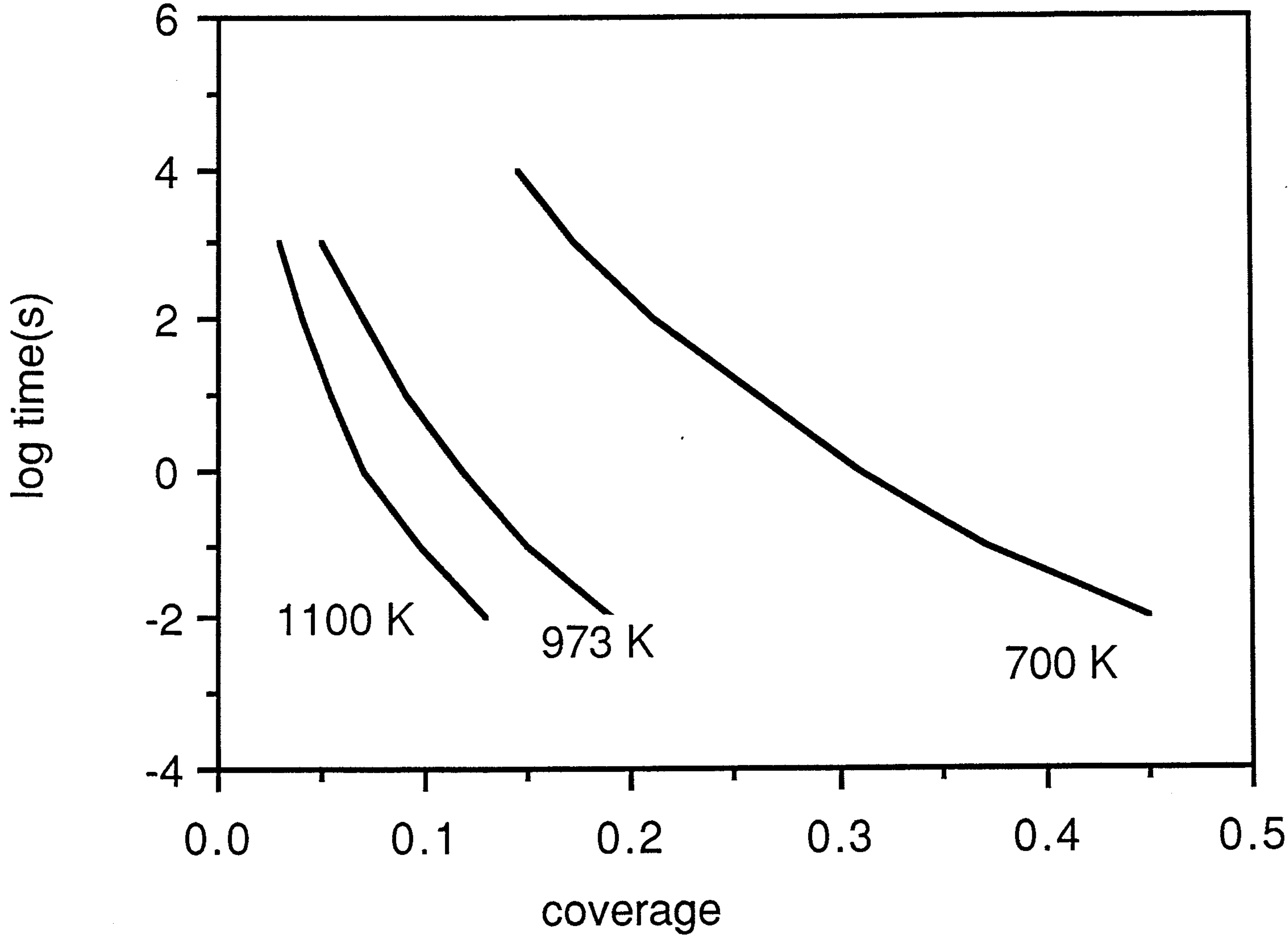


plate temperature gradient
($LiAlO_2$)
burn = 600 S
dwell = 48 S
ramp = 8 S
temp. grad. (k/m) ×10⁴
19.412
15.530
11.647
7.765
3.882
0.000
x-distance (m)
1.225
2.450
3.675
4.900
×10⁻³
time (seconds)
197.5
395.0
592.5
790.0
987.5
1185.0
1382.5
1580.0

