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LIQUID METAL BLANKET MODULE TESTING AND DESIGN FOR ITER/TIBER II

by

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ABSTRACT

A major goal for ITER is the testing of nuclear components to demonstrate the integrated performance of the most attractive concepts that can lead to a commercial fusion reactor. As part of the ITER/TIBER II study, the test program and design of test modules were examined for a number of blanket concepts. The work at Argonne National Laboratory focussed on self-cooled liquid metal blankets.

A test program for liquid metal blankets was developed based upon the ITER/TIBER II operating schedule and the specific data needs to resolve the key issues for liquid metals. Testing can begin early in reactor operation with liquid metal MHD tests to confirm predictive capability. Combined heat transfer/MHD tests can be performed during initial plasma operation. After acceptable heat transfer performance is verified, tests to determine the integrated high temperature performance in a neutron environment can begin. During the high availability phase of operation, long term performance and reliability tests will be performed. It is envisioned that a companion test program will be conducted outside ITER to determine behavior under severe accident conditions and upper performance limits.

A detailed design of a liquid metal test module and auxiliary equipment was also developed.

The module followed the design of the TPSS blanket. Detailed analysis of the heat transfer and tritium systems were performed, and the overall layout of the systems was determined. In general, the blanket module appears to be capable of addressing most of the testing needs. Because of the reduced size of the ITER/TIBER II module compared with a commercial reactor blanket, the need to perform tests in larger modules was evaluated. The larger module would provide a closer simulation of the fusion environment, and in particular would provide a better assessment of thermomechanical behavior. Therefore, it is recommended that space be provided in ITER to accommodate blanket test modules that occupy a full outboard sector.

1. INTRODUCTION

A major goal for ITER is the testing of nuclear components to demonstrate the integrated performance of the most attractive concepts that can lead to a commercial fusion reactor. As part of the ITER/TIBER study, the test program and design of test modules were examined for a variety of blanket concepts⁽¹⁾. The work at Argonne National Laboratory focussed on self-cooled liquid metal blankets. Individual tests were identified and a comprehensive test matrix was generated. A blanket module was designed and analyzed to determine the degree to which the behavior of advanced blankets could be simulated in ITER/TIBER. In addition, auxiliary equipment requirements and safety considerations were examined.

1.1 ITER/TIBER Baseline Design

ITER/TIBER was designed to meet several objectives⁽²⁾. The first is that it be reactor relevant; i.e., the physics and technology embodied, including blanket test modules, must lead to an attractive concept. Second, steady-state operation should be achieved. Not only is steady state a likely condition for a power reactor, but it also appears to be necessary for the engineering testing of nuclear components. ITER/TIBER is designed with sufficient auxiliary current-drive power for steady-state operation. The third objective is low cost. This is achieved by making ITER/TIBER a relatively compact device. Steady state operation helps in this regard by reducing the ohmic heating requirements and thus reducing the size of the center post.

A summary of the ITER/TIBER operating parameters is given in Table 1. The relatively high neutron wall loading and fluence parameters make it compatible with the nuclear testing mission. In the current drive mode, $Q \geq 5$ ($Q \equiv P_{\text{Fusion}}/P_{\text{Current Drive}}$), the plasma current, I_p , is 10 MA, the average neutron wall load is 1.3 MW/m^2 , and the total fluence is 5 MW-y/m^2 .

There are eight intercoil spaces available for nuclear test modules with a first wall area of 2 m (poloidal) by 1.2 m (toroidal) - see Fig. 1. An isometric view of the module is shown in Fig. 2⁽¹⁾. The ITER/TIBER operating schedule is divided into three phases, as shown in Table 2.

Table 1. ITER/TIBER Machine Parameters⁽²⁾

Parameter	Description	Value
R_0 (m)	Plasma major radius	3.0
a (m)	Plasma minor radius ^a	0.834
κ	Elongation ^a	2.4
δ	Triangularity ^a	0.4
V_p (m ³)	Plasma volume ^a	96
S_p (m ²)	Plasma surface area ^a	170
B_0 (T)	Toroidal field at R_0	5.55
$\Delta\phi$ (Vs)	Volt-sec capability	57.5
P_{fus} (MW)	Fusion power	314 (314) ^b
Q	Fusion power/input power	5.0 (=, IH -1.1) ^b
$\langle r \rangle; r$ (MW/m ²)	Average (peak) wall loading	1.3; 2.0 (1.3; 2.0) ^b
P_{NB} (MW)	Neutral beam power	44
P_{LH} (MW)	Lower hybrid power	19
τ_{burn} (s)	Burn pulse length	steady-state (141) ^b
ϕt (MWyr/m ²)	End-of-life fluence	5 (0.23-1.25) ^b
I_p (MA)	Total plasma current	10.0 (8) ^b
I_{bs} (MA)	Bootstrap current	2.7
I_{LH} (MA)	Lower hybrid driven current	3.9
I_{NB} (MA)	Neutral beam driven current	3.4
γ_{LH} (10 ²⁰ m ⁻² A/W)	Lower hybrid efficiency	0.47
γ_{NB} (10 ²⁰ m ⁻² A/W)	Neutral beam efficiency	0.25
γ_{CD} (10 ²⁰ m ⁻² A/W)	Overall current drive efficiency (NBI + LH + bootstrap currents)	0.52
$\langle T_e \rangle; T_e$ (keV)	Average (peak) electron temp.	19; 25 (10 av.) ^b
$\langle T_e \rangle; T_i$ (keV)	Average (peak) ion temp.	20; 26 (10 av.) ^b
$\langle n_e \rangle; n_e$ (10 ²⁰ m ⁻³)	Average (peak) electron density	1.1; 2.1 (1.78 av.) ^b
$n_{Greenwald}$ (10 ²⁰ m ⁻³)	Greenwald density limit	2.57
$n_{Murakami}$ (10 ²⁰ m ⁻³)	Murakami density limit	1.35
C_α	Thermal alpha concentration	0.05
C_{oxygen}	Thermal impurity concentration	0.024
Z_{eff}	Plasma effective charge	2.1
τ_E (s)	Gross energy confinement time	0.68

^a Values on the 95% flux surface.^b Values in parentheses are for inductive ignited operation.

Figure 1. Cross section view of ITER/TIBER showing a blanket test module.

Figure 2. "Fixed" shield components and blanket test module.

Table 2. ITER/TIBER Operating Phases

-
I.	Checkout Phase
I.a	1 year - hydrogen operation, 15% availability
I.b	1 year - DT operation, 10% availability
II.	Physics Mission Phase
	3 years - DT - 10% availability
III.	Nuclear Testing Mission Phase
	7 years - DT - 30% availability
	Steady-state for ≥ 1 week
•	Total machine lifetime - 12 years
•	Integrated peak neutron fluence - 4 MW-yr/m^2
-

The total machine lifetime is 12 years with the nuclear testing mission phase (Phase III) accounting for seven years. In principle, some nuclear testing could also take place during Phases I and II.

1.2 Module Design Guidelines

The operating parameters for the nuclear testing are shown in Table 3 for both the steady state and pulsed modes of operation. The peak neutron wall load is moderately high at $\sim 1.9 \text{ MW/m}^2$ in the steady-state mode. The overall geometry of the individual blanket modules is given in Table 4, and the module configuration is given in Fig. 3. Guidelines for specific areas are as follows.

Heat Removal

The total surface heat to each module is 0.6 MW. The nuclear heating is 4.25 MW in the steady state mode and 3.6 MW in the pulsed mode. No heat shall be transferred to the surrounding baseline blanket. Provision will be made to remove all heat via a separate module heat removal system. Provision shall be made to dump all heat into the primary heat removal system.

Tritium System

The tritium production per module is $\sim 0.5 \text{ g/d}$ (continuous operation). Each module must have its own tritium removal system. Provision must be made

Table 3. ITER/TIBER Operating Parameters for Nuclear Testing

	Steady State	Pulsed
Fusion Power	314 MW	264 MW
Major Radius		3.0
Minor Radius		0.8 m
Elongation		2.4
Burn Time	>1 week	1331 s
Dwell Time	NA	133 s
Cycles in 7 Years (Phase III)		44,730
Average Neutron Wall Loading	1.3 MW/m ²	1.1 MW/m ²
Peak Neutron Wall Loading	1.92 MW/m ²	1.7 MW/m ²
Average for Blanket Module	1.77 MW/m ²	1.5 MW/m ²
Fluence Goal	3.8 MW-y/m ²	3.2 MW-y/m ²
Availability Goal (Phase III)		<30%
Tritium Consumption (Phase III)	5.3 kg/y	4.5 kg/y
Surface Heat Flux		
First Wall (Uniform)		0.25 MW/m ²
Divertor (Peak)		2.2 MW/m ²

Table 4. Blanket Module Geometry

	Steady State	Pulsed
Poloidal Height		
At First Wall		2.0 m
At Back of Shield		2.2 m
Toroidal Width		1.2 m
Baseline Outboard B/S Thickness		1.2 m
Radial Distance to Module First Wall		3.97 m
First Wall Radius of Curvature		
Poloidal		3.29 m
Toroidal		3.97 m
Working Distance Between PF Coils		2.2 m
Radial Distance to Service Door at Vacuum Boundary		7.5 m
Number of Test Modules		8
<u>Heat Removal</u>		
Total Power to Module		
Surface		0.6 MW
Bulk	4.25 MW	3.6 MW

Figure 3. ITER/TIBER test module geometry.

to feed tritium to the primary tritium system. This shall be in the form of a gas stream containing helium and hydrogen isotopes.

There will be an interface system between the module tritium recovery system and the main reactor tritium system. This interface serves two functions: to provide isolation between the main tritium processing system and the tritium system for the fusion blanket test module, and 2) to allow maximum flexibility in the design of the tritium system for the fusion blanket test modules.

The interface utilizes a gas holding tank in which the feed from the tank to the main tritium processing system is delayed for about a day. The holding tank eliminates disruption of the main tritium processing system should an unexpected surge or impurity occur in a blanket test module. The presence of the delay tank allows the disruption to be handled before the feed is passed to the main tritium processing system. Thus, the interface allows the reliability of the main tritium processing to be separated from the reliability of an individual blanket test module's tritium system.

The holding tank interface also allows each blanket test module and its associated subsystems to function independently. Each blanket test module is easily replaced without disrupting the operation of other blanket test modules which provides greater flexibility in the design of the blanket test module and its subsystems.

Shielding Requirements

Module shielding must meet the same guidelines as the rest of the blanket/shield. In most cases the allowable heating to the TF winding pack is the most restrictive requirement and determines the shield requirements.

