REQUIRED MOMENTUM, HEAT, AND MASS TRANSPORT EXPERIMENTS FOR LIQUID METAL BLANKETS*

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ABSTRACT

The lack of experimental data for liquid metal blankets in the fusion environment restricts our ability to develop designs with demonstrated feasibility and adequately characterized performance. In order to confidently predict neutronic and thermal hydraulic performance of blankets, a variety of experiments will be needed. Ultimately, verification of all nuclear components will require testing in a fusion environment. However, a great deal of information can be obtained prior to fusion testing using non-neutron facilities to explore separate, multiple, and partially integrated effects. A large class of issues which can be effectively studied in a non-neutron environment are those impacted by MHD transport phenomena. A coordinated test program is described below to treat momentum, heat, and mass transport issues for liquid metal blankets.

I. INTRODUCTION

Self-cooled liquid metal blankets represent a class of potentially very attractive blanket designs. They have been analyzed in numerous design studies due to high breeding potential, simplicity, and good heat transfer capability.[1-3] However, large uncertainties exist in the effect of a magnetic field on their thermomechanical operation.[4] This leads to uncertainties in predicting the feasibility and/or attractiveness of these blankets.

Through the effects on fluid flow, many aspects of blanket behavior are affected by magnetohydrodynamic (MHD) effects, including pressure drop, heat transfer, mass transfer, and structural behavior. In this paper, the testing needs are summarized for this highly related set of issues dealing with momentum, heat, and mass transport under the influence of a strong magnetic field (i.e., magnetic transport phenomena). After reviewing the existing facilities, a proposed set of new experiments is examined which could be performed in order to reduce the present uncertainties. By improving our basic understanding and by providing direct experimental data on blanket behavior, these experiments will lead to improved designs and an accurate assessment of the attractiveness of liquid metal blankets.

II. TESTING NEEDS

II.A. MHD Fluid Flow

Some theoretical understanding of the flow of conducting liquids in simple geometries with strong magnetic fields has been developed in recent years,[5-7] but experimental verification at high values of the MHD parameters is very scarce. In addition, while the existing theory has established some features of flow in channels, large uncertainties remain in predicting key design parameters in the complex geometries of fusion blankets. Because of the limited extent of our basic understanding, the test program should start with exploration and verification of fundamental phenomena. But because of the large number of interrelated phenomena and the complex nature of blanket operation in the fusion environment, the test program must also include more integrated types of experiments to meet the goal of concept definition and verification.

MHD effects are most strongly dependent on the geometry and on a small number of dimensionless parameters, the most important being the Hartmann number (M), the interaction parameter (N), and the wall conductance ratio (C). (The Hartmann number is proportional to

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the magnetic field and measures the dominance of MHD forces over viscous forces. Similarly, the interaction parameter measures the dominance of MHD forces over inertial forces.) Figure 1 indicates that most existing experimental data are at values of M and N much lower than those found under actual reactor conditions.[8] Most of the data have also been accumulated in very simple geometries. More data are needed for higher values of M and N, and also for geometries more representative of actual blanket configurations.

II.B. MHD Heat Transfer

Because of the influence of the magnetic field on the velocity profiles within the blanket, the heat transfer characteristics are also strongly affected. MHD heat transfer can be predicted if the velocity profiles are sufficiently well known. However, the accuracy of velocity profile measurements and the ability to extrapolate such measurements to the more complex geometries of actual designs are serious concerns. Measurements of temperature profiles provide additional information that can be used directly to predict heat transfer and/or to provide a consistency check of velocity profile measurements. Thus, heat transfer experiments are an important supplement to fluid flow measurements. The engineering scaling requirements for testing include all of those for fluid flow testing, as well as several additional ones.[4] To correctly model the majority of blanket designs requires:

- correct core velocity distributions
- suppression of turbulence
- suppression of natural convection
- similar flow entrance length
- similar thermal entrance length
- negligible axial conduction
- negligible first wall bulk heating.

Some of these are automatically satisfied if the fluid flow requirements are met.

