TIME-RELATED PARAMETERS IN A FUSION ENGINEERING FACILITY FOR NUCLEAR TECHNOLOGY TESTING

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Abstract: An Engineering Test Reactor, to be built in the 1990's (e.g., ITER, NET, TIBER, FER), will have an important mission in nuclear technology testing. A number of device parameters have a large impact on its design, cost and required R&D, as well as the usefulness of testing information. The analysis reported in this paper focuses on two important time-related parameters: 1) plasma burn and dwell times, and 2) neutron fluence. A number of nuclear issues, such as neutronics and radiation shielding, can be tested with a plasma burn time of ~ 500 s. However, the results of analysis show that adequate testing of many key issues in the unique fusion environment of ITER requires striving for steady state operation. Examples of such issues are: tritium recovery from solid breeders, liquid metal corrosion/redeposition, structure response, failure modes, and subsystems interactions. These issues involve a number of processes that have widely varying time constants. Maintaining key performance parameters for these issues within 95% of equilibrium requires very long burn time (weeks) and/or very short dwell time (< 1 s). Minimum desirable fluence goals for ITER have been analyzed. Nuclear testing will most likely proceed in two stages: Stage 1 for scoping tests, and Stage 2 for concept verification tests. The goal of concept verification is motivated by the need to provide definitive data for concept selection of key components such as the blanket. The analysis shows that the device lifetime fluence must be significantly greater than the required fluence at the test module. The recommended design goal for the device lifetime fluence is ~ 6 MW•y/m^2.

1. Introduction

A fusion engineering test facility needs to be constructed in the 1990's as the next step in the development of fusion toward practical applications. Conceptual designs for such a facility have been explored in Europe (NET),[1] Japan (FER),[2] and in the USA (TIBER),[3] and through the international cooperative effort on INTOR.[4] Recently, plans were initiated to design an International Thermonuclear Experimental Reactor (ITER) for possible construction as an international cooperative effort among the European Community, Japan, USSR and USA.

A primary element of the mission of all these devices is the demonstration of the performance of nuclear components at reactor relevant conditions. Successful testing of fusion nuclear components imposes certain requirements on the key parameters and design features of such a device. Such requirements were studied in FINESSE.[5] In this paper, we report on more detailed analysis concerning the requirements of two key time-related parameters: 1) plasma burn and dwell times, and the need for steady state plasma operation, and 2) neutron fluence.

The analysis reported here is applicable to any fusion test device whose mission includes substantial nuclear testing. The name ITER is used here to refer generically to such a class of fusion engineering test facilities.

2. Plasma Burn and Dwell Times and Steady State

This section investigates the nuclear testing requirements of the length of plasma burn and dwell times. The analysis shows that successfully satisfying the objectives of nuclear testing requires striving for steady state plasma operation. Many of the specific examples selected are on solid breeders for clarity of presentation, but there are other equally important examples, e.g., liquid metal blankets.

2.1 Characteristic Time Constants for Nuclear Processes

Operating time requirements are based on analysis of the time dependent responses of all the important blanket phenomena. These include thermal hydraulic, corrosion, structural, tritium, and neutronic performance. The unsteady behavior of the blanket is usually very complex, but often the evaluation of burn cycle requirements can be related to relatively basic time constants for the processes involved. Many engineering processes can be described approximately with an exponential dependence on time, such as:

$$f = f_o(1 - e^{-t/\tau}) \qquad (1)$$

where τ is a characteristic time constant. Time constants for more complex processes can be expressed in terms of the percentage achievement of the equilibrium value (for example, the time to reach 99% of the equilibrium value). A partial list of basic time constants is given in Table 1. The time constants are evaluated using blanket characteristics from the reference designs described in Ref. 6.

Table 1. 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 MWt)	
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 mm 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 mm grains)	
67% of equilibrium	6 months
99% of equilibrium	4 years
Inventory in Liquid Breeder	
LiPb	30 minutes
Li	30 days

The time constants for various processes span a very wide range varying from very fast (< 1 s) to very slow (> months). In general, it is required that the burn time be longer and/or the dwell time be shorter than the time constant for a given process. How much longer or shorter depends on how long it takes to obtain the information at the "equilibrium" conditions. It should be noted that the objective is not merely to reach the equilibrium conditions for the various processes; rather, in most instances, the testing begins when equilibrium is reached.

In order to derive quantitative values for the burn and dwell times, one needs to specify the allowable variation in a given parameter. This depends on the effects of the phenomena or issues explored in testing. Consider, for example, tritium recovery in solid breeders, which is one of the most critical issues. Fig. 1 shows the relationship between the time constant for tritium diffusion in $LiAlO_2$ as a function of temperature. It is clear from the figure that a few percent change in temperature results in an order of magnitude change in the diffusion time constant with a correspondingly large change in the tritium inventory. The sensitivity is largest at the lower temperature (~ 700 K) where the magnitude of the tritium inventory is of great concern. For processes like this, 5% change is an approximate estimate for the maximum tolerable change.

