ENGINEERING SCALING AND QUANTIFICATION OF THE TEST REQUIREMENTS FOR FUSION NUCLEAR TECHNOLOGY[a]

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ABSTRACT

For integrated testing of fusion nuclear components, it is likely that the test device parameters will not match the device parameters of a full scale fusion reactor because of cost constraints. This will result in changes in the behavior of the test module and limit the ability of the test to resolve key nuclear issues. However, it may be possible to modify the test module in order to retain the important aspects of the issues over a range of test device parameters. In order to understand and quantify this range and set requirements for blanket testing, analyses of several aspects of blanket operation were performed. The results suggest that a useful integrated test device should have at least 1 MW/m^2 neutron wall load, 0.2 MW/m^2 surface heat flux, 20% availability, 500 s burn length, and 0.5 m^2 by 0.3 m per test module.

INTRODUCTION

Resolution of the fusion nuclear technology issues requires a range of experiments from property measurements and phenomenalogical tests, to complex interactive and integrated tests. The simpler experiments require a limited set of environmental conditions to be similar to those in an operating component. These tests have been surveyed recently.[1,2,3,4] The present paper, based on the FINESSE project,[1] is primarily concerned with the more integrated tests.

These tests address the issues of interactions among effects and among physical regions, including identifying unexpected interactions or their absence, quantifying complex phenomena that must be correlated in a global sense, and verifying performance predictions. These tests can establish the basic feasibility of the design concept ("proof-of-principle"), identify failure modes, and provide operational information (including instrumentation and control needs).

Ideally, such experiments should be conducted under actual operating conditions (e.g., thermal field) of the component in a fusion reactor. Otherwise, for example, there may still be unanticipated effects or failure modes when the component is placed into commercial operation. However, it is almost certain that the test device parameters (e.g., neutron wall load) will not match those of a fusion reactor because of cost constraints. Thus, these experiments raise the question of how close the test device needs to reproduce reactor parameters. For example, can testing a breeder module at a power density of 10 MW/m^3 be made to provide a reasonable simulation of reactor operation at 60 MW/m^3?

It is possible in many cases for which the phenomena are sufficiently well understood to modify the design (e.g., coolant flow rate) of the test module in order to recover the important aspects of the testing issues, even though the test device parameters are not the same as the commercial reactor. This process is known as engineering scaling. However, a change of device parameters beyond certain limits often results in the inability to maintain "act-alike" behavior. One of the goals of engineering scaling is to identify and determine these limits or test requirements. This procedure is often difficult because behavior usually varies continuously as a function of the device parameters, without an abrupt change in performance.

Thus, there are degrees of simulation that can be considered. The simplest is to keep the same regime (e.g., Re > 2000 for turbulent flow). The second is to maintain partial behavior (e.g., beginning-of-life

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stresses, but not end-of-life). Finally, for particular phenomena, it is necessary to closely duplicate the full behavior.

Blanket testing in a fusion device is emphasized here. Most of the unresolved nuclear testing issues involve the blanket, and a fusion test device provides the largest number of operating conditions - even if not full-scale. However, the results are more universally applicable. For example, an understanding of first wall thermal-hydraulic behavior under scaled conditions also applies to other high heat flux components such as limiters. Furthermore, a requirement on surface heat flux should apply regardless of the particular test facility.

For the analyses, four specific reference blankets were chosen; the MARS[5] self-cooled LiPb/HT-9 mirror blanket, the BCSS[2] self-cooled Li/V toroidal/poloidal flow tokamak blanket, the BCSS helium-cooled Li_2O/HT-9 design, and the BCSS water-cooled $LiAlO_2$/PCA design. These blankets were considered not because they necessarily represent the best designs for all possible reactor concepts; rather, they serve as tools to identify the problems of scaling plausible blankets. They cover a range of design features of general interest such as liquid versus solid breeder and, consequently, their consideration should lead to conclusions that are applicable to a large class of candidate blankets.