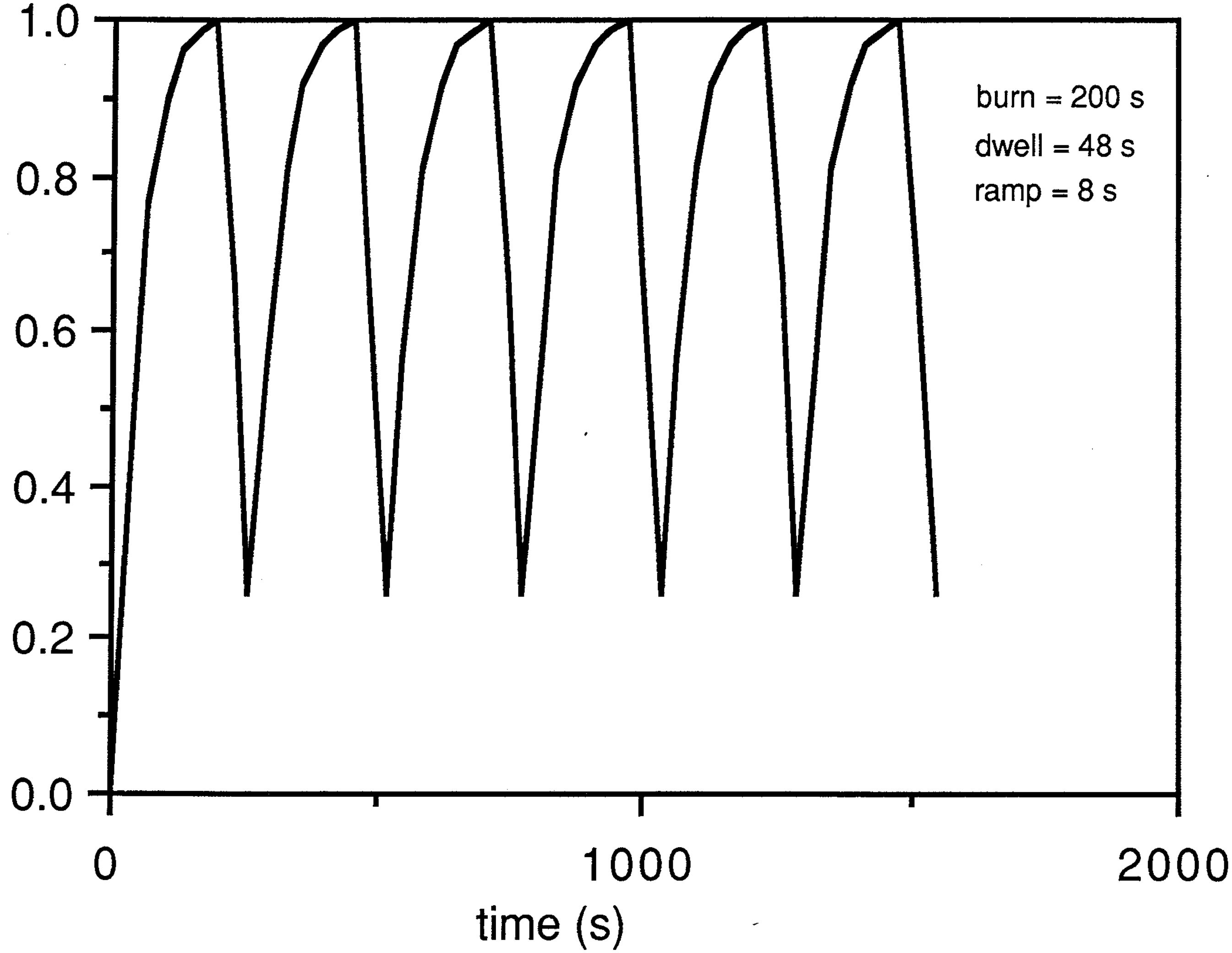
TIME-DEPENDENT TRITIUM CONCENTRATION (DIFFUSIVE) PROFILES
IN GRAIN, GRAIN BOUNDARY AND PORE



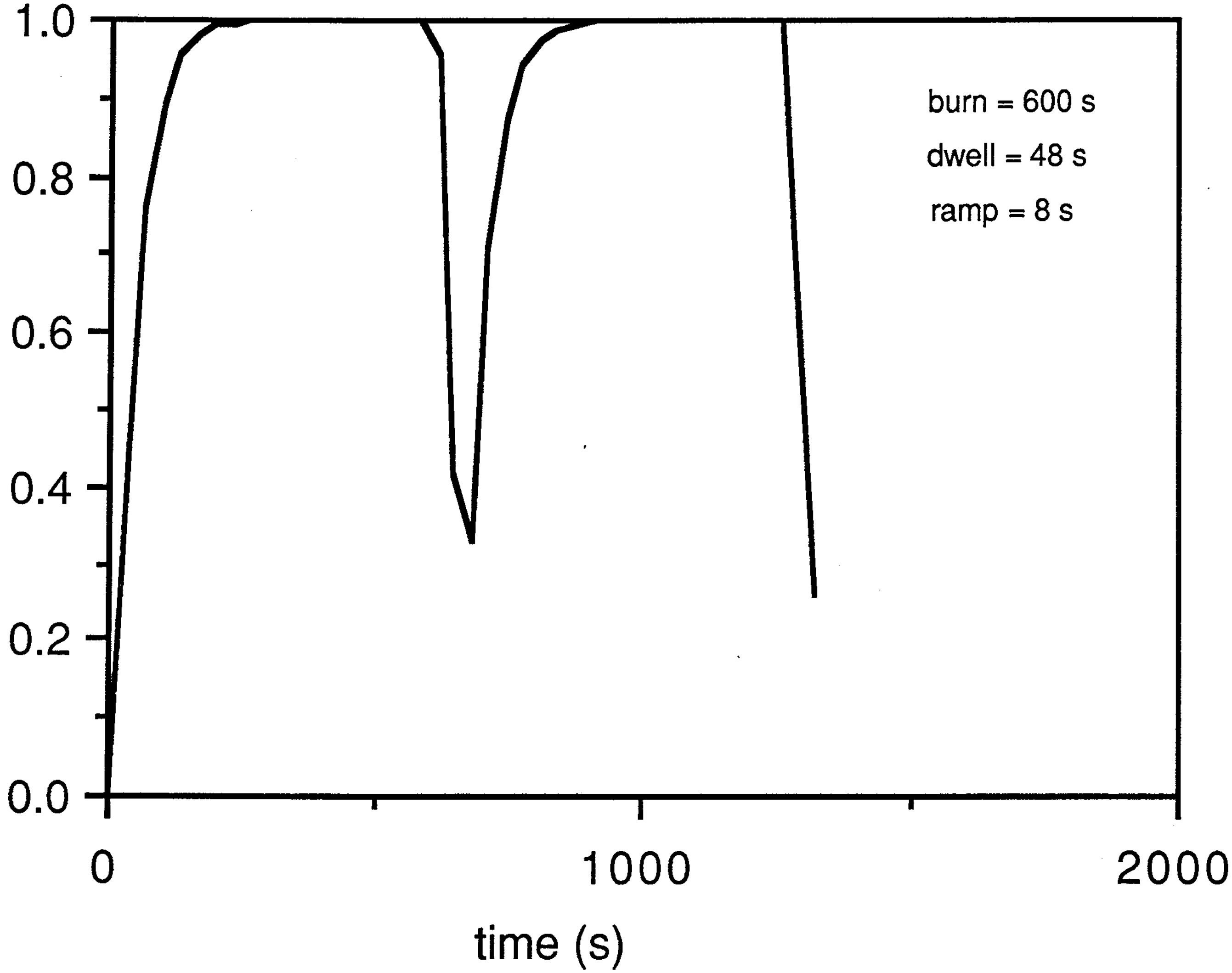
ESTIMATED H2O DESORPTION TIME FROM AL2O3 AS A FUNCTION OF COVERAGE AND TEMPERATURE



