STEADY STATE VS. PULSED OPERATION DURING THE NUCLEAR TESTING PHASE OF ITER

Mohamed A. Abdou
UCLA

Presented to the ETOC Meeting
PPPL
18 May 1987

Importance of Steady State Operation for the Nuclear Testing Phase in ITER

- To Substantially Increase the Capability for Meaningful Nuclear Technology Testing

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

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?

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

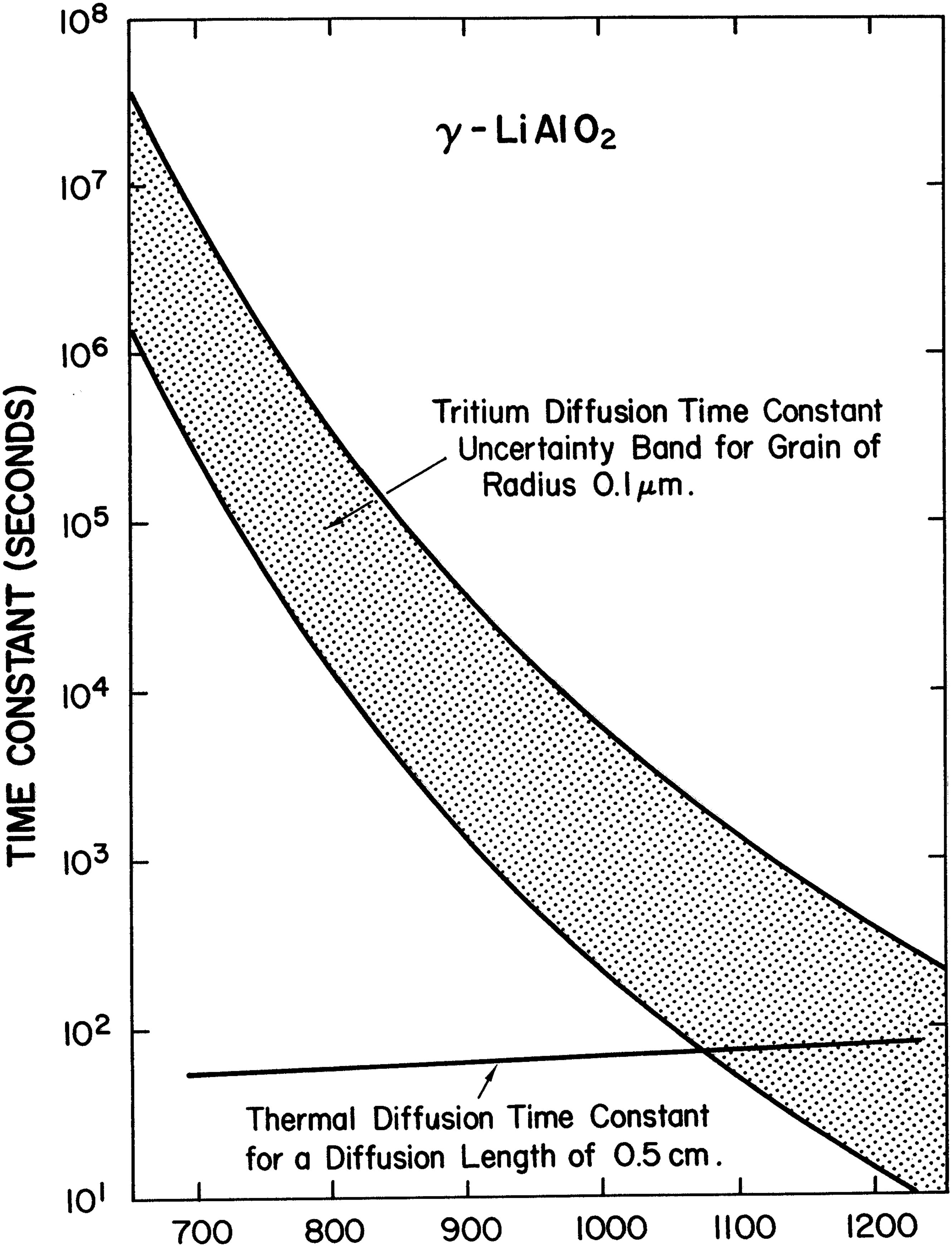
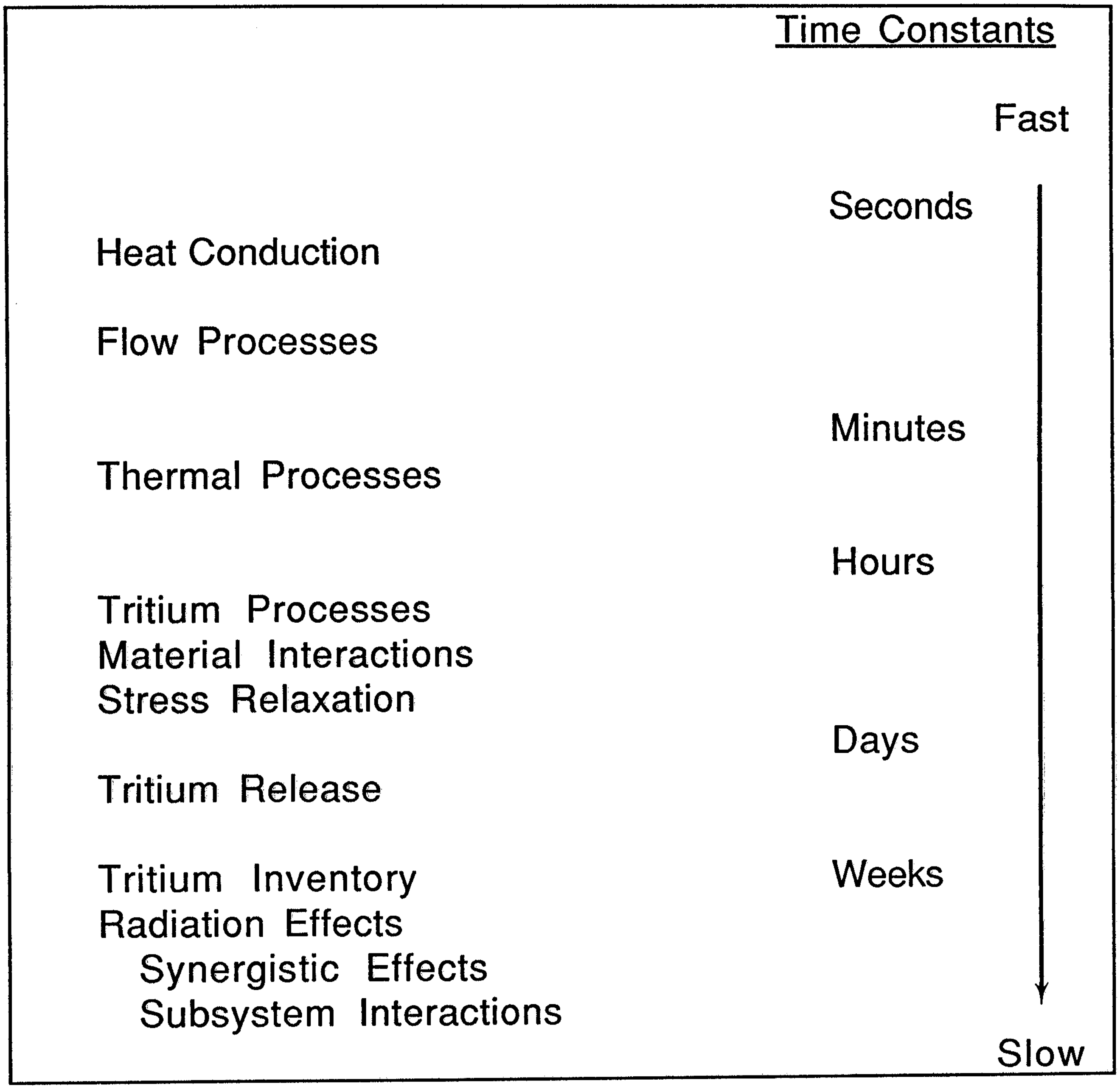

γ-LiAlO$_2$
Tritium Diffusion Time Constant Uncertainty Band for Grain of Radius 0.1 μm.
Thermal Diffusion Time Constant for a Diffusion Length of 0.5 cm.
TIME CONSTANT (SECONDS)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
700
800
900
1000
1100
1200
TEMPERATURE (K)

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 ($\frac{1}{2}$-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



<u>Time Constants</u>

Fast

Seconds

Heat Conduction

Flow Processes

Minutes

Thermal Processes

Hours

Tritium Processes
Material Interactions
Stress Relaxation

Days

Tritium Release

Tritium Inventory
Weeks
Radiation Effects
  Synergistic Effects
  Subsystem Interactions

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)

Most Critical Nuclear Issues For Testing in trhe Fusion Environment Involve Many Proceses/Phenomena

1) some with very short time constants
2) some with very long time constants

<u>Burn Time</u>?

Must be longer than 3 τ for the process with longest time constant

$\boxed{t_b > \text{Days for Many key Processes}}$

<u>Dwell Time</u>?