CRITICAL INTEGRATED TESTING ISSUES

In order to understand and quantify the scaling behavior and test requirements, analyses of blanket operation were performed, including thermal-hydraulics, structural mechanics, tritium recovery, neutronics and corrosion. It was not possible to treat all known issues and interactions due to resource and data limitations, nor was it possible to determine the requirements for retaining all the unexpected interactions (other than requiring operation in a fusion reactor). Instead, a limited number of specific but important issues were considered - particularly those known to be interactive or complex. If at least these effects are preserved, then their interactions should also reasonably be present. The results thus identify a minimum bound on the test requirements that should only be further restricted with additional analyses of other issues or interactions.

The most critical integrated testing issues for blankets[1,6] are thermomechanical performance and failure modes, tritium inventory and recovery (especially in solid breeder blankets), and materials compatibility (especially in liquid metal blankets). The device parameters expected to have the largest effect on these issues are summarized in Table 1.

Thermomechanical Performance

The uncertainties in thermomechanical performance and failure modes relate to both the complex thermal and structural loading conditions and response. While the structural behavior is clearly dependent on thermal conditions (e.g., thermal stress load, temperature dependent creep response), the thermal behavior can also be influenced by the structure (e.g., temperature profile in solid breeder changing due to cracking of breeder under stresses). Consequently it is important to preserve both thermal and structural behavior in an integrated test.

Tritium Inventory and Recovery

The basic processes describing tritium inventory, recovery and permeation from solid breeders are uncertain. These processes are very dependent on temperature, chemistry and breeder microstructure, and consequently on any interaction that affects these. Neutron radiation is anticipated to have a strong influence on all the factors. For example, swelling may cause cracking and increase the breeder temperature; burnup changes the local stoichiometry; and sintering changes the amount of porosity. Tritium recovery and permeation in self-cooled liquid metal designs are not a major concern in terms of the

Table 1. Device Parameters with Major Influence on Operation and Testing.

- Heat Source
  - Surface
  - Nuclear (power density)
- Neutron Radiation
  - Fluence
  - Flux
  - Spectrum
- Geometry
  - Test port surface area and depth
  - Total test surface area
  - Test device geometry
- Operating Time
  - Burn/dwell time
  - Continuous operating time
  - Availability
- Magnetic Field
  - Strength
  - Geometry

blanket, although a tritium extraction process needs to be developed and tested.

Materials Compatibility

Materials interactions depend on the chemical environment and the transport processes. The primary chemistry factors are the temperature and the basic material constituents. One important aspect of integrated testing is that it should realistically reproduce types and levels of impurities, which may dominate the compatibility behavior at long times. Transport processes additionally depend on flow conditions, geometry, magnetic field and possibly temperature or concentration gradients. Nuclear radiation affects both transport (e.g., producing trap sites which slow down diffusion) and chemistry (e.g., transmutation).

SCALING AND TEST REQUIREMENTS

It is no small task to determine how to preserve these complex phenomena and interactions simultaneously under altered test conditions. However, some scaling considerations and test requirements for these issues are discussed below, according to the device parameters outlined in Table 1. More details of the scaling procedures are given in Ref. 1.

Heat source

A primary device parameter is the heat source since this is the main energy input which activates most processes and interactions. A primary test requirement is to preserve the blanket temperature profiles. This is important for maintaining thermal stresses, material strength, structural response to radiation damage, transport processes and local thermochemistry.

The thermal field depends on the profile and magnitude of the heat sources. If the heating profile changes significantly (e.g., a very small plasma relative to the test module), it is difficult to retain more than local or average temperatures. If the module heat source is reduced, it is often possible to adjust dimensions (e.g., thickening the member will increase the temperature rise across it) and coolant flow conditions to compensate and so preserve the temperature profile (but not the temperature gradient).

However, there are limits to even this temperature control. For example, the temperature profile along the perimeter of lobed first walls, common in high coolant pressure solid breeder blankets, has a different dependence on the surface and volumetric heating. Consequently, it is not possible to arbitrarily change the heat source and still be able to compensate by changing dimensions and coolant flow rate (Fig. 1). In particular, both surface and volumetric heating should be changed such that their relative contribution to the first wall temperature rise is maintained. This leads to a minimum surface heat flux requirement for testing tokamak first walls, and a maximum surface heat flux for testing mirror first walls, of about 0.2 MW/m^2 at 1 MW/m^2 neutron wall load.