TYPICAL SOLID BREEDER NON-DIMENSIONAL TEMPERATURE AND TEMPERATURE GRADIENT VARIATION WITH TIME



TYPICAL SOLID BREEDER NON-DIMENSIONAL TEMPERATURE AND TEMPERATURE GRADIENT VARIATION WITH TIME



<u>Suggestions</u>

As Design *<u>Basis</u>* for the *<u>Nuclear</u>* Testing *<u>Phase</u>* in ITER

1. Steady State Plasma Operation
2. Test Module Fluence > 3 MW · y/m^2
   (i.e., Device Lifetime ~ 6 MW · y/m^2)

<u>Note</u>:

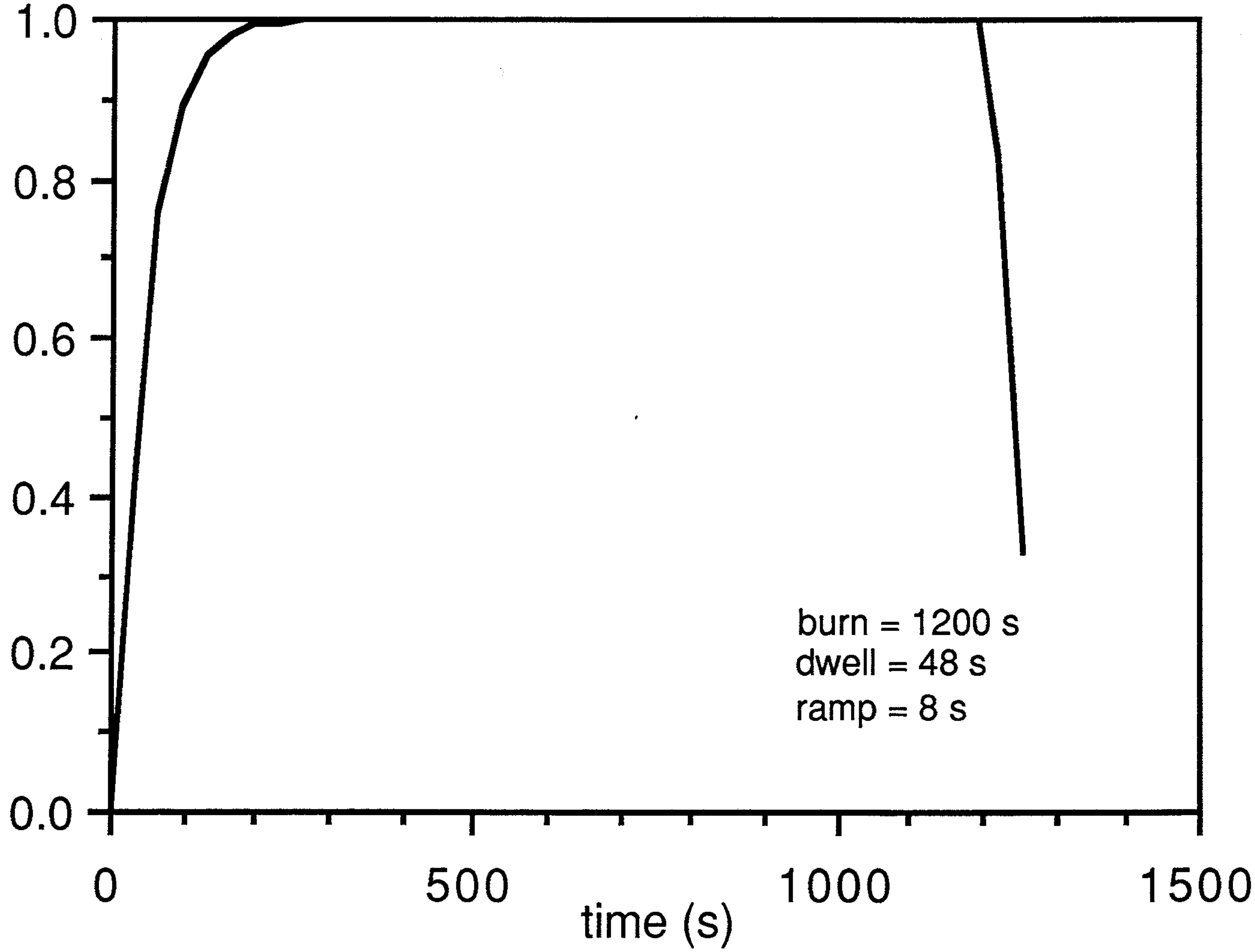
From Nuclear Testing Standpoint, Presently Quantifiable Specifications for Pulse Times are:

Dwell time: < 1 s
(key: temperature)

