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LIQUID METAL MHD PRESSURE DROP EFFECTS
IN THE PACKED BED BLANKET

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PREFACE

This report represents Volume 1 of 6 volumes directed towards the resolution of special topics associated with a reference fission-suppressed tandem mirror fusion breeder reactor design developed during 1981-1982 (D. H. Berwald, et. al., "Fission Suppressed Hybrid Reactor - The Fusion Breeder," Lawrence Livermore National Laboratory Report, UCID-19638, 1982). The other five special topic reports are as follows:

- Volume 1: Liquid Metal MHD Pressure Drop Effects in The Packed Bed Blanket by T. J. McCarville, D. H. Berwald, and C. P. C. Wong.
- Volume 2: Reactor Safety Assessment by I. Maya, C. G. Hoot, C. P. C. Wong, K. R. Schultz, J. K. Garner, S. J. Bradbury, W. G. Steele, and D. H. Berwald.
- Volume 3: Beryllium Lifetime Assessment by L. G. Miller, J. M. Beeston, B. L. Harris, and C. P. C. Wong.
- Volume 4: Structural Analysis by G. Orient, R. A. Westmann, and N. Ghoniem.
- Volume 5: Neutronics Issues and Optimization by J. D. Lee.
- Volume 6: Materials Compatibility Issues and Experimental Results by J. H. DeVan and P. Tortorelli.

The key result of the packed bed pressure drop analysis has been a several fold reduction in the packed bed pressure drop (from 260 psi to ~ 55 psi). As a result, the reference tandem mirror fusion breeder coolant outlet temperature was reduced from 490°C to 420°C (to limit corrosion). The resulting packed bed pressure drop (using the model described in this report) is about 100 psi.

D. H. Berwald

September, 1984

ABSTRACT

Magnetohydrodynamic (MHD) effects which result from the use of liquid metal coolants in magnetic fusion reactors include the modification of flow profiles (including the suppression of turbulence) and increases in the primary loop pressure drop and the hydrostatic pressure at the first wall of the blanket. In the reference fission-suppressed tandem mirror fusion breeder design concept, flow profile modification is a relatively minor concern, but the MHD pressure drop in flowing the liquid lithium coolant through an annular packed bed of beryllium/thorium pebbles is directly related to the required first wall structure thickness. As such, it is a major concern which directly impacts fissile breeding efficiency. Consequently, an improved model for the packed bed pressure drop has been developed. By considering spacial averages of the electric fields, currents, and fluid flow velocities the general equations have been reduced to simple expressions for the pressure drop. The averaging approach results in expressions for the pressure drop involving a constant which reflects details of the flow around the pebbles. Such details are difficult to assess analytically, and the constant may eventually have to be evaluated by experiment. However, an energy approach has been used in this study to bound the possible values of the constant, and thus the pressure drop. The upper bound on the pressure drop turns out to be a factor of five lower than that estimated by other methods. This improved estimate shows the MHD pressure drop may have much less effect on fusion reactor design and economics than previously anticipated. In anticipation that an experimental facility might be established to evaluate the undetermined constant as well as to address other uncertainties, a survey of existing facilities is presented.

ACKNOWLEDGMENT

The packed bed MHD pressure drop model was developed from a preliminary assessment by Albert Solbes of TRW. His contribution in this area is gratefully acknowledged.

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A KEY ISSUES WITH REGARD TO MHD PRESSURE DROP CALCULATIONS

It is clear from the Fusion Breeder 1982 lithium-cooled packed-bed blanket design for the mirror reactor (1) that critical design uncertainties exist in the calculations of MHD pressure losses through the blanket loop. Even though blanket design feasibility does not seem to be in doubt, better understanding of MHD pressure drops is essential to provide guidelines to blanket designers. The only equation that blanket designers can use with confidence to calculate liquid metal MHD pressure drop is for Hartmann flow (2) in a circular or rectangular channel. Many uncertainties still exist for more complicated flow configurations. The following is a listing of these uncertainties:

1. Flow through a packed pebble bed.
2. Flow through bends, including situations for both legs perpendicular to the B-field and one leg perpendicular, one parallel to the B-field.
3. Flow through a B-field gradient.
4. Flow through channels with varying conducting wall thickness.
5. Liquid metal flowing at an angle to the magnetic field.
6. Flow through contractions, expansions, and distribution plena.
7. The effectiveness of electrically insulating materials.