Within the solid breeder region, the temperature profile can be maintained at reasonably lower power densities. However, as the dimensions increase to accommodate low heating rates, axial conduction and azimuthal asymmetries around coolant channels will become more significant, while the temperature gradient (and associated pore migration or segregation processes) will decrease; leading to a lower limit on the heat source.

A possibility for enhancing nuclear heating in solid breeder blankets at low neutron wall loads is to add uranium. Calculations[7] indicate that on the order of 1% uranium is required in order to boost the power density from 1 MW/m^2 effective neutron wall load to the reference 5 MW/m^2. This amount of material is likely to affect the tritium behavior of the breeder, if not the materials compatibility.

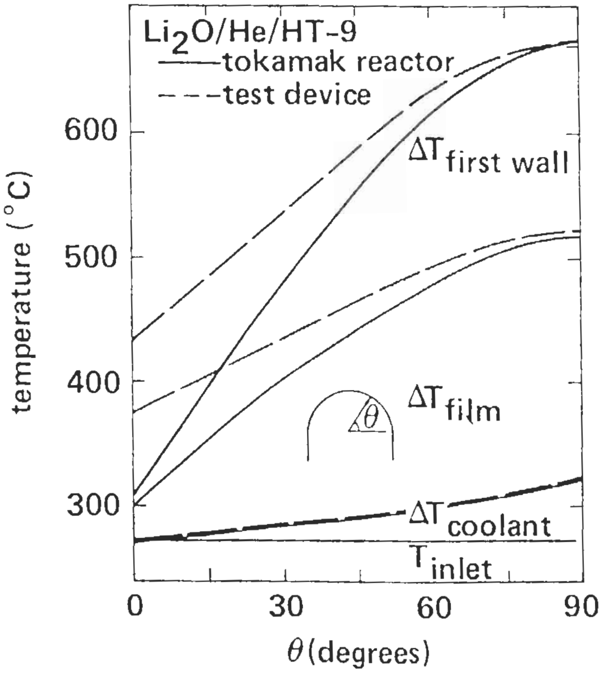

Figure 1: Heat source effect on the BCSS Li_2O/He/HT-9 first wall temperature profile (reactor at 5 MW/m^2 neutron and 1 MW/m^2 surface heat load; scaled test module at 2.5 and 0.1 MW/m^2).

Within liquid metal blankets like the BCSS toroidal/poloidal flow concept, it should be possible to preserve the first wall temperature differences without any nuclear heating if there is sufficient surface heating and coolant temperature control. However, uncertainties in liquid metal behavior may require appreciable bulk heating, at least in a thermal-hydraulic experiment.

For other liquid metal designs, such as the MARS mirror blanket, bulk heating is more important for two reasons: first, surface heating is a much less significant in mirrors (0.1 MW/m^2 rather than 1 MW/m^2); and second, the level of coolant temperature control available in the toroidal/poloidal flow design is not present in the MARS poloidal tube.

Neutron Radiation

Neutron radiation is both an energy source and a mechanism for change in properties and behavior. The effects of nuclear radiation include property changes, creep, swelling, sintering, transmutation and transport effects. These effects are primarily a function of the accumulated dose, and are not readily scalable to lower fluences. Test requirements can be identified based on achieving fluences where significant changes in behavior occur or saturate.

In general, the uncertainties in key properties associated with the strength and fracture behavior of the structural materials are significantly reduced after neutron testing to 1-3 MW-yr/m^2.

Irradiation creep has a strong impact on the middle-of-life structural response. First wall studies including irradiation creep indicate that, as shown in Fig. 2, irradiation creep changes the stresses over about 5-10 dpa or 0.5-1 MW-yr/m^2.

Structural materials typically exhibit an incubation period of low (or zero) swelling, then undergo a transition to the "breakaway" swelling regime. Based upon very limited data and theoretical considerations, it is anticipated that the incubation fluence will be 5-8 MW-yr/m^2 for PCA, and over 10 MW-yr/m^2 for HT-9 and V-15 Cr-5Ti. Consequently, if the blanket goal fluence is < 10 MW-yr/m^2, then the "breakaway" swelling behavior of HT-9 and V-15Cr-5Ti is not an issue. If the goal fluence is 20 MW-yr/m^2, then the projected uncertainties for swelling and related structural behavior will remain large until measurements are performed 2-4 MW-yr/m^2 beyond the onset of swelling.