Maximum Heating at TF Winding Pack	0.1 mW/cm ³
Fast Neutron Fluence to Nb ₃ Sn	2 x 10 ¹⁹ n/cm ²
Dose to GFF Polyimide Insulator (w/o safety factor)	4 x 10 ¹¹ rad

Safety

1. The maximum possible concentration of hydrogen gas in the vacuum vessel will be kept below the deflagration limit (18%). This would prevent a hydrogen explosion in the torus in the event of hydrogen filling the torus volume coupled with contact with air and an ignition source. A worst-case mixture of hydrogen and air in a 300 m³ vacuum vessel would release 0.9 GJ of energy (200 kg-TNT).
2. The maximum possible production of hydrogen gas will be kept a factor of 10 below the flammability limit (4%) in the reactor hall. The factor of 10 margin is designed to prevent locally higher concentrations from exceeding this limit. This would prevent hydrogen combustion or explosions in the reactor hall.
3. The maximum possible mobilization of radioactivity would be limited to that which could cause an off-site prompt dose of 10 mSv (1 rem).
4. The ITER/TIBER design should be tolerant of test module failure.

For liquid metals, this means minimizing the liquid metal volume and/or minimizing the amount of liquid metal at risk for a spill.

Disruption Response

The disruption parameters and the calculated mechanical loads on the module are as follows:

Thermal Quench	0.1 ms
Current Quench	10 ms
Frequency	TBD
Energy Deposition	TBD
L/R Time for ITER/TIBER	
First Wall	18.5 ms

Field from Plasma Current at Radius

3.8 m	1.35 T
4.05 m	0.97 T
4.3 m	0.72 T

Inductance of Module Outer Shell 0.7 μ Hm

Resistance of Module Outer Shell 471 $\mu\Omega$ m

Disruption Induced Eddy Current in Module

Low Resistance Limit 0.8 MA/m

High Resistance Limit 0.13 MA/m

Induced Torques (Li Module)

Low Resistance Case 2.2 MN·m

High Resistance Case 0.3 MN·m

1. If the module first wall is electrically connected to the rest of the ITER/TIBER first wall (continuously along the edges), then it will act to shield the module from induced magnetic torques.
2. If the module is electrically insulated from the rest of the ITER/TIBER first wall and blanket, then there will be induced torques of the level indicated above. The torques will act to rotate the module around the radial vector.
3. The worst case would occur if there were only partial electrical connections between the module and the rest of the ITER/TIBER blanket and first wall. In this case large eddy currents could travel poloidally in the module producing large body forces.
4. It is therefore recommended that module first wall be either continuously connected with the ITER/TIBER first wall, or that it be completely isolated. In the later case, the module must be designed to accommodate the induced torques.

Blanket modules and sub-systems will be maintained remotely. The interfaces with the reactor and with the subsystems should be standardized. Where possible the same remote equipment can be used to service all modules. Key components such as manifold joints and instrumentation leads will be

accessible by the remote equipment. The need for remote operations during post-test examinations shall be incorporated into the blanket module design.

2. TEST PROGRAM

ITER/TIBER will provide the first prototypic fusion environment for testing the leading blanket concepts. The environment provided by ITER/TIBER can be divided into four categories:

Surface and Bulk Heating

ITER/TIBER represents the first time when prototypic surface and bulk heating are produced simultaneously. The surface and bulk heating environment are particularly important in testing the thermal-hydraulic and thermomechanical response of the blanket modules.

14 MeV Neutron Damage

14 MeV neutron damage will affect thermomechanical response and materials properties. ITER/TIBER provides the opportunity to study neutron damage to moderate fluence levels (10-30 dpa).

Extended Neutron Source

Testing in ITER/TIBER will provide the first opportunity to experimentally determine neutronics parameters with a neutron source that has both the prototypical energy spectrum and spatial variation.

Magnetic Field

Both the spatial and temporal variations of the magnetic field of tokamak power reactors will be well simulated in ITER/TIBER. Magnetic field effects are particularly important for liquid metal designs where pumping power requirements, pressure stresses, and flow profiles are affected.

The overall test emphasis would be on determining the integrated performance of the leading blanket concepts. The performance would be determined for both normal operation and for transient operation which includes off-normal events and startup/shutdown events.

The results are aimed at providing two basic types of information. First, the results would be used to confirm the predicted behavioral response of the module, and second, the tests would be used to build an engineering data base. The data base would include information on the identification of design flaws plus the long term reliability and safety of the blanket module.

In developing the test programs for blanket modules, several assumptions have been made covering the level of technology development prior to and during testing in ITER/TIBER. First, it has been assumed that blanket technology will be aggressively developed and tested in non-fusion facilities. This means that to the extent possible, all key issues will be resolved and engineering models and codes will be developed to the point where there is a high degree of confidence in the design and operation of the test modules. This degree of development is necessary to insure that no unexpected defects are present in the blanket modules which might jeopardize the operation of the entire ITER/TIBER device. Second, it has been assumed that the large number of blanket designs present today will be culled down to a relatively small number of candidates. During the course of non-fusion testing, some concepts will prove to be more attractive than others, and the tests in ITER/TIBER will be focused on the most attractive designs. Finally, certain tests where there is a high risk of failure will be performed outside of ITER/TIBER. Such tests include severe transient tests and tests which explore the ultimate performance limits of the blankets.

2.1 Overall Description of Tests

The types of tests for blankets follow from the key issues which must be resolved before a blanket concept can be qualified for commercial application. The key issues for blankets have been previously identified through the FINESSE, BCSS, and TPA studies⁽³⁻⁵⁾. The major issues are:

- (1) Tritium Breeding-Self Sufficiency,
- (2) Tritium Inventory, Transport, and Recovery,
- (3) Tritium Permeation and Release,
- (4) Corrosion/Compatibility and Mass Transfer,
- (5) Thermomechanical Behavior,
- (6) Liquid Metal MHD Effects,
- (7) Structural Response and Component Lifetime.

The relative emphasis of different issues depends upon the specific blanket concept. The test times will depend on a number of considerations including the specific blanket concept, the times required for the relevant phenomena to reach steady state, and the times needed to reach goal fluences.

The test types are divided into the major categories of predictive capability, engineering performance, and engineering reliability. A summary of the test types is presented in Table 5. The predictive capability tests would be conducted to confirm and benchmark engineering codes developed prior to blanket module testing. Tests that fit into this category include the measurement of temperature profiles, tritium concentration profiles, and thermomechanical response. The measurements are usually made in-module during reactor operation, and the tests are usually short term. The need for in-module measurements means that there will be special instrumentation requirements, since any instrumentation placed in the module must operate in a severe thermal, neutron, and chemical environment, and must also be small enough not to interfere with the normal performance of the module. Clearly, instrumentation development will be a high priority for predictive behavior tests, since ultimately the specific tests which are possible will depend upon the availability of suitable instrumentation.

Engineering performance tests are those where specific gross performance characteristics of the blanket module are measured. Items of interest include overall coolant pressure drop, average coolant outlet temperature, overall tritium breeding ratio, and shielding efficiency. Since these measurements would be made largely out-of-module, the instrumentation needs are less severe than those for predictive behavior tests. In most cases, the test durations are a short to moderate (minutes to days).

Engineering reliability tests are conducted to establish the data base necessary to determine the long range potential of various blanket concepts. The tests in this area focus on the lifetime and possible failure modes of the modules, and therefore tend to be long term (years). The tests include the determination of design flaws, identification of failure modes, and long term reliability. In contrast to the tests described above, much of the information on engineering reliability comes from post-test examinations of the modules. The information obtained from post-test examinations would be

Table 5. Types of Tests -- Blanket Modules

Test Type	Items Measured	Measurement Type	Comments
Predictive Capability	Neutron Flux/Energy Temperature Profiles Thermomechanical Response MHD Velocity Profiles Corrosion Loss Rates Gap Conductance Tritium Concentration Profiles	In-Module In-Module In-Module In-Module Post-Operation In-Module In-Module/ Out-of Module	Usually short term tests. Measurements can be difficult due to need for high degree of instrumentation. Emphasis on integrated behavior.
Engineering Performance	Pressure Drop Thermal-Hydraulic Performance Overall Tritium Breeding Overall Tritium Loss Rate/Inventory Shielding Efficiency Tritium Release Rate Coolant Impurity Levels	Out-of-Module Out-of-Module Out-of-Module Out-of-Module Out-of-Module Out-of-Module Out-of-Module	Measurements are relatively easy. Test duration is short to moderate.
Engineering Reliability	Short Term Failure Modes Determination of Design Flaws Remote Maintenance Operations Long Term Failure Modes Long Term Reliability Mass Transfer Effects Post-Test Examinations	Post-Operation In-Module Out-of-Module Post-Operation Out-of-Module Out-of-Module Post-Operation	Data are largely statistical or taken from post-test observations. Test duration is long.

combined with information on the module operating history to assess long term operating potential of different types of blankets.

Besides blanket module tests, sub-module and element tests would be conducted. The purpose of these tests would be to explore areas which are difficult or not possible to perform with module tests. An example of an element test is material specimen irradiation. The materials irradiated would be the same as those used in the blanket module, and the element tests would provide a means of monitoring the irradiation-induced property changes in the module. Specimens could be removed at frequent intervals, and property measurements would then be performed in hot-cells. An example of a sub-module test is coolant corrosion and mass transfer. Sub-module tests are likely to be easier to control and could be conducted for a longer period of time compared with full module tests.

2.2 Self-Cooled Liquid Metals

The specific tests for liquid metal blankets are related to the key issues identified earlier. The tests to be conducted in ITER/TIBER are MHD tests, combined MHD-thermal hydraulic tests, short and long term performance tests, materials irradiation tests, corrosion/mass-transfer tests, and post-test examinations.

MHD Tests

Liquid metals flowing in high magnetic fields can result in high pressure drops, high blanket operating pressures, and coolant flow profile modifications which can affect heat and mass transfer in the coolant. Resolution of MHD-related issues requires investigation in two areas: 1) MHD pressure drop, heat transfer, and fluid flow, and 2) electrical insulators for flowing liquid metal systems. ITER/TIBER provides both the correct magnetic field configuration and blanket test volume needed for testing MHD effects. Since no neutron flux is needed to conduct these tests and the test times needed to achieve equilibrium flow conditions are short (~100 s), these tests can be conducted in the early phase of TIBER operation. The MHD tests would be aimed at confirming the predictive capability of MHD models and codes.

