ITER

Nuclear Testing Requirements

Mohamed A. Abdou

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ROLE OF ITER IN TECHNOLOGY DEMONSTRATION

TWO ELEMENTS OF ITER

1) Basic Machine

   Conservative design of the machine components (including basic blanket) maximizes reliability, flexibility and safety of ITER

2) Test Program

   Space for test modules allows for testing of advanced concepts and partial (powerful) demonstration of the ultimate potential of fusion

IS TECHNOLOGY TESTING IN ITER NECESSARY?

Technology testing in ITER may be:

The Least Expensive

Nearest - Term

Option to Accomplish the Objectives of Fusion R&D

Logical part of the answer to do something "exciting" in the near term at a modest cost

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REMARKS

- Technology tests in the fusion environment have to be done sooner or later
  - Cannot go to the DEMO without these tests
- If they are not done in ITER, they have to be done in another machine
  - Cost of additional machine
  - 15 or 20 years later

EXAMPLES OF "ACCOMPLISHMENTS" THROUGH TESTING IN ITER

- Performance and Economic Attractiveness
  - demonstrate ability to generate electricity efficiently
  - demonstrate operation of the entire fuel cycle
  - demonstrate temperature limits of materials
  - obtain data crucial to tritium self-sufficiency
- Safety Demonstration
  - inherent safety
  - response to transients and off-normal operating modes
  - effects of afterheat
  - operating experience with tritium, radioactive materials, hazardous chemicals (e.g., liquid metals, Be)
- Environmental Demonstration
  - Direct measurement of induced radioactivity after heat
  - Demonstration of low activation options (e.g., Li/V, Li_20/SiC)
- Other

  Not yet studied

  - Can ITER environment be sold to other applications? (e.g., burning actinides?, medical-related applications?)

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-yr/m^2)			
at test module [b,d]	1-2	3-4	15-20
(device fluence, MW•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

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: $F = F_0 (1 - e^{-t/\tau})$

Dwell: $F = F_0 e^{-t/\tau}$

τ = characteristic Time Constant

Allowable Variation (During a Specific Test)

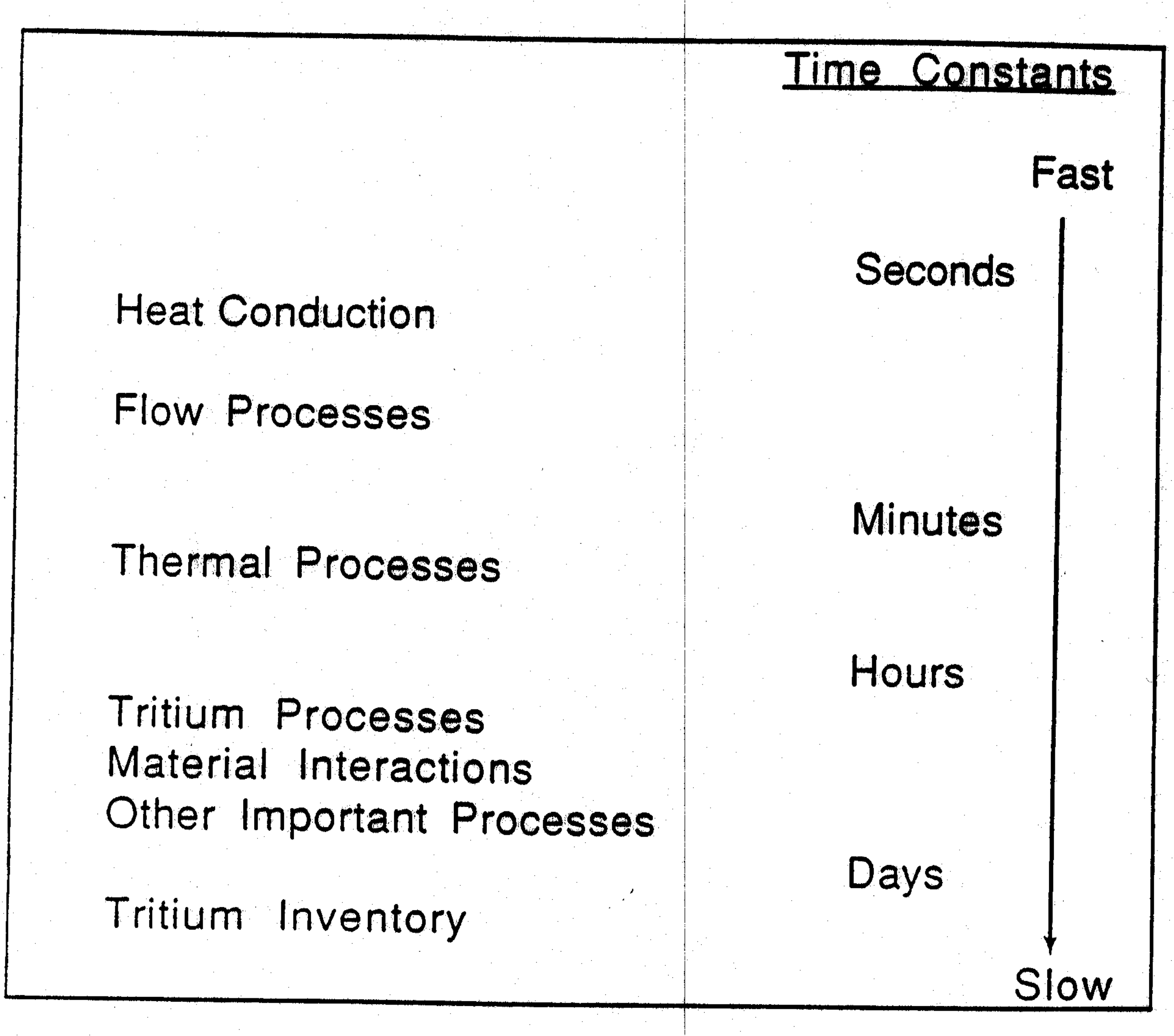
- The goal is not just reaching equilibrium. It is to stay at equilibrium during test
- Small changes in some fundamental quantities result in large changes in key parameters