Must be shorter than 0.05 τ for the process with shortest time constant

$\boxed{t_s \ll 5 \text{ s for Many key Processes}}$

Examples of Critical Issues Involving Processes with Widely Different Time Constants

Issue	Fast Response	Slow Response
Tritium Release from Solid Breeders	Tritium Production (~0 s) Nuclear Heating (~0 s) Temperature (seconds) Tritium Diffusion (high temp. 1200K) (seconds) Temperature Gradient (seconds)	Low Temp. (700K) Tritium Diffusion (days) Surface Adsorption/Desorption (hours) Radiation Effects (very long) (can markedly slow down pore diffusion)
Corrosion/ Redeposition	Nuclear Heating (~0 s) Temperature (<5 s) Temperature Gradients (<5 s)	Loop Temperature ($\frac{1}{2}$ hr) Dissolution of Fe in Li (40 days) Chemical Equilibrium - Concentration Buildup (months)
Structural Response	Primary Stresses (seconds) Thermal Stresses (minutes)	Thermal & Irradiation Stress Relaxation (months) Radiation Damage (months to years) Effects of Cycling and Power Variations (months to years) Surface Damage (e.g., erosion, corrosion)

Significant Plasma Dwell Time Impacts Many Critical Nuclear Tests

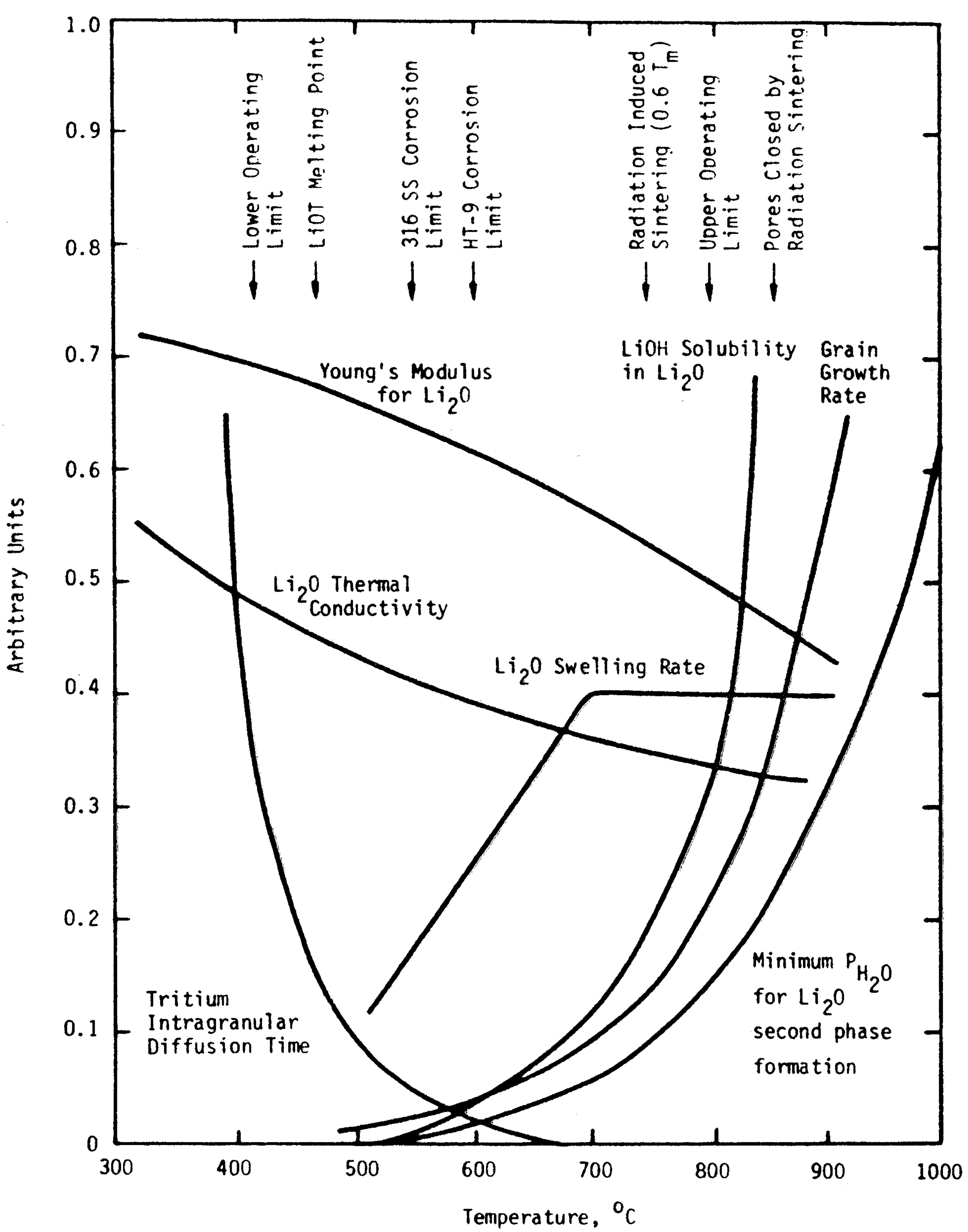
Fast Changes (e.g.)