A model for estimating the pressure drop in a packed pebble bed has been developed for this study, and is presented in Section B. The model provides a method of computing the pressure drop through a packed pebble bed with greater accuracy than models used previously; however, involves a constant which can only be bounded and not precisely determined. It may eventually prove necessary to evaluate this constant experimentally. Assuming an experimental

determination will be made, and that issues 2 through 7 are to be addressed, it will be necessary to establish a suitable experimental facility. In preparation for such a facility, a survey of existing experimental facilities was conducted and is reported in Section C along with some recommendations.

References, Section A

1. D. H. Berwald, "Fission-Suppressed Hybrid Reactor - The Fusion Breeder," Lawrence Livermore National Laboratory Report, UCID-19638, Dec. 1982.
2. G. W. Sutton and A. Sherman, Engineering Magnetohydrodynamics, McGraw-Hill 1965.

B A MODEL FOR THE MHD PRESSURE DROP IN A PACKED PEBBLE BED

Estimates of the MHD pressure drop in a tandem mirror fusion reactor pebble bed blanket are needed in reactor design studies to determine the plant power balance and the cost of capital equipment related to coolant pumping. Previous estimates of the pressure drop have not been accurate enough to serve these purposes. In an attempt to satisfy the need for improved estimates the general equations of electro-hydrodynamics have been revisited. By considering spacial averages of the electric fields, currents, and fluid flow velocities the general equations have been reduced to simple expressions for the pressure drop. The averaging approach results in expressions for the pressure drop involving a constant which reflects details of the flow around the pebbles. Such details are difficult to assess analytically, and the constant may eventually have to be evaluated by experiment. However, an energy approach has been used in this study to bound the possible values of the constant, and thus the pressure drop. The upper bound on the pressure drop turns out to be a factor of five lower than that estimated by other methods (1). This improved estimate shows the MHD pressure drop may have much less effect on fusion reactor design and economics than previously anticipated.

The problem of interest is formally introduced in Section B.1, and the results of the analysis are summarized there. That section has been written to be self-contained and the details of the analysis in Section B.2, which are reserved for the truly patient reader, can be skipped without loss of continuity.

B.1 Problem Definition and Summary of the Analysis

The geometry of interest is shown in Figure 1. A liquid metal coolant flows radially outward from the inner surface at R_0 to the outer surface at R_1 . The unperturbed magnetic field B_0 is assumed to be uniform, and is oriented along the Z axis of the cylinder. Two different boundary conditions are of interest. The first is when the blanket is segmented by perfectly conducting radial boundaries. With this boundary condition the average

Figure 1. The Coordinates, Geometry, and Current Paths When Boundaries Are Either (a) Conducting, or (b) Insulating.

azimuthal electric field is zero in the blanket. This is equivalent to having no radial boundaries at all. The second is when the blanket is segmented by perfectly insulating radial boundaries. With this boundary condition the average azimuthal current is zero in the blanket. Either boundary condition is an option in blanket design.

The non-linear differential equations of electro-hydrodynamics result in a simple linear differential equation for the pressure drop if

- the flow is laminar,
- variations in the magnetic are negligible on the scale length of a pebble,
- inertial forces are small compared to the magnetic force,
- viscous forces are small compared to the magnetic force.

The degree to which this criteria are satisfied can be determined by examining some dimensionless numbers. The dimensionless numbers of interest are the Reynolds number Re , the magnetic Reynolds number Rm , the Hartmann number H , and the interaction number N . The criteria stated above are satisfied if

$$Re = dU \frac{\rho}{\eta} < 5 \times 10^5 B_0, \quad (1)$$

$$Rm = \sigma U \mu d \ll 1, \quad (2)$$

$$H = dB_0 \left(\frac{\sigma}{\eta} \right)^{1/2} > 1, \quad (3)$$

$$N = \sigma B_0^2 \frac{d}{\rho U} > 1, \quad (4)$$

where d is the on the order of a pebble diameter, U is the coolant speed, and ρ , η , σ , and μ are the coolant density, the absolute viscosity, electrical conductivity, and the magnetic permeability, respectively. The numerical constant on the right hand side of Eq. (1) was suggested by Hoffman and Carlson for flows with $H > 2000$ and B_0 given in Tesla (2).