  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

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



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

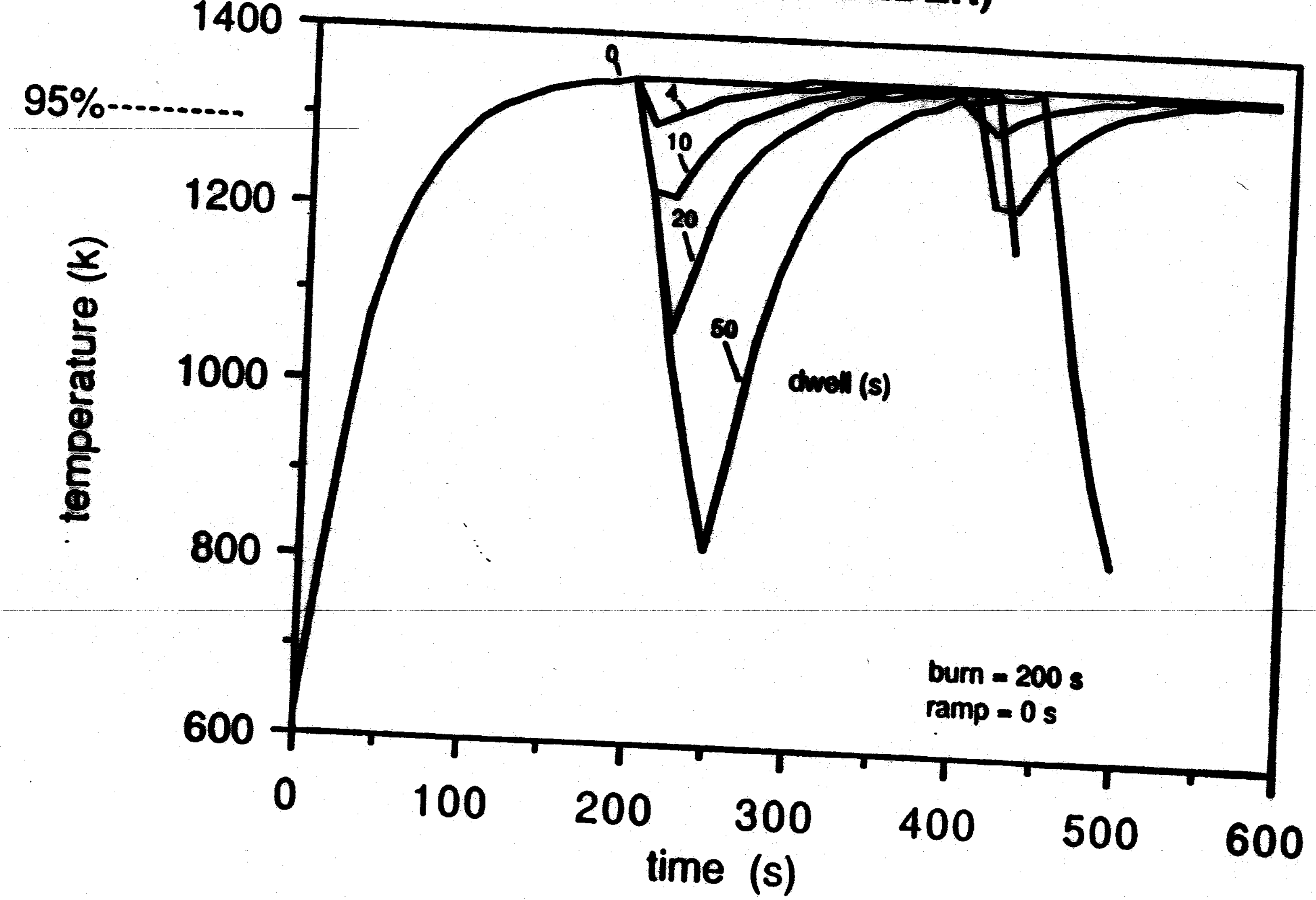
1) Processes with long time constants
2) Crucial dependence on other processes with short time constants

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

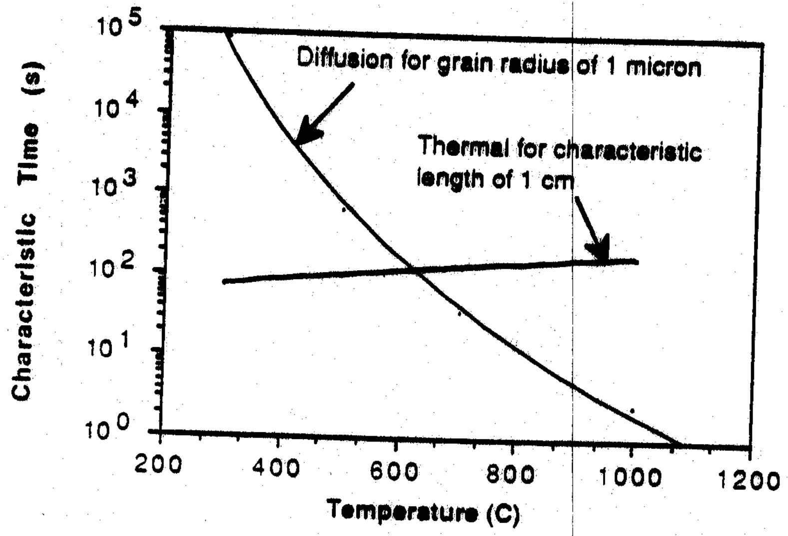
Approximate Characteristic Time Constants in Representative Blankets

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 MWt)	
Li	100 s
LiPb	1500 s
Solid Breeder Bulk Temperature Rise (LiA10$_2$, 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 (LiA10$_2$, 1 μm grains)	
400°C	~6000 s
600°C	~150 s
800°C	~10 s
Surface Adsorption (LiA10$_2$)	~1 hour
Diffusion Through SS316	
800 K	10 days
600 K	150 days
Inventory in Solid Breeder (LiA10$_2$, 1 μm grains)	
67% of equilibrium	hours–days
99% of equilibrium	months
Inventory in Liquid Breeder	
LiPb	30 minutes
Li	30 days

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



Thermal and Tritium diffusion times for $LiAlO_2$ as a function of temperature



Transient Tritium Analysis of $LiAlO_2$ Plate in ITER Test Module Using the MISTRAL Code

Objective: Explore time required to establish equilibrium and observe a **controlled** transient for fission/fusion correlation

Approach: Establish quasi-equilibrium steady-state release and inventory levels, and then observe tritium behavior following the transient.

1200 s burn time and 200 s dwell time are used to establish a quasi-equilibrium after ~8 cycles.

The front of a breeder plate (closest to plasma) of a He-cooled plate design was analyzed, including spatial dependence of temperature.

1. Controlled Temperature Transient

Initial conditions:

- tritium concentration=0
- breeder temperature of 325°C

Transient:

- instantaneous increase in temperature of 100°C

2. Controlled Purge Composition (H_2) Transient

Initial conditions:

- tritium concentration=0
- H_2 concentration in purge gas=0.1%
- breeder temperature of 325°C

Transient:

- instantaneous increase in H_2 concentration to 1%

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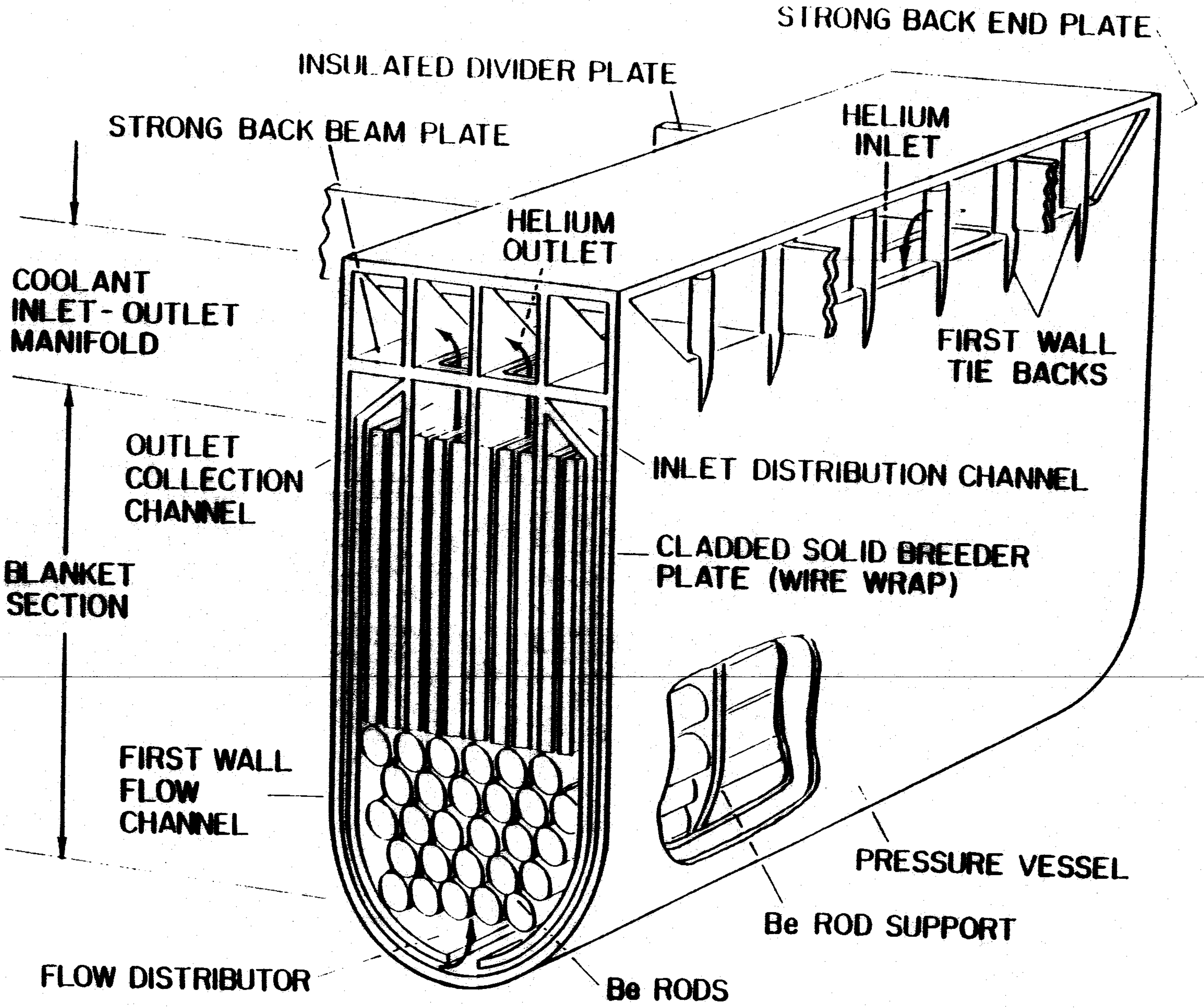
STRONG BACK END PLATE
INSULATED DIVIDER PLATE
STRONG BACK BEAM PLATE
HELIUM INLET
HELIUM OUTLET
COOLANT INLET-OUTLET MANIFOLD
FIRST WALL TIE BACKS
OUTLET COLLECTION CHANNEL
INLET DISTRIBUTION CHANNEL
BLANKET SECTION
CLADDED SOLID BREEDER PLATE (WIRE WRAP)
FIRST WALL FLOW CHANNEL
PRESSURE VESSEL
Be ROD SUPPORT
FLOW DISTRIBUTOR
Be RODS

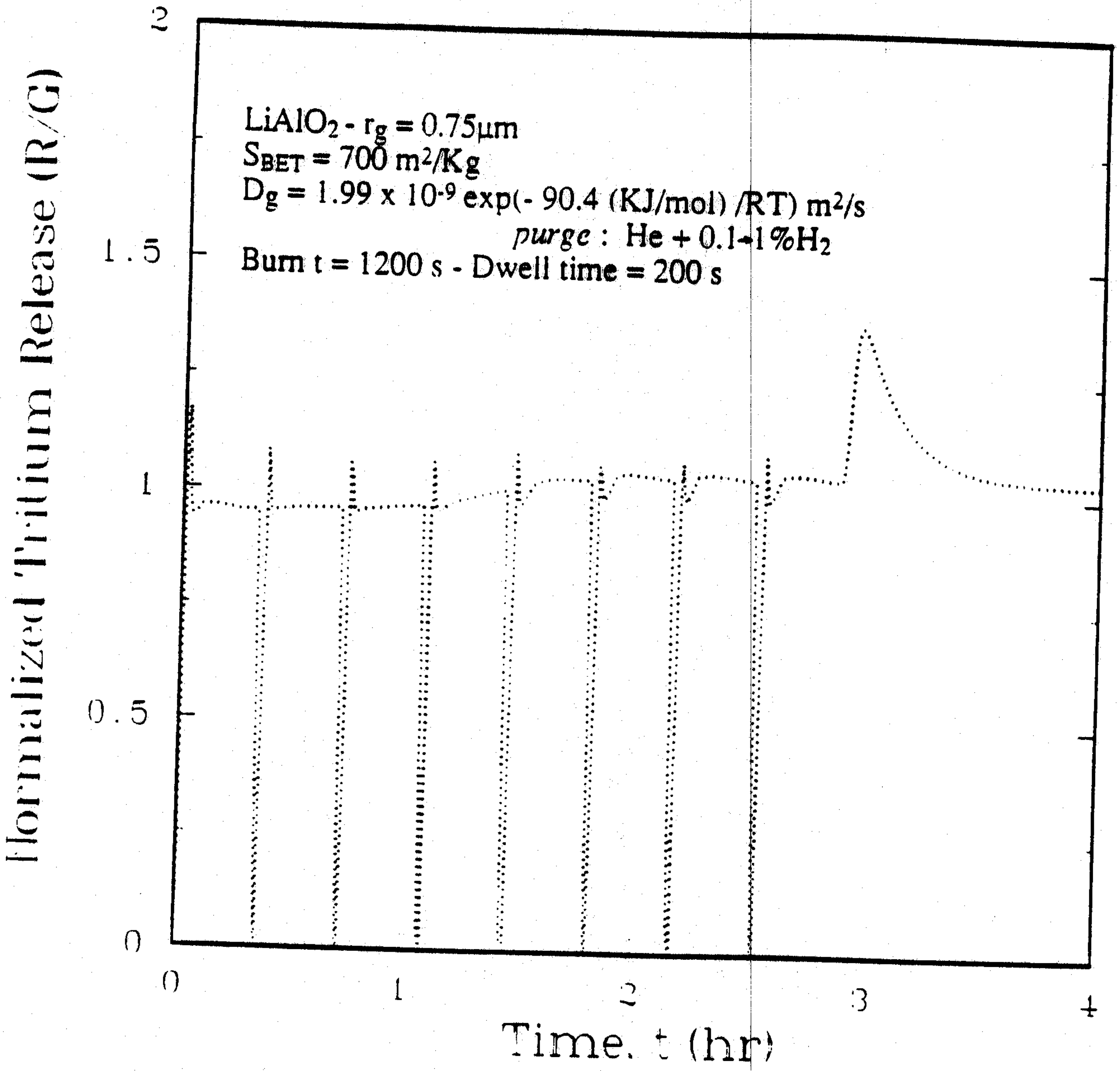

Figure 12. Tritium release history for a 1-cm thick LiAlO$_2$ plate from start-up over a series of operating cycles followed by a controlled purge hydrogen content transient