MHD-Thermal Hydraulics Tests

Changes in the coolant flow profiles will alter the heat transfer within the blanket. In order to optimize the performance of the blanket, heat transfer within the coolant needs to be thoroughly understood. ITER/TIBER will be the first facility where both the coolant flow and the surface and bulk heating of the blanket will be properly simulated, and thus it provides the first opportunity to completely verify predictions of heat transfer in the fusion environment. The temperature profiles within the blanket will be measured for a variety of mass flow rates, and these results will be compared with model predictions. The test times involved are relatively short, (~100 s) and the neutron fluence will be low. Therefore, these tests will also be conducted during early ITER/TIBER operation.

Short Term Performance Tests

Following confirmation of the predictive capability of MHD and MHD-thermal-hydraulics effects, the high temperature performance characteristics of liquid metal blankets would be explored. These tests represent the first completely integrated tests to be performed. Items to be measured are coolant temperature increase, overall tritium breeding and release, overall pressure drops, coolant impurity levels, etc. In addition the short-term thermomechanical response (stresses, strains) would be determined. These tests would largely cover the engineering performance phase of testing.

Long-Term Performance Tests

These tests would help determine the engineering reliability and provide a data base for extrapolations of blanket life cycle performance of liquid metal blankets. The tests would emphasize the lifetime and possible failure modes of the modules, and the item of greatest interest is the long-term thermomechanical response of the blanket structures. The thermomechanical response will depend upon the neutron flux and fluence, the first wall heat load, the internal coolant pressure, the blanket geometry and structural constraints, as well as the types of materials used in the blanket. The tests would be conducted over a period of 2-3 y (~10 dpa), after which the module would be removed for destructive examination in the hot-cell. The long time period is needed to study the effects of moderate neutron fluences on

structural response and to provide a sufficient amount of information on blanket performance and reliability to be able to extrapolate to reactors beyond ITER/TIBER.

Materials Irradiation Tests

In parallel with the module tests, irradiation surveillance tests using elements would be conducted. Material samples would be removed at frequent intervals to determine their properties. The samples would be irradiated under the same environmental conditions as the blanket modules, and the materials should be identical (composition, heat treatment, etc.) to the materials in the module. When the specimens are removed, they would be tested in the reactor hot-cells. The tests would include mechanical property and microstructural characterizations, and they would provide a means for tracking the changes in properties of the blanket module.

Corrosion/Mass Transfer Tests

Sub-module tests would be conducted to examine the corrosion/mass transfer characteristics of self-cooled liquid metal systems. Small samples would be removed from time to time to measure corrosion loss and creep strain. These tests could also be run for the entire life of the reactor, thus allowing extrapolation of the results from the module. A variety of element and submodule tests can be run for the different concepts for self-cooled liquid metal blankets. In each case, these tests would be conducted at the identical conditions experienced by the blanket module.

Post-Test Examination

Additional information about the performance of the blanket modules can be obtained through post-test examinations. There are numerous nondestructive and destructive tests which can be used to characterize the module structure. The information from post-test examinations, combined with the operating history of the module, can be used to interpret the thermomechanical response. This approach is similar to that used in fission reactors to study the behavior of fuel pins. The two keys to being able to correctly interpret the results are that first the test assembly must be very well characterized prior to irradiations, and second that the power history must be well documented.

Information gaps in either area will severely limit the utility of data gathered during post-test examinations.

2.3 Test Matrix and Schedule

There are some unique features of liquid metal systems that will affect the test schedule. First, one of the most important items to be tested is MHD effects on fluid flow, which needs only a prototypic magnetic field and module configuration. Second, safety considerations for liquid metal systems, particularly where water is present, suggest that a gradual and systematic buildup to full performance is desirable, in order to ensure safe operation of the module. Finally, as long as a substantial first wall heat flux is present, heat transfer models for self-cooled liquid metal systems can be adequately assessed, without neutron heating.

Much of the confirmation of predictive capability can therefore be conducted in the early stages of TIBER operation. In the case of MHD effects, it is even possible to test fluid flow when there is no plasma. There are several advantages to conducting the tests in this manner. To begin with, the test module can be more highly instrumented in the absence of neutrons. Second, the test can be conducted at low temperatures which will reduce safety concerns. Third, the absence of neutrons for these tests also means that repair and maintenance operations will be easier. It is proposed that special modules be constructed for this early phase of operation. They can be constructed out of stainless steel and can utilize NaK as the coolant. They would be highly instrumented with voltage probes to measure the flow characteristics, and temperature monitors to measure the heat transfer characteristics.

Testing during Phase III would emphasize thermomechanical response, which is the one area for liquid metal blankets where TIBER is a unique test facility. These tests would use an advanced test module constructed from advanced materials and using either Li or LiPb as the coolant. The first tests would confirm the predictive capability for high temperature operation. Following this check-out it would run continuously for a period of ~2 y (~10 dpa) before it is removed for destructive examination and testing in the hot cells.

Because of the high neutron flux, it is expected that there will be limited in-module instrumentation to monitor operation. Performance

monitoring will be done primarily by overall measurements (e.g., inlet and outlet coolant temperatures and pressure, mass transfer, mass flow rate). It is still desirable to more closely monitor performance, and two methods are proposed. Since the presence of neutrons will degrade the structural materials properties, it is proposed that the materials properties changes be monitored with element and sub-module tests. Specimens would be removed from the reactor at frequent intervals (~6 mo.) and then tested. The elements and sub-modules would operate at the same conditions as the full-size module. The results of the tests on small specimens would provide a means for studying the degradation of materials, and would be used in the interpretation of data from the module. A second approach is to make a limited number of cooling channels in the blanket module into a separate loop. The same measurements would be made on the coolant, but local rather than gross effects could be measured.

The overall test schedule for self-cooled liquid metal blankets is shown in Fig. 4. Testing begins in Phase I with Module "A" (low temperature SS - NaK). Isothermal tests at room temperature would be conducted to confirm MHD predictive capability. The primary variable would be mass flow rate and the pressure drop and flow distribution would be measured. This would be followed by combined MHD/heat-transfer tests. Surface heating in non-DT plasmas would be used as the primary heat source. In addition to MHD response, temperature profiles would be measured. Following these tests the module would be removed and destructively examined. Two or three different module geometries could be studied during this period.

Assuming that these early tests are successful, a Type "B" module would be inserted in the reactor. An example of a Type "B" module is the TPSS module which was examined in some detail⁽⁶⁾. A series of short tests would be conducted to ensure that the module is operating up to expectations. It would then be nondestructively examined for major flaws. If it checks out satisfactorily, then the long term tests would begin. The major purpose of this test period is to determine long term performance and to investigate thermomechanical response and some limited corrosion effects. The module would remain in the reactor for ~2 Y which is long enough to reach stress relaxation near the first wall.

At the same time as the module tests, parallel materials tests would be conducted in elements and sub-modules to monitor mechanical properties and corrosion of structural materials.

Figure 4. Liquid metal tests plan.

Finally, when the test module is removed, it will be destructively examined using a full battery of tests. The tests would include measurements of gross dimensional changes, determining whether any cracks had developed, mechanical property testing of the structure, and microstructural examinations. The results of these tests would be combined with data on the operating history of the module along with the results of the element and sub-module tests to develop an overall assessment on long term potential of that concept for self-cooled blankets. During Phase III, approximately 3 long term test series could be conducted.

In parallel to the ITER/TIBER tests, a number of tests would be conducted in other facilities. The types of tests to be conducted are those where a failure of the module is possible.

A further breakdown of the individual tests is given in Table 6. This table provides information on a number of test parameters. Items included in the table are test type, test purpose, test requirements, primary test variables and parameters, the test phase, and the test vehicle size (i.e. element, sub-module, or module). The test requirements indicate the reactor performance needed for an individual test. The test time indicates the time needed to run a series of tests for a specific blanket design and the fluence indicates the desired total fluence level for a series of tests on a specific blanket type.

3. MODULE DESIGN AND ANALYSIS

3.1 Module Design

The module design, which is based upon the TPSS design⁽⁶⁾, employs a vanadium alloy structure and uses liquid lithium as a coolant and tritium breeder. The module is composed of three major sections: 1) the Li cooled module, 2) a He cooled boundary shell, and 3) a He cooled shield. The design is shown in Figs. 5 and 6.

The module is composed of an advanced vanadium alloy and it incorporates an insulator coating on the coolant channel walls to reduce the MHD pressure drop. It includes both the breeding blanket and the reflector zones in the dimensions shown in Figs. 7 and 8. The reflector material can be either CaO or tungsten; the choice of material will depend upon the shielding needs of the module. Detailed neutronic calculations will be needed to determine the

Table 6. Summary of Tests for Self-cooled Liquid Metal Blankets

Test Name	Test Type	Test Purpose	Test Requirements								Primary Variables	Measured Parameters	Phase	Module Size
			Burn Time (s)	Av. (%)	Dwell Time (s)	Neutron Flux MW/m2	Heat Flux MW/m2	Fluence MW-y/m2	Test Time (d)					
System Check out	System Check Out	Verify Operation	NA	NA	NA	NA	NA	NA	NA	60	NA NA NA NA	NA NA NA NA	0	Module
Pressure drop and flow distribution determination	MHD	Predictive Capability	NA	NA	NA	NA	NA	NA	NA	20	Magnetic Field Mass Flow Rate	Pressure Flow Patterns	1	Module
Non-destructive examination of MHD module	Post Exposure	Verify Integrity	NA	NA	NA	NA	NA	NA	NA	20		Visual Obs. Eddy Current	1	Module
Surface Heat Flux Testing	Thermal Hydraulics	Predictive Capability	100	10	100	0.	0.1	0.	0.	20	Magnetic Field Mass Flow Rate Heat Flux	Pressure Flow Patterns Temperature	1	Module
Low temperature thermal hydraulics with bulk heating	Thermal Hydraulics	Predictive Capability	200	10	100	0.5	0.1	0.	0.	20	Magnetic Field Mass Flow Rate Surface Heat Neutron Flux	Pressure Flow Pattern Temperature	1	Module
Examination of thermal hydraulics modules	Post Exposure	Verify Integrity	NA	NA	NA	NA	NA	NA	NA	20		Visual Obs. Eddy Current Surface Chem. Microstructure	2	Module
Check-out high performance modules	System Check Out	Verify Operation	NA	NA	NA	NA	NA	NA	NA	20			2	Module
High Temperature Performance Verification	Thermal Hydraulics	Predictive Capability Engineering Performance	200	25	60	1.7	.25	0.	0.	40	Magnetic Field Mass Flow Rate Heat Flux Neutron Flux	Pressure Flow Pattern Temperature Strain	2	Module
Engineering Performance of liquid metal blanket	Integral	Engineering Performance	SS	25	NA	1.7	.25	0.	0.	40	Magnetic Field Mass Flow Rate In Temperature Neutron Flux	Pressure Flow Pattern Temperature Strain	3	Module
Integrated Performance Examinations	Post Exposure	Verify Integrity	NA	NA	NA	NA	NA	NA	NA	20		Visual Obs. Eddy Current	3	Module
High temperature/long duration neutron testing	Integral	Engineering Reliability	SS	25	NA	1.7	.25	1.0	1.0	700	Magnetic Field Mass Flow Rate In Temperature Neutron Flux	Pressure Temperature Out Temperature	3	Module