The solid breeder/clad interaction is another structural behavior for which fluence is likely to be important. For example, the changes in several of the key properties with neutron exposure are given in Fig. 3 for the BCSS Li_2O/He/HT-9 blanket. Thermal expansion and cracking/redistribution of the Li_2O acts primarily in the early operation of the component (0-0.2 MW-yr/m^2). After about 2 MW-yr/m^2, most of the strength and fracture property changes have saturated, and the major properties responsible for the interaction are the balance between Li_2O swelling and the creep of Li_2O and HT-9 (not shown in the figure), until HT-9 swelling becomes important above 10 MW-yr/m^2.

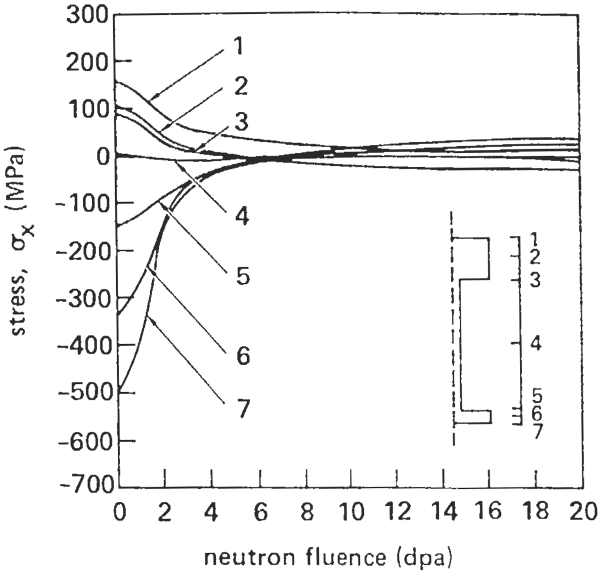

Figure 2: Stress relaxation in BCSS lithium self-cooled tokamak first wall due to irradiation creep.

For structural materials and coolants, neutron damage over the blanket lifetime is not expected to cause significant overall transmutation. For solid breeder and multiplier, however, typical end-of-life burnups are about 20% for natural Li_2O blankets, and up to 100% in heavily multiplied blankets. Assuming 10% burnup as a reasonable goal to establish effects due to appreciable transmutation, then solid breeder blankets should be irradiated to 1-5 MW-yr/m^2.

Geometry

Geometry is both a test device parameter (e.g., first wall radius, test volume), a handle for "scaling" the test module (e.g., increasing thickness to preserve temperature profile at reduced heating), and a prime

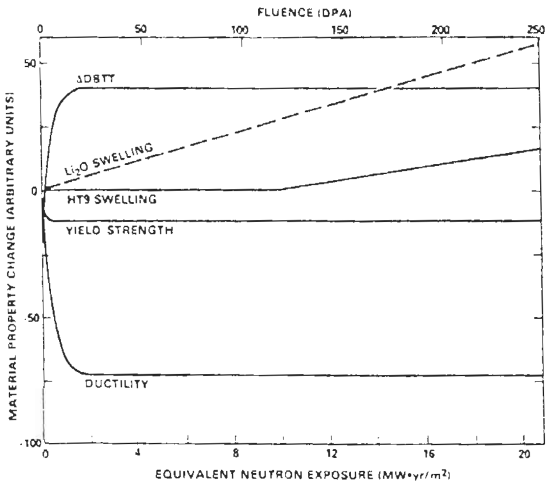

Figure 3: Variation of key properties with fluence for Li_2O/clad interaction.