The average radial speed $\langle U \rangle$ of the coolant in a pebble bed blanket is related to the volumetric flow rate Q , the void fraction ϵ , the blanket length L , and the radial position r by

$$\langle U \rangle = \frac{G}{\epsilon, 2 \pi r L} \quad (5)$$

The volumetric flow rate is determined by the desired temperature rise across the blanket. The void fraction has a theoretical minimum of 0.25 for spherical pebbles, but for random packing a more likely value is 0.4. Typical blanket parameters are $G = 0.3 \text{ m}^3/\text{s}$, $L = 4 \text{ m}$, and $R_0 = 1.5 \text{ m}$. The average radial coolant speed at the inner radius, denoted as $\langle U_0 \rangle$, is then 2.0 cm/s. A typical magnetic field strength is about 4 T, and if lithium is the coolant then $\sigma = 3.1 \times 10^6 \text{ mho/m}$, $\eta = 3.8 \times 10^{-4} \text{ kg/m/s}$, $\rho = 490 \text{ kg/m}^3$, and $\mu = 4 \pi \times 10^{-7} \text{ H/m}$. With these parameters and a pebble diameter on the order of a centimeter, Eqs. (1) through (4) are easily satisfied.

This criteria being satisfied, the momentum and field equations reduce to (see Section B)

$$\nabla P = \vec{J}_f \times \vec{B} \quad \text{and} \quad \nabla \times \vec{B} = \mu \vec{J}, \quad (6)$$

where P is the pressure in the fluid, $\vec{J}$ is the current density, and the subscript f denotes quantities specifically in the fluid. Averaged over the blanket the pressure gradient is radial and the currents in the fluid and pebbles are azimuthal. The average azimuthal current in the fluid follows from Ohm's law:

$$\langle J_f \rangle = \sigma_f \langle U \rangle B \quad (K-1), \quad (7)$$

where K is defined as the ratio of the average electric field in the fluid divided by $\langle U \rangle B$. The magnetic induction B may vary with r , as discussed below. The quantity K is an intrinsic property of only the pebble-to-fluid conductivity ratio, the volume fraction ϵ , and the boundary conditions on either the average azimuthal current or electric field. This constant can be evaluated precisely if the local flow field can be precisely described. However, because of the complex nature of the local flow field it will suffice for now to point out that K is between zero and unity.

The magnetic induction B follows from an integration of Ampere's law. Before the integration can take place the boundary conditions on either the

azimuthal current $\langle J \rangle$ or the azimuthal electric field $\langle E \rangle$ averaged over the blanket must be specified. The boundary conditions for the two cases of interest are

$$\langle E \rangle = 0 \text{ for conducting boundaries,} \quad (8)$$

$$\langle J \rangle = 0 \text{ for insulating boundaries.} \quad (9)$$

These boundary conditions lead to

$$B(r) = B_0 \left(\frac{r}{R_0} \right)^{Rm[1+K(S-1)]} \text{ for conducting boundaries} \quad (10)$$

$$B(r) = B_0 \text{ for insulating boundaries,} \quad (11)$$

where S is the conductivity of the pebbles divided by that of the fluid.

Having specified the average azimuthal current in the fluid and the magnetic induction B , the momentum equation can be integrated for the average pressure drop across the blanket:

$$\langle \Delta P \rangle = \sigma_f \langle U_0 \rangle B_0^2 R_0 (1-K) \frac{(R_1/R_0)^{2Rm[1+K(S-1)]} - 1}{2Rm[1+K(S-1)]} \text{ conducting boundaries} \quad (12)$$

$$= \sigma_f \langle U_0 \rangle B_0^2 R_0 (1-K) \ln(R_1/R_0) \text{ insulating boundaries.} \quad (13)$$

Both the fluid pressure gradient and the Lorentz force acting on the pebbles will result in a distributed load on the outer wall of the blanket. The pressure on the outer wall from this load is

$$\langle P_s \rangle = \langle \Delta P \rangle (1-\epsilon) \left[1 - S \frac{K}{1-K} \frac{\epsilon}{1-\epsilon} \right] \text{ for conducting boundaries,} \quad (14)$$

$$\langle P_s \rangle = 2 \langle \Delta P \rangle (1-\epsilon) \text{ for insulating boundaries.} \quad (15)$$

It is desirable to minimize this pressure because the amount of structure required to withstand it can adversely affect the breeding performance.