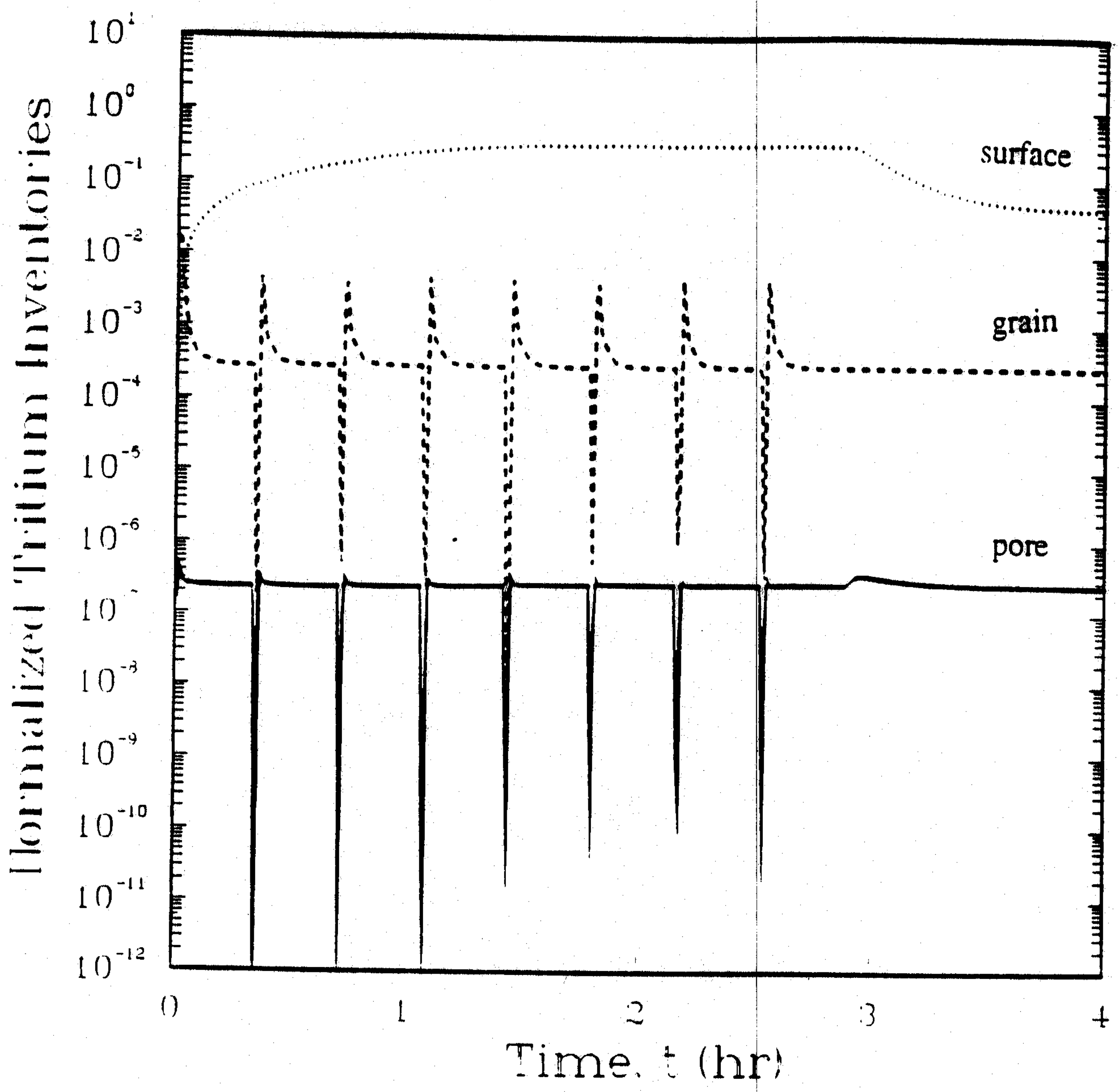

Figure 15. Tritium inventory history for a $LiAlO_2$ plate from start-up over a series of operating cycles followed by a controlled purge hydrogen content transient

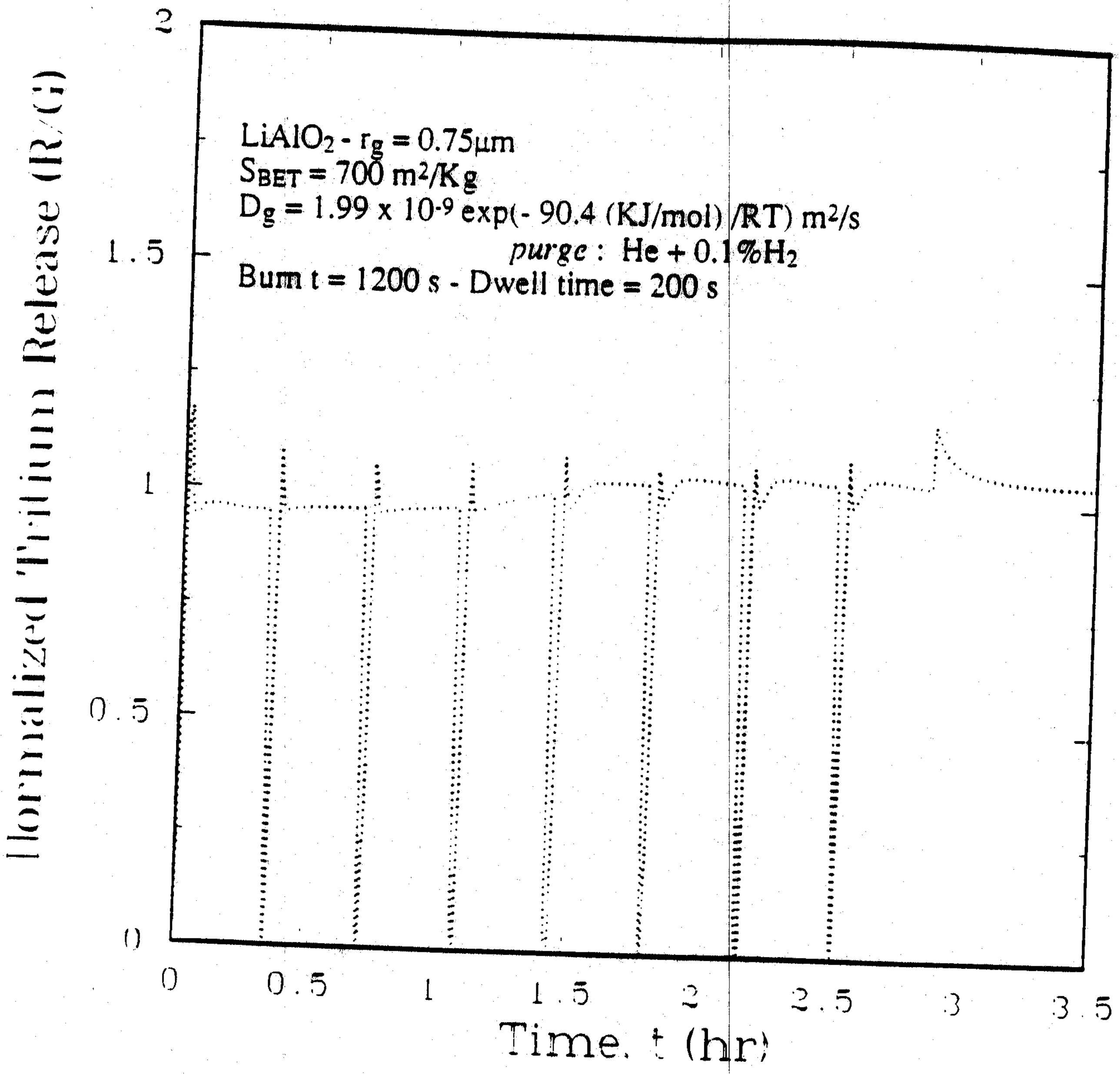

Figure 17. Tritium release history for a $LiAlO_2$ plate from start-up over a series of operating cycles followed by a controlled temperature increase transient