Table 6. Summary of Tests for Self-cooled Liquid Metal Blankets (Cont'd)

Test Name	Test Type	Test Purpose	Test Requirements							Primary Variables	Measured Parameters	Phase	Module Size
			Burn Time (a)	Av. (%)	Dwell Time (a)	Neutron Flux MW/m ²	Heat Flux MW/m ²	Fluence MW-y/m ²	Test Time (d)				
Safety Performance of Liquid Metal Blankets	Transient Behavior	Safety Engineering Reliability	100	10	100	1.7	0.25	1.0	20	Mass Flow Rate Disruption Neutron Flux Surface Heat	Afterheat Temperature	3	Module
Corrosion/mass transfer surveillance	Corrosion Mass Transfer	Engineering Reliability	1000	25	60	1.7	0.	1.0	700	Temperature Mass Flow Rate Impurity Levels Fluence	Temperature Mass Flow Rate Impurity Levels Fluence	3	Sub-module
Structural material irradiation	Irradiation Response	Predictive Capability Engineering Performance	NA	25	NA	1.7	NA	3.5	2200	Temperature Fluence Stress	Temperature Stress Fluence	3	Element
Post exposure tests of liquid metal blankets	Post Exposure	Predictive Capability	NA	NA	NA	NA	NA	NA	180		Strain Stress Mech. Properties Microstructure	3	Module
Structural materials testing	Post Exposure	Predictive Capability	NA	NA	NA	NA	NA	NA	180	Temperature Stress Strain	Temperature Stress Strain Mech. Properties	3	Element

Figure 5. Cross section self cooled Li module.

Figure 6. Exploded view of self-cooled Li module.

Figure 7. Cross section of the integrated first wall and breeding zone of the TPSS reactor. The dimensions shown are for the inboard blanket. The outboard blanket is similar but has a thinner breeding zone. The toroidal duct dimension of 5.0 cm corresponds to the first wall channel. For simplicity, the decrease of this dimension with radial position is not shown.

Figure 8. Cross section of the inboard reflector of the TPSS reactor. The outboard reflector is similar but thicker. The shaded area is the reflector material (tungsten for the inboard and CaO for the outboard). The toroidal dimension of 4.7 cm corresponds to the mean radial position of the reflector. This dimension increases towards the breeding zone and decreases towards the shield.

materials choices. Table 7 shows the distribution of materials in the blanket.

Table 7. Distribution of Materials in Blanket

Blanket Thickness with Tungsten in Reflector		Volumetric Fractions
First Wall	1 cm	0.5 Li, 0.5 V*
Breeding Zone	35 cm	0.925 Li, 0.075 V
Reflector	30 cm	0.1 Li, 0.1 V, 0.8 W
Blanket Thickness with CaO in Reflector		
First Wall	1 cm	0.5 Li, 0.5 V
Breeding Zone	30 cm	0.925 Li, 0.075 V
Reflector	55 cm	0.1 Li, 0.1 V, 0.8 CaO

The flow length of the blanket and reflector is 1.5 m, with an additional 20 cm on each end devoted to manifolding. The flow length is ~1/2 that of TPSS and the manifold size is roughly consistent with the TPSS design. There is confidence that the flow patterns will be fully developed in a short distance beyond the manifold so that 1.5 m is sufficient to study MHD effects on flow profiles. There is still a question about the manifolds, however. MHD models are not sophisticated enough, at present, to accurately model manifold flow so that it is not possible to completely assess the manifold requirements.

Once the vanadium pipes leave the module they will be joined to double wall pipes, with the outer wall being austenitic stainless steel. The double wall will serve as both a secondary barrier for Li leakage or tritium release and as a protective covering for the vanadium to prevent interactions with the environment. The double wall piping will continue up to the first heat exchanger.

The boundary shell was first proposed as a way of preventing heat generated in the test module from being transferred to the baseline blanket. However, calculations indicate that this is not a concern. There are two other reasons for including a boundary shell. First, it represents a safety

barrier for a possible Li spill, and second it works as a buffer for the neutrons. The water in the adjoining blanket will moderate the neutrons along the outer walls. This will result in an altered neutron spectrum which will produce higher heating near the outer walls as well as altered tritium breeding and materials damage profiles. A moderate Z material, He cooled, placed between the water blanket and Li module will reduce these alterations and produce a better simulation of the neutron environment.

The shell is composed of austenitic stainless steel and it is cooled by low temperature He gas. The He gas can be linked directly into the main reactor cooling system. The outside of the shell is sized to fit the module cavity in TIBER.

The shield is a He cooled stainless steel structure whose purpose is to provide radiation protection to personnel and components at the same level as the rest of the reactor shield system. At this time, there does not appear to be a problem in meeting the radiation protection goals. If possible, only stainless steel would be used, but tungsten could be substituted if additional shielding protection is needed. The helium cooling for the shield would be part of the same system used for the boundary shell.

3.2 Sub-system Design and Analysis

3.2.1 Sub-system Layout

The layout of the sub-systems is dictated by the maintenance requirements, safety requirements, and space needs for other reactor systems. For the self-cooled liquid module, all the subsystems have been placed near the reactor and below the reactor hall, as shown in Fig. 9. This placement will minimize the total volume of liquid metal needed for the module and will also maximize accessibility to the reactor. The subsystems are relatively small, with the total room size being ~7 m x 4 m x 4 m. A detailed layout of the room is shown in Fig. 10.

3.2.2 Rejection System

The total power to be removed from the module is estimated to be approximately 5 MW. The liquid lithium temperature from the discharge side of the module is ~500°C. The heat sink temperature is ~30°C (water). Therefore, there is a temperature drop of ~470°C from liquid lithium to the heat sink.

Figure 9. Sub-system layout for liquid metal module.

Figure 10. Liquid metal sub-system layout.

It is suggested that the heat removal system be divided into three stages to minimize the effect of large temperature gradient in any one heat exchanger. Figure 11 shows the schematic of the proposed heat rejection system. The system is divided into three stages. The working fluids for the first heat exchanger is from lithium to Na. The second heat exchanger is from Na to organic coolant. The purpose of using an organic coolant is to reduce the total amount of liquid metal in the reactor building. The temperature range for the second heat exchanger is sufficiently low enough for an organic coolant. The third stage is an organic to water heat exchanger. Preliminary analysis of the first heat exchanger (lithium/Na) was performed to determine its size and internal structure.

Table 8 shows the key parameter of the lithium/Na heat exchanger. It is a shell-and-tube heat exchanger with lithium in the tubes. The overall length is 1.50 m, and the diameter is 0.50 m. The tubes are made of vanadium alloy so that lithium will be in contact with only one material. The tube diameter is 2.54 cm and has a wall thickness of 2 mm. The overall heat transfer area required is $\sim 20 \text{ m}^2$. It should be pointed out that if double-walled tubes are required (a second barrier for lithium leakage or tritium release) in the heat exchanger, the size of the Li/Na heat exchanger will have to be increased. For the present scoping analysis, it is assumed that the double-walled tube is made of a 1 mm thick vanadium tube on the inside and a 1 mm thick stainless steel tube on the outside with perfect bonding (no resistance to heat transfer) between them. The results shown in Table 8 should apply to such a double walled tubular heat exchanger.

The heat rejection system shown in Fig. 11 assumes that the heat sink is ambient water (baseline blanket heat sink). The selection of organic coolant in the intermediate heat exchanger is to reduce liquid metal inventory in the reactor building. Otherwise, organic coolant can be replaced by NaK which should fit well in the temperature range of 130-200°C. If ambient air can be used as the heat sink, the organic coolant and water can be replaced by air which simplifies the heat rejection system since only three coolants (Li/Na/air) instead of four coolants (Li/Na/organic/water) are used. However, the size of the (air) heat exchanger will have to be increased.

Table 8. Key Parameters of Heat Exchanger 1

Type	Counterflow shell and tube
Fluid	
Tube side	Lithium
Shell side	Na
Tube Material	V-15Cr-5Ti
Length	1.50 m
Shell Diameter	0.50 m
Tube Diameter	2.54 cm
Number of Tubes	150
Tube Wall Thickness	2.0 mm
Heat Transfer Area	17.6 m ²
Overall Heat Transfer Coefficient	$0.29 \times 10^4 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$
Logarithmic Mean Temperature Difference	98.2°C
Tube Side Velocity	$V_{\text{Li}} = 0.148 \text{ m/s}$
Shell Side Velocity	$V_{\text{Na}} = 0.63 \text{ m/s}$
Lithium Flow Rate	6.0 kg/s
Na Flow Rate	50 kg/s
Lithium Temperature	
Inlet	500°C
Outlet	300°C
Na Temperature	
Inlet	235°C
Outlet	350°C
Power Rating	5 MW

Figure 11. Heat transfer system for liquid lithium module.

Heat Transfer Analysis

If the liquid flow is fully developed (slug flow) and the surface heat flux is the only heating source, then the following two parameters appear in the solution of the governing equation,

$$t^* = \text{dimensionless residence time} = \frac{\ell a}{Va^2},$$

and

$$T^* = \text{dimensionless temperature} = \frac{(T - T_o)k}{qa}$$

where ℓ is the axial length of the coolant channel, α is the thermal diffusivity of the coolant, V is the velocity of the slug flow, a is width of the coolant channel, T is the temperature of the liquid metal, T_o is the reference (inlet) temperature of the coolant, k is the thermal conductivity of the coolant, and q is the surface heat flux. The more precise relationship between T^* and t^* is

$$T^* = \sqrt{t^*} \tag{1}$$

If liquid lithium is used in the module and the blanket of the commercial power reactor (TPSS or BCSS), then α and k are the same in the two cases (neglecting the small difference due to temperature dependence). The characteristic dimension, "a" can be maintained the same in the module and the blanket since there is no need to scale the module in the radial direction. Equation (1) can then be written as

$$T - T_o \propto q(\ell/V)^{1/2} \tag{2}$$

Thus, the liquid metal temperature in the module can always be scaled properly by adjusting the ratio ℓ/V in Eq. (2). It makes no difference whether a module ($\ell = 2$ meters) or a full sector ($\ell = 4$ meters) is tested in ITER/TIBER since the coolant velocity can always be adjusted to get the proper temperature distribution for a given surface heat flux.