The only quantity not yet precisely defined is the intrinsic constant K . So far it has only been stated that K is between zero and unity. As part

of this analysis the energy equation was used to reduce the uncertainty in K. It was found

$$0 < K < 1/(1 + \frac{Se}{1-\epsilon}) \text{ for conducting boundaries,} \quad (16)$$

$$1/(1 + \frac{S(1-\epsilon)}{\epsilon}) < K < 1 \text{ for insulating boundaries.} \quad (17)$$

Eq. (16) can be used to show the exponent in Eq. (12) is much less than unity even if $S \rightarrow \infty$. Thus, Eq. (12) reduces to the same form as Eq. (13). Although the expressions for the pressure drop turn out to be the same for conducting and insulating boundaries, the bounds on K vary as given by Eqs. (16) and (17). It is interesting to note that with infinitely conductive pebbles K is exactly zero for conductive boundaries, but is somewhere between zero and unity for insulating boundaries. On the other hand, with perfectly insulating pebbles K is exactly unity for insulating boundaries, but is somewhere between zero and unity for conducting boundaries.

As a practical application of the above analysis consider the blanket previously described. For beryllium pebbles and lithium coolant $S \approx 2$. From Eq. (13)

$$51 \text{ psi} > \langle \Delta P \rangle > 29 \text{ psi for conducting boundaries,} \quad (18)$$

$$38 \text{ psi} > \langle \Delta P \rangle > \text{psi for insulating boundaries.} \quad (19)$$

These results show it may be preferable to utilize insulating boundaries when possible. However, a definitive conclusion cannot be made until K is evaluated more precisely. The maximum pressure drop of 51 psi is a factor of five lower than the previous estimates (1). The reaction on the outer wall follows from Eqs. (14) and (15):

$$30 > \langle P_s \rangle > 17 \text{ psi for conducting boundaries,} \quad (20)$$

$$45 > \langle P_s \rangle > 0 \text{ psi for insulating boundaries.} \quad (21)$$

Although the maximum possible pressure drop is greater for conducting boundaries, the maximum possible pressure on the wall is greater for insulating boundaries.

To summarize, expressions for bounding the MHD pressure drop across a packed bed with either conducting or insulating radial boundaries have been derived. The expressions for the pressure drop have been shown to be the same regardless of the boundary conditions. However, the limiting value of the undetermined constant K which appears in the expression is boundary dependent. For a machine producing thousands of megawatts electric the recirculating power fraction required to drive the coolant is negligible even for the maximum pressure drop. However, the cost of liquid metal pumps and the degradation of breeding performance which accompanies structural material motivates as small a pressure drop as possible. Hence, there is strong motivation for better understanding and more precisely determining values of the constant K as a function of the conductivity ratio S and the packing fraction ϵ .

B.2 Model Development

B.2.a General Equations

The fluid and field equations governing the steady-state evolution of an incompressible conducting fluid are

$$\text{Continuity} \quad \nabla \cdot \vec{U} = 0, \quad (22)$$

$$\text{Momentum} \quad \rho(\vec{U} \cdot \nabla)\vec{U} + \nabla P = \vec{J} \times \vec{B} + \eta \nabla^2 \vec{U}, \quad (23)$$

$$\text{Ohm's Law} \quad \vec{J} = \sigma [\vec{E} + \vec{U} \times \vec{B}], \quad (24)$$

$$\text{Faraday's Law} \quad \nabla \times \vec{E} = 0, \quad (25)$$

$$\text{Ampere's Law} \quad \nabla \times \vec{B} = \mu_0 \vec{J}, \quad (26)$$

$$\text{Gauss' Law} \quad \nabla \cdot \vec{E} = q/\epsilon \text{ and } \nabla \cdot \vec{B} = 0, \quad (27)$$

where the preceding symbols are defined as:

- $\vec{U}$ = fluid velocity vector (m/s)
- ρ = fluid specific mass (kg/m³)
- P = pressure (N/m²)
- $\vec{J}$ = current density vector (A/m²)
- η = fluid absolute viscosity (kg/m/s)
- $\vec{B}$ = magnetic induction vector (Tesla)
- σ = electrical conductivity (mho/m)
- $\vec{E}$ = electric field vector (V/m)
- μ_0 = vacuum permeability ($4\pi \times 10^{-7}$)
- q = electric charge density (coulomb/m³)
- ϵ = permittivity (8.85×10^{-12} F/m)

The fluid viscosity is assumed to be constant. The Hall effect, magnetization of the fluid, and gravitational effects are assumed to be negligibly small.