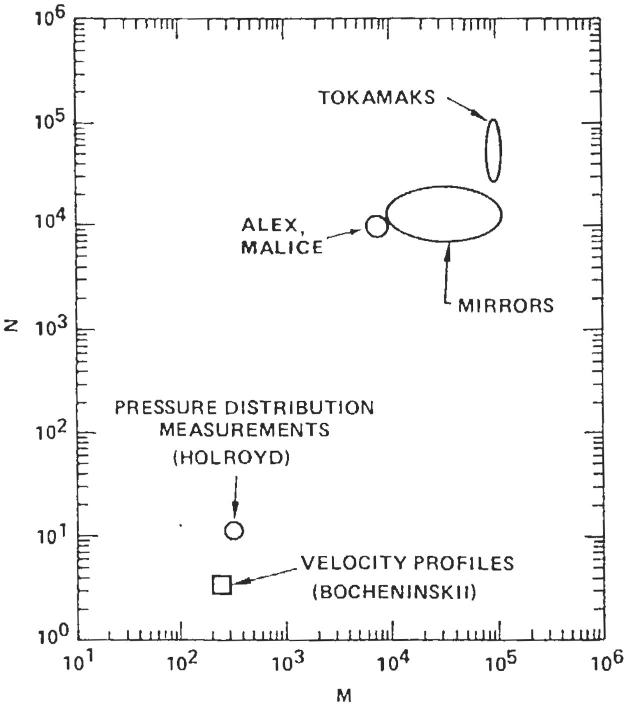

Fig. 1. Hartmann number (M) and interaction parameter (N) ranges for existing data and reactor conditions[8]

II.C. Material Interactions

Material compatibility is a dominant concern for nearly every liquid breeder blanket design; however, the nature and importance of the issues depend strongly on the materials. There are a large number of phenomena relating to material interactions, including both mass transfer and structural degradation. Table 1 shows the most important material interaction issues.

Compared to heat transfer and fluid flow, additional environmental conditions can be critically important for material compatibility, such as materials, impurity levels, absolute temperature, temperature gradient, out-of-blanket geometry, and long-term exposure. The concentration potential to be considered in the mass transfer can be discontinuous at the solid/liquid interface due to the dissolution kinetics. The boundary conditions on mass transport are not easily defined. This is different from the heat transfer and velocity distribution calculations. Thus, experiments are needed to develop empirical correlations for the behavior under fusion-relevant conditions.

In order to confidently design blankets, temperature and impurity limits must be adequately established. Impurity control techniques should also be explored. While a number of methods to control corrosion and mass transport have been proposed (inhibitors, coatings, getters, etc.), further study is

Table 1. Material Interaction Issues

A. Mass Transport
  1. Wall erosion from dissolution and spalling
  2. Erosion/redeposition phenomena, including tube plugging and activation product transport

B. Structural Property Degradation
  1. Liquid metal embrittlement
  2. Removal of alloying elements
  3. Embrittlement and surface chemistry changes due to interstitial element transport
  4. Stress-corrosion interactions
  5. Radiation-corrosion interactions

Table 2. Existing U.S. Fusion Liquid Metal Experimental Facilities

NAME	LOCATION	STATUS	OPERATING PARAMETERS
A. LIQUID METAL MHD			
ALEX	ANL	Operating	$B = 2.0T$, $N \approx 10^4$, $V \approx 0.2\ m^3$, NaK
Liquid Metal Flow Loop	Univ. of Texas	Operating	$N \sim 10^3$, $V = 7x10^{-4}\ m^3$, $B \sim 0.6T$
B. LIQUID METAL THERMAL HYDRAULICS			
Li-FS	ETEC	Not Operating	Forced flow, high-velocity, medium size (5-50 ℓ), ΔT, impurity control, corrosion tests
C. LIQUID METAL CORROSION			
Li-SS	ANL	Operating	Forced flow, medium size (5-50 ℓ), impurity control, ΔT, corrosion mechanical testing
Li-V	ANL	Not Operating	Forced flow, small size (< 5 ℓ)
Li-FS	ANL	Upgrade	Forced flow, medium size (5-50 ℓ) high velocity, ΔT, impurity control, corrosion/mass transfer
Li-SS -FS	ORNL	Operating	Thermal convection loop, small size (< 5 ℓ), ΔT, corrosion tests
Li-SS	UW	Not Operating	Forced flow, high-velocity, medium size (5-50 ℓ), ΔT, impurity control, corrosion tests
Li-SS	HEDL	Not Operating	Forced flow, high-velocity, large size (3800 ℓ), low T
LiPb-Iron	ANL	Operating	Forced flow, small size (< 5 ℓ), ΔT, corrosion and mechanical tests
LiPb-SS	ORNL	Operating	Thermal convection loop, small size(< 5 ℓ), ΔT, corrosion
Na-SS	Various	Some Operating	Forced flow, large loops, (pumps, instrumentation, etc. could be used with new loops), Li or LiPb

required to indicate the likelihood of success and the limits of applicability.