- 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

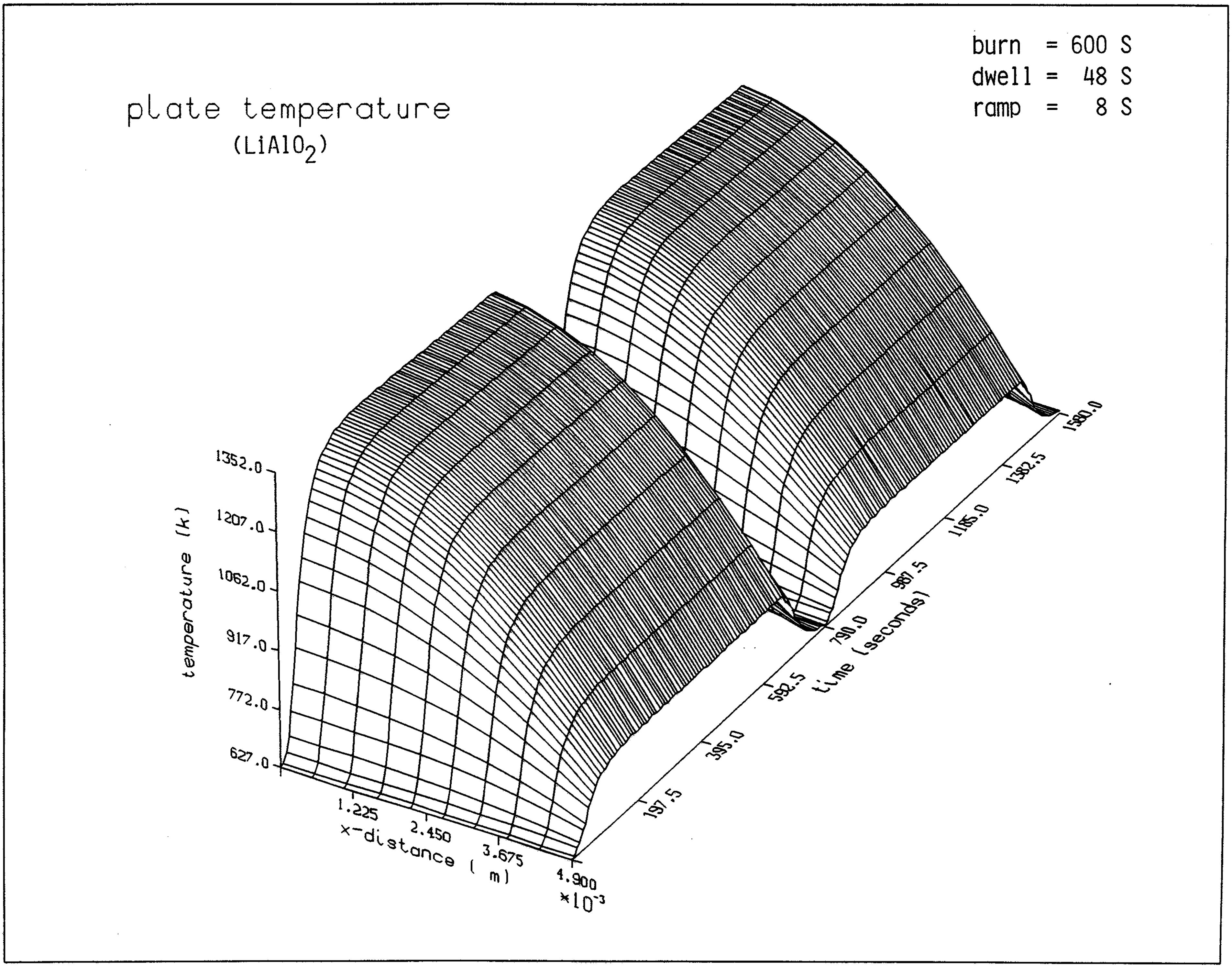


plate temperature

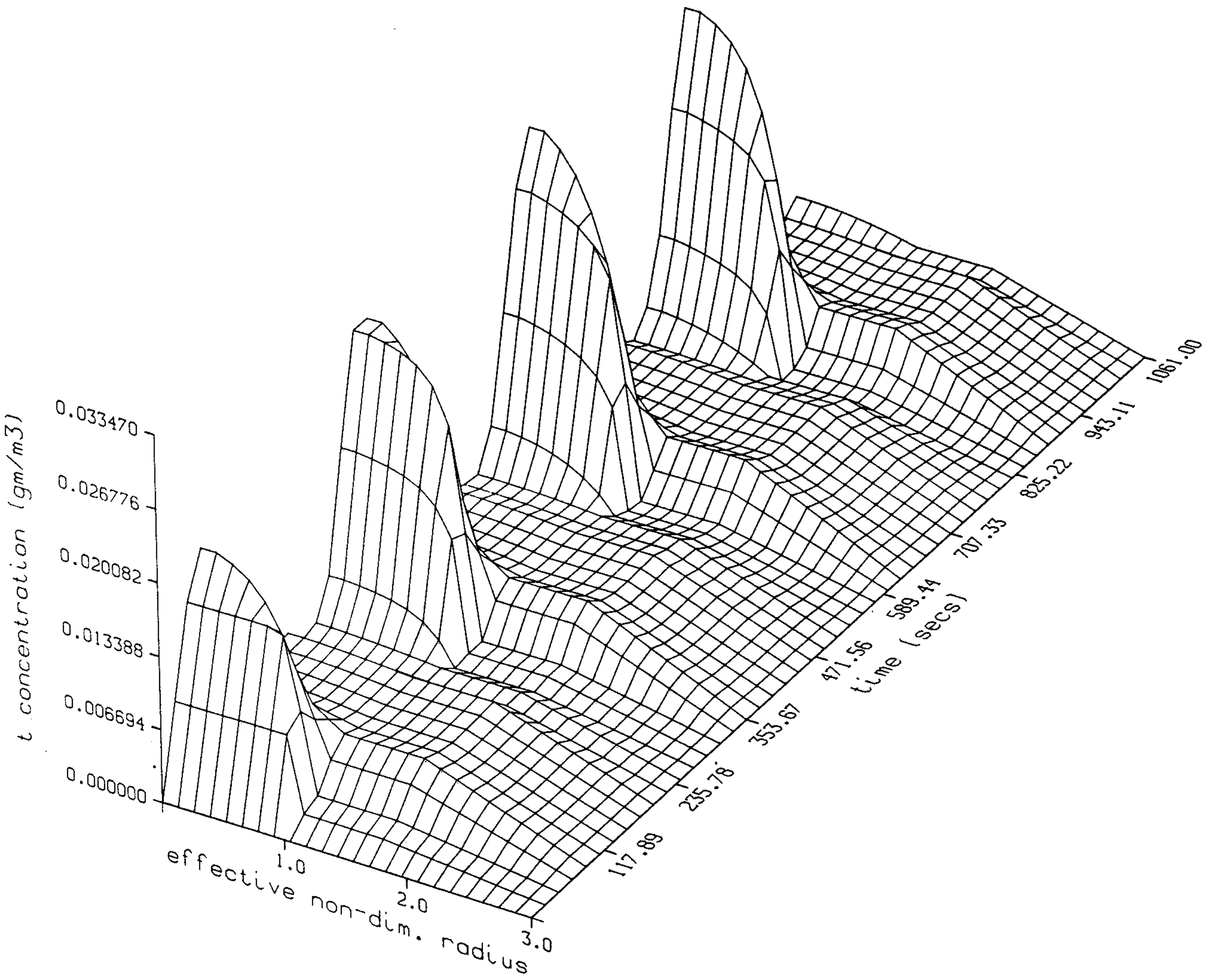
($LiAlO_2$)

burn = 600 S

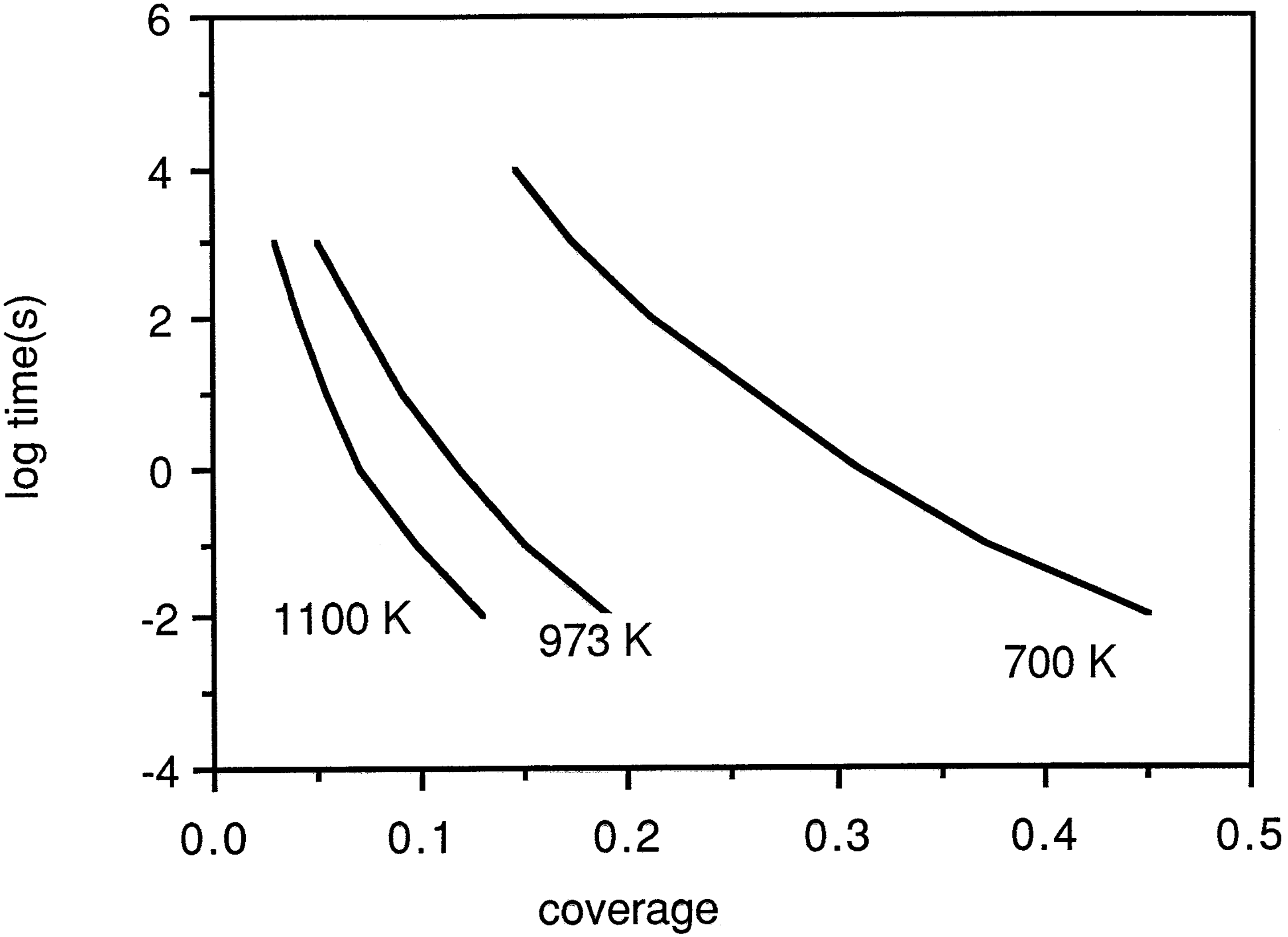
dwell = 48 S

ramp = 8 S

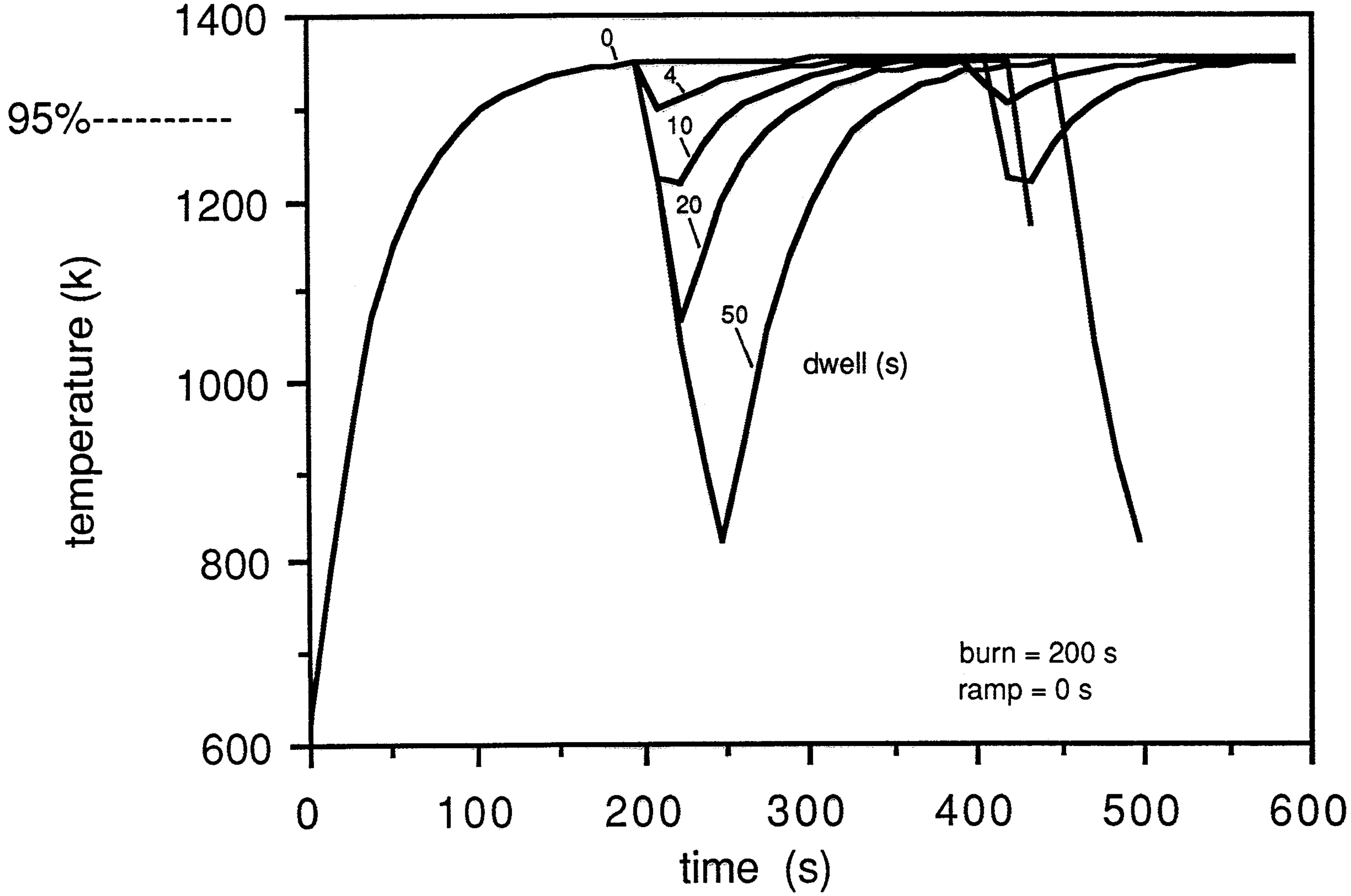
TIME-DEPENDENT TRITIUM CONCENTRATION (DIFFUSIVE) PROFILES IN GRAIN, GRAIN BOUNDARY AND PORE