We introduce the following dimensionless variables for velocity, pressure, current density, electric field, magnetic field, and physical coordinate:

$$u = \frac{\vec{U}}{U_0}$$

$$\vec{b} = \frac{\vec{B}}{B_0}$$

$$p = \frac{P}{\sigma U_0 B_0^2 R_0} = \frac{P}{P_0}$$

$$x = \frac{\vec{x}}{R_0}$$

$$\vec{j} = \frac{\vec{J}}{\sigma U_0 B_0}$$

$$e = \frac{\vec{E}}{U_0 B_0}$$

where U_0 , a reference velocity for the fluid at the inner radius R_0 of the bed, is related to the volumetric flow rate G and the length of the module L through

$$U_0 = \frac{G}{2 \pi R_0 L}$$

The quantity B_0 is the axial component along the axis of the cavity of the magnetic induction at R_0 . The fluid and field equations then become (using dimensionless differential operators)

$$\nabla \cdot \vec{u} = 0,$$

$$\nabla p = \vec{j} \times \vec{b} + \frac{1}{H_0^2} [\nabla^2 \vec{u} - Re_0 (\vec{u} \cdot \nabla) \vec{u}],$$

$$\vec{j} = \vec{e} + \vec{u} \times \vec{b},$$

$$\nabla \times \vec{e} = 0,$$

$$\nabla \times \vec{b} = Rm_0 \vec{j},$$

$$\nabla \cdot \vec{j} = 0 \text{ and } \nabla \cdot \vec{b}^2 = 0$$

The three dimensionless numbers appearing above are:

$$\text{Hartmann Number} \quad H_0 = B_0 R_0 (\sigma/\eta)^{1/2},$$

$$\text{Reynolds Number} \quad Re_0 = \frac{\rho U_0 R_0}{\eta},$$

$$\text{Magnetic Reynolds Number } Rm_0 = \mu_0 \sigma U_0 R_0$$

Representative values are

$$G = .31 \text{ m}^3/\text{s}, R_0 = 1.5 \text{ m}, L = 4 \text{ m}, B_0 = 4.2 \text{ T},$$

$$\sigma = 3.1 \times 10^6 \text{ mho/m}, \eta = 3.8 \times 10^{-4} \text{ kg/m/s}, \rho = 486 \text{ kg/m}^3$$

We find for the characteristic velocity, pressure, current density, and electric field

$$U_0 = 8.2 \times 10^{-3} \text{ m/s,}$$

$$P_0 = \sigma U_0 B_0^2 R_0 = 6.7 \times 10^5 \text{ N/m}^2 = 100 \text{ psi,}$$

$$\sigma U_0 B_0 = 1.0 \times 10^5 \text{ A/m}^2 = 10 \text{ A/cm}^2,$$

$$U_0 B_0 = 3.4 \times 10^{-2} \text{ V/m.}$$

The dimensionless numbers are

$$H_0 = 5.7 \times 10^5,$$

$$Re_0 = 1.5 \times 10^4,$$

$$Rm_0 = 4.8 \times 10^{-2}.$$

The following conclusions can be drawn from the preceding estimates:

- MHD forces dominate the fluid reaction and if eddy currents are not impeded the MHD drop is dominate.
- Viscous effects are confined to very thin layers at walls or the pebble surfaces.
- The induced magnetic field is small in comparison with the applied field.

It should be pointed out that in the presence of pebbles at high packing factors fluid velocities could be locally ten times larger than U_0 ($u = 10$). In such a case current densities are potentially one order of magnitude larger, and if currents are allowed to circulate the induced magnetic field may no longer be negligibly small. However, over the length scale of a pebble radius ($\sim 1.5 \times 10^{-2} \text{ m}$) the magnetic Reynolds number is only $\sim 1.5 \times 10^{-3}$ despite the large fluid velocity. The local magnetic field may be assumed

constant. Over the characteristic length of a pebble the Reynolds number is also ten times smaller than the original estimate. The Hartmann number is 100 times smaller.

It is clear that in all cases viscous effects are confined to very thin layers of characteristic thickness δ of the order of

$$\delta = \left(\frac{\eta}{\sigma}\right)^{1/2} \frac{1}{B_0} = 3 \times 10^{-6} \text{ m.}$$

Although the viscous stresses are very large locally, the fluid motion can nevertheless be considered inviscid and the viscous pressure drop remains negligibly small in comparison with potential MHD pressure drops.

Induced electric fields are also very small (~ 0.34 V/m at $u = 10$), and over a characteristic length of the order of a pebble voltages are of the order of millivolts. Surface effects (contact potential) may be important in determining the current flow. Finally, the ratio of Reynolds number to the Hartmann number is small enough that the flow should be well within the laminar regime.