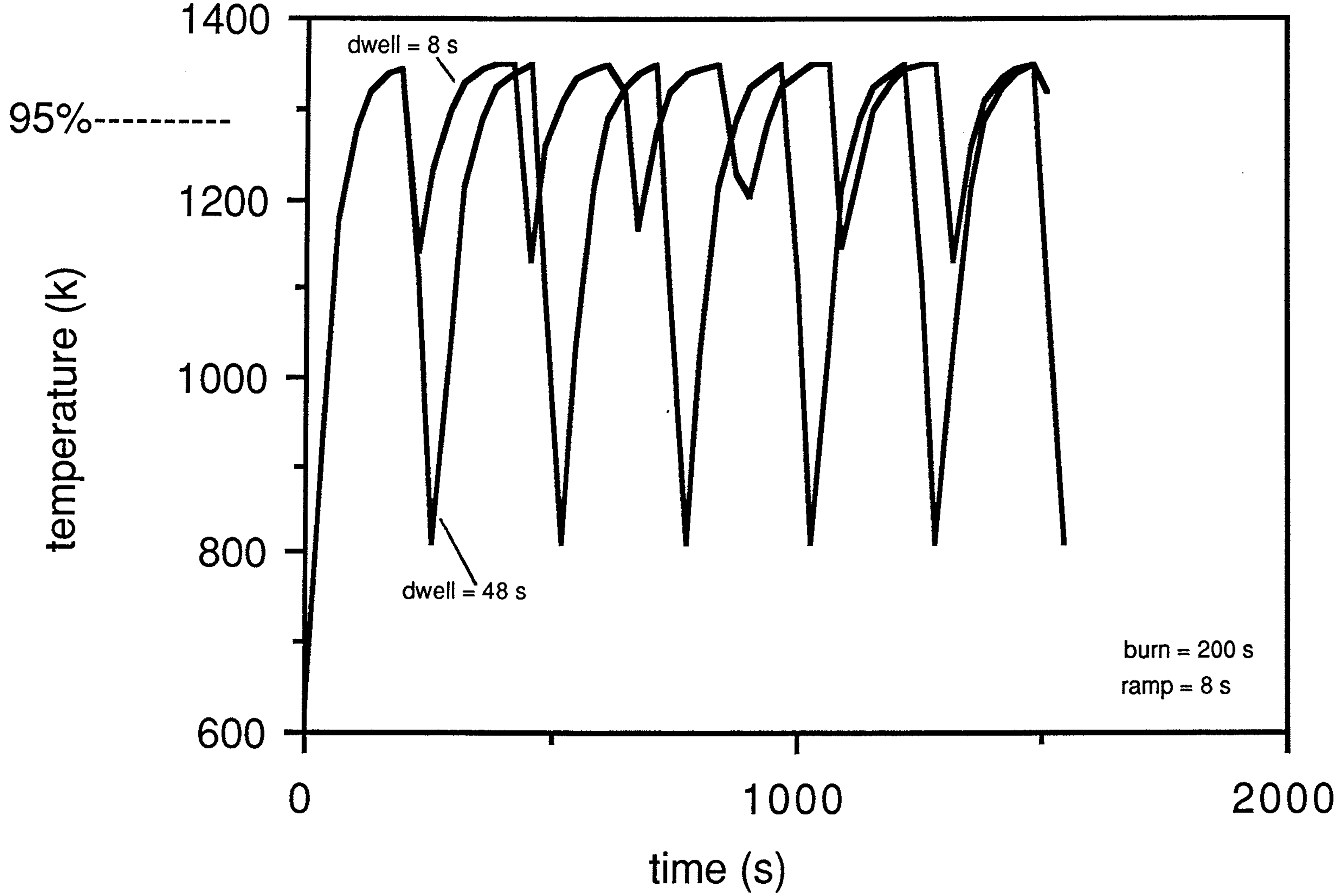
Burn time: > 1 month
(key: e.g., tritium recovery from SB)

This is equivalent to steady state

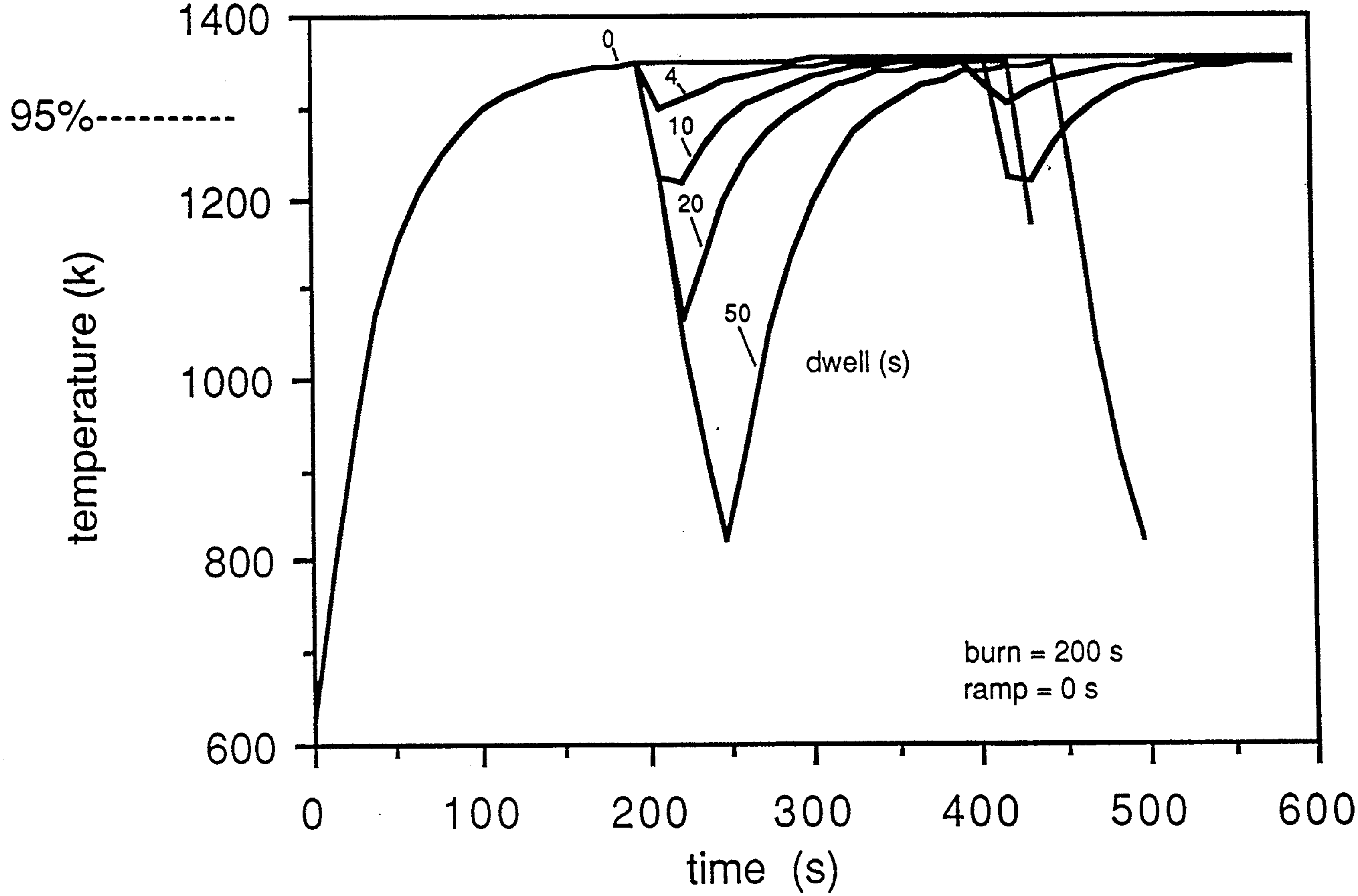
TYPICAL VARIATION OF TEMPERATURE AND TEMPERATURE GRADIENT (NON-DIMENSIONAL) WITH TIME (LIALO2)