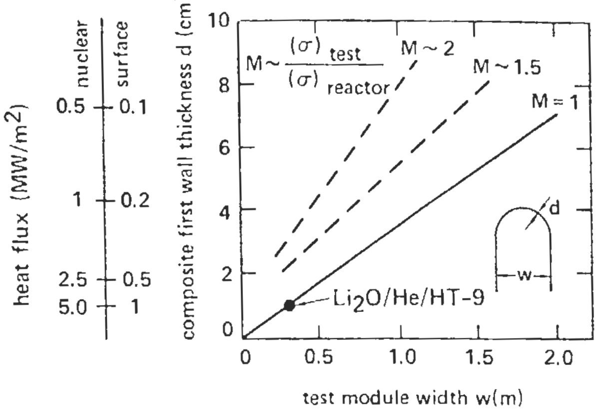

Figure 4: Test module width and device heat source effects on BCSS Li_2O/He/HT-9 tokamak first wall elastic stresses.

factor in blanket behavior.

Consider the structural behavior. It has been shown[1] by theory (for elastic stresses) and by example (for radiation effects) that, for the same loading conditions (temperature profile, pressure stresses, fluence profile), the structural response is similar if geometric aspect ratios are preserved. Note that cycling effects were not considered.

For solid breeder blankets, where the coolant heat transfer and pressure drop characteristics are reasonably well known, it is possible to consider scaled structural response at substantially different heating rates by increasing the member dimensions as the heat source is reduced, and correspondingly altering the coolant flow rate. However, there are geometric limits to this modification. For example, consider a lobed first wall under a reduced heat load. If the module first wall width is increased in proportional to the first wall thickness increase needed to maintain the temperature profile (so preserving geometric ratios), then the elastic stresses are preserved (Fig. 4). However, if there is limited test volume available, then it may not be possible to make the first wall as wide as desired, leading to appreciable changes in the stress profile.

Preserving the structural response to radiation damage depends on maintaining the temperatures, elastic loading, fluence and fluence profiles. The radiation damage profiles are difficult to scale because the neutron mean free path is relatively independent of geometry. Thus, a consequence of increasing first wall dimensions (to preserve temperature profiles at reduced power, for example) is that neutron attenuation eventually becomes significant and leads to an appreciable variation in flux, and consequently creep and swelling rate, across the first wall. For example, an increase in thickness by a factor of four (roughly a factor of five reduction in heat source for a tokamak first wall) leads to a factor of two variation in flux or fluence across a 1 cm composite first wall. The impact of altered fluence profiles on testing is illustrated in Fig. 5, which compares the MARS blanket response due to irradiation swelling with the response of a smaller test module that has the same initial stresses. The responses are quite different.

Geometry also influences thermal-hydraulic behavior, particularly in liquid metal blankets where the velocity profiles may depend not only on the immediate channel dimensions, but also on the channel wall thickness and the structure outside the channel. Thus, changing dimensions may be a less desirable scaling option.

Liquid metal flow in magnetic fields can have extremely long entry lengths - the entire blanket may be in a state of development in which heat, mass, and momentum transfer coefficients are rapidly varying. (Note that it is precisely this simultaneous variation in many phenomena that is desired in integrated testing.) As a result, shortened channels may not be able to simulate the entire thermomechanical state of the blanket. Reducing the flow velocity (i.e., preserving the fluid residence time) or the channel dimensions may

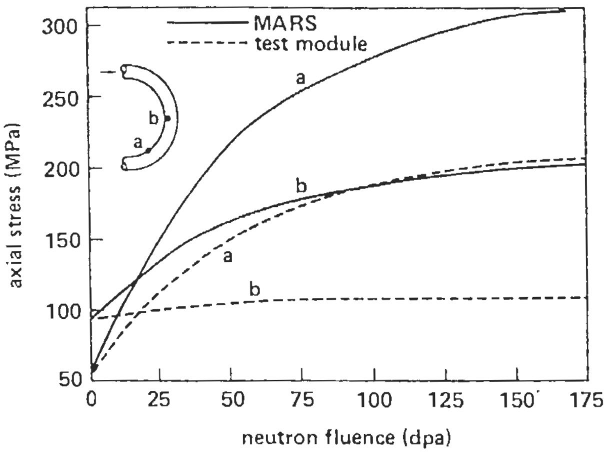

Figure 5: Effect of fluence gradient on swelling and creep behavior of MARS blanket at two locations along the tube.

help to recover the entire development region for some of the important transport processes.