B.2.b A Simple Limiting Case

To illustrate the general approach consider the simple limiting case of a uniform fluid in pure radial motion. Assume $\vec{B}$ is in the axial direction. The momentum equation may be written as

$$\nabla \left(P + \rho \frac{u^2}{2} + \frac{B^2}{2\mu_0} \right) = \eta \nabla^2 \vec{u} + \frac{(\vec{B} \cdot \nabla) \vec{B}}{\mu_0} + \rho \vec{u} \times (\nabla \times \vec{u}). \quad (28)$$

From the preceding discussion, the stagnation pressure change is nearly equal to the static pressure change and the right hand side is small or equal to zero. Hence,

$$\nabla \left(P + \frac{B^2}{2\mu_0} \right) = 0. \quad (29)$$

The fluid pressure drop $\Delta P = P_0 - P_1$ across the module is hence equal to

$$\Delta P = \frac{B_0^2}{2\mu_0} (b_1^2 - 1) = \frac{P_0}{2 Rm_0} (b_1^2 - 1), \quad (30)$$

where b_1 is the dimensionless magnetic induction at R_1 . The problem is reduced to finding the B field variation in going from R_0 to R_1 .

For this Ampere's law and Ohm's law are used. Dotting Ohm's law by $\vec{J}^*$ and dividing by σ ,

$$\frac{\vec{J}^2}{\sigma} = \vec{E} \cdot \vec{J} - (\vec{J} \times \vec{B}) \cdot \vec{J}.$$

The left hand side is the joule dissipation. The second term on the right hand side is the work done by the Lorentz force. The term $\vec{E} \cdot \vec{J}$ is the electric power extracted from the volume. This power is negative because we don't have an external electric power supply and is dissipated in the external current return paths. For the geometry considered here $\vec{J}$ is in the azimuthal direction ($\theta < 0$), and

$$J_\theta = \sigma [E_\theta - U_r B] = -\sigma U_r B (1 - K), \quad (31)$$

where we have defined the load factor K as

$$K = \frac{E_\theta}{U_r B}, \text{ and } 0 < K < 1. \quad (32)$$

The load factor is equal to zero if there is no azimuthal segmentation to impede the current flow and is at most equal to 1 when the current flow is impeded. From the divergence equation,

$$U_r = U_0 \frac{R_0}{r}. \quad (33)$$

Ampere's law may then be written as

$$\frac{db}{dr} = Rm_0 (1 - K) \frac{b}{r}. \quad (34)$$

This integrates immediately to

$$b = \left(\frac{r}{R_0}\right)^{Rm_0 (1 - K)}. \quad (35)$$

Finally, substitution into the pressure drop equation yields

$$\Delta P = P_0 (1 - K) \frac{(R_1/R_0)^2 Rm_0 (1 - K) - 1}{2 Rm_0 (1 - K)} \approx P_0 (1 - K) \ln (R_1/R_0). \quad (36)$$

For small magnetic Reynolds numbers the radial dependence is simply logarithmic.

For lithium in the absence of pebbles and for $R_1/R_0 = 1.25$ we find $\Delta P = 0.22 P_0 (1 - K) < 22$ psi. The magnetic field at $r = R_1$ is only 1% larger than at R_0 , indicating the self imposed field can indeed be ignored.

B.2.c Global Equations For The Case Of Pebbles

In the case of pebbles the medium (fluid plus pebbles) behaves as a two-phase fluid. The volume averages for any function f are

$$\langle f \rangle_i = \frac{\iiint_i f dV}{\iiint_i dV},$$

where the subscript $i = f$ will indicate integration over the volume of the fluid, $i = s$ will indicate integration over the volume of the solid, and the absence of a subscript will indicate integration over the combined volume. The volumes are assumed large compared with the pebble dimensions but small compared with the module volume.

We will make the following general assumptions:

- The magnetic Reynolds number based on a pebble diameter is much smaller than 1.
- The distribution of pebbles is uniform and isotropic.
- Over a length scale large compared with a pebble diameter average field and flow properties are independent of axial and azimuthal position; i.e., $\frac{\partial}{\partial z} = \frac{\partial}{\partial \theta} = 0$.

In general, the relationship between averaged quantities is

$$\epsilon \langle \rangle_f + (1 - \epsilon) \langle \rangle_s = \langle \rangle, \quad (37)$$

where ϵ is the volume fraction occupied by the fluid and is independent of position. By definition

$$\epsilon = \frac{V_f}{V_f + V_s} \quad (38)$$

It also follows that ϵ is the ratio of the area occupied by the fluid over the total area for any cross-section taken through the bed. The same holds for a line average.