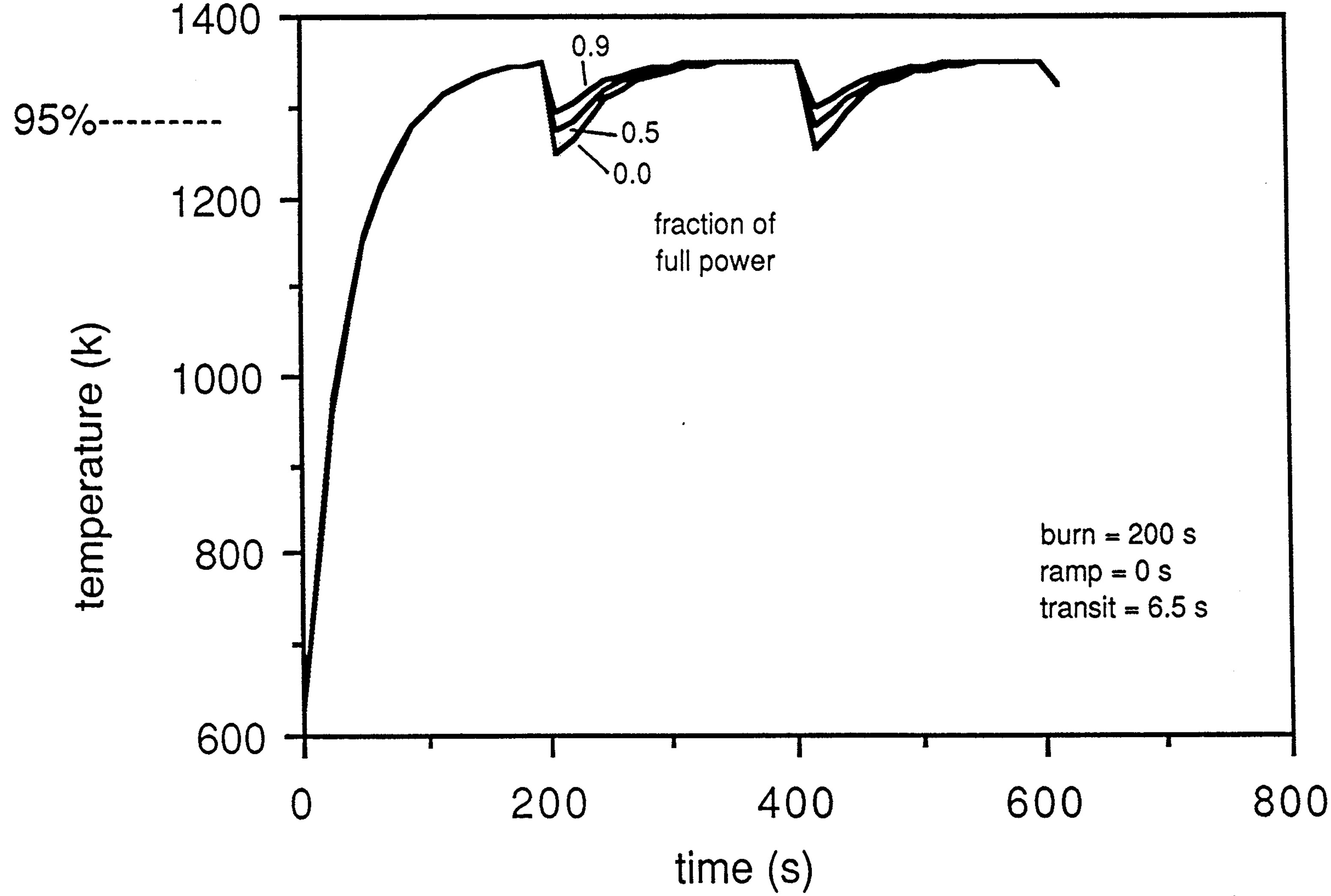
VARIATION OF TEMPERATURE WITH TIME FOR DIFFERENT DWELL TIMES (LIALO2 BREEDER)