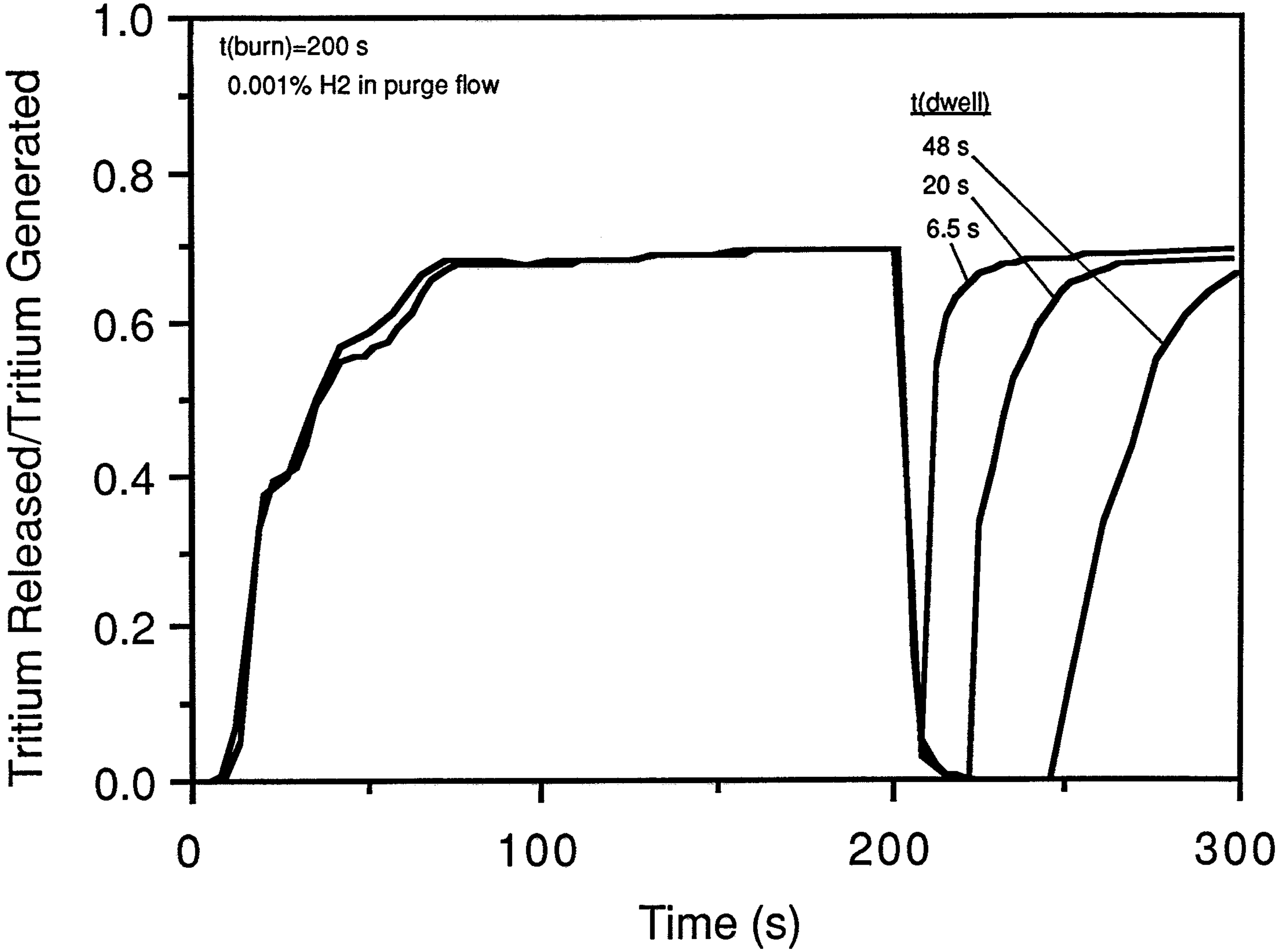
ESTIMATED H2O DESORPTION TIME FROM AL2O3 AS A FUNCTION OF COVERAGE AND TEMPERATURE



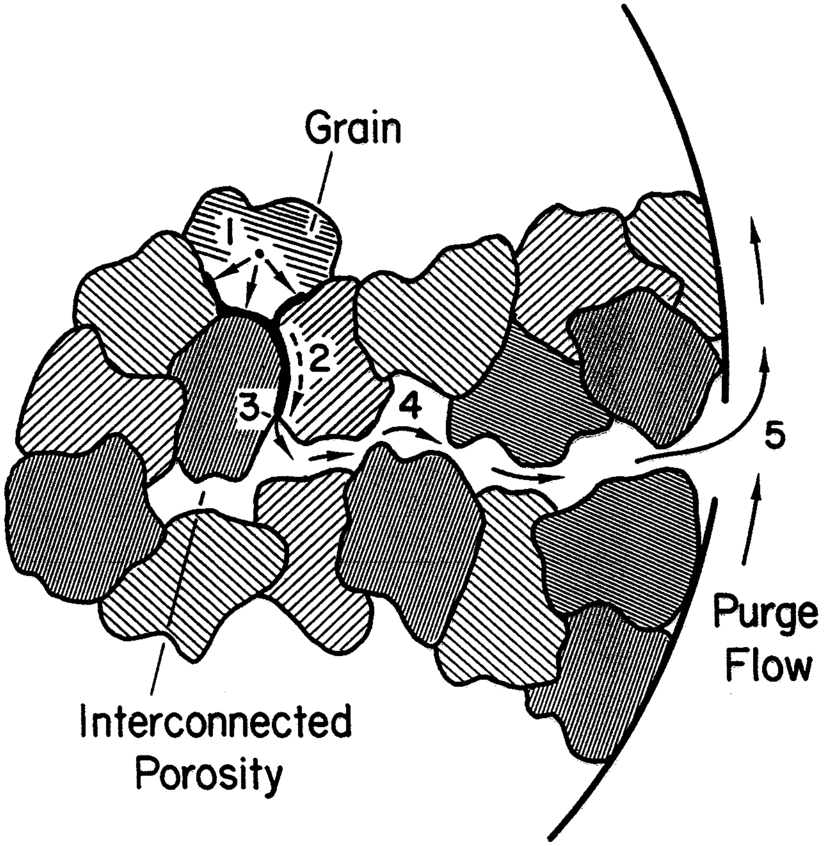
VARIATION OF TEMPERATURE WITH TIME FOR DIFFERENT DWELL TIMES (LIALO2 BREEDER)



Different Dwell Times (tritium release)