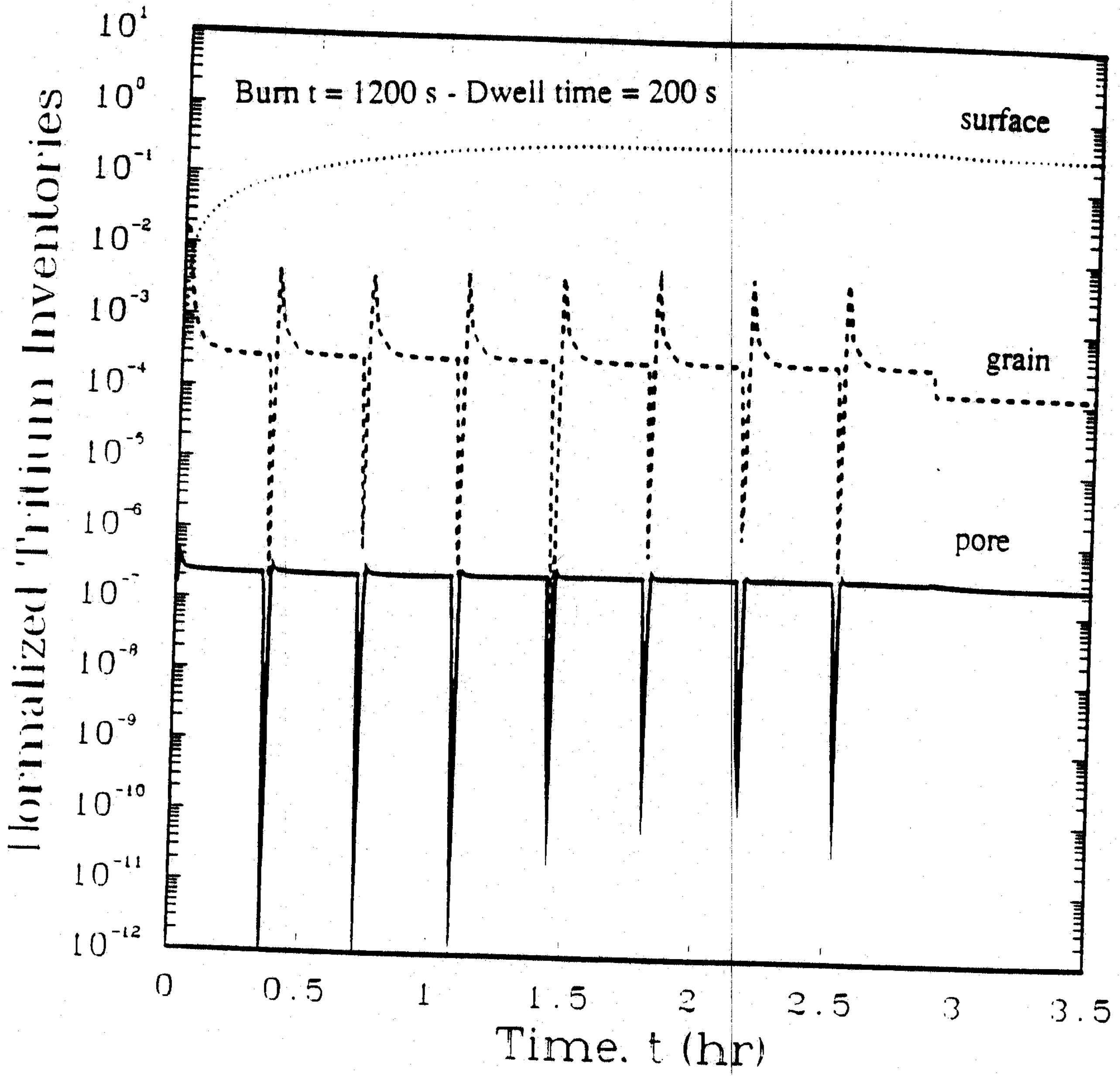

Figure 18. Tritium inventory history for a $LiAlO_2$ plate from start-up over a series of operating cycles followed by a controlled temperature increase transient

Integrated Tritium Analysis
– Conclusions –

- Tritium inventory and release can have significantly different characteristic times, and are both important for establishing quasi-steady-state.

  Tritium release (**without** radiation effects) can approach steady-state quite rapidly, within a single burn time.

  Tritium inventory requires several cycles (up to ~10) to reach quasi-steady-state for a newly inserted solid breeder test article.

- Engineering tests and controlled transient tests have very different requirements

  For engineering tests where the objective is to demonstrate tritium release, the required burn time could be relatively modest (perhaps as low as several hundred seconds).

  The burn time requirement based on performing controlled transients is more severe, since an overall quasi-steady-state must first be reached during the burn time before the transient is initiated. This would ensure that the observed behavior is not affected by changes in other conditions.

Integrated Tritium Analysis Conclusions, cont'd.

- For the $LiAlO_2$ case analyzed, tritium release behavior is caused by different source terms for thermal and purge transients

  Tritium release following a transient temperature increase is mostly due to a decrease in the bulk diffusive inventory

  Tritium release following a purge composition transient is mostly due to a decrease in the surface coverage inventory

  However, in both cases, surface processes play an important role in determining the characteristic time for a return of the tritium release to its steady-state level upon which burn time requirements should be based.

- The characteristic time for purge composition transients is very dependent on the breeder material and microstructure, but can be quite high (of the order of an hour). In this case, the required burn time must be at least 1-2 hours.

  (Note that the calculations were done with relatively high purge hydrogen content and, thus, the corresponding burn time requirement is already low)

Factors Considered in Developing Recommendations

Analysis of Blanket Behavior

Inherent differences between steady and pulsed operation (for any burn time)

Characteristic time constants of physical processes in components and systems

Detailed time-dependent calculations for selected types of tests

Analysis of Test Program Strategy

Examination of test scenarios and relationship to test requirements

Consideration of the various objectives of testing
    - model benchmarking
    - fission/fusion correlations
    - empirical correlations
    - integrated performance measurements
    - concept validation

Loss of Information Resulting from Restrictions on Burn and Dwell Time

Steady-State

scaled testing possible for most key issues

Non-Steady-State

- some irreversible changes in behavior due to cycling, e.g.,
  - stress relaxation/reversal
  - chemical changes
- difficulty interpretting and extrapolating data

Short dwell time (<50 s)

not practical

Moderate dwell time (> 100-200 s)

- unavoidable loss of temp. & temp. gradients
- unavoidable loss of other test conditions during off-burn (some irreversible changes at non-prototypic conditions)
- longer burn time required to attain equilibrium within a single pulse

~200–500 s Burn	**~1000 s Burn**	**~1-3 hour Burn**
difficult to achieve thermal equilibrium – few useful tests can be performed	equilibrium temp. attained except some systems (e.g., LiPb, back of SB) loss of tritium release data for some solid breeders	equilibrium temp. attainable equilibrium T release for most breeders (not inventory)
~100,000 cycles during life	~20,000 cycles during life	<5000 cycles during life

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Recommendations

1. Steady state is very desirable for ITER
   - to qualify DEMO components (assuming DEMO is S.S. or very long burn)
   - to prevent irreversible changes due to cycling
   - to prevent difficulty interpretting and extrapolating data

   If ITER operates in a pulsed mode, substantial additional experiments and model development will be needed to help extrapolate results to DEMO

2. If steady state can not be achieved, then burn time of 1000 s or longer is **extremely important** to:
   - provide thermal equilibrium during tests
   - provide useful information on tritium behavior
   - reduce high-cycle structural effects

3. Burn time greater than ~1 hour provides most of the test value which can be obtained under cyclic conditions
   - ability to maintain equilibrium conditions for long periods of time
   - ability to complete many tests within a single burn time

4. The dwell time should be kept as short as possible; however, if the dwell time is longer than ~10–50 s, then prototypical conditions are unavoidably lost between burn times

COT Requirements and Issues

Ability to perform concept validation tests

- Thermal hydraulics
  Assuming long burn time, thermal-hydraulic measurements can be performed with several back-to-back cycles. Validation under a range of operating conditions can be done within a period of several days.