From Equation (1), a 5% allowable variation means that the burn time must be larger than 3 τ to stay within the 95% level. Similarly, the dwell time should be less than 0.05 τ.

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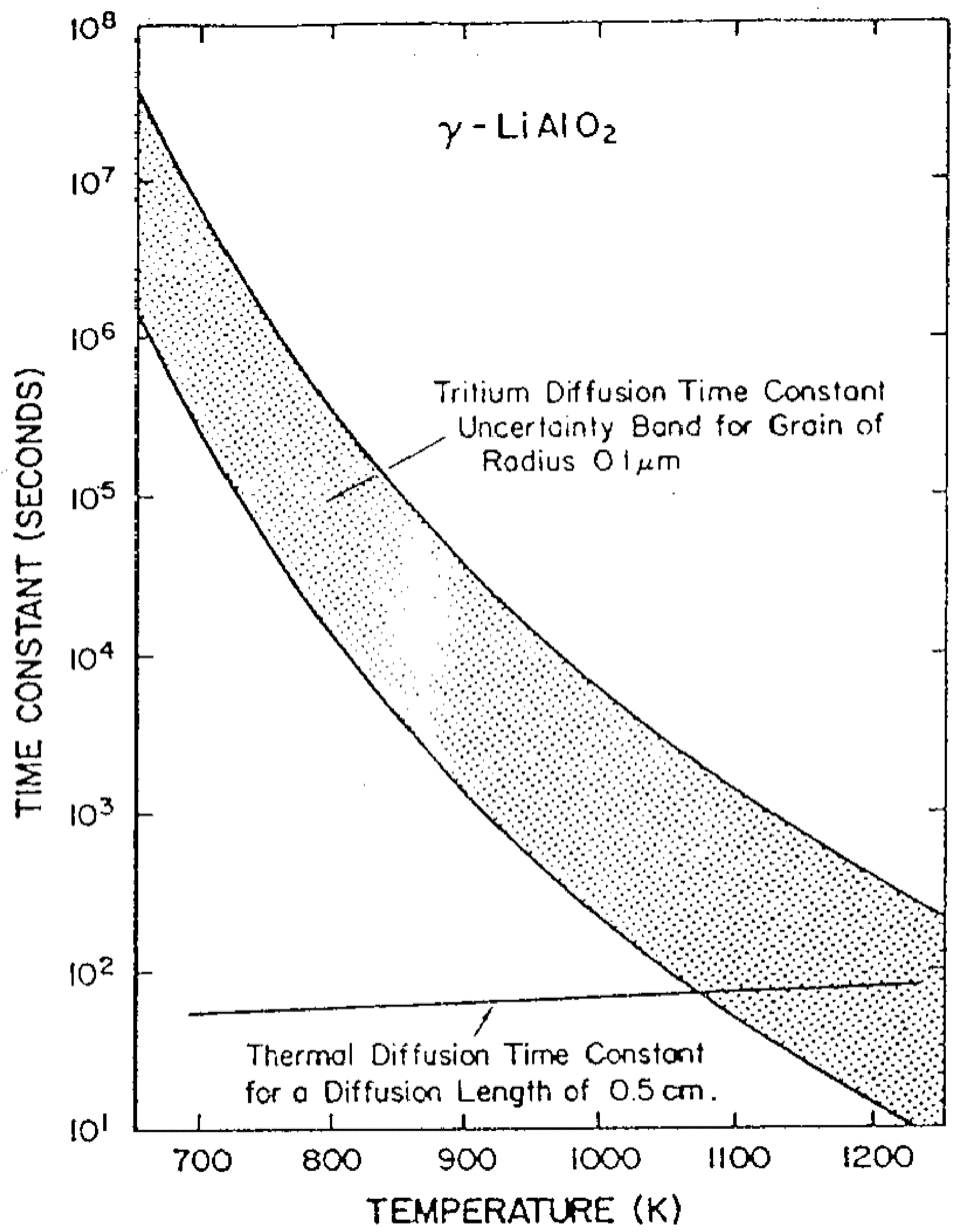

Figure 1. Time constant for tritium and thermal diffusion in LiAlO$_2$ as a function of temperature

The simple information presented above can help in developing an approximate estimate of the required burn and dwell times and to indicate the basic nature of the problems with testing in a pulsed environment. More supporting analysis is given below. Referring back to Table 1, the fast processes such as the fluid flow and heat conduction are in the range of a few to tens of seconds. Thus, a burn time of 100 seconds, which is not difficult to achieve in ITER, is sufficient. However, to stay within the 95% level, the dwell time must be less than one second. This is extremely difficult to achieve in a pulsed device since a typical practical minimum for plasma evacuation, as dictated by the vacuum pumping system consideration, is about 30 seconds or longer.