Tritium Transport in Solid Breeders

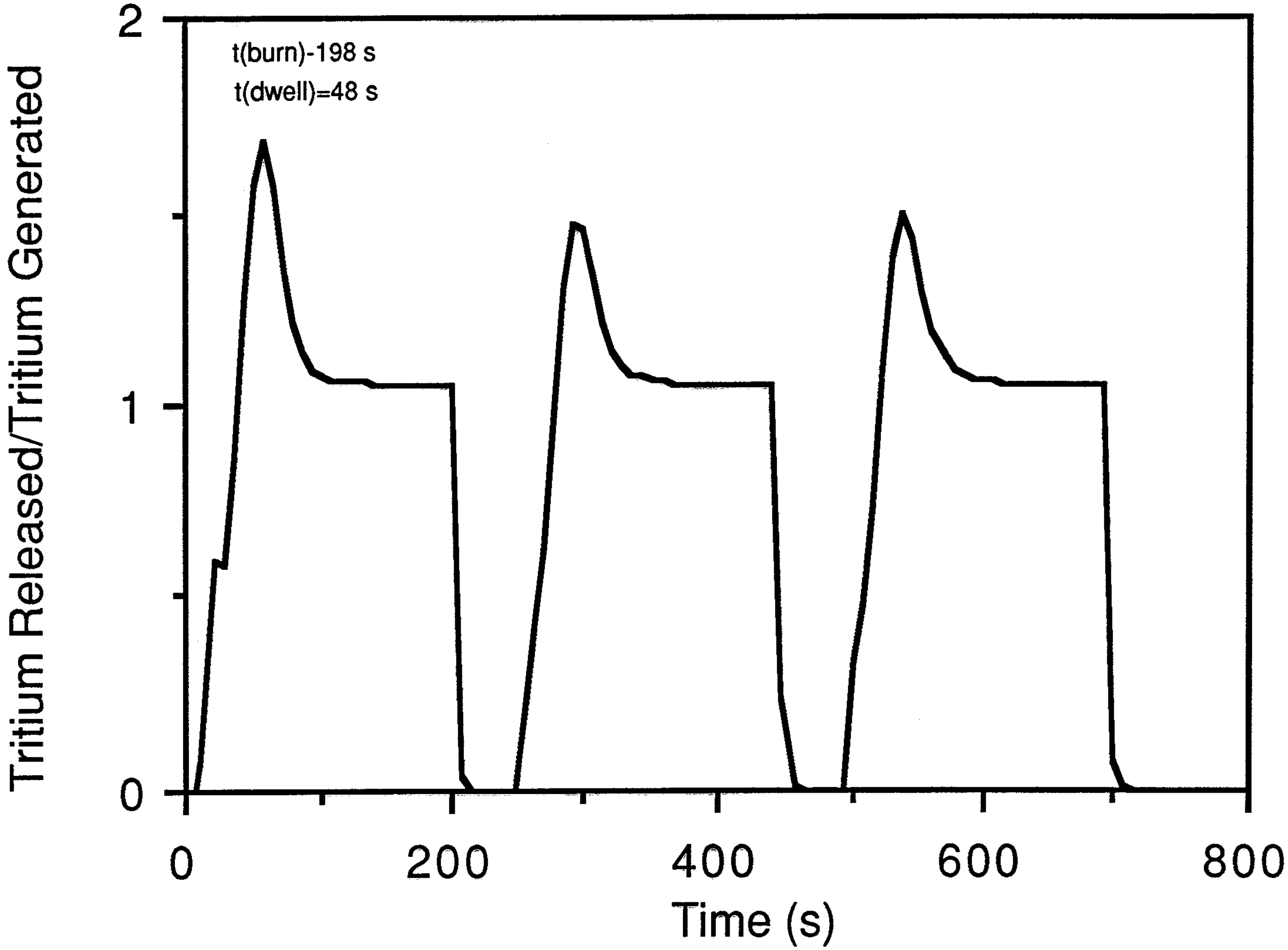


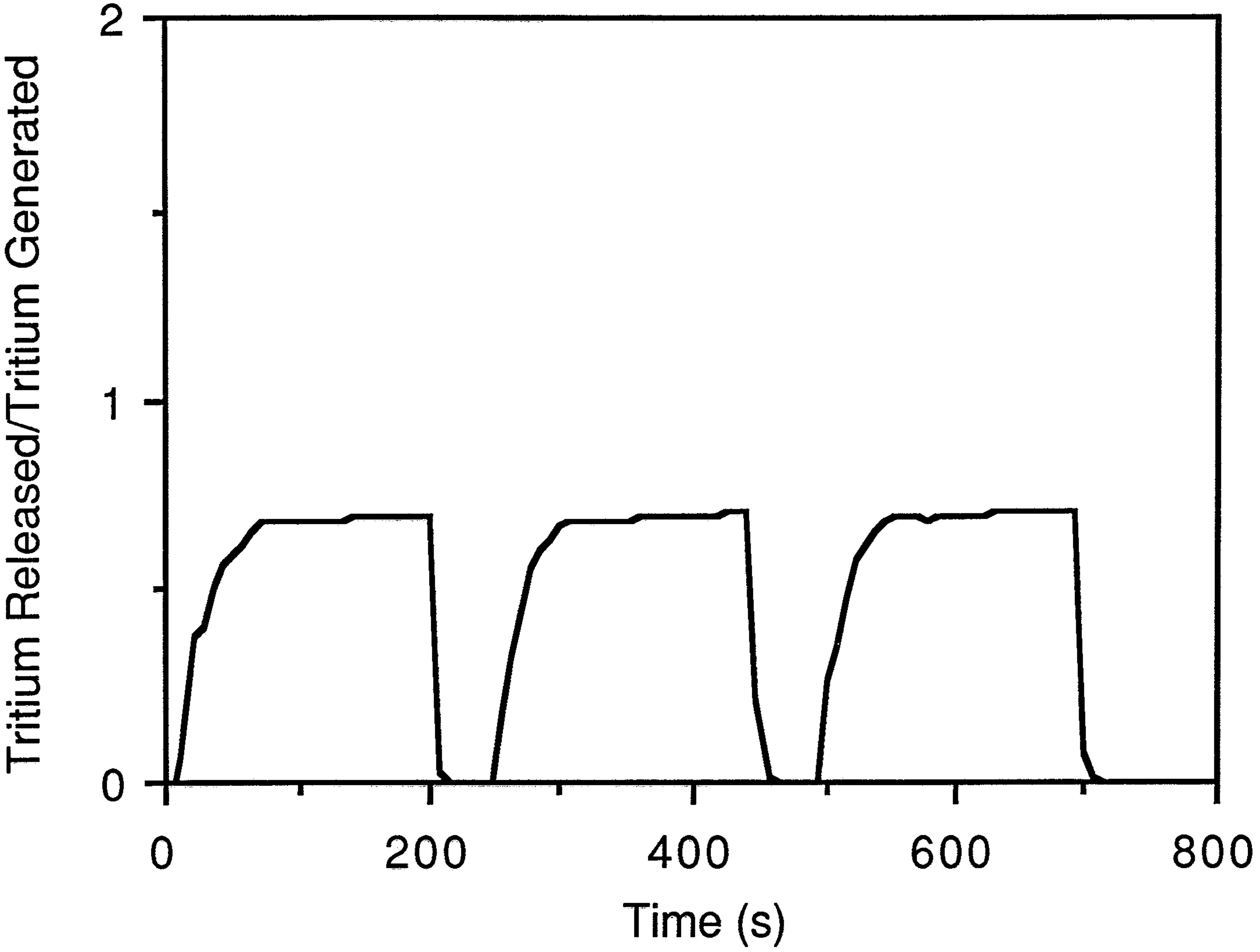
Mechanisms of Tritium Transport

1) Intragranular Diffusion
2) Grain Boundary Diffusion
3) Surface Adsorption/Desorption
4) Pore Diffusion
5) Purge Flow Convection

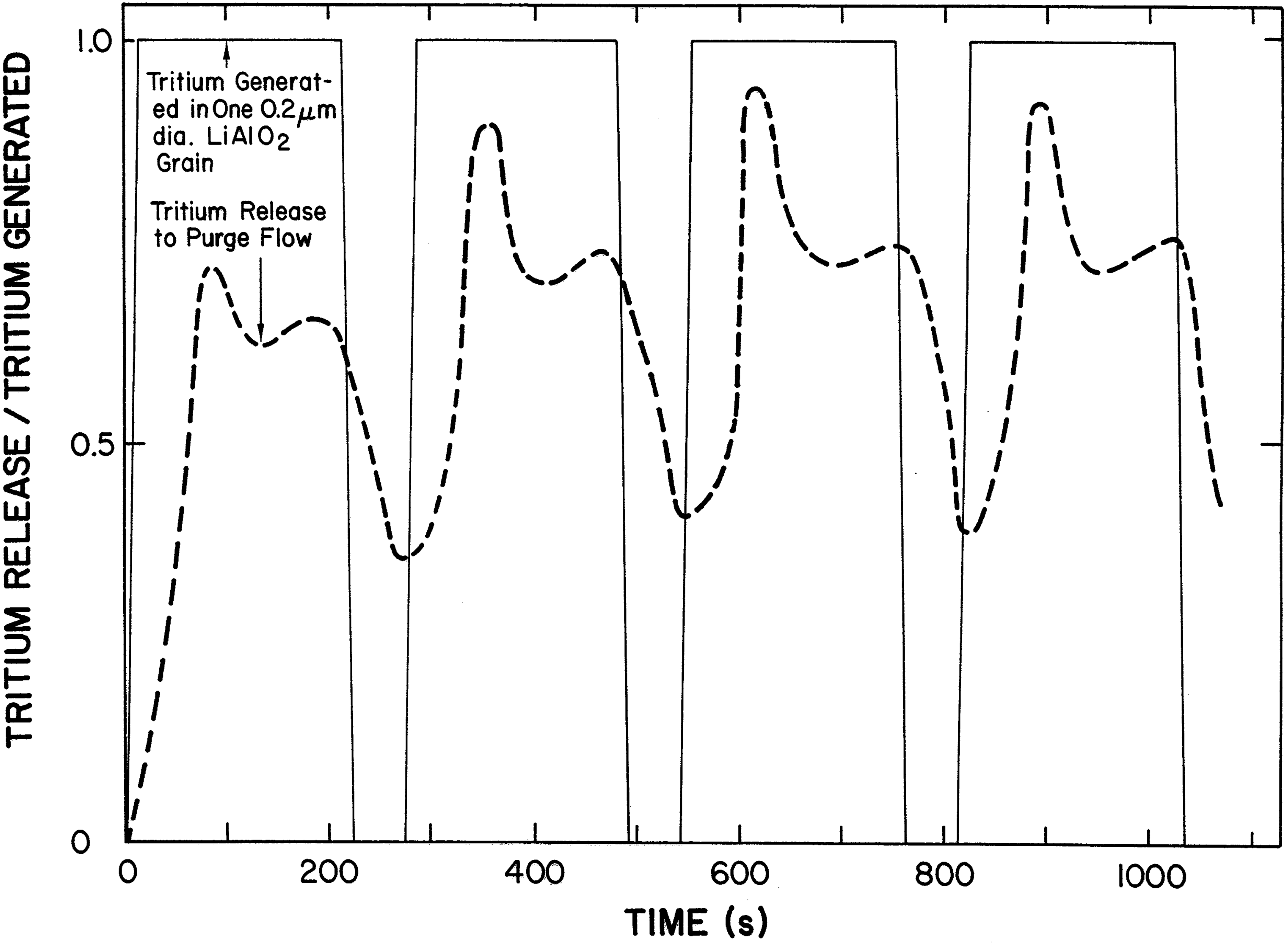
- These mechanisms have different time-dependent behavior
- Results from pulsed tests will be very difficult to understand and extrapolate