- Tritium Issues
  Performance validation requires longer testing times compared to thermo-mechanical issues.
  - test time of ~days may be adequate for tritium release
  - longer time (~weeks) is necessary for inventory
  - complete tritium processing system testing requires more time

- Corrosion
  Can take 100's to 1000's of hours to observe mass transfer effects in cooling and purge systems. Changes in temperature and thermal gradient during shut-down can substantially affect chemistry.

- Mechnical behavior, including stress relaxation
  Thermal creep, dimensional changes, element interactions, etc. can have characteristic times of a month or longer.

COT Requirements and Issues, cont'd.

Test Schedule Issues

- It is desirable to complete a test campaign before the machine is shut down for a long period of time

  The operating schedule of ITER is ,uncertain. Low availability may result in long periods of time with no testing. (10% availability could mean 1 week operating and 10 weeks down or1 month operating and 10 months down).

- The objective of concept improvement requires timely data acquisition as input to redesign and construction of new test modules. It is therefore desirable to complete test campaigns as quickly as possible.

Requirements on environmental control

- The level of control over conditions within test modules and ancillary systems during shutdown is uncertain.

Achievable Continuous Operating Time

Long continuous operating time requires good overall device availability:

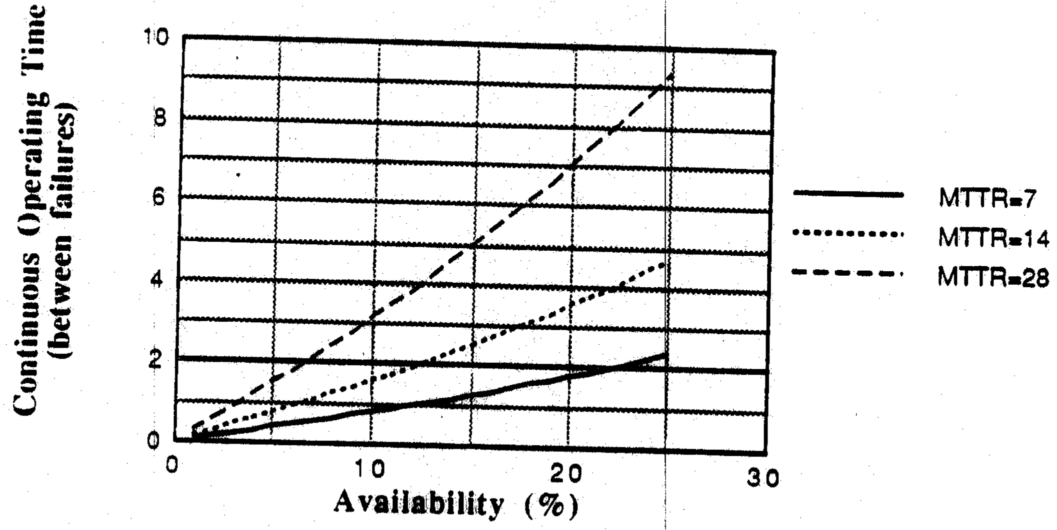
COT of 1–2 weeks is possible if the availability goal of 25% can be reached during the technology phase.

Availability is defined by:

$$A = \frac{1}{1 + \left(\frac{MTTR}{MCOT}\right)}$$

where MCOT = mean continuous operating time (=MTBF)
MTTR = mean time to restart after shut-down

Mean Continuous Operating Time vs. Availability



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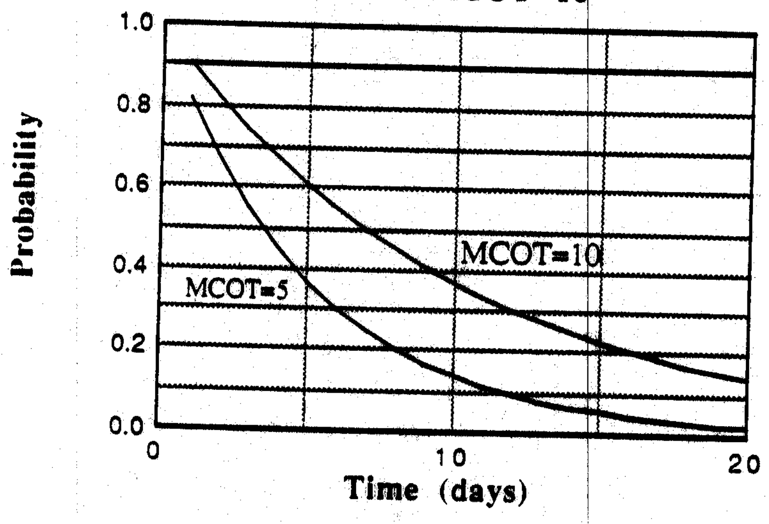
Achievable Continuous Operating Time

If the continuous operating time is driven by the device availability, then periods of continous operation longer than the mean are likely.



Probability of Continuous, Uninterrupted Operation for MCOT=5 and MCOT=10

This treatment is highly simplified. Other factors need to be considered to determine the achievable COT. The schedule of operations for this device will be complicated, and true availability difficult to predict. If periods of intensive testing are planned, then the machine may be suitably prepared to enhance the short-term reliability.

Fluence Goals

Device Fluence ($MW \cdot y/m^2$)

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

Model Fluence ($MW \cdot y/m^2$)

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

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 ($MW \cdot y/m^2$) accumulated at the test module and corresponding accumulation at the device first wall