III. REVIEW OF EXISTING FACILITIES

III.A. MHD Fluid Flow and Heat Transfer

Existing experiments in technical disciplines relevant to liquid breeder blanket issues are summarized in Table 2. The primary element in the current U.S. MHD program is the ALEX facility at Argonne National Laboratory.[8] ALEX is capable of magnetic fields up to 2 Tesla in a field volume 1.8 m x 0.76 m x 0.15 m. This will provide Hartmann numbers and interaction parameters much closer to reactor conditions than any previous experiment. Information expected to come from ALEX includes single channel pressure drops and velocity profiles in straight channels, bends, and magnetic field entrance regions. In addition to the measurements of pressure drop and velocity profiles, the MHD program at ANL will contribute to the development of velocity profile instrumentation. The ability to develop techniques to accurately measure velocity profiles at high magnetic field will have a large impact on the remainder of the MHD test program.

III.B. Material Interactions

Several corrosion loops are currently in operation to explore material compatibility (see Table 2). These loops provide valuable information for identifying compatible material combinations. However, large uncertainties remain in defining accurate

Table 3. Features bjectives of Major Liquid Breeder Experiments

		Magnetic Transport Phenomena Facilities			
	ALEX[a]	LMF[b]	MHDM[c]	TMIF[d]	PITF[e]
Features of Experiments	• Simple geometry of a channel • NaK	• Basic elements of relevant geometry	• Basic elements of relevant geometry • Relevant materials combination • Transport loop • Relevant T, ΔT, impurities, V • Long operating time per experiment	• Actual materials and geometry • Transport loop • Relevant environmental and operating conditions	• Prototypic blanket module • Transport loop • Prototypic environmental and operating conditions
	• Measure velocity profile, electric potential pressure drop (may be upgraded)	• Measure velocity and temperature profiles; pressure drop, temperature, electric potential	• Measure dissolution and deposition rates	• Measure integral quantities (ΔP, T, corrosion and deposition rates)	• Measure integral quantities
Objectives	• Develop and test velocity profile instrumentation in NaK environment • Validate MHD in simple geometry (basic heat transfer data may be possible in upgrade)	• Develop and test instrumentation • Validate MHD, MHD heat transfer • Design data (ΔP, T) for configuration screening and provide input information to design TMIF • Explore techniques to reduce ΔP and enhance heat transfer	• Develop and test instrumentation in relevant environment • Design data on MHD heat and mass transfer • Verify techniques to reduce corrosion and corrosion effects	• Design data for blanket test module • Confirm and refine configurations	• Engineering design data • Reliability data in non-fusion environment

[a] Exists (ANL)

[b] Liquid Metal Flow Facility

[c] MHD Mass Transfer Facility

[d] ThermoMechanical Integration Facility

[e] Partially Integrated Test Facility (may be an upgrade of TMIF)

temperature limits, the effects of impurities, effects of strong magnetic fields, and methods of controlling corrosion.

IV. REQUIRED NEW FACILITIES

IV.A. MHD Fluid Flow and Heat Transfer

A range of experiments have been explored to fulfill the need for further testing of MHD related effects. Table 3 shows the relationship between the major facilities by specifying the principal features and objectives of the experiments. Also included in the table are an MHD mass transfer facility and two partially integrated test facilities (TMIF and PITF), which are considered later. Table 4 indicates approximate ranges for the major experimental parameters.

Beyond ALEX, experimentation on MHD effects should progress to more complex geometries and conditions closer to the fusion reactor environment. This is particularly important in order to develop the ability to predict fluid flow, heat transfer, and pressure drop behavior in self-cooled blanket designs with complex flow paths. Two advanced Liquid Metal Flow facilities, LMF1 and LMF2, have been examined.