There are many processes with long time constants in Table 1. These range from hours to months. For a process with a single time constant that is long (hours or longer), a dwell time of a few tens of seconds is acceptable. Unfortunately, most processes with long time constants in Table 1 are crucially dependent on other processes with short time constants. An example is the dependence of the diffusion time constant, which is long, on the temperature of the breeder, which is short, as shown previously in Fig. 1.

Most critical nuclear issues for testing in the fusion environment relate simultaneously to a number of processes with long time constants and other processes with short time constants. Table 2 shows examples of such critical issues involving processes with widely different time constants. The goal is not just to reach equilibrium, but to stay at equilibrium during that test. It takes a long time to establish equilibrium for many critical processes, but a short time to ruin it through variation in short time-related processes. For example, even though corrosion is dominated by long time constant processes, it is also strongly affected by blanket temperatures, which have relatively short time constants. The cyclic effects on temperature could result in significantly different corrosion behavior, such as temperature-sensitive chemical reactions and redeposition. Other examples are tritium release from solid breeders and the structural response, as illustrated in Table 2.

2.2 Transient Thermal Behavior in Solid Breeders

Material temperature changes rapidly with variation in the magnitude and time-related behavior of the heat source due to the short thermal diffusion time constant. These changes in temperature affect numerous engineering processes which are temperature-dependent, as discussed in Ref. 7. To illustrate the effect of cyclic operation on the temperature, the temperature distribution in a typical LiAlO$_2$ solid breeder plate has been calculated.

Table 2. 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 Temperature ~1200 K) (seconds) Temperature Gradient (seconds)	Tritium Diffusion, Low Temperature ~700 K (days) Surface Adsorption and 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 (months)

As an example, Figure 2 shows the temperature variation with time for different dwell times at the point of highest temperature in a solid breeder plate of a typical blanket. The burn time is 200 seconds and there is no ramp up or down time. The temperature drop decreases as the dwell time is reduced, but even for a short 4 second dwell time, the drop in temperature is 5%. As discussed in the previous section, the variation in temperature should be limited to within about 5% to avoid large changes such as in the tritium diffusion time constants.

2.3 Transient Tritium Behavior in Solid Breeders

The tritium behavior in solid breeders is quite complex during pulsed operation since it is affected both by the change in power (i.e., in temperature) and by the change in tritium production rate. It is used here as an example to show how pulsed operation could render the interpretation of data extremely difficult. There are several different mechanisms of tritium transport in solid breeders. They include diffusion through the grain and grain boundary, desorption to the pore, diffusion through the pore and convection by the purge flow.