As another example, diffusion-limited mass transfer in liquid metal systems (i.e., at low flow rates or magnetic field strength) depends heavily on the solubility of the corrosion products, which is a very temperature-dependent property. Changes in the average temperature as well as the temperature rise along the coolant channels will affect corrosion. In order to observe the initial corrosion rate in the channel entrance, the saturation as corrosion product builds up in the coolant, and the final dependence on the temperature gradient, a minimum channel length is necessary. In some cases, these competing factors may exist over half of the channel length. It has been shown that, by reducing the coolant velocity in proportion to the decrease in channel length (again preserving the fluid residence time), the same corrosion rate profiles can be obtained.

Finally, consider how much space must be provided for each test module. Full blankets range from 0.3 x 2 m^2 for some solid breeder designs, to 9 x 1 m^2 sector-sized liquid metal blankets. If a representative subsection can be identified, then this would reduce the needed test volume. The technical question concerns the influence of structural and thermal-hydraulic boundary conditions.

In an integrated test, it is important to preserve the multiple channel nature of most blankets to allow for possible interactions such as flow oscillations. At least three channels are needed to allow the center one to have some representative boundary conditions, and about ten channels can be shown to have flow redistribution characteristics similar to a much larger number of channels. These considerations, plus the expanded dimensions usually needed to preserve temperatures at reduced heating rates, suggest test modules of at least 0.5 m^2 surface area. If global eddy currents strongly affect the velocity profiles in a liquid metal blanket, then modelling of the entire blanket may be required.

The depth should be sufficient to include first wall, multiplier (if any) and breeder zones, plus space for coolant manifolds. It is also desirable to have enough depth for appreciable variation in neutron flux and fluence. A 14 MeV neutron mean free path is about 10-15 cm.

The influence of test device geometry is not large for most tests, as long as the first wall radius is not smaller than the dimensions of the module first wall - in which case differences in the nuclear and surface heating profiles along the first wall, relative to the reactor, will occur.

Operating Time

Ideally, tests should be operated under steady-state or long pulse conditions as in the reference reactor. Cycling is generally undesirable since it introduces uncertainties in interpreting experimental results and can activate processes that are not normally significant such as fatigue, crack growth or thermal ratchetting.

While long pulses may be difficult to achieve in a test device, each pulse should at least extend beyond any significant startup transients and allow the phenomena of interest to reach measurably towards equilibrium. In practice, this might be achieved by single, relatively long burns or a series of pulses maintaining quasi-equilibrium conditions for the needed cumulative operating time. There are several time constants that can be considered: flow, thermal, tritium transport, corrosion and structural.

Flow time constants are typically 1-30 s; 1 s for solid breeder coolant, 6 s for solid breeder purge, and 30 s for liquid metal coolants. These residence times are usually preserved or increased in test modules designed to retain corrosion behavior, entry length effects, or overall temperature profiles under reduced test module size and heating.

Thermal time constants are on the order of 1 minute for most blankets (full size), except for some solid breeder designs (e.g., BCSS $LiAlO_2/H_2O/Be$) where the rearmost breeder unit cells may take upwards of an hour to reach thermal equilibrium. Any change in dimensions in a scaled test module will correspondingly change the thermal response time.

Pulsing is of particular concern for solid breeder blankets since it may alter the temperature profile, which in turn will strongly affect the tritium behavior. For the BCSS Li_2O/He plate breeder, the resulting burn and dwell time requirements are shown in Fig. 6 as a function of neutron wall load. This curve is based on requiring at least three thermal time constants during the burn, and at most one thermal time constant during the dwell period, which calculations show is needed in order to preserve a quasi-steady temperature field similar to the steady-state reactor case.

The verification of tritium behavior is accomplished by monitoring the tritium release rate and final inventory. Generally, 67% of the equilibrium release rate occurs early in the test and can be accurately measured, but 99% recovery or inventory requires substantial operating times (Fig. 7). Present calculations assuming hydrogen addition into the purge stream indicate that intragranular diffusion is the largest contributor to the total inventory. Consequently, the Li_2O and $LiAlO_2$ designs will probably achieve 67% of the equilibrium release rate within about one minute, independent of the neutron wall load. In order to reach inventory equilibrium, however, total operating times of minutes, days and months are needed for Li_2O, hot $LiAlO_2$ (over 510°C), and cold $LiAlO_2$ (over 350°C) breeder designs, respectively. Other processes have time scales on the order of a day (solubility, surface adsorption) or months (fluence effects), which will increase as the neutron flux and tritium generation rate decrease.