LMF1 In LMF1, the emphasis is on developing a better understanding of the "microscopic" MHD behavior, especially the velocity profiles, in basic elements of relevant geometries. If the electric current distributions and velocity profiles can be predicted theoretically, then many of the other important "macroscopic" parameters can be derived, such as pressure drop and heat transfer characteristics. Therefore, great importance should be attached to the development of velocity profile instrumentation, and measurement of velocity profiles in a variety of relevant geometrical configurations. Instrumentation development should be done prior to commissioning LMF1 – in ALEX, ALEX upgrade, or a similar facility. The experiments will involve elements of complex geometries, e.g., expanding or contracting ducts, orifices, or bends with different alignments relative to the magnetic field.

In addition to simple velocity measurements for validation of MHD theory, the

Table 4. Characteristics of Major Liquid Breeder Experiments

		Magnetic Transport Phenomena Facilities			
Characteristic	ALEX	LMF	MHDM	TMIF	PITF
Fluid	NaK (100°C)	NaK	actual materials	actual materials	actual materials
Testing Volume (m x m x m)	1.83 x 0.76 x 0.15 (0.21 m^3)	3 x 1 x 0.5 (1.5 m^3)		3 x 1 x 0.5	3 x 1 x 0.5
Magnetic Field	2 T	4-6 T		4-6 T	4-6 T
Configuration	simple geometry	elements of complex geometry		submodule	prototypic

facility has a secondary mission to measure temperature profiles, explore heat transfer characteristics, and develop methods to improve heat transfer and fluid flow, such as geometric modifications, use of insulators, and flow tailoring. This secondary mission will likely follow a period of 2-4 years of basic velocity profile measurements. Temperature profiles resulting from a surface heat flux also serve as an integral check on the validity of the microscopic measurements and as a back-up source of data.

LMF1 is designed for flexibility and to provide high capabilities for magnetic field strength and field volume. This allows the experiments to treat a wide variety of geometric configurations and reactor relevant conditions. Analysis of fluid flow behavior indicates that certain minimum ranges of the Hartmann (M) and Reynolds (Re) numbers must be provided in order to maintain similar fluid flow behavior. As an example, Figure 2 indicates the operating region for the Hartmann and Reynolds numbers which provide fluid flow behavior similar to that expected to occur in the poloidal manifolds of the reference BCSS design.[4] The criteria imposed include (1) suppression of turbulence, (2) size of inertial and shear layers less than 1/10 of the channel half-width, and (3) dominance of inertial forces over viscous forces.

The conditions shown in Fig. 2 are minimum requirements for act-alike behavior; true dimensionless scaling requires exact similarity of the dimensionless numbers. This is generally very difficult to obtain, primarily because high Hartmann number requires both high field <u>and</u> large volume. Additional criteria may be required, for example, on the wall conductivity ratio, C. Also, other blanket designs may require different parameters for similarity.

From the figure, it can be concluded that the Hartmann number should be maintained higher than 10^3 or 10^4. This can be achieved in small channels (1-5 cm) if the magnetic field strength is above 1-2 Tesla. Other concerns also suggest a high magnetic field strength for relevant MHD behavior. For example, if ferritic materials are utilized, they must be fully saturated. In addition, experimental results indicate that it might be possible to generate and sustain some flow fluctuations at high magnetic field.[9] The possible impact on heat transfer may be critical and needs to be verified.

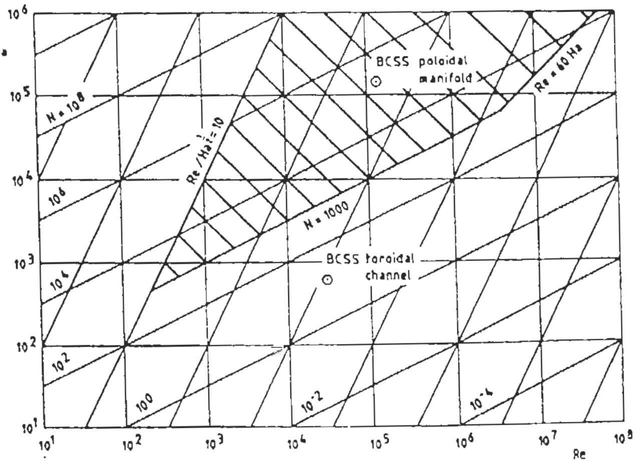

Fig. 2. Required parameter range of the Hartmann number (Ha), Reynolds number (Re), and interaction parameter (N) for MHD fluid flow experiments