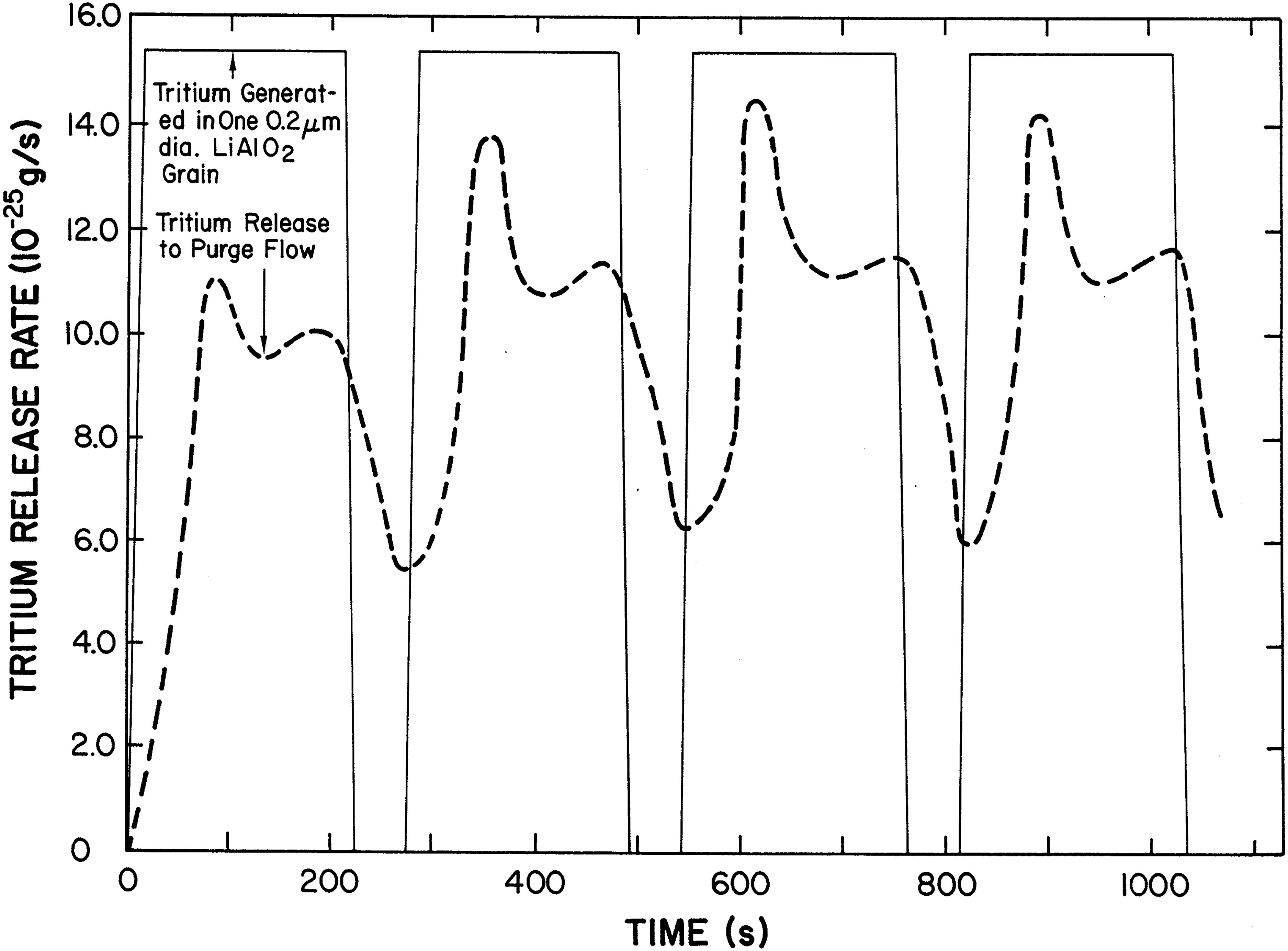


VARIATION OF TEMPERATURE WITH TIME FOR DIFFERENT DWELL TIMES (LIALO2 BREEDER)