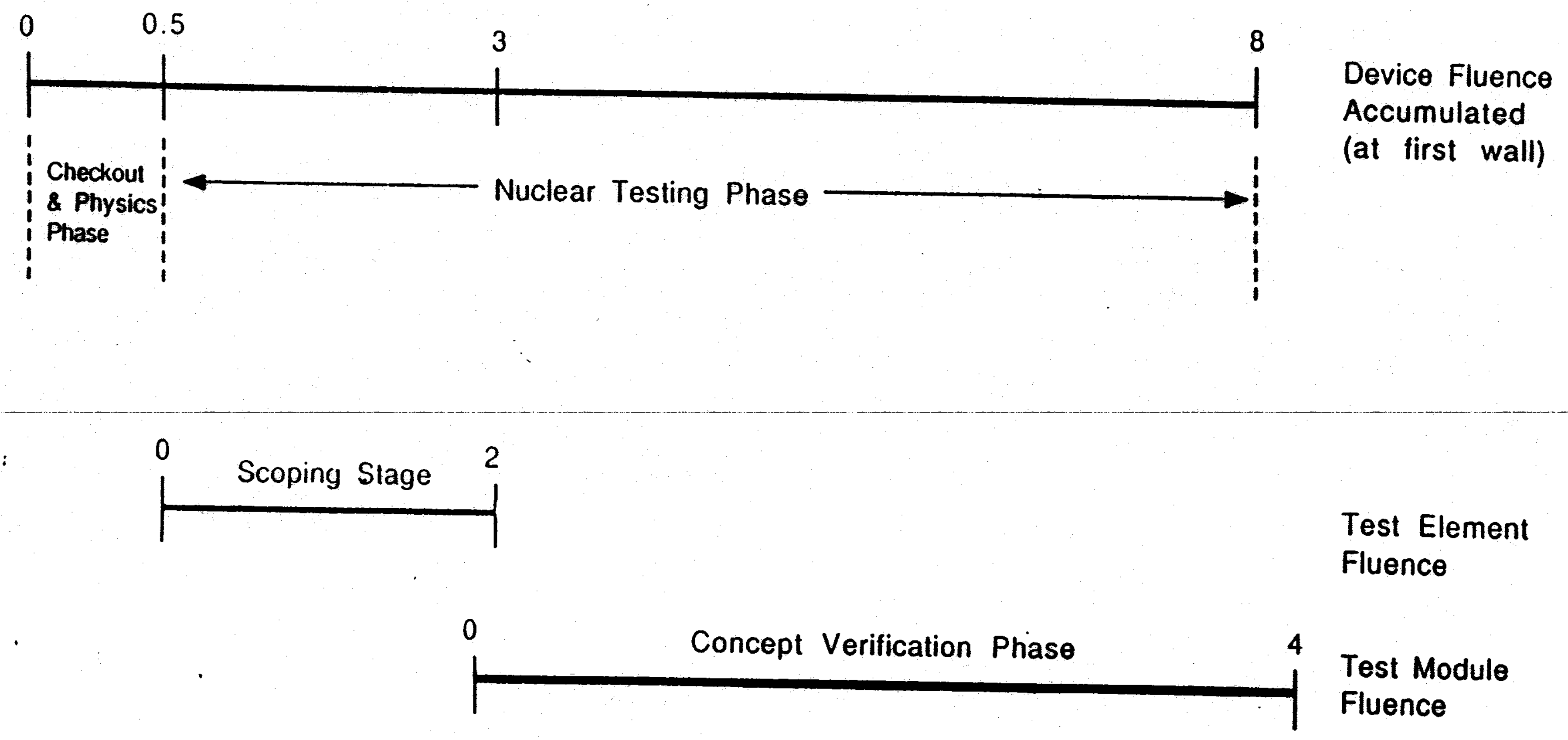
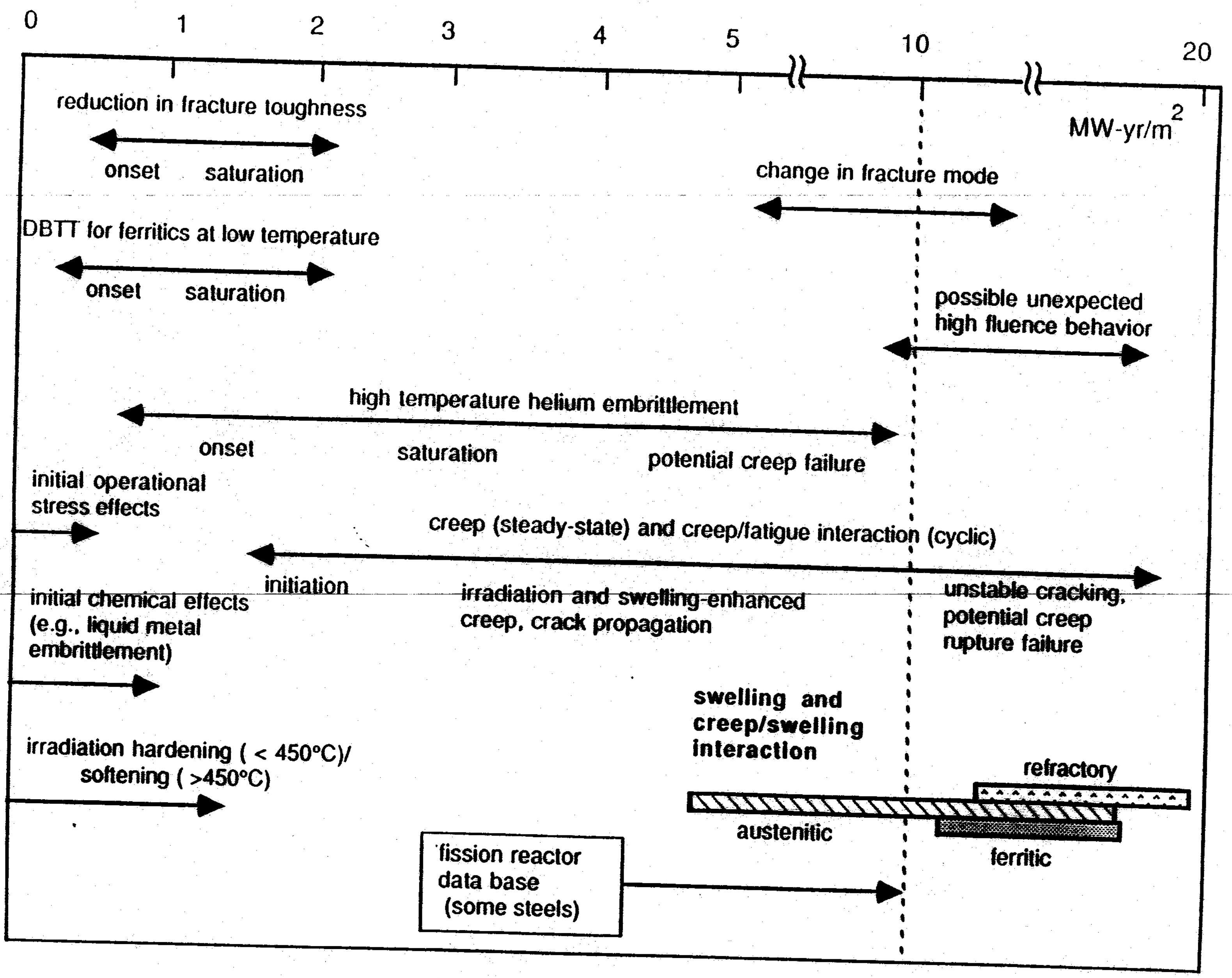
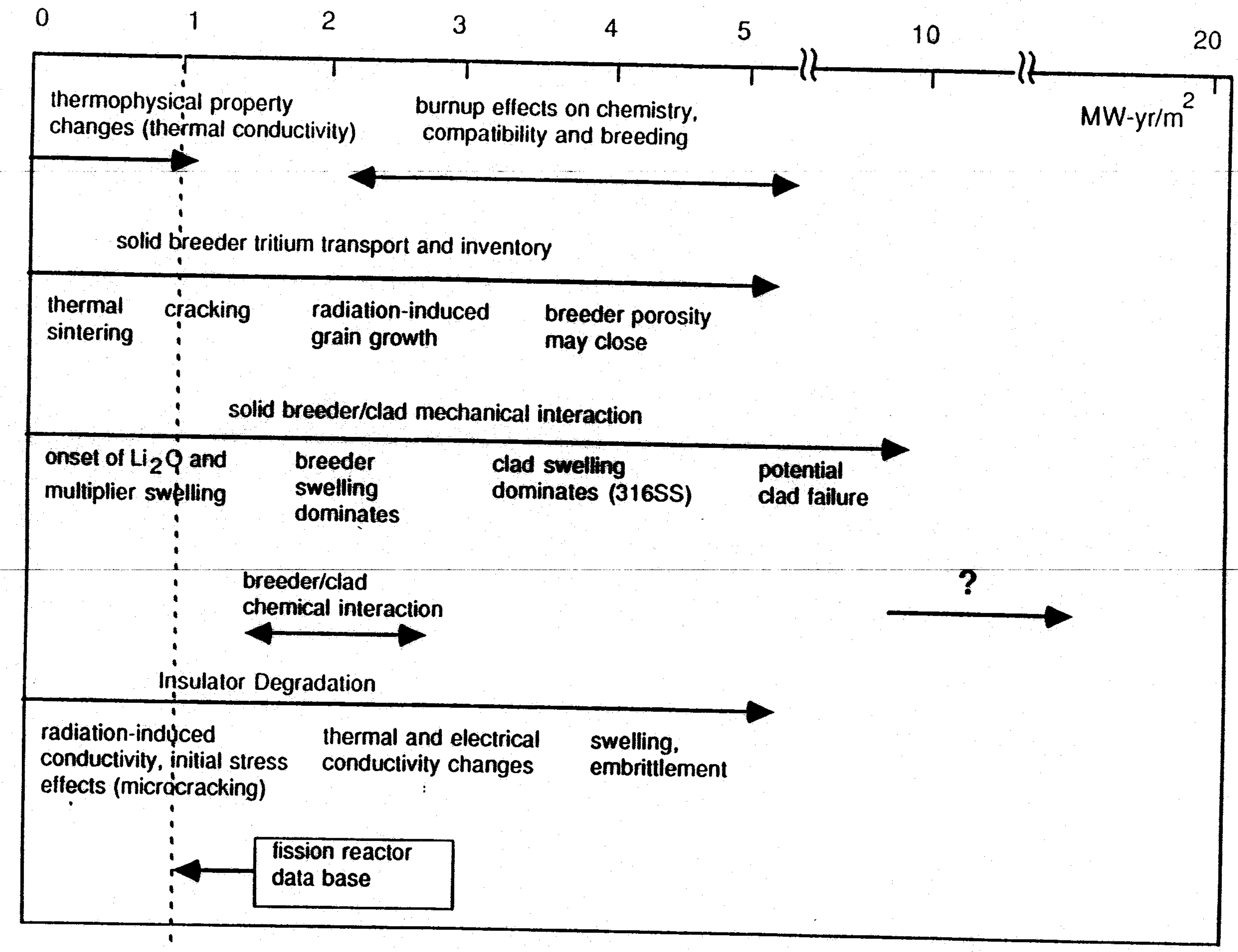