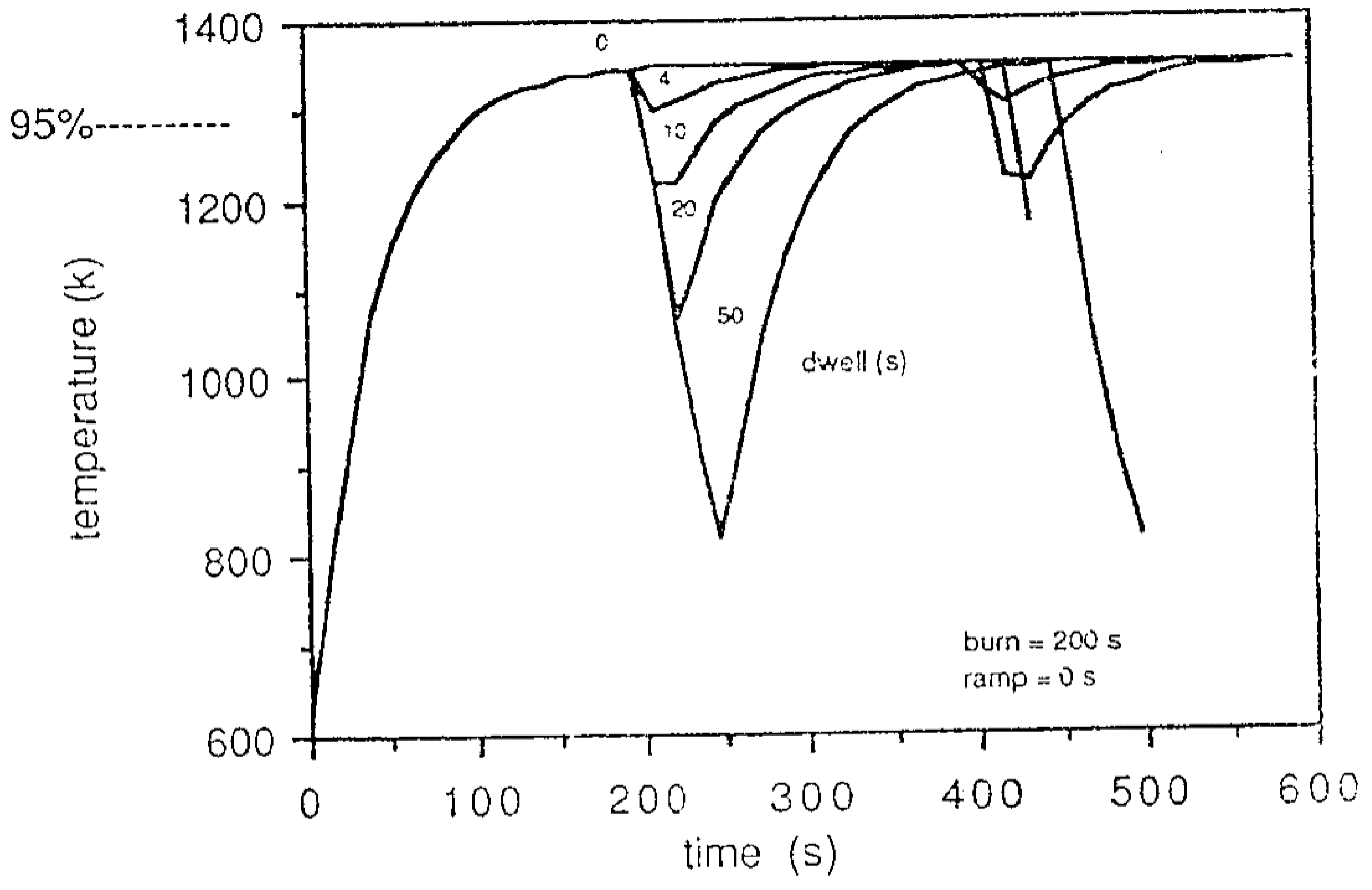

Figure 2. Maximum temperature of a LiAlO$_2$ plate as a function of time for pulsed plasma operation and different dwell times

Figure 3 shows the tritium release rate, expressed as a fraction of the tritium generation rate, as a function of time for different dwell times and a fixed burn time of 200 seconds. The location considered