Tritium Release: Diffusion



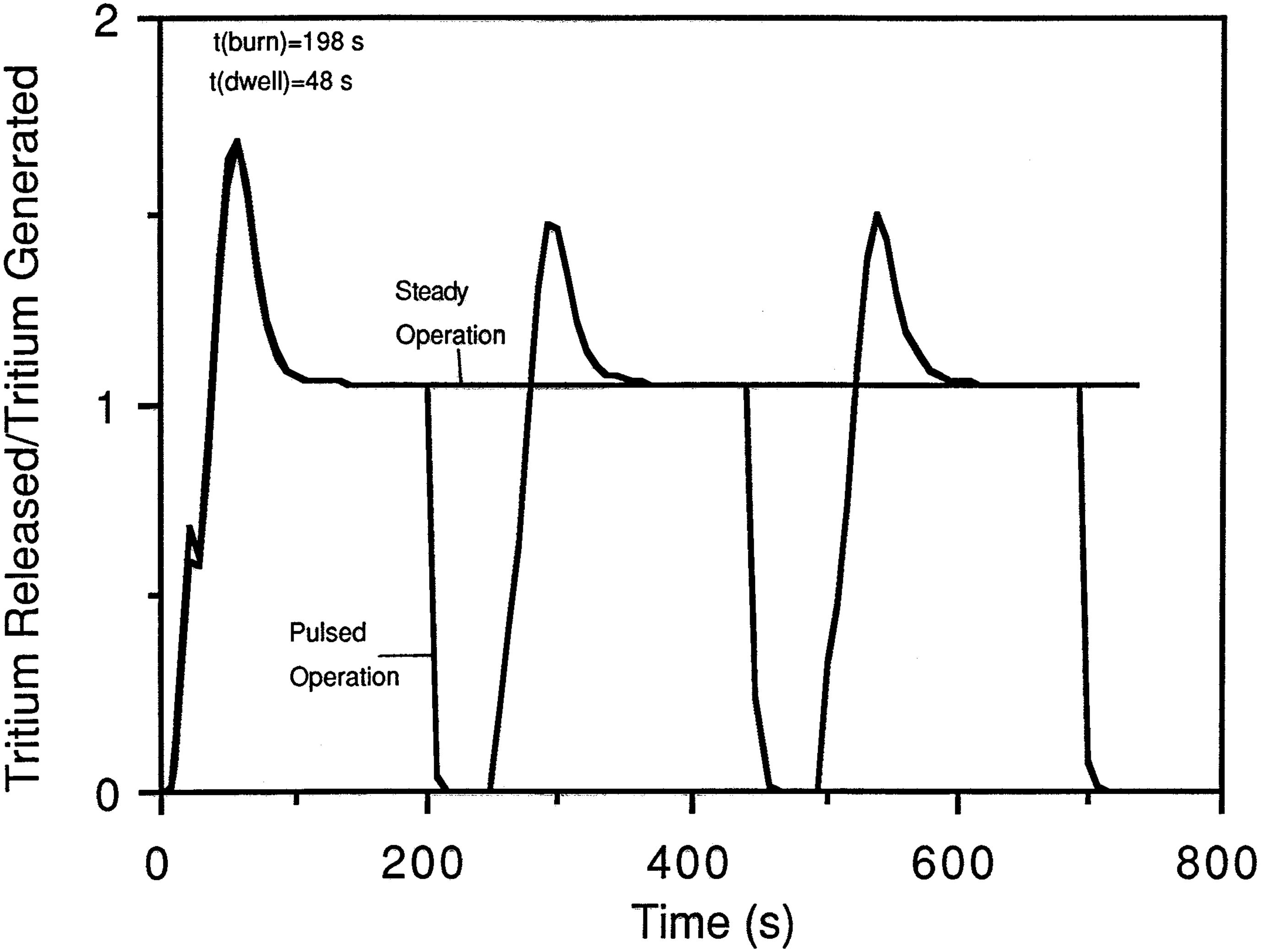


Tritium Release: Adsorption/Desorption

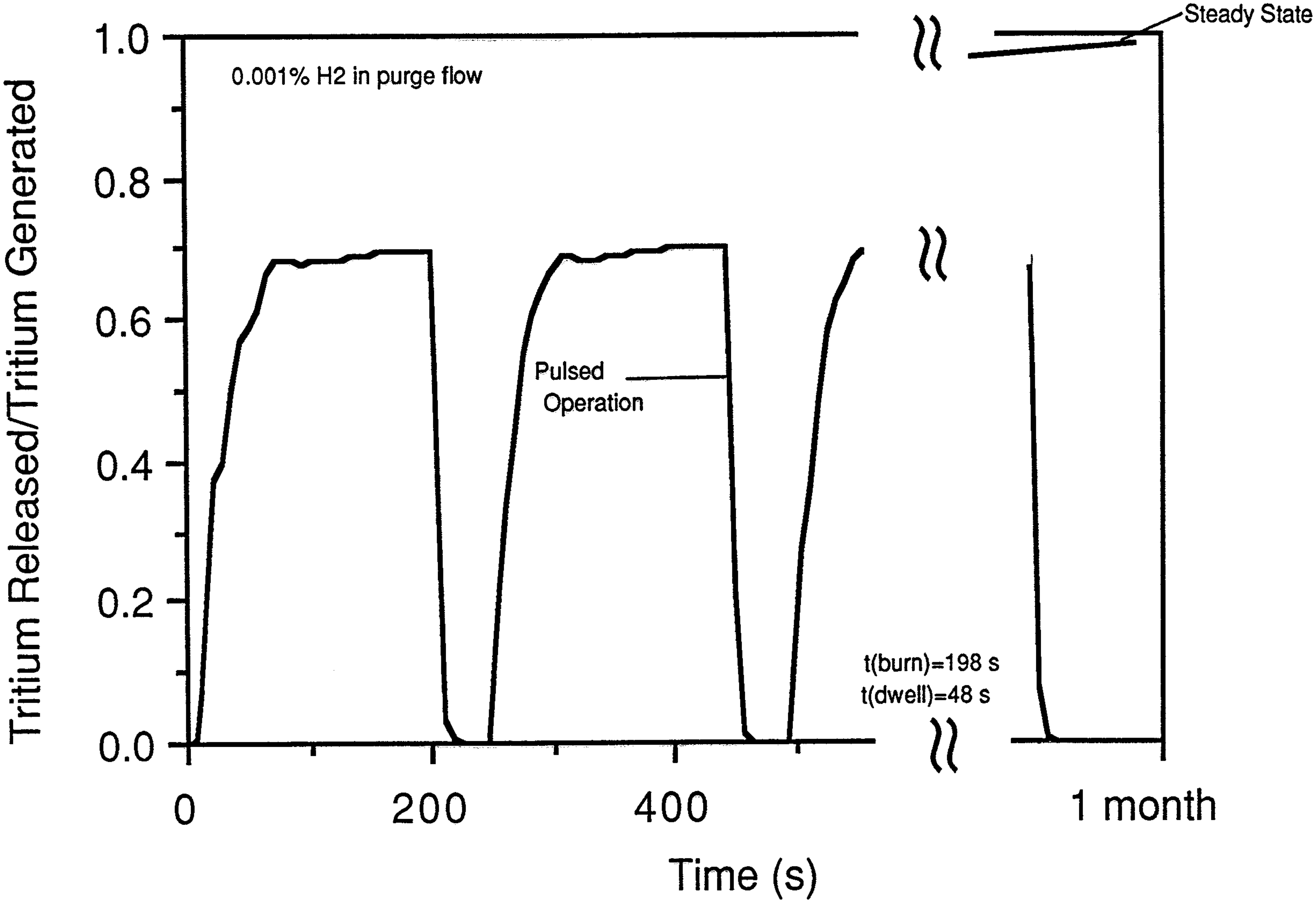


Tritium Release: Solubility

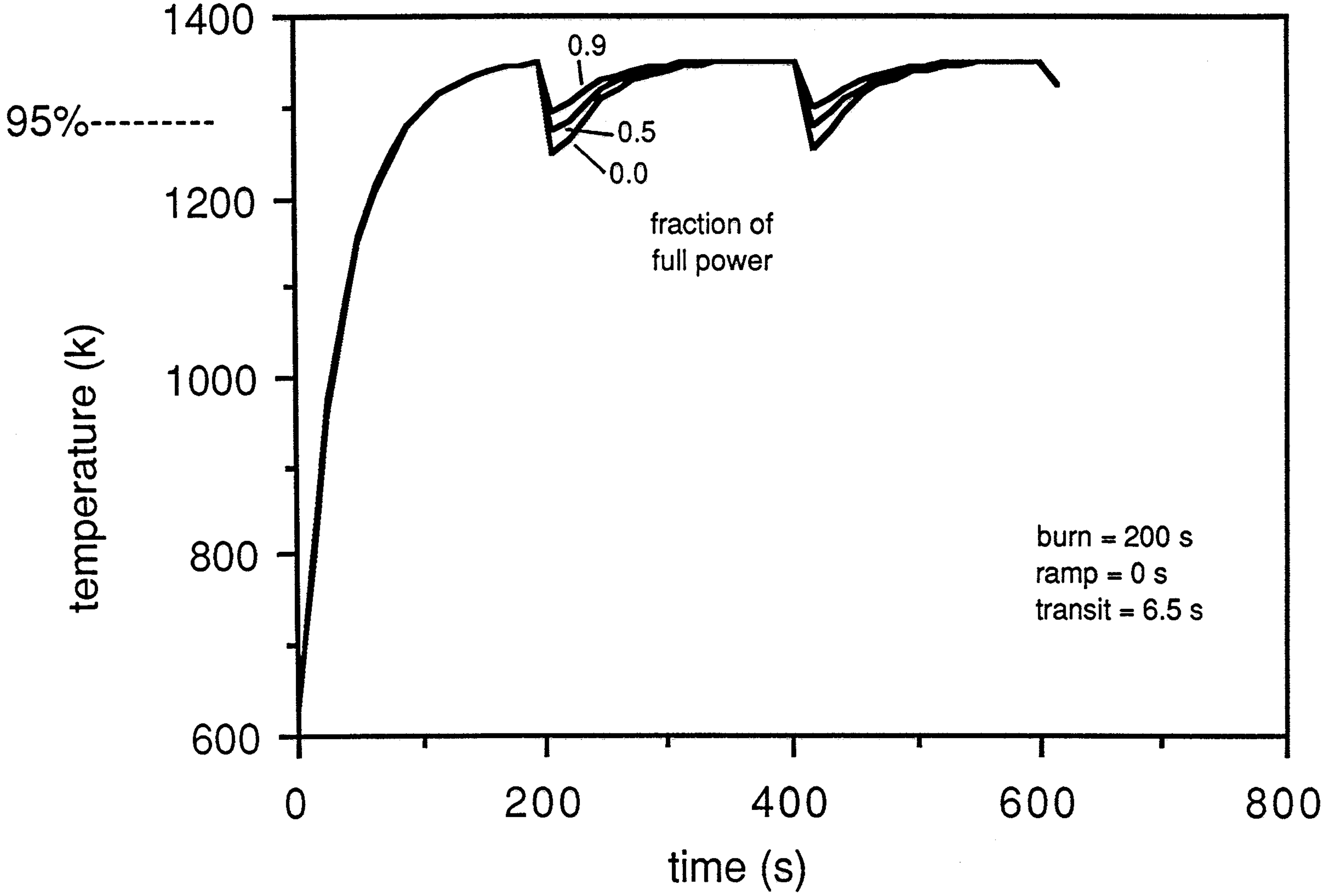
Tritium Released as a Function of Time for Steady vs. Pulsed Operation (No Adsorption/Desorption)