Table 2 Contributors to the Required Fluence Lifetime of ITER

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

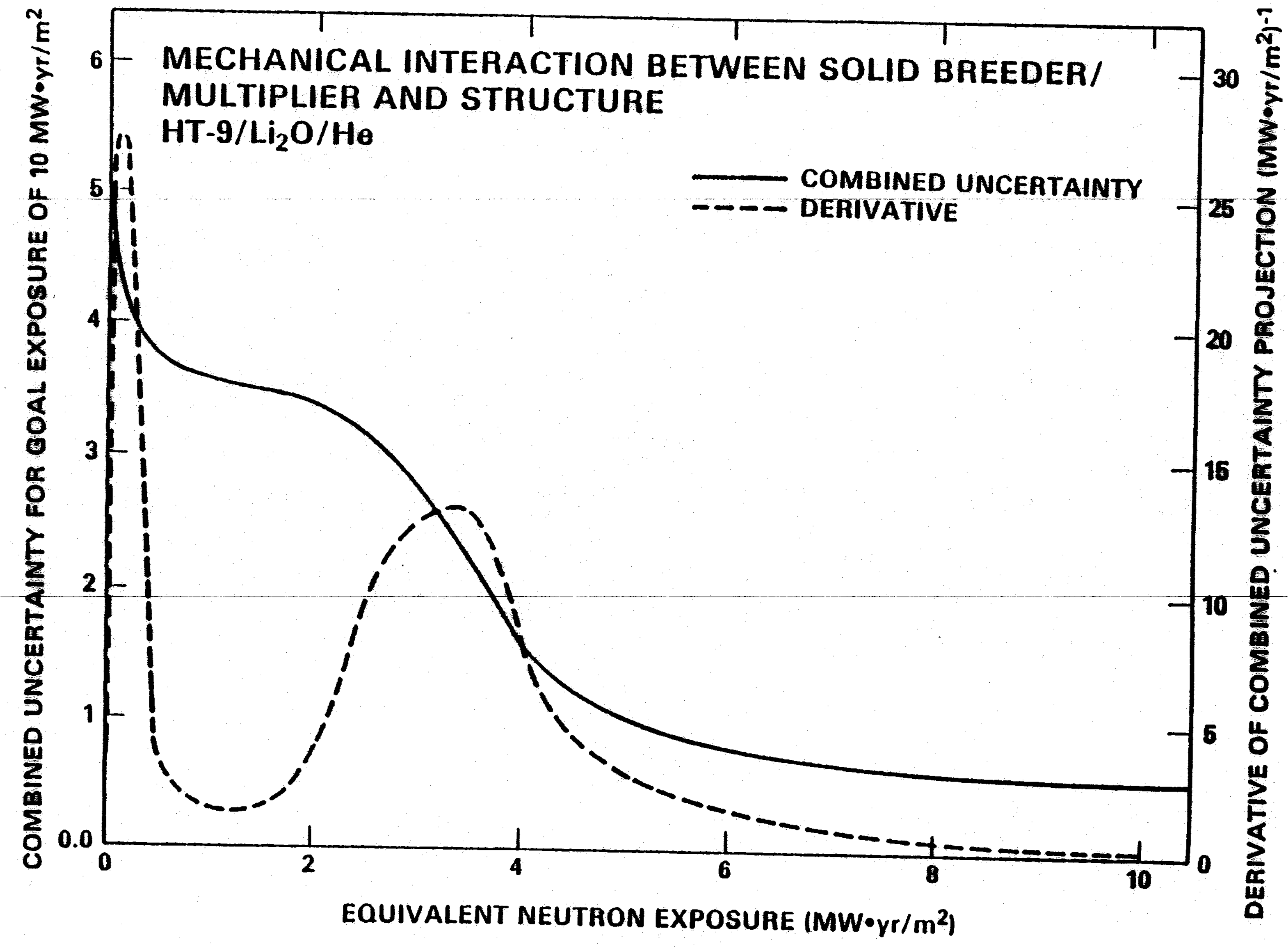


A1: Fluence-Related Effects in Blanket Structural Materials



A2: Fluence-Related Effects in Solid Breeders and Insulators

EXAMPLE OF BENEFIT Vs. FLUENCE



HEDL 8409-219.36

Examples of Key FNT Issues Requiring Substantial Fluence

- 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

Notes

- Substantial fluence needed based on:
  - long time constants for important processes
  - radiation effects
- Can not wait for DEMO: DEMO needs to operate reliably and safely. Reliability growth is the key in DEMO

NEUTRON WALL LOAD

Desired Value Determined by

1) **Engineering Scaling Requirements**
2) **Fluence Requirements (and number of years to complete mission)**

Device Availability %	Neutron Wall Load* MW/m^2	
	Fluence=$3MW.y/m^2$	Fluence=$6MW.y/m^2$
40	0.75	1.5
30	1.0	2
20	1.5	3
10	3	6

*Assume 10 years to complete mission