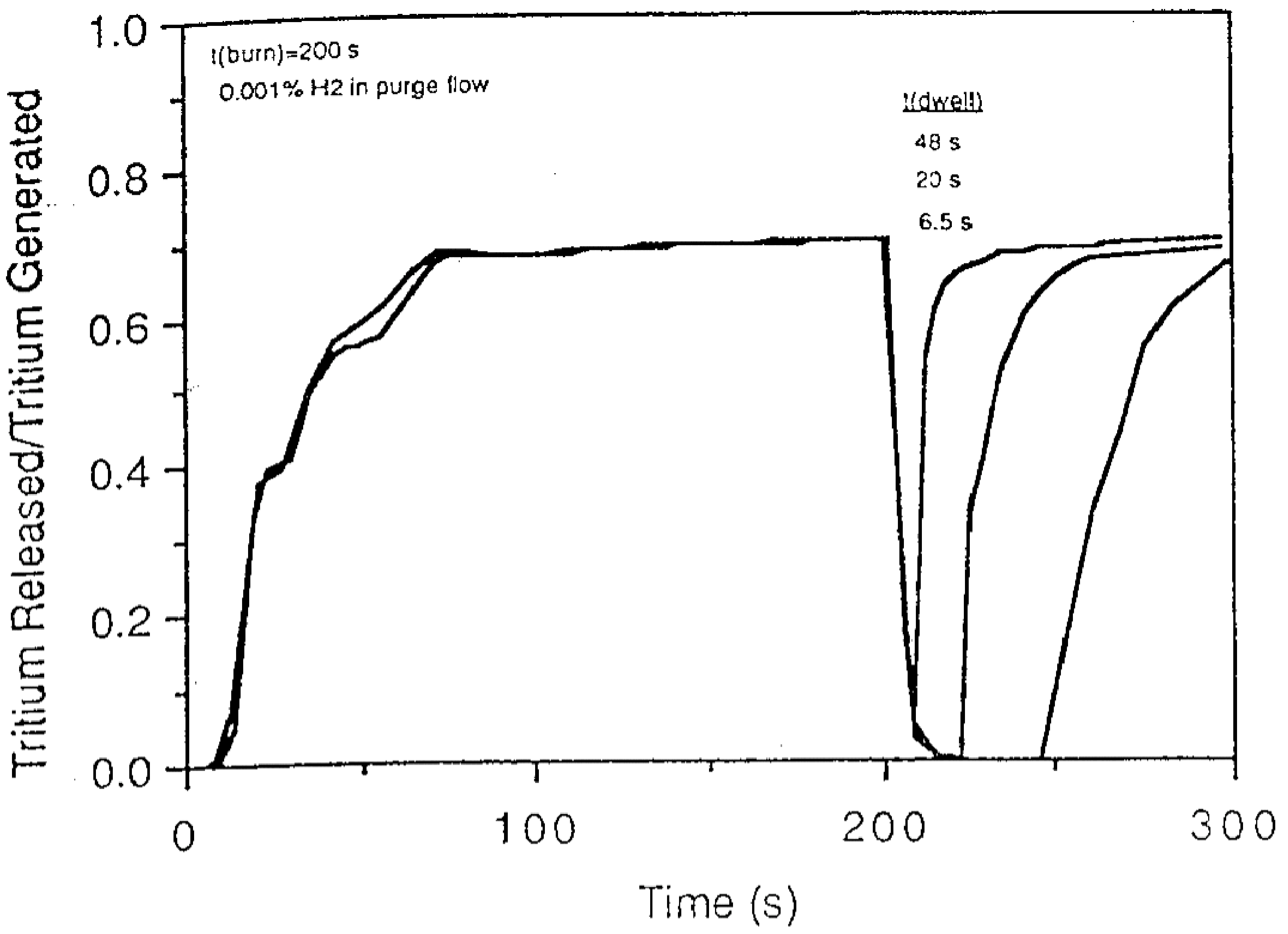

Figure 3. Normalized tritium release rate from the center of the front tip of a $LiAlO_2$ plate as a function of time for pulsed plasma operation and different dwell times

is that of maximum temperature at the tip of the solid breeder plate. This figure relates to Fig. 2, but whereas, in Fig. 2 the temperature drop during dwell time would decrease to about 90% of the maximum temperature, here the tritium release falls close to zero for a short dwell time of 6.5 seconds. This is explained by the combination of the temperature falling, which slows down the diffusive processes and of the tritium generation being instantaneously reduced to zero as the fusion power drops to zero during the dwell time.

Figure 4 shows the tritium release rate as a function of time for a burn time of 198 seconds and a dwell time of 48 seconds. In this case, the tritium release rate shows a cyclic behavior, falling close to zero during the dwell time and rising to stay at a nearly constant value during the burn time. The maximum tritium released during the initial 400 seconds is only about 70% of the tritium generated because of the slower adsorption process. It is estimated that the system will approach true steady state (i.e., tritium released = tritium generated) within about a month,[7] depending on the exact operating conditions and the dominance of particular tritium transport mechanisms.