Thus, the average fluid velocity is such that

$$\epsilon \langle \vec{U} \rangle_f = \langle \vec{U} \rangle = U_0 \frac{R_0}{r} \vec{i}_r, \quad (39)$$

where $\vec{i}_r$ is a unit vector in the radial direction.

Ohm's law can be averaged by assuming the magnetic field to be locally constant, so that

$$\langle \vec{J} \rangle_f = \sigma_f \langle \vec{E} \rangle_f + \sigma_f \langle \vec{U} \rangle_f \times \vec{B}, \quad (40)$$

$$\langle \vec{J} \rangle_s = \sigma_s \langle \vec{E} \rangle_s. \quad (41)$$

From assumption 3 it follows that $\frac{\partial}{\partial \theta}$ or $\frac{\partial}{\partial z}$ of $\langle \vec{U} \rangle$, $\langle \vec{J} \rangle$, $\langle \vec{E} \rangle$, and $\langle \vec{B} \rangle = 0$. We select boundary conditions such that

$$\langle J_z \rangle = \langle J_r \rangle = \langle U_z \rangle = \langle U_\theta \rangle = \langle E_z \rangle = \langle E_\theta \rangle = 0.$$

It follows that the average current is in the azimuthal direction and

$$\begin{aligned} \langle J_\theta \rangle_f &= - \frac{\sigma_f \langle U \rangle B}{\epsilon} (1 - K) \\ \langle J_\theta \rangle_s &= - \frac{\sigma_f \langle U \rangle B}{1 - \epsilon} KS \end{aligned} \quad (42)$$

$$\langle J_{\theta} \rangle = -\sigma_f \langle U \rangle B [1 + K(S - 1)]$$

where K is defined as

$$K = \frac{\langle E_{\theta} \rangle_f \epsilon}{\langle U \rangle B}, \quad (43)$$

and we have used the fact that the average electric field is zero; i.e.,

$$\epsilon \langle E_{\theta} \rangle_f + (1 - \epsilon) \langle E_{\theta} \rangle_s = 0. \quad (44)$$

The factor S is the ratio of the electric conductivity of the pebbles, σ_s , to that of the fluid. The factor K is only a function of S and of ϵ . Thus, in the absence of pebbles $\epsilon = 1$, so that for Eq. (44) $\langle E_{\theta} \rangle_f$ and K are zero. The factor K is also equal to zero for pebbles of infinite conductivity, and $\langle E_{\theta} \rangle_s$ and hence $\langle E_{\theta} \rangle_f$ are both equal to zero in this case. Note furthermore, that when the conductivity of the pebbles is equal to that of the fluid ($S = 1$) the average current is the same as in the absence of pebbles. Once the function K (S, ϵ) is determined, the problem will be solved. The magnetic field varies according to

$$b = \frac{B}{B_0} = \left(\frac{r}{R_0} \right)^{Rm_0 [1 + K(S - 1)]}, \quad (45)$$

which is a generalization of Eq. (35), applicable here only when $\langle E_{\theta} \rangle = 0$. The pressure drop for the fluid follows immediately as

$$\Delta P = P_0 \frac{1 - K}{\epsilon} \frac{(R_1/R_0)^2 Rm_0 [1 + K(S - 1)]}{2 Rm_0 [1 + K(S - 1)]} - 1 \approx P_0 \frac{1 - K}{\epsilon} \ln \left(\frac{R_1}{R_0} \right), \quad (46)$$

where the logarithmic approximation holds provided $2 Rm_0 [1 + K(S - 1)] \ll 1$.

Finally, as a result of the imbalance between the "boundary" force on the pebbles resulting from the fluid pressure gradient and the Lorentz force on the pebbles due to $\langle \mathbf{j}_\theta \rangle_s$, the bed will exert a force per unit area P_s transmitted as a result of pebble-to-pebble contact on either the inner or outer cylinder. This pressure is

$$P_s = \Delta P (1 - \epsilon) \left[1 - S \frac{K}{1 - K} - \frac{\epsilon}{1 - \epsilon} \right], \quad (47)$$

where $P_s > 0$ indicates the reaction load of the bed is transmitted to the outer cylindrical surface. The pressure P_s will be > 0 if

$$\frac{\langle \mathbf{j}_\theta \rangle_s}{\langle \mathbf{j}_\theta \rangle_f} = S \frac{K}{1 - K} - \frac{\epsilon}{1 - \epsilon} < 1. \quad (48)$$

This will be shown subsequently to be always the case.