Corrosion tests typically run for 1000-10000 hours. It is desirable to achieve similar exposures in an integrated test. The influence of pulsing on such experiments was not studied.

Structural response is rapid for elastic stresses and strain, but long-term for creep, sintering, swelling and irradiation-related changes. For example, a 10 dpa goal (e.g., HT-9 irradiation creep relaxation) takes 1500 hours at 5 MW/m^2.

In summary, a 500 s burn and 150 s dwell at 1 MW/m^2 (less at higher wall loads) maintains a reasonable temperature profile in many solid breeder blankets. Liquid metal blankets have generally faster time constants and are not as sensitive. In quasi-steady operation, each test run should ideally be long enough to attain tritium, structural and corrosion equilibrium. Since these can range from minutes to years, it is difficult to specify a minimum

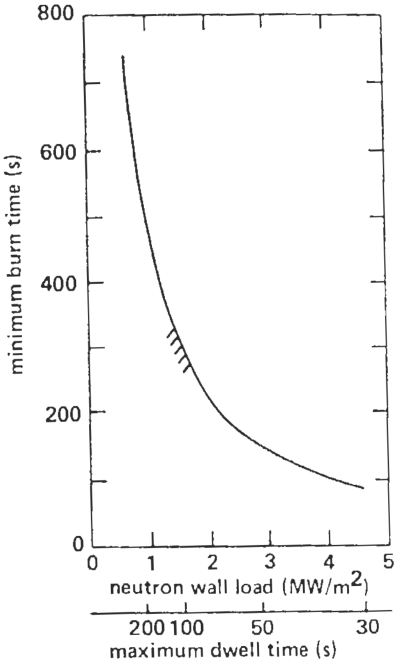

Figure 6: Burn and dwell time requirements for preserving the time-averaged temperature profile in the BCSS Li_2O/He plate breeder.

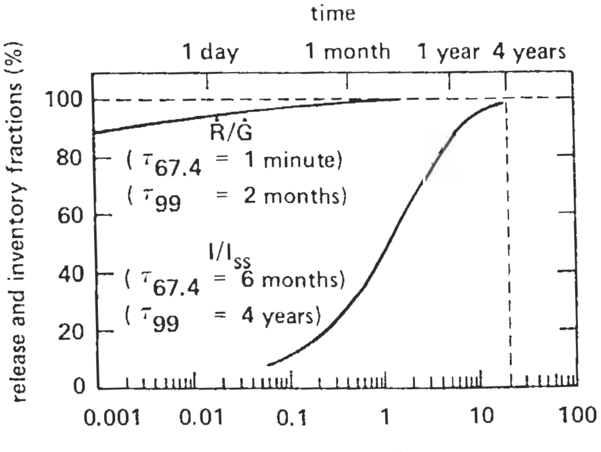

Figure 7: Time-dependence of tritium recovery and inventory in BCSS $LiAlO_2/H_2O$/Be blanket.

continuous operating time. However, a run length of about 4 days (100 hours) should approach equilibrium, or at least measurable effects, for many time-dependent phenomena within 10-100 test runs.

Finally, consider the overall machine machine availability. Although not formally required by any particular issue, it should be as large as practical in obtain test results in a timely manner. If, as minimal requirements, the test device must provide 1 MW-yr/m^2 within 5 calendar years or 0.2 MW-yr/m^2 each calendar year, then the availability (including duty cycle if pulsed) should be at least 20% at 1 MW/m^2 neutron wall load.

Magnetic Field

The primary effect of a magnetic field is on the MHD behavior of flowing liquid metals. The actual velocity profiles are not well known and depend on the specific design features. Thus it is somewhat arbitrary to separate magnetic field requirements from geometry since the scaling of MHD flow can be characterized by dimensionless quantities (e.g., Hartmann number, $Ha = aB\sqrt{\sigma/\mu}$) combining field intensity, dimensions and fluid properties. On the basis of presently understood scaling, magnetic field strengths under 1 T could still duplicate the MHD-limited thermal-hydraulic behavior of present blankets. Only at much lower fields (same dimensions) do other factors like wall friction or natural circulation affect the flow behavior.