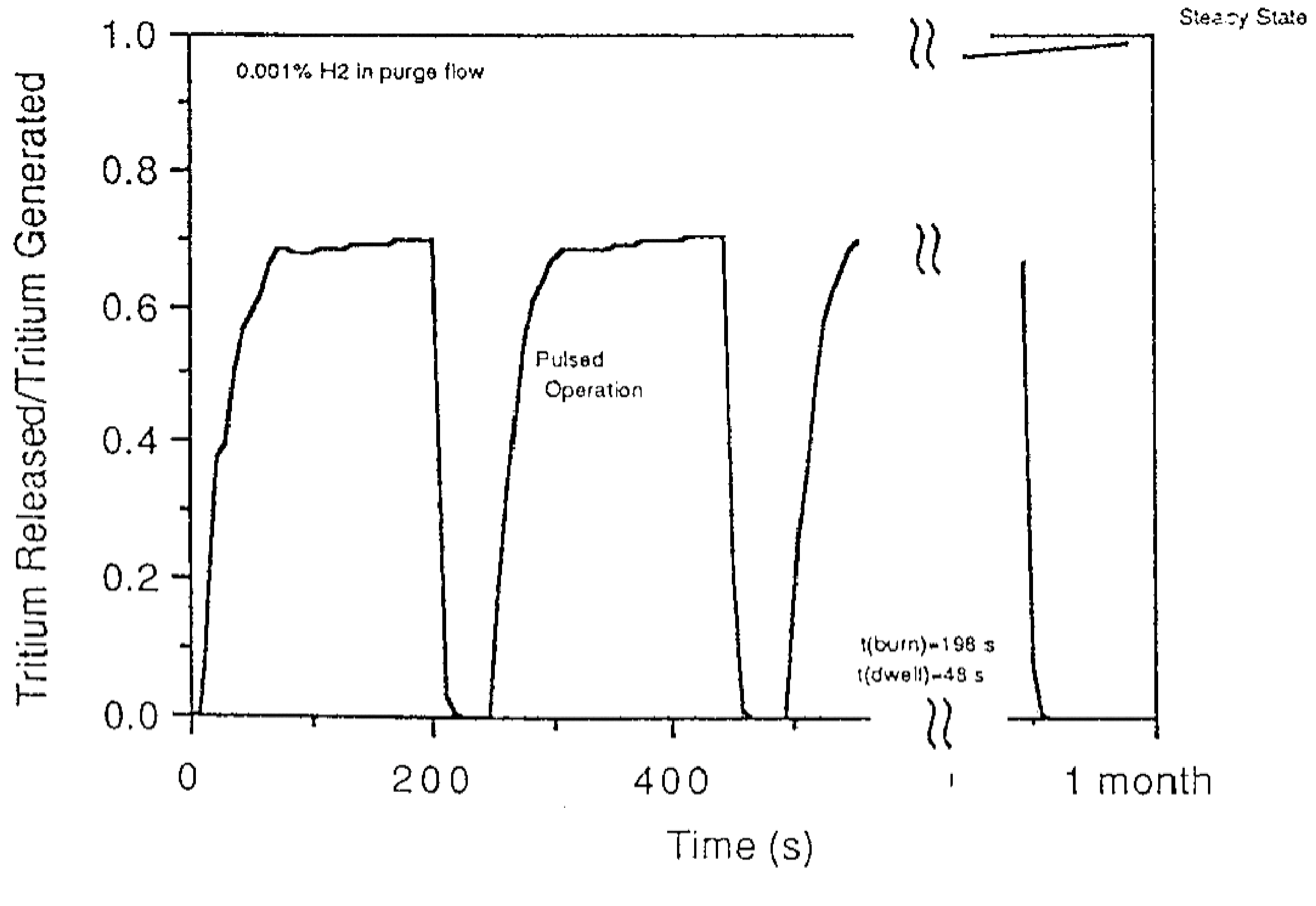

Figure 4. Normalized tritium release rate from the center of the front tip of a $LiAlO_2$ plate as a function of time for pulsed plasma operation

2.4 Summary of Burn Cycle Requirements

The analysis presented here indicates a strong motivation to strive for steady-state operation in ITER. Pulsing substantially degrades the engineering simulation, making it difficult to understand the experimental results and to extrapolate to future fusion devices.

Some issues, such as neutronics, shielding, and some fluid flow processes can be tested with about a 500 second plasma burn. However, many critical issues have longer time constants, and require steady or near-steady operation. These include, for example, tritium recovery from solid breeders, liquid metal corrosion/redeposition and structure response and failure modes.

If a 5% allowable variation in the steady-state level for the different parameters is assumed, then the burn time must be longer than three times the longest characteristic time constant (months) and the dwell time shorter than 5% of the shortest characteristic time constant (seconds). From an examination of the characteristic time constants for the key processes, the burn time should be longer than several weeks and the dwell time shorter than one second. This is essentially equivalent to steady-state operation. This conclusion is not significantly changed even if the allowable variation is doubled or tripled.

Many critical nuclear tests are affected by even very short dwell times. Fast changes (such as nuclear heating, temperature, temperature gradients, and tritium production) seriously impact processes with long time constants such as tritium processes, corrosion and redeposition processes). Even a short dwell time of 4 s results in too large a change in temperature-dependent processes. Based on these observations, the plasma dwell time should be near zero, unless tests can be completed during the burn period within one cycle.

3. Fluence Goals

ITER is unique in that it will be the first test device capable of supplying the flux and volume of fusion neutrons needed for fusion nuclear component testing. These neutrons are the primary source of nuclear heating and tritium production, as well as radiation-induced changes in behavior. One measure of the neutron exposure is the device fluence, which is defined here as the product of the average neutron wall load (at the first wall) and the operating time.

The device lifetime fluence is much greater than the fluence at the test modules for three reasons. First, no test module is inserted for the entire lifetime of the device. There will be at least two sequential stages of nuclear tests: scoping and concept verification. Different test articles will be used in each stage. Second, the fluence received at the test module is lower than that at the first wall because of the attenuation in the first wall, test module enclosure (if the module is not directly exposed to the plasma), and other in-vessel components, such as graphite protective tile. Thirdly, some test elements and modules are likely to fail and will need to be removed for repair or replacement, representing lost irradiation time for these elements and modules.

3.1 Neutron-Induced Changes in Component Behavior

Many new behaviors are expected to occur in components simultaneously exposed to neutrons, high heat loads, stresses, magnetic fields, and other conditions in the fusion environment. Specific reactions resulting from neutron radiation include tritium and helium production, atomic displacements, and transmutations. Since the irradiation environment in fusion devices is largely unexplored, the potential for unanticipated or unknown phenomena to occur in components is great.

The benefits of numerous fusion tests will depend on the ability to supply adequate neutron exposure to the test articles. Changes in behavior often result from interactions of different effects (such as creep and swelling, or radiation and chemical embrittlement), or different parts of a component (such as solid breeder/clad interactions); hence, a knowledge of material property changes alone is not sufficient to determine test requirements.

While it is probably not possible to achieve end-of-life fluences in test modules, many of the key radiation effects can be observed earlier in life. For structural materials, this includes changes in hardness and fracture toughness, high temperature helium embrittlement, and irradiation creep. These phenomena are all important in establishing design limits and lifetime estimates for the blanket. In general, the effects activate gradually, so it is impossible to specify an exact fluence to observe them; however, it is anticipated that important observable changes in behavior will occur in the range of 3-4 MW•yr/m^2. Figure 5 summarizes some of the important phenomena predicted to occur as a function of fluence in structural materials.