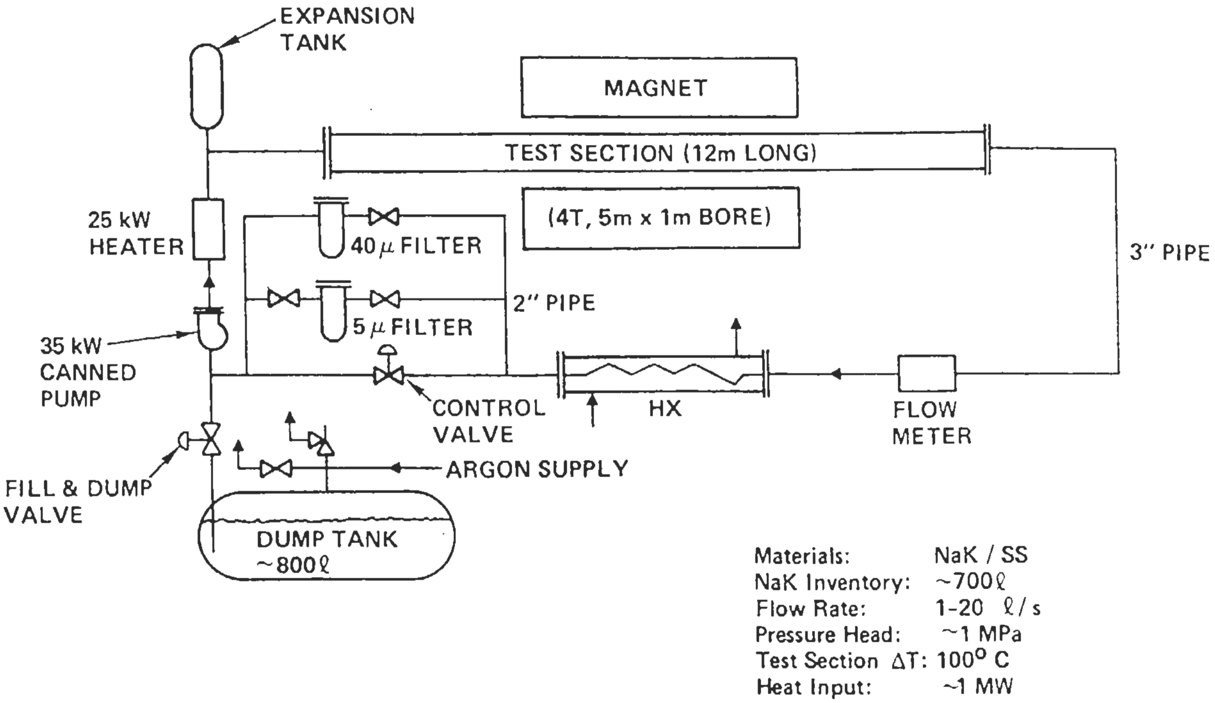

Fig. 3. Preliminary facility characteristics of LMF1

Another desired feature of the LMF1 facility is expandability. Beyond Phase I, and assuming that self-cooled blankets continue to be strong candidates, MHD heat and mass transfer experiments will be required. By providing the capability for large volume, high temperature operation in the initial facility, the same facility can be used for the follow-up experiments with significant savings on the integrated cost.

A preliminary sketch of LMF1 is shown in Figure 3. The experiments require a large volume of moderately high magnetic field, power supplies for the magnets and for surface heating, heat rejection systems, instrumentation, and work space. It is envisioned that several different flow loops may be inserted into the test volume, making this a "user facility". The total cost, including capital and operating expenses, has been estimated at $10-15M.

LMF2 While LMF1 will focus on developing predictive capability by focusing on measurement and understanding of "microscopic" parameters such as velocity profiles, it is suggested that a series of experiments would also be performed with a greater focus on "macroscopic" parameters such as the pressure drop and heat transfer characteristics. These experiments serve a complementary role to LMF1, providing data which is not affected by the limitations of velocity and temperature profile instrumentation at high field, high temperature, and in complex geometries.

Although in principle these experiments can be conducted in LMF1, practical considerations suggest that another facility, called LMF2, would be devoted to this purpose. Macroscopic measurements would serve as a check on the validity of the velocity profile models and measurements, and also provide a back-up source of data if the velocity measurements turn out to be inadequate. This might happen, for example, if reliable velocity measurements cannot be obtained at high fields, complex geometries, high temperatures, or lithium operation.