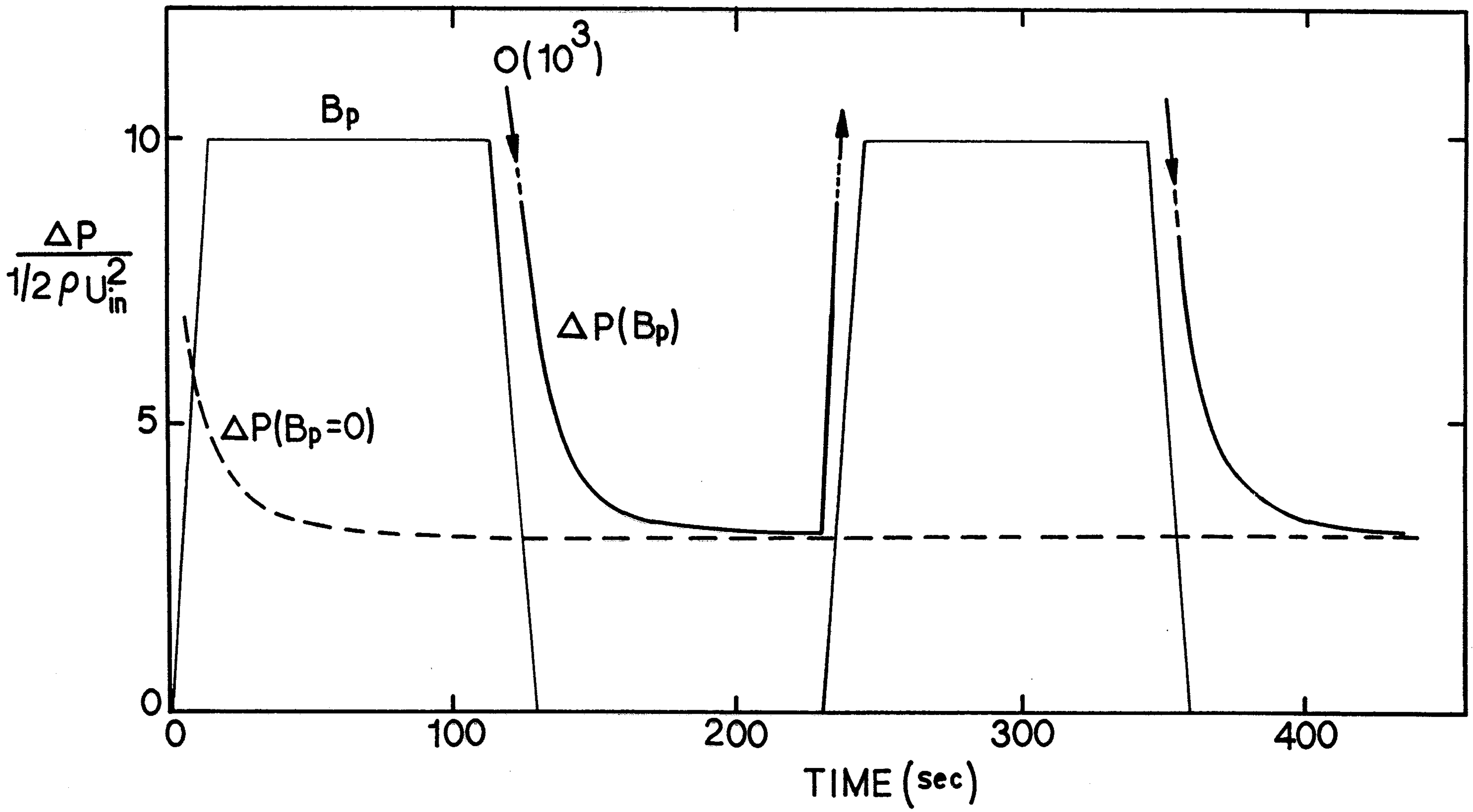
TRITIUM RELEASED AS A FUNCTION OF TIME FOR STEADY STATE VS. PULSED OPERATION



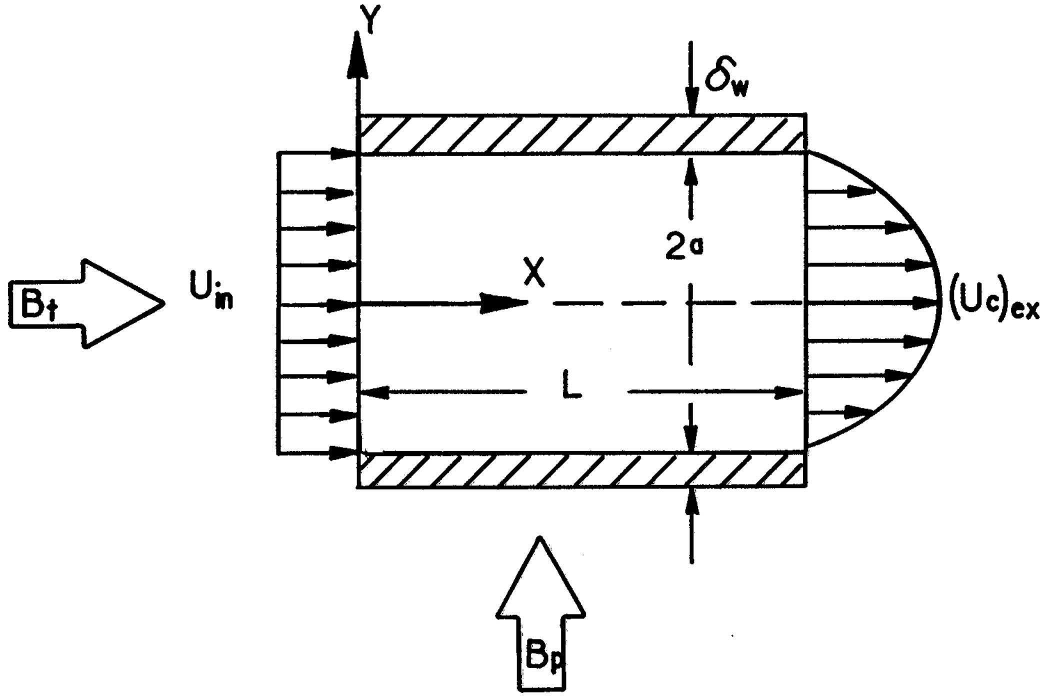
VARIATION OF TEMPERATURE WITH TIME FOR DIFFERENT FRACTIONS OF FULL POWER DURING TRANSIT TIME (LIALO2 BREEDER)