In the module and the blanket, nuclear heating is also present. Nuclear heating rate is a function of radial distance and simple scaling relationship

is not available. In a given coolant channel, the coolant temperature rise at locations closer to the first wall will be higher than those located farther away from the first wall. This effect can only be included in numerical calculations described in the next section.

In addition to calculating the maximum interface temperature, the average temperature rise through the blanket module is also important. This average temperature rise in a given coolant channel is scaled by the following relationship (assuming no surface heat flux),

$$T - T_o = Q\dot{\epsilon}/V\rho C_p \quad (3)$$

where Q is the nuclear heating rate, ρ is the density of the coolant, and C_p is the specific heat of the coolant. If the same coolant is used in the module and the blanket, ρ and C_p are constants and Eq. (3) can be written as

$$T - T_o = Q\dot{\epsilon}/V \quad (4)$$

If both surface heat flux and nuclear heating are present, Eqs. (2) and (4) indicate that the interface temperature and the average temperature cannot be scaled properly simultaneously since one is proportional to $\dot{\epsilon}/V$ and the other is proportional to the square root of $\dot{\epsilon}/V$. Fortunately, this happens only in the first wall coolant channel and the overall temperature distribution (both the interface and the average coolant temperature) can be simulated approximately as shown in the next section.

Prediction of Temperature Distributions

To calculate the temperature distribution in the module, the TPSS blanket geometry is adopted. There are a total of seven coolant channels in the first wall and blanket region (excluding the reflector region). The following input parameters are employed in the calculations.

Parameter	ITER/TIBER (module)	TPSS
Surface Heat Flux, $\frac{\text{MW}}{\text{m}^2}$	0.25	1.0
Neutron Wall Loading, $\frac{\text{MW}}{\text{m}^2}$	1.7	5.0
Axial Length, m	1.8	2.7

Radial dimensions remain the same in the ITER/TIBER module and the TPSS blanket. Numerical calculations were performed by neglecting the presence of the solid boundaries of the coolant channels and by assuming slug flow in each coolant channel. No mixing (no momentum exchange) occurs between adjacent channels and the only mechanism for energy transfer between adjacent coolant channels is through conduction. The results should represent approximately the temperature distributions in the blanket module.

To obtain similar temperature distribution in the ITER/TIBER module and the TPSS blanket, the coolant velocity in each channel must be scaled down. Except the first wall channel, all the coolant velocity can be scaled by using Eq. (4) since only nuclear heating is present. The velocity in the first wall channel has to be greater than that determined by either Eq. (2) or (4). By using the method of trial and error, the coolant velocity in the first wall channel that gives proper interface temperature in the ITER/TIBER module can be determined.

Figure 12 shows the results of scaled down velocity distribution in the ITER/TIBER module and the velocity distribution in the TPSS blanket. The corresponding temperature distributions are shown in Fig. 13. Two radial temperature distributions are plotted in Fig. 13, one at the midplane and the other at the discharge of the vertical blanket. It can be seen that the temperature distributions in the module represent well those in the blanket except in the region near the first wall. The interface (coolant/first wall) temperatures also agree well between the two cases. For example, the interface at discharge is 528°C for TPSS blanket while that for ITER/TIBER module is 535°C. The average temperature rise through the module is 162°C and that for the TPSS blanket (excluding reflector) is 155°C. Thus, even though the

Figure 12. Comparison of coolant velocities in the ITER/TIBER module and the TPSS blanket.

Figure 13. Comparison of temperature distributions in the ITER/TIBER module and TPSS blanket.

temperature distribution near the first wall region does not agree well between ITER/TIBER module and TPSS blanket, the interface temperature and the average temperature rise of TPSS blanket can be simulated very well by the ITER/TIBER module.

If a sector, instead of a module, is used in the ITER/TIBER for blanket testing, the vertical length will be approximately 4 meters. To get similar temperature profiles in the blanket sector, the coolant velocity must be increased. Figure 14 shows the velocity distribution in each coolant channel of the blanket sector. The corresponding temperature distribution is shown in Fig. 15. As mentioned previously, there is no difference from the heat transfer point of view whether a blanket sector or module is used for testing since proper temperature distribution can be obtained in either case.

The numerical results described here provide more information than the scaling parameters described previously. They give not only the quantitative temperature distributions in the module and blanket, but also includes some other effects not considered by the simple scaling relationship. For example, the numerical calculations included the effects of axial conduction and the effect of temperature variation on thermal conductivity of the coolant. However, the results presented here depend on the assumption of slug flow (fully developed). Near the blanket inlet and discharge, the flow will not be fully developed. These transition regions are only a few characteristic dimensions long and their impact on heat transfer (temperature distribution) will be resolved before the module is ready for testing in ITER.

Heat Transfer Between Module and the Baseline Blanket

The liquid metal module operates at average temperatures between 300-500°C while the baseline blanket operates at an average temperature of ~100°C. A simple analysis was performed to determine the impact of heat transfer between the module and the baseline blanket. Figure 16 shows the simplified geometry and the nomenclature used in the analysis, assuming that the module is supported at the back so that there is no contact between the module and the blanket as shown in Fig. 16. This simplifies the problem to thermal radiation only. The view factor between two large parallel plates is approximately 1. Neglecting the radioactive heat transfer from the blanket to the module, the net heat transfer is

Figure 14. Comparison of coolant velocities for an ITER outboard sector and TPSS blanket.

Figure 15. Comparison of temperature distributions for ITER outboard sector and TPSS blanket.

Figure 16. Configuration used for heat transfer calculations between module and baseline blanket.

$$q = \epsilon_{\sigma} G_{\sigma} T_{\sigma}^4 AF$$

where ϵ is the emissivity of the module (vanadium alloy), σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \frac{W}{m^2 \cdot K^4}$), T , is the absolute temperature of the module, A is the surface area of the module, and F is the view factor (~ 1). Figure 17 shows the temperature rise in the side wall of the baseline blanket as a function of wall thickness (t_w). If the wall thickness is 5 mm, the temperature rise, due to radioactive heat transfer, is 5°C if the emissivity is conservatively assumed to be 1.0. If the wall thickness is 10 mm, the temperature rise is approximately 10°C if an emissivity of 0.5 is assumed. Thus, the impact is relatively small even on the discharge side of the module where the temperature is high. There is no need to add another barrier from the heat transfer point of view.

3.2.3 Tritium Recovery System

Each blanket module will have its own tritium recovery system which then feeds into the main tritium system. In order to enhance system reliability and flexibility, an interface system will be placed between the module system and the main tritium system. A schematic of the interface system is shown in Fig. 18. Its primary function is to provide isolation between the test modules and main tritium system.

The interface is basically a gas holding tank in which the feed from the tank to the main tritium processing system is delayed about a day. The holding tank eliminates disruption of the main tritium processing system if an unexpected surge or impurity occurs in a blanket test module. The presence of the interface allows the disruption to be handled before the feed is passed to the main tritium processing system. The interface allows the reliability of the main tritium processing to be separated from the reliability of an individual blanket test module's tritium system.

The holding tank interface also allows each blanket test module and its associated subsystems to function as an independent unit. Each blanket test module is a modular unit which is easily replaced without disrupting the operation of other blanket test modules. This characteristic provides greater flexibility in the design of the blanket test module and its subsystems.

Figure 17. Calculated temperature rise in sidewall of baseline blanket due to presence of test module.

Figure 18. Tritium systems in ITER/TIBER.

A diagram of the tritium recovery system for a liquid lithium blanket module, including all secondary systems, is shown in Fig. 19. The reference tritium recovery system for the lithium breeder module for ITER, is a molten salt extraction system. The main components of a molten salt extraction system are a centrifugal contactor unit, an electrolysis unit, and a getter system. The extraction system is linked to several secondary tritium systems to minimize tritium losses from the lithium module, the module's heat exchanger and other tritium subsystems. The design of each of these systems is described below.

The molten salt method^(7,8) of recovering tritium from liquid lithium is a three-step process. First, lithium which contains tritium is intimately mixed with a salt mixture of lithium halides in a centrifugal contactor. The tritium which is in the form LiT, lithium tritide, preferentially distributes to the salt phase. The salt phase, which is denser than the lithium, is separated from the lithium by centrifugal force. Second, the salt phase is circulated to an electrolysis unit in which the LiT is dissociated to form molecular tritium. The molecular tritium is swept from the salt phase by bubbling helium through the electrolysis unit. Third, the helium is circulated to a cleanup unit which removes the tritium and impurities from the helium gas.

The required size of the centrifugal contactor can be estimated from Ref. 7.

$$X = R (e D n + 1) / I(e D n)$$

R is the breeding ratio, g/h, which corresponds to 0.5 g/d for the lithium module. I is the steady-state tritium inventory, g, which corresponds to 1 wppm tritium in the 2000 L of lithium. D is the distribution coefficient, 0.5, n is the contactor efficiency, 0.9, and e is the electrical efficiency, 0.85. X is the fraction of lithium to be processed, which we calculated to be 304 L/hr. Since the lithium to molten salt volume should be 1:3 to ensure good separation of the salt from the lithium, the total throughput through the contactor is 1216 L/hr.

Entrainment of either the lithium or the molten salt into the other liquid is undesirable. Therefore, the centrifugal contactor is not a stand-

Figure 19. Tritium systems for liquid lithium test module.

alone unit but three contactor units in series to ensure that minimal lithium is entrained into the molten salt and that minimal molten salt is entrained into the lithium during operation.

Separation of the lithium from the salt prevents recombination of the dissociated tritium with excess lithium in the electrolysis unit. Separation of the halide salt from the lithium keeps the halides out of the fusion reactor in which they could be activated, could enhance corrosion, and could precipitate out in the colder parts of the lithium coolant loop. Although the three contactors in series prevent entrainment, mutual solubility of the two liquids can cause the above problems to a limited extent. The upper limit is assumed to be the solubility limits of the two liquids. A duplicate set of contactors is provided to increase system reliability. If a problem arises, the lithium flow is switched to the alternate set.

The entrained tritium in the helium is separated from impurities e.g. radioactive gases and entrained halides, in a cleanup unit. A sacrificial bed, which may be simply a refrigerated unit is used to remove entrained halides. Other impurities, ammonia, etc. are removed in low temperature getter beds. The tritium is separated from the helium and other inert gases by a palladium diffuser. Duplicate systems are provided so that a continuous process is achieved.

The conditions a blanket tritium recovery unit sees on ITER/TIBER may not represent conditions present in large-scale recovery systems because the ITER/TIBER units process less than a gram of tritium each day. Scaling to larger units from the results on ITER/TIBER would be easier if the blanket tritium recovery systems tested were larger. The size needed would require blanket units the size of 1-3 reactor sectors.