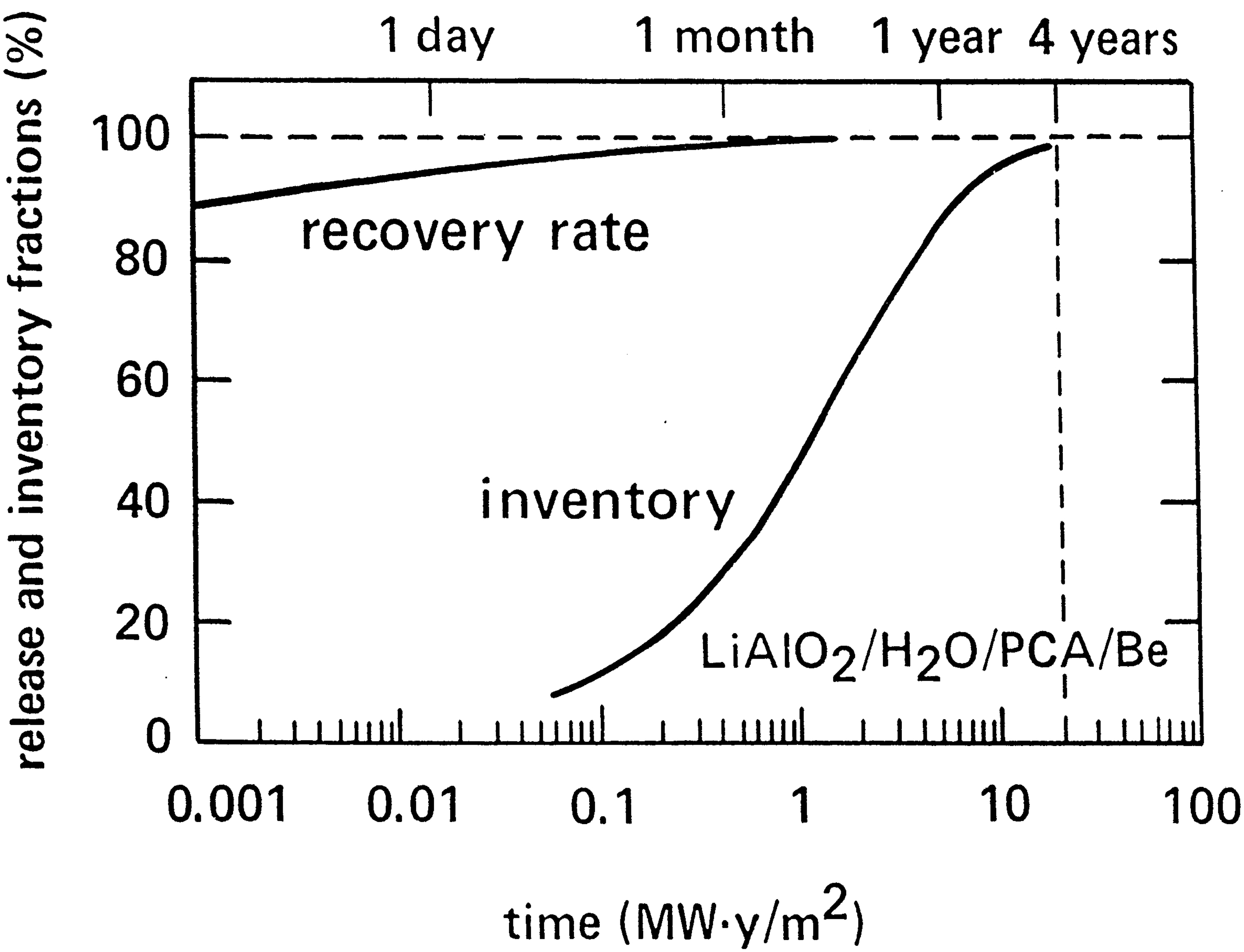


VARIATION OF TEMPERATURE WITH TIME FOR DIFFERENT FRACTIONS OF FULL POWER DURING TRANSIT TIME (LIALO2 BREEDER)

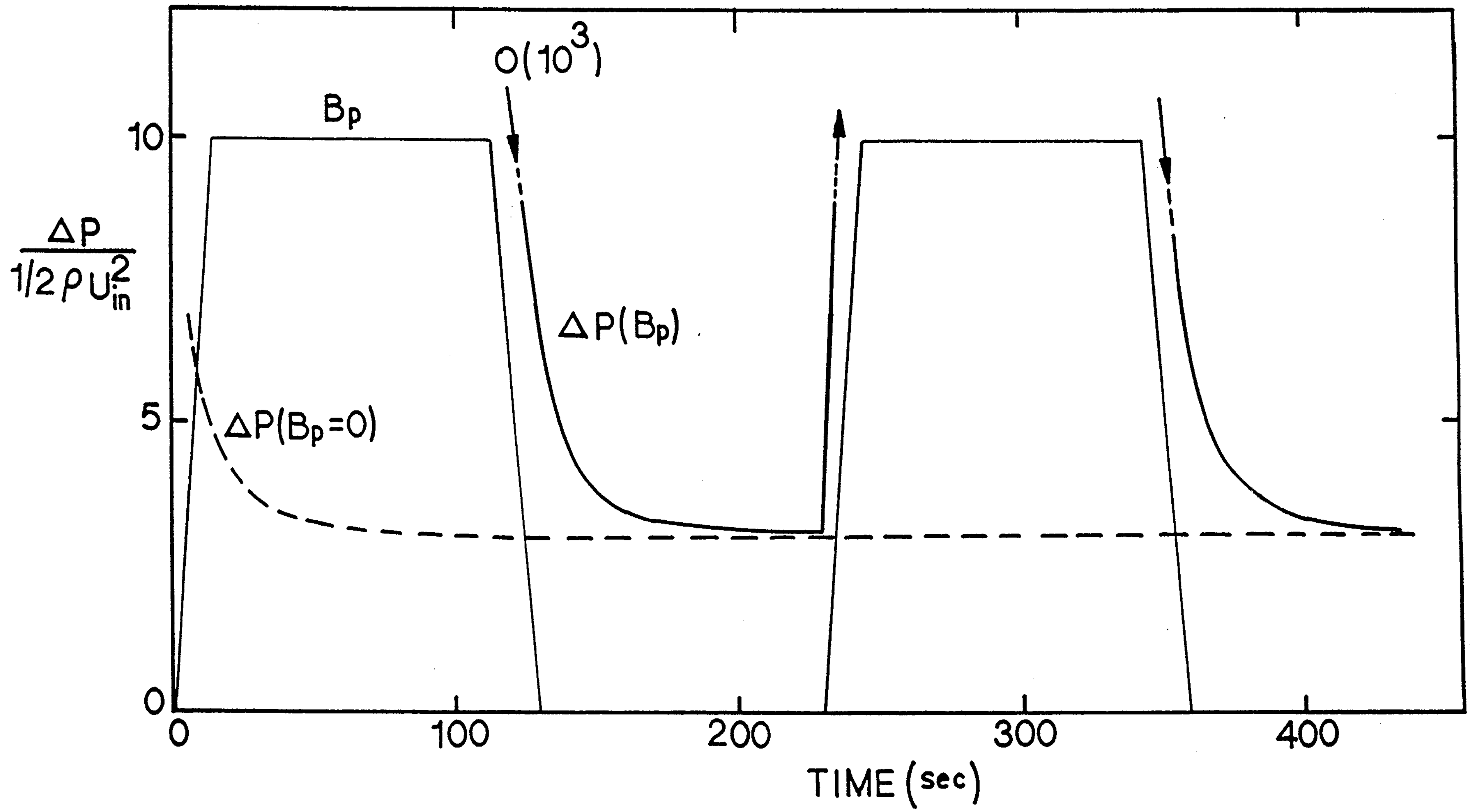



Tritium Generated in One 0.2 μm dia. LiAlO2 Grain
Tritium Release to Purge Flow
TRITIUM RELEASE RATE (10^-25 g/s)
TIME (s)
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
0
200
400
600
800
1000