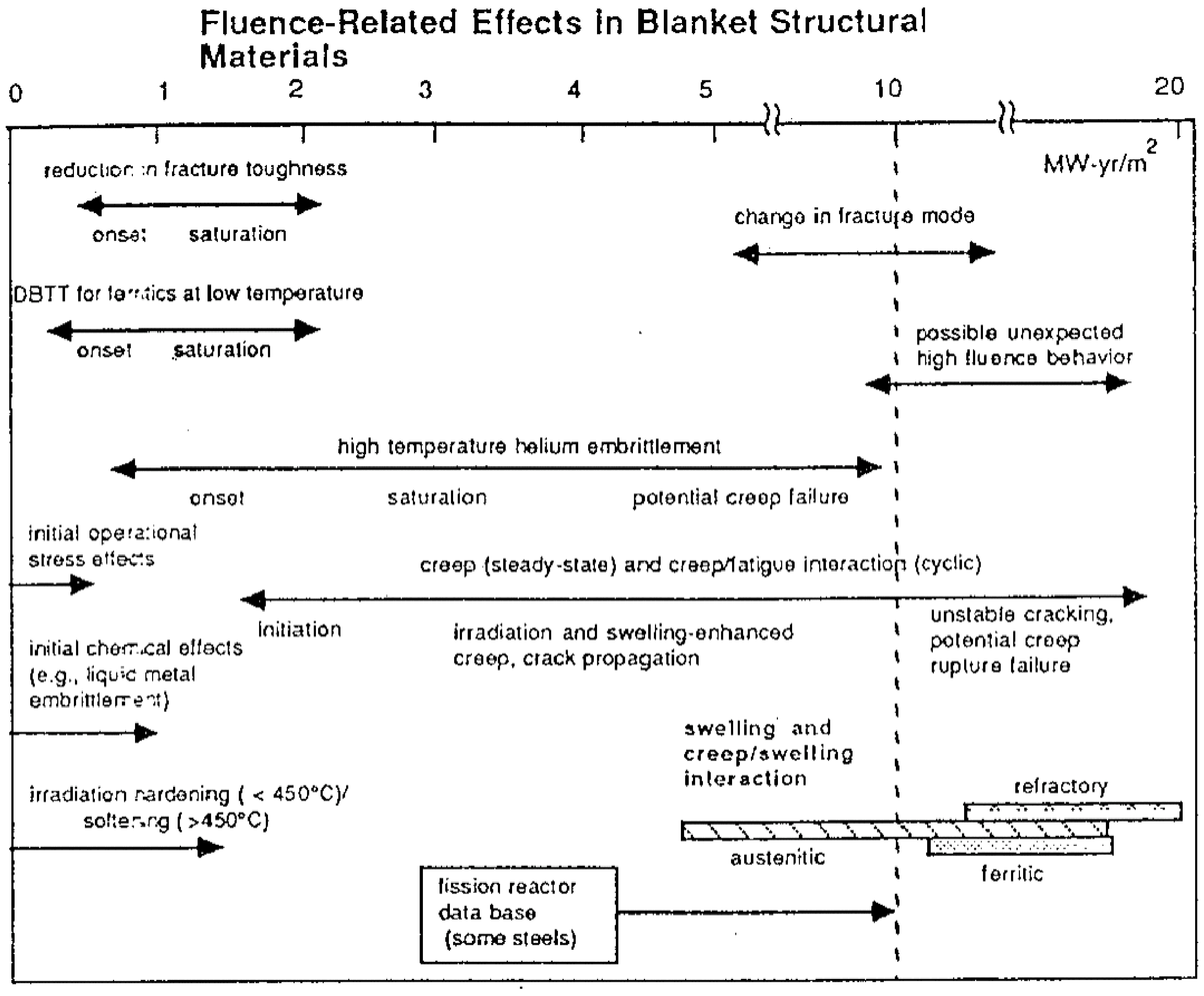

Figure 5. Fluence-related effects in blanket structural materials

In solid breeder and some plasma-facing materials, radiation effects are expected to occur somewhat earlier. However, the desire to observe interactions between different phenomena or different elements of a design leads to higher goal fluences than for the activation of individual effects. Several of these effects are expected to occur in the range of 3-4 MW•yr/m^2, for example, solid breeder/clad mechanical interaction and radiation-induced changes in tritium transport. Higher fluences are obviously better - the consequences of fluence effects are generally not fully felt until long after initiation of the phenomena. Figure 6 summarizes changes in behavior as a function of fluence in solid breeders and ceramics.