The extent to which our understanding would be furthered by this kind of test and the amount of data to support model development are less than the MHD "microscopic" parameter experiments in LMF1; however, integral benchmark data could be used to indicate the most serious problems and to provide in an empirical data base for design improvement. The cost and time to perform such testing might be small enough to make it very attractive. Although the device parameters should be very similar to those of LMF1, much of the LMF1 instrumentation (which will be required to develop "microscopic" data such as flow profiles) can be avoided and the device need not provide as much flexibility as the LMF1. Additionally, the operating costs are expected to be reduced because of the smaller amount of associated analysis.

The operation of two facilities, LMF1 and LMF2, early in the program provides considerable benefits in terms of obtaining information on a timely basis and the ability to carry out the many required experiments. However, the cost of two facilities may be too high for the fusion program in any one country. This is a good example of an area where international cooperation can be very effective. Other alternatives to dividing the mission between the two facilities might also be considered.

Instrumentation The measurement of MHD velocity profiles is a key issue which will determine to a large extent the type of information, accuracy, and benefits of testing for MHD fluid flow phenomena. While a number of experiments have been performed at low field in NaK, mercury, and sodium, velocity profile measurements are expected to become more difficult at higher magnetic field, higher temperatures, and in corrosive liquids such as lithium. At high magnetic field, the flow becomes so strongly laminarized that the heat transfer becomes nearly independent of velocity.[10] This makes standard instruments such as hot film probes ineffective. At high temperature and in corrosive liquids, fouling and desensitization of probes may become a serious problem. In addition to these environmental effects, the important characteristics of the velocity profiles themselves may be unmeasurable at very high field. It is anticipated that as the field increases, the thickness of boundary layers becomes smaller and a large part of the flow may be contained in extremely narrow layers. The spatial resolution of any available technique may not be adequate to discern the important characteristics of the flow.

Some work is already ongoing to improve existing measurement techniques and develop new ones. Because of the importance of measuring velocity profiles, a continued and stronger program of instrumentation development should be implemented. Facility requirements for instrumentation are smaller than for MHD measurements. Small, bench-top loops or existing MHD facilities could be used.

MHD Insulators MHD pressure drop can be significantly reduced through the use of electrically insulating coatings or laminates. Due to the large potential impact that electrical insulators will have on the feasibility and design of liquid metal blankets, early scoping tests should be performed to explore their potential problems and benefits. Initial efforts should be placed on determining whether or not insulated structures can meet requirements on compatibility and structural integrity under irradiation. Three kinds of scoping tests are recommended: (1) fabrication of the various proposed insulated structures (coatings and laminates) and simple mechanical testing, (2) mechanical testing after high fluence irradiation, and (3) compatibility tests in lithium and LiPb.

IV.B. Material Interactions

Although there are a small number of thermal and forced convection corrosion loops (TCLs and FCLs) currently operating,[4] more will be required for thorough studies of fusion relevant materials. The most critical information required includes dependence on temperature and impurities, loop effects, and methods of controlling corrosion/mass transport. Experiments on bimetallic loops will be required to adequately address the feasibility of blankets made of refractory alloys, since a non-refractory heat transport system would likely be employed.

These experiments do not require magnetic fields; however, after studying the basic material interactions in TCLs and FCLs, experiments with strong magnetic fields will be needed to explore the effects of the magnetic field on mass transport. A particular facility, called the MHD Mass Transport Facility (MHDM), was defined with a large enough volume and field strength such that prototypical velocity features can be obtained (see Tables 3 and 4).

Table 5 shows the relevant environmental conditions for material compatibility as compared with heat and momentum transport, and Table 6 compares the importance of these environmental conditions for different aspects of material compatibility, including local attack, dissolution and deposition. Temperature, temperature difference, material constituents, and impurity levels have the largest

Table 5. Reactor Relevant Conditions Required for Testing Momentum, Heat, and Mass Transport Issues

	Momentum Transfer	Heat Transfer	Mass Transfer
Magnetic Field	X	X	X
Velocity	X	X	X
Geometry Inside Magnetic Field	X	X	X
Temperature Gradient		X	X
Temperature			X
Impurity Level			X
Material			X
Long Time Exposure			X
Geometry Outside Magnetic Field			X

Table 6. Relative Importance of the Different Environmental Conditions Required for Testing Corrosion and Mass Transport Issues