3.3 Safety Considerations

3.3.1 Liquid Metal Safety

Safe use of liquid metals in ITER/TIBER is a key design issue. There are several ways to minimize the consequences of possible liquid metal spills.

1. Minimize the total volume of liquid metal in the system.
2. Provide multiple barriers between the liquid metal and air/water.
3. Incorporate passive techniques which would minimize the quantity of liquid metal "at risk" in the case of an accident.

4. Provide an inert gas environment to eliminate any air-liquid metal reactions.
5. Provide an extensive monitoring system which could be used to anticipate operating problems.

Minimize Volume of Liquid Metal

The present blanket module occupies a volume of $\sim 1.3 \text{ m}^3$, 60% of which is liquid lithium. This translates into a lithium volume of $\sim 0.8 \text{ m}^3$ which is close to the proposed volume safety limit. Additional lithium is required for coolant lines, the primary heat exchanger, and the tritium system.

The total volume of lithium can be minimized by placing the main subsystems as close as possible to the reactor, and the lithium "at risk" can be minimized by placing those subsystems in the basement below the reactor, leaving only the cooling lines and the module itself in the reactor hall. A separate room could be more carefully monitored and controlled than the entire reactor hall and would provide an additional barrier between the lithium and the water/air in the reactor hall.

Assuming that the lithium coolant can be carried in pipes, 10 cm in diameter, the total volume of lithium in the pipes in the reactor hall is estimated to be 0.13 m^3 . Thus the total volume in the reactor hall can be kept below 1 m^3 . This volume could be reduced by reducing the size of the blanket module, but then the degree of geometric simulation of an advanced blanket would be reduced.

Multiple Barriers

It is proposed that multiple barriers be used wherever there is a possibility for Li/water/air accidents. This means that the blanket module be surrounded by a boundary shell to prevent possible Li/water contact with the baseline blanket. The shell would be cooled by low temperature He gas. Second, all of the cooling lines leaving the module would be composed of duplex tubes. The inner structure would be a vanadium alloy, and the outer structure would be austenitic stainless steel. Finally, the subsystems would be placed in an isolated room which is free of water and which is filled with an inert gas or dry nitrogen during operation. Due to testing requirements to the one spot where multiple barriers are not desirable is at the first wall.

Because of disruption damage, a leak into the plasma vessel is possible. The consequences of such an accident need to be more carefully assessed.

Passive Safety

The Li dump tanks will be located below the subsystems. In case of an accident, even involving the complete loss of power to valves and pumps, the lithium would drain, by gravity feed, into the dump tanks and be removed from the high risk areas.

Inert Gas

In order to eliminate the possibility of a Li/air reaction, all areas at risk will be filled with an inert gas or dry nitrogen. This includes the reactor hall and the room containing the subsystems.

Monitoring System

An important part of safely operating a liquid metal module is to be able to monitor performance and be able to shut down the module if a leak or accident appears to be imminent. It is suggested that the performance be monitored in two ways. First, direct measurements of the module operating parameters would be made (pressure drop, inlet and outlet temperatures, etc.). In addition, the secondary barriers would be monitored for possible Li leaks. Second, test samples would be placed in element and sub-module capsules that mimic the environment of the blanket module. These samples would be removed at frequent intervals, and properties would be measured to determine the degree of degradation. (The approach here is similar to that used in the fission industry to monitor changes in the DBTT of the pressure vessels.) If property degradation is excessive, the module could be shutdown and removed before any accident occurs.

Although there are concerns about using Li in systems that also contain water, there are several ways of enhancing safety. In most respects, safety imposed restrictions should not severely hamper testing of the liquid metal module. Two areas that need more careful analysis are the volume limits of the liquid metal and the potential for a leak through the first wall.

3.3.2 Disruption Considerations

Electromagnetic Considerations

Typically, the two major electromagnetic problems of a first wall, blanket and shield (FWBS) system are:

- (1) Shielding of the plasma region by the FWBS system, thus delaying or distorting the penetration of the poloidal field (PF) from the external PF coils into the plasma.
- (2) Forces, torques, and arcing in the FWBS components due to a plasma disruption. Eddy currents are induced in the FWBS by the decay of the magnetic field of the decaying plasma current. These eddy currents interact with the PF or, worse yet, with the toroidal field (TF) to produce forces and torques.

The first of these can be overcome by making the electromagnetic time constant (L/R time) short, the second by making the L/R time of the first wall long and the first wall eddy current path toroidal.

In general, the first wall L/R time is chosen through a compromise between these two considerations. But for the ITER, planned continuous or near continuous operation, electromagnetic shielding of the poloidal field is unimportant, and the first wall L/R time can be chosen long enough to protect the FWBS system from the effects of a current disruption.

Electromagnetic effects in the blanket module depend on how the module is electrically connected to the rest of the FWBS system. There are three major possibilities.

- (1) ITER has a continuous first wall. The module is mounted behind the first wall. Then the first wall shields the module from severe electromagnetic effects.
- (2) The ITER first wall is missing in front of the module, but the module itself has a substantial first wall (say, 1 cm thick stainless steel) in good electrical and mechanical contact with the ITER first wall. Then the combined first walls shield the module from severe electromagnetic effects.

- (3) The module is not electrically connected to the first wall. (Worse yet would be partial connection, as this would permit vertical eddy currents in the module that would interact with the TF to produce large, unbalanced forces on the module.)

Illustrative Calculations

1. First wall L/R time: For a stainless steel first wall of thickness $w = 0.01$ m, and a hollow torus of radii $R = 3$ m, $a = 0.8$ m, self inductance L , electrical resistance R_e are as follows:

$$\begin{aligned}
 L &= \mu_0 R \left(\ln \frac{8R}{a} - 2 \right) & R_e &= \frac{\rho}{w} \frac{2\pi R}{2\pi a} \\
 &= 0.4 \pi \times 3 \left(\ln \frac{8 \times 3}{0.8} - 2 \right) & &= \frac{0.76 \times 3}{0.01 \times 0.8} = 285 \mu\Omega \\
 &= 5.28 \mu\text{H}
 \end{aligned}$$

$$\tau = L/R_e = 5.28/285 = 0.0185 \text{ s} = 18.5 \text{ ms}$$

Additional thickness could readily make $\tau = 20$ to 40 ms.

2. Field from Plasma (Treat as Filament at Radius $R = 3$ m)

Field on Z axis

$$B = \frac{\mu_0 I}{2} \frac{R^2}{(R^2 + z^2)^{3/2}} = \frac{\mu_0 I}{2} \frac{R^2}{z^3} \left[1 + \frac{R^2}{z^2} \right]^{-3/2}$$

Series expansion:

$$B = \frac{\mu_0 I}{2R} \left(\frac{R}{z} \right)^3 \left[1 - \frac{3}{2} \left(\frac{R}{z} \right)^2 + \frac{15}{8} \left(\frac{R}{z} \right)^4 - \frac{35}{16} \left(\frac{R}{z} \right)^6 + \frac{315}{128} \left(\frac{R}{z} \right)^8 \right]$$

Series expansion in midplane (using Legendre polynomials):

$$\begin{aligned}
 B = - \frac{\mu_0 I}{2R} \left[0.5 \left(\frac{R}{r} \right)^3 + 0.5625 \left(\frac{R}{r} \right)^5 + 0.5859 \left(\frac{R}{r} \right)^7 + 0.5981 \left(\frac{R}{r} \right)^9 \right. \\
 \left. + 0.6056 \left(\frac{R}{r} \right)^{11} \right]
 \end{aligned}$$

Position	r	B	
First Wall	3.8 m	1.35 T	The number of terms kept is adequate, except possibly at r = 3.8 m. As average value, we will use B = 1 T.
Center	4.05 m	0.97 T	
Back	4.3 m	0.72 T	

3. Module with Continuous Conducting Shell:

Inductance (L), Resistance (R), L/R Time (τ), and Current (I)

As the module is 0.5 m x 1.2 m x 2 m high, with field and eddy currents strongest away from the top and bottom, we approximate it as infinitely high and calculate current, inductance, and resistance per unit length: I/l , L/l , and R/l .

a. Inductance

Flux = Φ = AB, A = area

$B = \mu_0 I/l$ from Ampere's Law

$$\therefore L/l = \frac{\Phi l}{I} = \frac{ABl}{Bl/\mu_0} = \mu_0 A$$

$$\text{for } A = 0.5 \text{ m} \times 1.2 \text{ m} = 0.6 \text{ m}^2, L/l = 0.6 \times 0.4 \pi \times 10^{-6} = \underline{0.7 \text{ } \mu\text{Hm}}$$

b. Resistance

$$R/l = \rho \sum_{i=1}^4 \frac{a_i}{w_i}$$

where a_i and w_i are respectively the length and thickness of the i th side.

$$= 0.76 \times 10^{-6} \left[\frac{1.2 \text{ m}}{0.01 \text{ m}} + \frac{1.2 \text{ m}}{0.004 \text{ m}} + \frac{0.5}{0.005} + \frac{0.5}{0.005} \right] = 0.76 \times 620 = \underline{471 \text{ } \mu\Omega\text{m}}$$

c. Eddy Current - Low Resistance Limit (as Determined by Inductance) (Disruption Induced)

$$I/l = B/\mu_0 = 1 \text{ T}/0.4 \pi \times 10^{-6} = \underline{0.80 \text{ MA/m}}$$

d. Eddy Current - High Resistance Limit (as Determined by Resistance)
(Disruption Induced)

$$RI = R_L \frac{I}{L} = \dot{\Phi} = A \dot{B} = \frac{AB}{\tau_0}$$

$$\frac{I}{L} = \frac{AB}{\tau_0} / R_L = \frac{0.6 \text{ m}^2 \times 1 \text{ T}}{.01 \text{ s} \times 471 \text{ } \mu\Omega\text{m}} = 0.127 \text{ MA/m}$$

e. Eddy Current - General Case

$$\tau = L_L / R_L = 0.75 \text{ } \mu\text{Hm} / 471 \text{ } \mu\Omega\text{m} = 0.0016 \text{ s} = 1.6 \text{ ms}$$

Note that the high resistance case can be written $\frac{I}{L} = \frac{B}{\mu_0} \frac{\tau}{\tau_0}$.

($\tau = L/R$ time; $\tau_0 =$ plasma current decay time)

Figure 20 shows the behavior of I/L as a function of $\frac{\tau}{\tau_0}$.

Note that both the low resistance and high resistance limits overestimate the eddy currents, but that except when $\tau = \tau_0$, one or the other limit is a good estimate of I/L .