The magnetic field has at least two effects on corrosion: laminarization of the flow resulting in a decrease in cross-flow transport compared to turbulent flow, and thinning of the boundary layer (in Hartmann or certain streaming flows) which enhances corrosion by making the velocity boundary layer transparent to the diffusing species. In Fig. 8, the corrosion rate in Li/steel is plotted as a function of the Hartmann number using two different assumptions for the mass diffusion coefficient.

A minimal test goal would be for a Hartmann number of 500-1000, enough to establish the test module beyond the low Hartmann flow corrosion regime. This could be obtained by increasing dimensions at lower fields, or by limiting the field to above about 0.2-0.5 T in a full-sized blanket section.

However, while this is an important device parameter for controlling blanket behavior, it is also likely to be near design values (a few Tesla, as opposed to several Tesla) in any plausible fusion test device. Perhaps the more important question is whether the magnetic field geometry is similar enough.

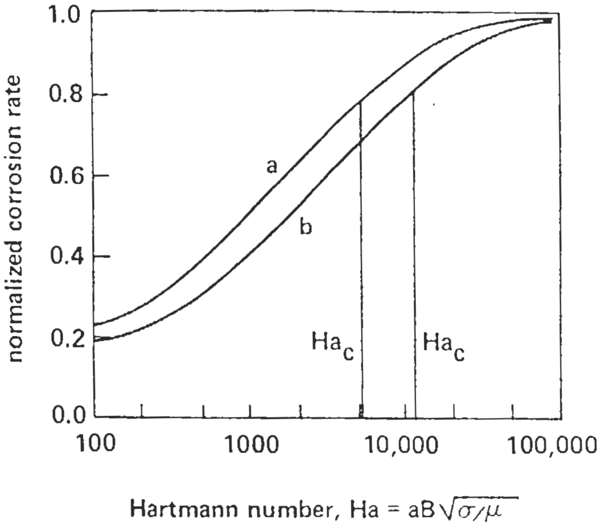

Figure 8: Magnetic field effects on diffusion-limited corrosion in Li/steel system.

SUMMARY

By modifying blanket modules and restricting the range of test device parameters, it is possible to retain key features of fusion reactor blanket operation in a less ambitious test device. While it is difficult to determine exact requirements for the test device parameters, the results of technical analyses presented here combine to suggest a reasonable compromise between the cost of high performance parameters and the reduced testing benefits of scaled down device parameters. Table 2 summarizes these limits for the most important parameters of a fusion test device.

The requirements indicate the importance of high power density (neutron wall load > 1 MW/m^2), long plasma burntime (> 500 s) and surface area available for testing (> 0.5 m^2 per test module) in a fusion test device. High fluence (4-10 MW-yr/m^2) is important for near end-of-life prediction, but critical information about many interactive effects can be learned at lower fluences (~ 1-2 MW-yr/m^2).

Table 2: Recommended Requirements on Key Parameters of a Fusion Engineering Research Facility

Neutron Wall Load	
- Minimum:	1 MW/m^2
- Substantial benefits:	2-3 MW/m^2
Surface Heat Load	
- Tokamak blankets:	> 0.2 MW/m^2
Mirror blankets:	< 0.2 MW/m^2
Fluence (for integrated tests)	
Minimum:	1-2 MW-yr/m^2
Substantial benefit:	2-6 MW-yr/m^2
Test Port Size	
- Minimum:	0.5 m^2 x 0.3 m
- Substantial benefits:	1 m x 1 m x 0.5 m
(Some liquid metal blanket designs may require larger test volumes)	
Total Test Surface Area	
- Minimum:	5 m^2
- Substantial benefits:	10 m^2
Plasma Burn Cycle	
- Minimum burn time:	500 s
- Maximum dwell time:	100 s
- Prefer steady state	
Continuous Operating Time	
- Minimum:	days
- Substantial benefits:	weeks
Availability	
- Minimum:	20%
- Substantial benefits:	50%
Magnetic Field Strength	
- Minimum:	1 T

ACKNOWLEDGEMENTS

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