	Local Attack	Dissolution	Deposition
Magnetic Field	--	X	XX
Velocity	—	X	X
Geometry Inside the Magnetic Field	--	X	X
Axial Temperature Gradient	X	X	--
Temperature	XX	XX	XX
Impurity Level	XX	XX	XX
Material	XX	XX	XX
Long Time Exposure	X	X	X
Geometry Outside the Magnetic Field	—	--	XX

— not very important (20-50% effect)
X important (factor of 2 or more)
XX very important (exponential)

effects and should be emphasized in near term testing. When the basic material interactions are better understood and the velocity and temperature profiles have been determined from MHD testing, magnetic field effects on corrosion can be tested. This will be important only if it is determined that mass transfer rates are dominated by liquid phase diffusion rather than solid phase diffusion and chemical reactions.

Material compatibility experiments would ideally include at least one loop for each proposed primary coolant/structural alloy combination. The material systems currently being considered include lithium, 17Li-83Pb, and Flibe breeder/coolants, helium coolant, and structural materials of ferritic steel, vanadium based refractory alloy, and possibly austenitic steel (although not a favored class of alloys). The tests with a refractory structure should be performed in a bimetallic loop, since reactor primary cooling systems will almost certainly not be fabricated out of vanadium alloy due to economic considerations. In addition, every potential structural material actually represents a class of alloys (for example, ferritic steels include HT-9, 2-1/4Cr-1Mo, etc.). Since different alloys in the same class can exhibit very different material compatibility characteristics, it is desirable to test more than one specific alloy in an alloy class. Clearly, a very large number of loops is desirable; the actual number will depend on practical limits of funding and balance with other tasks in the program.

Other compatibility issues may be important depending on the design of the blanket and tritium extraction systems. For example, if beryllium is contained in the blanket, then mass transfer and formation of intermetallic compounds may be important issues. If molten salt extraction is used for tritium recovery, then the effects of associated impurities in the primary cooling system should be explored.

Because of the influence of the magnetic field on velocity profiles, it is quite likely that material interactions between the coolant and structure will also be affected. Earlier studies have shown that there could be a large effect, especially in localized regions.[11] A mass transfer facility is proposed to explore the influence of MHD velocity effects on mass transfer, called the MHDM facility.

IV.C. Partially Integrated Tests

Beyond the first 5-10 years of testing, experiments will become progressively more integrated as they treat a larger number of environmental conditions and components resembling actual reactor blankets. A class of non-neutron experiments has been defined to provide information contributing to concept verification, rather than phenomena exploration alone (as with separate and multiple interaction experiments).

Two types of tests with different missions have been considered for providing this engineering data. Since their operation would occur after 5-10 years of more fundamental testing, it is difficult to anticipate the exact features of the facilities. However, certain key features and objectives have been studied.

The first concept explored is the Thermomechanical Integration Facility (TMIF). It combines thermal, hydraulic, materials' compatibility and structural issues in a system which includes the blanket, chemical control system (including corrosion inhibition and impurity control), primary cooling system components, and possibly even a tritium extraction system (without actual tritium operation). The purpose of TMIF is to aid in the selection of a small number of leading configurations and to begin to develop empirical relations describing the global behavior of the blanket. TMIF will be a larger facility than the early MHD experiments, with more prototypical blanket geometries present. Because of the presence of a number of attached subsystems, the thermal and material environment of the blanket will be more accurately represented.

The second facility is called the Partially Integrated Test Facility (PITF). The PITF would test a full- or near-full-scale submodule of a power reactor blanket, with all attached subsystems. Although neutrons are absent, PITF simultaneously provides high test volume, high heat flux, and extended test time, which will allow for some testing of failure modes and component reliability. For liquid breeder blankets, the omission of neutrons results in large cost savings, with many of the critical issues still addressed. For many important parameters, such as surface heat flux, velocity, and geometry, partially integrated experiments can provide a good simulation of the operating characteristics of a power reactor.

The PITF facility has characteristics similar to the TMIF, and may be built as an upgrade of that facility. Partially integrated testing will ensure that when fusion integrated testing of blanket modules is performed, failure modes due to non-neutron effects can be anticipated and eliminated. Tables 3 and 4 show the characteristics, objectives, and main features of the partially integrated experiments as well as the other major liquid metal facilities.

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