4. Liquid Li Module

Assume a geometry similar to that of the TPSS blanket. If the Li and the shells are electrically insulated from each other, their time constants are largely independent.

a. Shell, $\tau = 1.6 \text{ ms}$, as found in 3e.

b. Li call near first wall, dimensions $0.05 \text{ m} \times 0.025 \text{ m}$. Assume each leg of current path has full length and half width.

$$R_L = \rho \sum_{i=1}^4 \frac{a_i}{w_i} = 0.353 \times 10^{-6} \text{ } \Omega\text{m} \times \left[\frac{.05}{.0125} + \frac{.025}{.025} + \frac{.05}{.0125} + \frac{.025}{.025} \right] = 3.53 \text{ } \mu\Omega\text{m}$$

$$L_L = \mu_0 A = 0.4 \pi \times 10^{-6} \times \left[\frac{.025 \times .05}{2} \right],$$

assuming half the area is effective

Figure 20. Eddy current generation as a function of τ / τ_0 .

$$L\ell = .000785 \mu\text{Hm}$$

$$\tau = L\ell/R\ell = .000785/3.53 = \underline{0.22 \text{ ms}}$$

c. If they are not electrically insulated, current can flow around the module, mostly in Li. Assume it flows in the first line of Li cells.

$$R\ell = 0.353 \times 10^{-6} \left[\frac{1.2 \text{ m}}{.025 \text{ m}} + \frac{0.5 \text{ m}}{0.05 \text{ m}} + \frac{1.2 \text{ m}}{0.08 \text{ m}} + \frac{0.5 \text{ m}}{0.05 \text{ m}} \right]$$

$$= 0.353 \times 83 = \underline{29.3 \mu\Omega\text{m}}. \text{ As in 3a, } L\ell = 0.75 \mu\text{Hm}.$$

$$\tau = 0.75/29.3 = 0.025 \text{ s} = \underline{25.6 \text{ ms}} > \tau_0$$

5. Forces and Torques

Take 1 m of height to be the distance over which the current flows. Only the radial current interacts with the toroidal field. The toroidal field varies inversely with radius.

$$\text{at } r = 4.05 \text{ m, } B = B_0 \frac{R}{r} = \frac{6 \text{ T} \times 3 \text{ m}}{4.05 \text{ m}} = \underline{4.44 \text{ T}}$$

$$F = I B a = 0.80 \text{ MA} \times 4.44 \text{ T} \times 0.5 \text{ m} = \underline{1.8 \text{ MN}} \text{ in Low Resistance (un-insulated) case.}$$

$$= 0.127 \text{ MA} \times 4.44 \text{ T} \times 0.5 \text{ m} = \underline{0.28 \text{ MN}} \text{ in insulated case.}$$

Of course, the current flows one way on one side and the other on the other, so there is no net force. There is a net torque

Low Resistance (un-insulated)

$$F \cdot a = 1.8 \text{ MN} \cdot 1.2 \text{ m} = \underline{2.2 \text{ MN}\cdot\text{m}}$$

High Resistance (insulated)

$$F \cdot a = 0.28 \times 1.2 \text{ m} = \underline{0.34 \text{ MN}\cdot\text{m}}$$

Disruption Stress Analysis

The finite element code ANSYS has been used to perform a finite element stress analysis of the liquid metal module. The blanket module including the first wall has been modelled as an open box structure (Fig. 21), 1 m (radial) by 1.2 m (toroidal) by 2 m (vertical). The front 0.5 m of the box which is closer to the plasma is made of V-15Cr-5Ti, while the rear 0.5 m which is supported at the back by the bell-jar is assumed to be made of PCA. The module is assumed to be cantilevered from the support (shown by hatch lines in Fig. 21) at the bell-jar. The thicknesses of all the faces of the box are assumed to be 1 cm. The surface plates of the box have been divided into 167 nodes (Fig. 21) and 152 plate elements (Fig. 22). The stiffening effects of the structures which are inside the box have not been taken into account, it being realized that if the present analysis shows the stresses to be low, then the actual stresses in the fully stiffened structure would be still lower. Figure 21 also shows the two equal and opposite static forces, each equal to 1.8 MN (applied as a uniformly distributed pressure on all the V-15Cr-5Ti elements), acting on two opposite faces of the V-15Cr-5Ti structure. No loading is assumed to be applied on the PCA structure. The two forces together create a moment of 1.8 MN x 1.2 m, which tends to tip the blanket module in the toroidal direction but is restrained from doing so by the support. As a result, the blanket module structure is subjected to a torsional deformation about the x axis (radial), as shown in a highly exaggerated manner in Fig. 23. A maximum displacement of about 1 mm occurs at nodes 106 and 16.

The contours of maximum effective stress in the V-15Cr-5Ti structure and the first wall are shown in Figs. 24 and 25. The maximum stress in the structure is 77 MPa, while that in the first wall is 52 MPa. The maximum stress in the PCA structure, shown in Fig. 26, is 120 MPa. These stresses are calculated assuming that the disruption forces act like static forces. In reality, the disruption event is over in a matter of milliseconds. Consequently, the actual stresses in the blanket module can only be determined by a dynamic analysis of the problem, and will depend upon the natural frequency of the blanket module. However, even if we use a magnification factor of 2 (as was used in the BCSS), the maximum stresses are well within the allowable primary stress limit of V-15Cr-5Ti. Although the stresses in the PCA

ANSYS 4.2
MAY 15 1987
14:35:37
PLOT NO. 1
PREP7 NODES

ORIG SCALING
XV=-1
YV=1
ZV=1
DIST=1.21
XF=.5
YF=.6
ZF=1

Figure 21. Geometric model used for calculating eddy current stresses in blanket module.

ANSYS 4.2
MAY 15 1987
14:32:13
PLOT NO. 1
PREP7 ELEMENTS
ENUM=1

ORIG SCALING
XV=-1
YV=1
ZV=1
DIST=1.21
XF=.5
YF=.6
ZF=1

Figure 22. Geometric model showing plate elements used in calculations.

ANSYS 4.2
MAY 15 1987
13:03:29
PLOT NO. 2
POST1 DISPL
STEP=1
ITER=1

ORIG SCALING
XV=-1
YV=1
ZV=1
DIST=1.21
XF=.5
YF=.6
ZF=1
DMAX=.000899
DSCA=135

Figure 23. Distortion generated in blanket module during disruption.

ANSYS 4.2
MAY 15 1987
13:35:32
PLOT NO. 2
POST1 STRESS
STEP=1
ITER=1
SEFB

ORIG SCALING
XV=-1
YV=1
ZV=1
DIST=1.1
XF=75
YF=6
ZF=1
DMAX=.000899
DSCA=122
MX=77067122
MN=10406292
NCON=18
VMIN=13914795
VINC=3308463

Figure 24. Maximum stress contours generated in module during a disruption.

ANSYS 4.2
 MAY 15 1987
 13:37:12
 PLOT NO. 2
 POST1 STRESS
 STEP=1
 ITER=1
 SEFB

 ORIG SCALING
 XV=-1
 YV=1
 ZV=1
 DIST=.988
 XF=1
 YF=.6
 ZF=1
 DMAX=.000899
 DSCA=.110
 MX=52333720
 MN=40258372
 NCON=18
 YMIN=40893914
 VINC=.635545

Figure 25. Maximum stress contours in first wall during a disruption.

ANSYS 4.2
 MAY 15 1987
 13:27:29
 PLOT NO. 2
 POST1 STRESS
 STEP=1
 ITER=1
 SEFB

 ORIG SCALING
 XV=-1
 YV=1
 ZV=1
 DIST=1.1
 XP=.25
 YP=.8
 ZP=1
 DMAX=.000589
 DSCA=193
 MD=119660427
 MN=42607748
 NCON=18
 YMIN=48663145
 YINC=4035405

Figure 26. Maximum stress contours in blanket module during a disruption.

structure are higher, the stiffening effects of the interior structures, which have been ignored here, will reduce these stresses. Consideration of these effects will also reduce the maximum stresses in the V-15Cr-5Ti structure, which should provide enough margin for additional stresses caused by coolant pressure loading.

Conclusions

The major points from the disruption analysis are summarized below.

L/R time for ITER/TIBER	
First Wall	18.5 ms
Field from Plasma Current at Radius	
3.8 m	1.35 T
4.05 m	0.97 T
4.3 m	0.72 T
Inductance of Module Outer Shell	0.7 μ hm
Resistance of Module Outer Shell	471 μ hm
Disruption Induced Eddy Current in Module	
Low Resistance Limit	0.8 MA/m
High Resistance Limit	0.13 MA/m
Induced Torques (Li Module)	
Low Resistance Case	2.2 MN•m
High Resistance Case	0.3 MN•m

There are several general conclusions that can be made concerning disruption effects.

- (1) If the module first wall is electrically connected to the rest of the ITER/TIBER first wall (continuously along the edges), then it will act to shield the module from induced magnetic torques.
- (2) If the module is electrically insulated from the rest of the ITER/TIBER first wall and blanket, then there will be induced torques of the level indicated above. The torques will act to rotate the module around the radial vector.

- (3) The worst case would occur if there were only partial electrical connections between the module and the rest of the ITER/TIBER blanket and first wall. In this case large eddy currents could travel poloidally in the module producing large body forces.
- (4) It is therefore recommended that module first wall be either continuously connected with the ITER/TIBER first wall, or that it be completely isolated. In the later case, the module must be designed to accommodate the induced torques.

3.4 Module vs. Sector Comparison

3.4.1 Module Behavior

The ITER/TIBER module is significantly smaller than the configurations envisioned for a commercial reactor, and a key issue for testing is the degree to which such a module simulates the behavior of the larger system. A comparison has been made for the areas of MHD, thermal hydraulics, corrosion, and thermomechanical response. The parameters which can be used to compare behavior of ITER/TIBER and a commercial system (TPSS) are given in Table 9, and the comparison between ITER/TIBER and TPSS is shown in Table 10.

Liquid Metal MHD

The four dimensionless parameters are the Hartmann number, M , the interaction parameter N , the conductivity ratio, C , and the length to duct width ratio, l/a . Both the ITER module and sector provide a test environment that can properly simulate MHD effects. (See Table 11).

Thermal Hydraulics

Two parameters were chosen to indicate the degree of simulation for thermal hydraulics. The first is a dimensionless parameter, t^* , which is an indication of the residence time of the liquid metal in the blanket. By lowering the average velocity, it is possible to have the same residence time in either the module or the sector as in TPSS. The second parameter, $q \sqrt{l/v}$, is proportional to the radial temperature difference across the blanket. In this case, it is difficult to achieve the same radial temperature difference in the blanket module, but it can more easily be achieved in the sector.