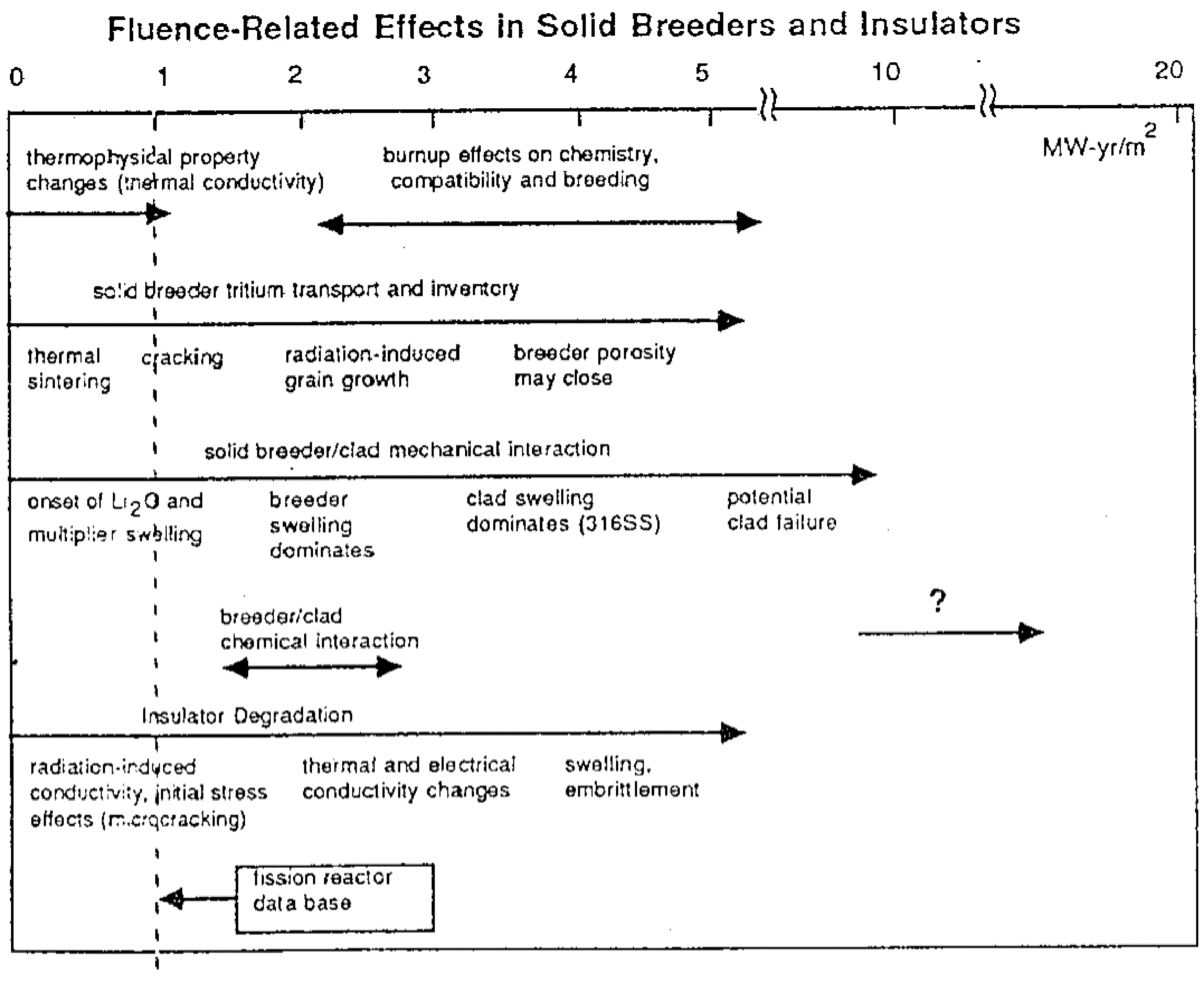

Figure 6. Fluence-related effects in solid breeders and insulators

Component behavior under irradiation is very complex, poorly understood, and strongly dependent on material choices, design configuration, and operating conditions. Temperature is especially important in determining behavior under irradiation. Some effects may be dominant in one particular material or temperature range, and nonexistent in another. A general lack of data makes the existence and severity of radiation effects even more difficult to predict. A more detailed study of radiation effects in specific fusion components is needed to further refine these goals.

3.2 Estimate of Required Device Lifetime Fluence

ITER will be operated in at least two phases: Phase I for checkout and physics testing, and Phase II for nuclear testing. During Phase I, some limited nuclear tests can be performed for a short period of time (e.g., neutronics tests). However, most nuclear tests require reproducible (steady-state) plasma, and will have to wait until Phase II.

During Phase II, nuclear tests will most likely proceed in two stages: Stage 1 for scoping tests, and Stage 2 for concept verification tests. Stage 1 will be the first opportunity for fusion tests. Small size test elements will be used to scope a number of blanket concepts in the fusion environment and calibrate results to those obtained from non-fusion facilities. While it is desirable to obtain exposures in the range of 3-4 MW•yr/m^2, the risk of testing to lower fluences may be acceptable, since a number of different concepts will still remain following the scoping stage. Many initial effects are expected to occur between 1-2 MW•yr/m^2, which will aid in the selection process.

In Stage 2, larger size and more prototypical test modules will be inserted for a small number of blanket concepts. The objective of Stage 2 is concept verification, which will require at least 3-4 MW•yr/m^2 of exposure.

Table 3 summarizes the various contributions to the fluence goal. The various stages of testing are considered, as well as an allowance for attenuation and possible test module failure and replacement. Overall, a device fluence goal of 6 MW•yr/m^2 is strongly recommended.

Table 3 Contributors to the Required Fluence Lifetime of ITER

Contributor	Approximate Fluence (MW•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

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