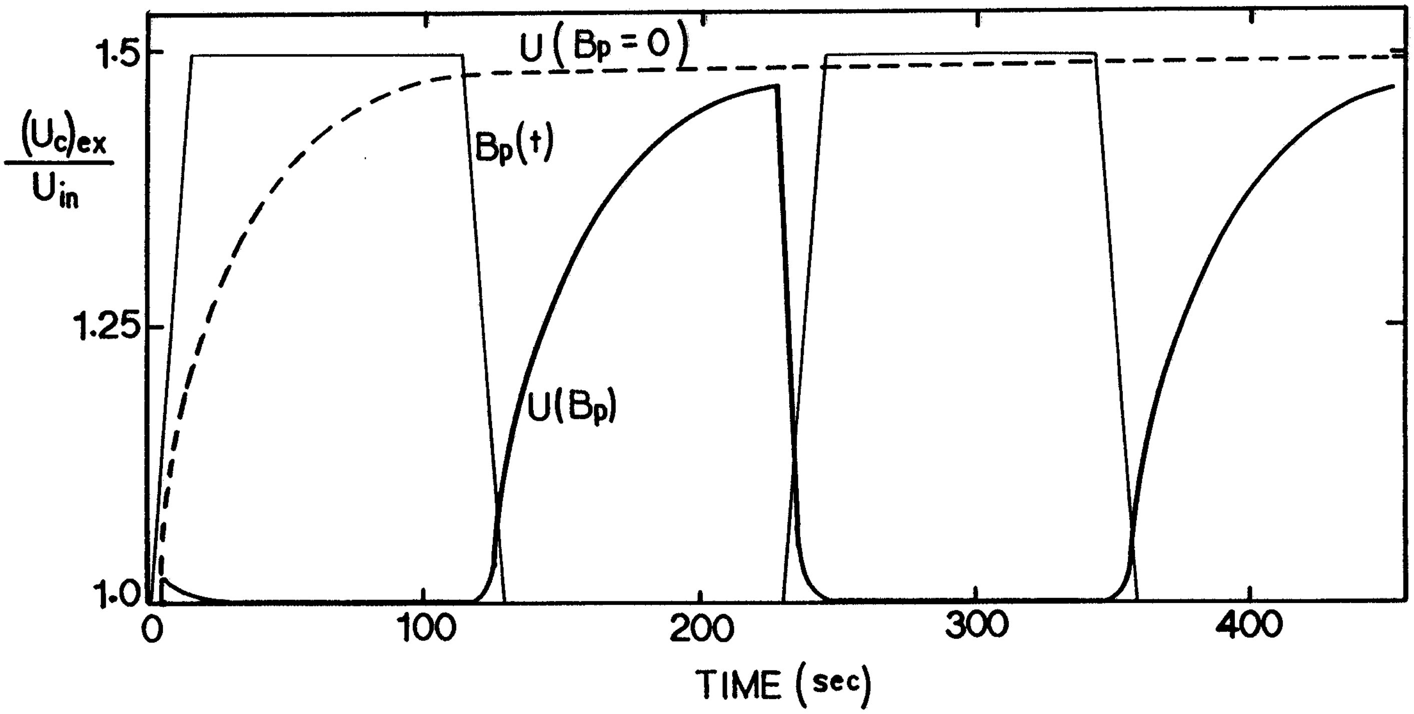


Effect of Time-Dependent Changes in Poloidal Magnetic Field on Pressure Drop in Liquid Metal Tests

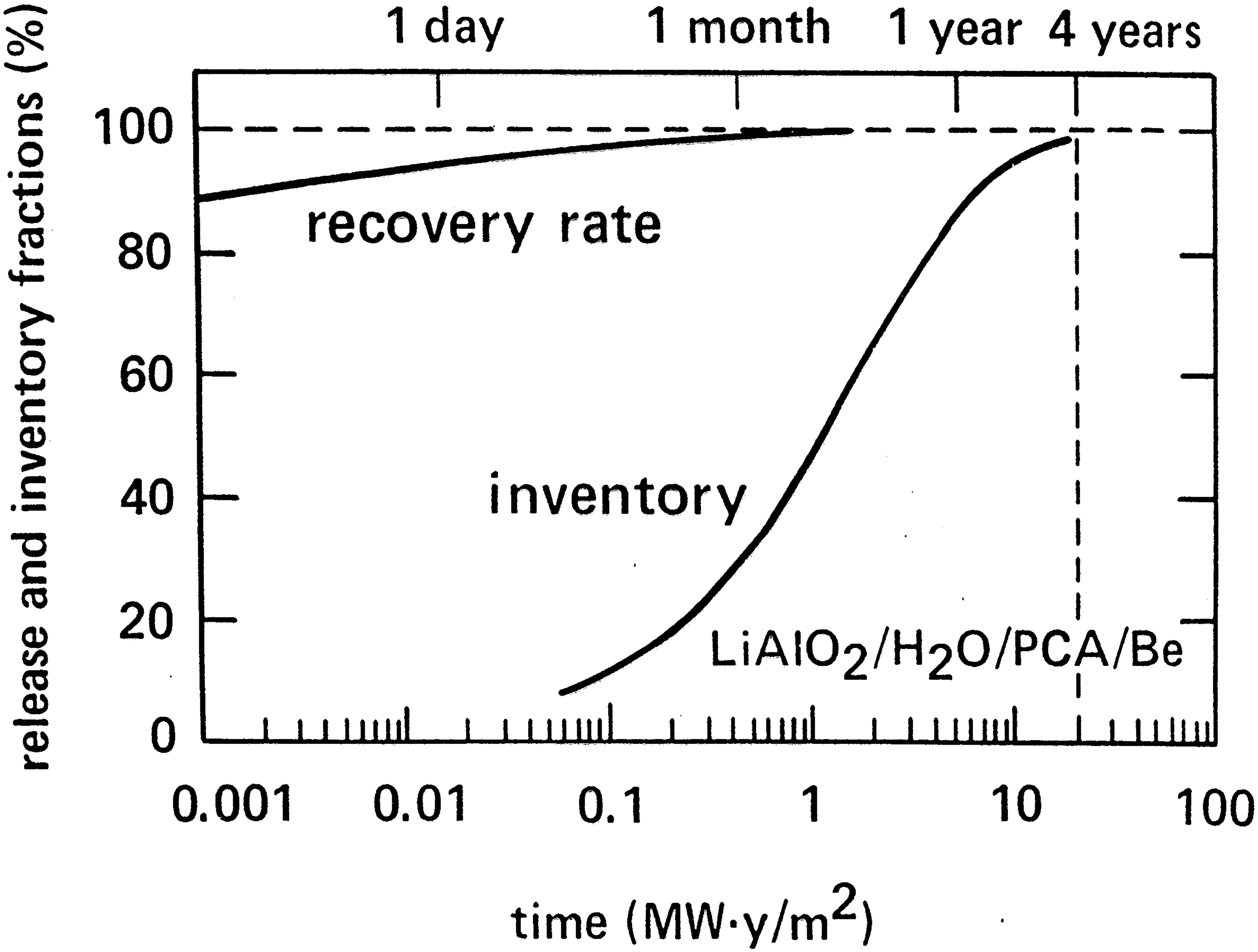


Effect of Time-Dependent Changes in Poloidal Magnetic Field on Velocity Profile for Liquid Metal Tests





Reaching tritium inventory and recovery equilibrium may require long test times



Important Remarks on Pulsed vs. Steady State Operation During Nuclear Testing Phase in ITER

- There are some issues that can be tested with ~500 s plasma burn
  e.g., neutronics
  shielding
  (some) fluid flow processes

- However, most critical nuclear issues for testing in the unique fusion environment of ITER require striving for steady state operation
  e.g., Tritium Recovery from Solid Breeders
  Liquid Metal Corrosion/Redeposition
  Structure Response and Failure Modes
  Subsystems Interactions

- Pulsing does not yield average response in many cases. It often yields different results (activate different phenomena and threshold effects)

- Many key nuclear issues involve several processes with widely varying time constants
  - require very short dwell time(near zero)
  - require very long burn time (days)
  - difficult to reproduce synergistic effects with pulsing

- <u>In Summary</u>: Pulsing substantially degrades the engineering simulation; makes it difficult to understand the results and extrapolate to future fusion devices

Suggestions

As Design *Basis* for the *Nuclear* Testing *Phase* 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)

Note:

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