Table 9. Definitions of Parameters

M	$\equiv$ Hartmann number
N	$\equiv$ Interaction parameter
C	$\equiv$ Conductivity ratio
l	$\equiv$ Flow length in blanket
a	$\equiv$ Duct radius or 1/2 duct transverse dimension
q	$\equiv$ Surface heat flux
v	$\equiv$ Average coolant velocity
Δx	$\equiv$ First wall thickness
ΔT	$\equiv$ Temperature difference in blanket
T	$\equiv$ Peak temperature in blanket
ϕt	$\equiv$ Total neutron fluence
P	$\equiv$ Primary stress level
α	$\equiv$ Thermal expansion coefficient
$\dot{m}$	$\equiv$ Mass flow rate

Table 10. Values of Parameter

Parameter	Value		
	TPSS	ITER Module	ITER Sector

l	2.7 m	1.5	3.5 m
a	18 cm (Bl.)	18 cm (Bl.)	18 cm (Bl.)
	2.5 cm (Channel)	2.5 cm (Channel)	2.5 cm (Channel)
q	1.5 MW/m ²	0.25 MW/m ²	0.25 MW/m ²
v	0.15 m/s	0.03-0.15 m/s	0.03-0.15 m/s
Δx	4 mm	4 mm - 15 mm	4 mm - 15 mm
ΔT	250°C	160°C	160°C
T	700	700	700
ϕt	25 MW-y/m ²	3.5 MW-y/m ²	3.5 MW-y/m ²

Table 11. Comparison of Test Parameters

Performance Coefficient	ITER/TIBER		
	TPSS	Module	Sector
MHD			
M	10^4	5×10^3	5×10^3
N	5×10^3	5×10^4	5×10^4
C	0	0	0
λ/a	120	80	160
Thermal Hydraulics			
$t^* = \lambda a / v a^2$	2.37×10^{-3}	$4.8 - .96 \times 10^{-3}$	$11.2 - 2.2 \times 10^{-3}$
$q / \lambda / v$	2.08	1.2 - 0.5	1.9 - 0.8
Corrosion			
ΔT_v	37.5	4.8	12.0
Thermomechanical Resp.			
$\lambda \Delta T$	675	240	560
ϕt	25	3.5	3.5
$q \Delta x$	4.8×10^{-3}	$1 - 3.7 \times 10^{-3}$	$1 - 3.7 \times 10^{-3}$

(Note, by further reducing the average velocity, the same temperature drop can also be achieved in the module). Therefore, these figures indicate that thermal hydraulics can also be properly simulated in either a module or sector. (See Sec. 3.2.2 for further details).

Corrosion

It is possible that the corrosion rate will be a function of the peak temperature, the ΔT through the blanket, and the velocity of the liquid metal. The peak temperature in the blanket can be set at any desired value. However, ΔT and v are closely tied together. Therefore, the parameter chosen to represent the simulation of the corrosion environment is the product of ΔT and v . Table 11 indicates that neither the module or sector fully simulate the corrosion environment, but that the sector is significantly better than the module. (Note that if corrosion is not velocity dependent, then either the module or sector would be acceptable.)

Thermomechanical Response

The overall dimensional change in the blanket is proportional to $\lambda \Delta T$. The sector, as shown in Table 11, comes reasonably close to matching this

parameter, whereas the module does not. Plastic deformation, resulting from radiation creep and swelling, is a function of the total fluence. Because the total fluence in TPSS is ~8 times that ITER/TIBER, these effects will not be well characterized. Finally, the thermal stress in the first wall is proportional to $q\Delta x$. This parameter can be reasonably well matched by increasing the wall thickness to compensate for the decreased surface heat load. However, when the surface thickness is increased, the stiffness of the entire blanket is altered resulting in a poorer simulation of the overall thermomechanical response. It is concluded that a module does not adequately simulate the thermomechanical response, while the sector could be acceptable. Even with the sector, a complete simulation of thermomechanical response is not possible because of the reduced neutron fluence.

Other Considerations

The size of the blanket test section affects other areas. For example, the sizes of the heat removal and tritium subsystems are proportional to the module or sector size. It is desirable to have subsystems which are representative of systems on future reactors so that performance and reliability data can be extrapolated. However, the module subsystems may be too small to be representative, and thus information gathered during operation could be of limited use for future systems.

The surrounding blanket will affect the neutronics within the module. The effects will be greatest at the edges of the module, and a larger test section would provide a better neutronics simulation. Neutronics calculations will be needed to evaluate the impact of size.

Conclusions

- (1) The ITER/TIBER module size is adequate to assess MHD and thermal hydraulics.
- (2) If velocity is an important factor in corrosion, then a module is not likely to provide a good simulation of a power reactor environment.
- (3) The module is almost certainly not adequate to test thermomechanical effects. The sector provides a marked improvement, but it also has deficiencies.

3.4.2 Thermomechanical Response

As indicated in the last section, ITER/TIBER test modules may be inadequate to simulate the thermomechanical response of an advanced blanket. This section elaborates on the various types of thermomechanical response and the possible need for sector testing in this area.

Ideally, the purposes for conducting thermomechanical testing of liquid metal cooled blankets, as far as stress is concerned, are

(1) to validate the stress and thermal hydraulics analyses used to design the blanket,

(2) to ascertain that the blanket will not "fail" during operation.

Possible failure modes are:

- (a) failure by rupture
- (b) failure by plastic collapse
- (c) failure by excessive deformation or ratcheting
- (d) failure by fatigue, creep or creep-fatigue
- (e) failure by crack growth and brittle fracture
- (f) failure by stress corrosion cracking or corrosion fatigue

The principal driving force for all these failure mechanisms is stress. Generally, failure mechanisms a, b, and c depend on average stresses through the structure, while mechanisms d, e, and f depend additionally on the peak stresses or peak stress ranges. The failure mechanism and the time to failure are determined by a whole series of complex interactions between blanket geometry and support, coolant temperature and pressure, average and peak temperatures of the structure, plasma-on and plasma-off times, fluence, coolant chemistry, disruption scenarios, and last but not the least, the physical and mechanical properties of the blanket materials. Although every effort is made in the design stage to try to guard against each individual failure mechanism by following simple design rules, and sometimes by conducting very detailed analyses, it is virtually impossible to model all the complexities of geometry, loadings and material behavior, and to take into account all the myriads of possible synergisms between the various factors that can potentially contribute towards the failure of the blanket. Necessarily, various simplifying assumptions are made regarding blanket

geometry, constraints, loadings, and material behavior. One of the primary purposes of the thermomechanical testing of any blanket is to verify, directly or indirectly, that the stresses and deformations calculated during design are reasonable approximations to what exist in a real blanket. Further, depending on the time available for testing, thermomechanical testing should also detect failure modes or mechanisms (preferably in their incipient stages) that were not anticipated or were inadequately accounted for during the design phase. It is, of course, not necessary and not always possible because of other constraints to test a complete blanket sector duplicating all aspects of the blanket operation simultaneously. The purpose here is to separate those aspects of the design, from the viewpoint of stress, that can be reasonably verified by testing small modules of the blankets from those that require testing of full sectors.

Stresses and failure mechanisms that are local in nature and depend primarily on local parameters can likely be adequately tested in a module provided the driving forces are properly simulated. On the other hand, stresses and failure mechanisms that are global in nature and depend critically on the interactions between various parts of the blankets cannot be properly evaluated by testing modules and will require testing of full sectors. The first category includes stresses such as simple membrane or bending stresses in the coolant channel walls due to coolant pressure, thermal and swelling stresses in a partially constrained first wall due to surface heat flux and swelling strain gradient, etc., and failure mechanisms involving rupture, fatigue, creep, creep-fatigue, crack growth, brittle fracture, stress corrosion cracking, and corrosion fatigue. These can be tested in modules provided the relevant driving forces and geometrical parameters, as listed below, are properly simulated:

- (1) Coolant pressure stresses - coolant pressure, geometry of the coolant channel, and wall thicknesses.
- (2) Thermal stresses - surface heat flux, wall thicknesses, and coolant temperature and heat transfer coefficient.
- (3) Swelling stresses - fluence gradient through the first wall, wall thicknesses, temperature.

- (4) Rupture, tensile and creep - maximum and thickness-averaged values of principal tensile stress, temperature, and fluence during plasma burn.
- (5) Fatigue, creep-fatigue - maximum effective plastic strain range between plasma on and plasma off conditions, maximum principal tensile stress during plasma burn, maximum and minimum temperatures during plasma on-off cycle, plasma burn time, and fluence.
- (6) Crack growth and brittle fracture - maximum stress intensity factor, maximum range of stress intensity factor between plasma on and plasma off conditions, temperature, and fluence.
- (7) Stress corrosion and corrosion fatigue - maximum stress intensity factor and stress intensity factor range for cracks initiating from the coolant side, coolant chemistry, temperature, and fluence.

Within the second category, i.e., stresses and failure mechanisms that cannot reasonably be simulated by the testing of modules, and would require testing of full blanket sectors, are the following:

- (1) Stresses due to coolant pressure acting on a whole blanket sector (e.g., manifold coolant pressure acting on BCSS-type blankets).
- (2) Stresses due to mismatch of deformations between inboard and outboard blankets when they are connected rigidly, as in ITER/TIBER.
- (3) Stresses due to earthquake and electromagnetic loadings during disruptions.
- (4) Stresses due to poloidal and toroidal variations of temperatures and fluence.
- (5) Plastic collapse of a whole blanket sector.
- (6) Incremental ratcheting of a whole blanket sector due to cyclic thermal stresses and irradiation induced creep and swelling.

3.4.3 Design Considerations

The ITER/TIBER design is fixed and can only accommodate modules for testing. The present ITER baseline design is larger than TIBER II and can potentially accommodate larger test vehicles, and it is possible to consider testing sub-sectors (defined as the blanket/shield located in the outboard area, between divertor modules).

It is presently envisioned that a test sub-sector would consist of an outer shell plus test module that would fit inside the shell. This arrangement is similar to that proposed for the TIBER II modules shown in the previous sections. The sub-sector could be designed to accommodate either a singly large, module, as shown in Fig. 27a, or a number of smaller modules, as shown in Fig. 27b. The choice of module size will depend on the need to test the global behavior of prototypical blankets and the number of different tests and designs that are to be put into the test program. A possible test scenario would utilize a sub-sector that can test a number of smaller modules early in the test program. When a lead blanket design is selected, the shell could be replaced with one which would hold a single large module. This arrangement would then allow the integrated behavior of the lead blanket design to be more completely tested.

Additional work in this area is required to integrate the test needs with the ITER design and maintenance.

Figure 27a. Subsector arrangement for a single, large, test module.

Figure 27b. Example of sub-sectors design for testing several smaller modules.

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