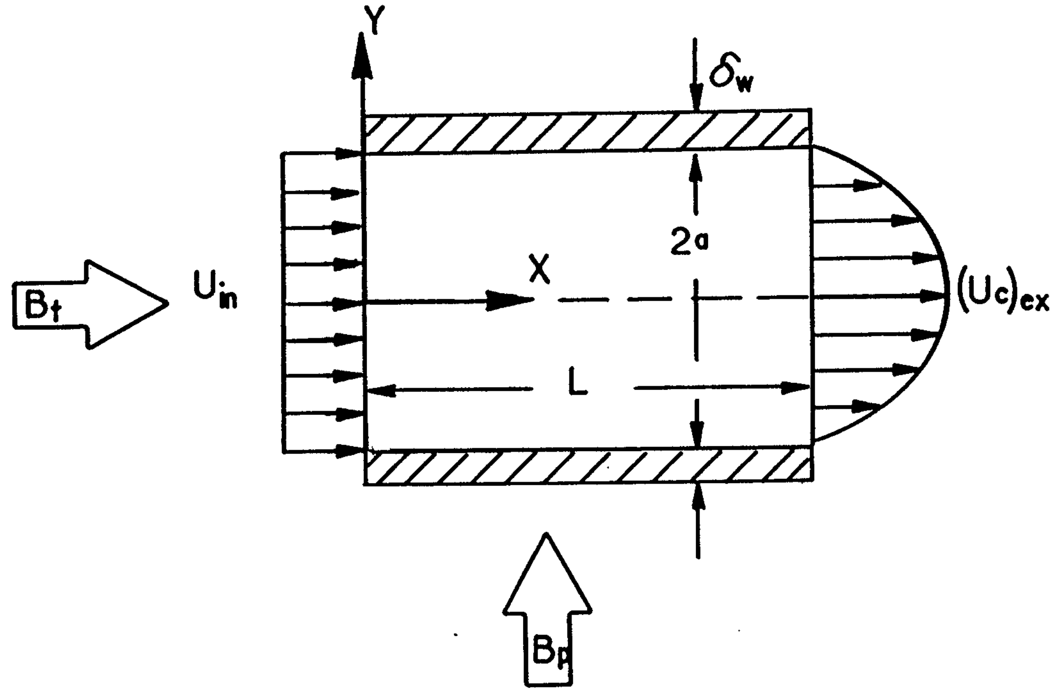
Reaching tritium inventory and recovery equilibrium may require long test times

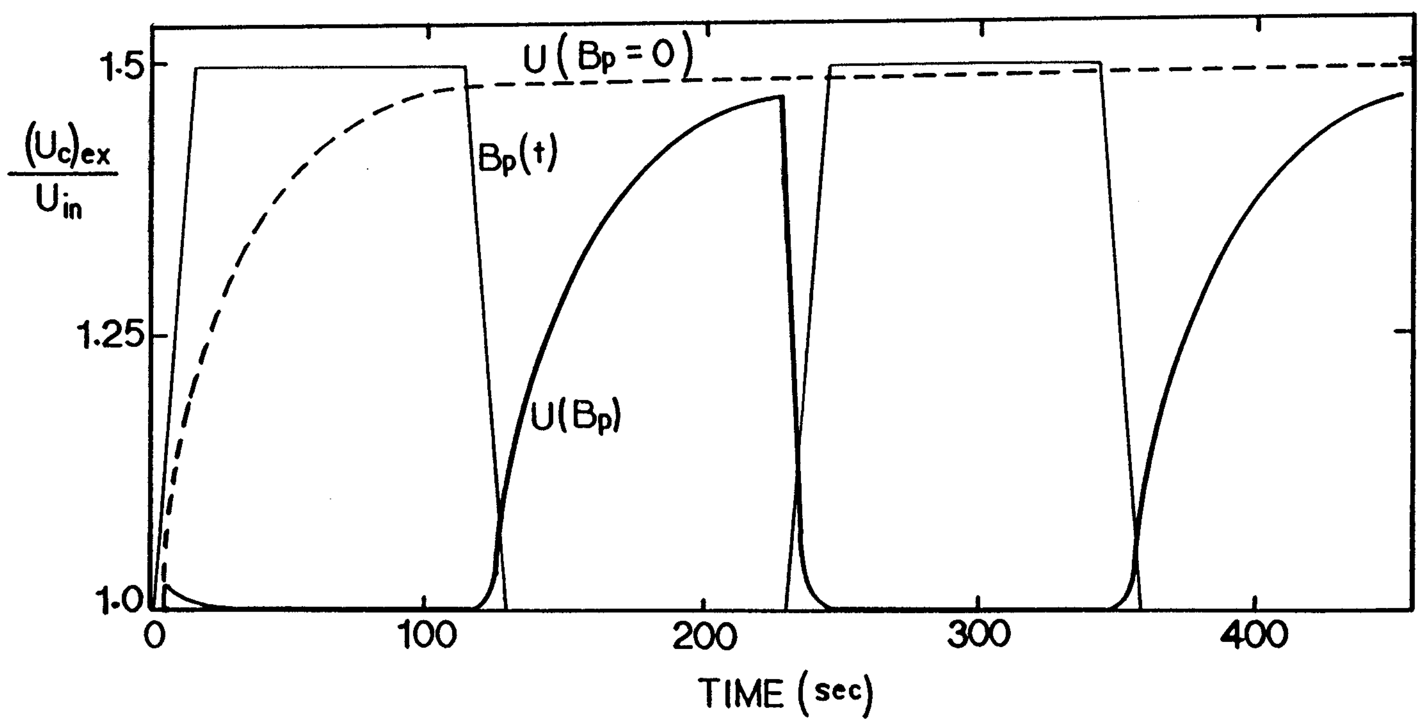


Effect of Time-Dependent Changes in Poloidal Magnetic Field on Pressure Drop in Liquid Metal Tests



Effect of Time-Dependent Changes in Poloidal Magnetic Field on Velocity Profile for Liquid Metal Tests





FNT RECOMMENDED PARAMETERS

Parameters	ETR		Reference Reactor
	Minimum	Recommended	
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	steady[a]	steady
Magnetic Field[b], T	3	5	7
Continuous Operating Time Availability, % Fluence[b], MW-y/m^2	days 20 1-2	weeks 30-50 3-6	months 70 15-20
Test Port Size, m^2 x m Total Test Area, m^2	0.5 x 0.3 5	1 x 0.5 10-20	

[a]See text

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

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