B.2.d Some Limiting Values

Although the function $K(S, \epsilon)$ is still unknown, some limiting cases are considered which help define the limits for the various quantities of interest. As previously pointed out, $0 < K < 1$. The factor K is zero either for infinite pebble conductivity ($S \rightarrow \infty$) or in the absence of pebbles ($\epsilon = 1$). To evaluate the fluid pressure drop in this case also requires knowledge of the limiting value of the product KS , unless it can be shown the magnetic field perturbation is small and the logarithmic approximation applies in Eq. (46).

We will first show that in general Eq. (48) applies, so that KS is bounded as $S \rightarrow \infty$; i.e.,

$$\lim_{S \rightarrow \infty} (KS) < \frac{1 - \epsilon}{\epsilon}.$$

For this we dot Ohm's law by $\vec{\jmath}$ and average, which yields

$$\frac{\langle \vec{\jmath}^2 \rangle}{\sigma} = (1 - \epsilon) \frac{\langle \vec{\jmath}^2 \rangle_s}{\sigma_s} + \epsilon \frac{\langle \vec{\jmath}^2 \rangle_f}{\sigma_f} - \langle (\vec{\jmath} \times \vec{B}) \cdot \vec{\jmath} \rangle_f = - \langle \nabla P \cdot \vec{\jmath} \rangle_f,$$

where we have taken into account the fact that $\langle \vec{E} \cdot \vec{J} \rangle = 0$. This simply expresses that the work done by the Lorentz force (equal to the pressure work) goes into joule heating of the fluid pebbles. From Schaurtz' inequality it follows that

$$\langle J_{\theta S} \rangle^2 < \langle J^2 \rangle_S < S \frac{\epsilon}{1 - \epsilon} \left(\frac{\sigma_f \langle -\nabla P \cdot \vec{U} \rangle_f}{\epsilon} - \langle J_{\theta f} \rangle^2 \right)$$

The ratio of the currents is a function of S , K , and ϵ (independent of position) and the pressure work can be simply evaluated from the pressure drop and the volumetric flow rate. Over the whole volume of the module

$\langle -\nabla P \cdot \vec{U} \rangle_f$ is simply equal to $\langle J_{\theta f} \rangle B \langle U \rangle$ times $\langle U \rangle$. It follows from the above that

$$\langle J_{\theta S} \rangle^2 < S \frac{\epsilon}{1 - \epsilon} \frac{K}{1 - K} \langle J_{\theta f} \rangle^2.$$

From Eq. (42) the inequality given by Eq. (48) automatically follows, from which it results that

- The pebble bed is always pushed outward.
- As $S \rightarrow \infty$, (KS) does not exceed $(1 - \epsilon)/\epsilon$, which for $\epsilon = 0.4$ yields a limiting value of 1.5.
- For pebbles of infinite conductivity (worst case) $Rm_0[1 + K(S-1)]$ does not exceed $2.5 Rm_0$, where $Rm_0 = 4.8 \times 10^{-2}$ can be assumed. From Eq. (45) it follows that the magnetic field at $r = R_1$ is at most 6% larger than B_0 .
- From the preceding it follows that the fluid pressure drop does not exceed

$$\Delta P < \lim_{S \rightarrow \infty} (\Delta P) < \frac{.23 P_0}{\epsilon}.$$

For $P_0 = 100$ psi and $\epsilon = 0.4$, the vacuum fluid pressure drop is hence estimated to be at most of the order of 55 psi.

- e) The bed reaction is in the positive radial direction and at most
- $$P_S < \Delta P (1 - \epsilon),$$

i.e., the load on the outer wall due to the pebble bed does not exceed 33 psi.

- f) Note that in the case of beryllium pebbles with $S = 1.6$ the total current $\langle J_\theta \rangle$ does not exceed 1.6 times the current in the absence of pebbles, i.e., the magnetic field increase across the bed is smaller than 3.5%.

- g) More precise determination of the pressure drop and bed reaction will require knowledge of the function $K(S, \epsilon)$. From the preceding we have only ascertained so far that

$$0 < K < \frac{1}{1 + S \frac{\epsilon}{1 - \epsilon}}. \quad (49)$$

The upper value of K corresponds to a flow of liquid of conductivity σ_f in the presence of metallic fins of conductivity σ_s , where the radial fins extend over the length of the module and occupy a fraction $(1 - \epsilon)$ of the cavity volume. This is not a pebble bed but provides an easy reference solution to the general problem at hand.

B.3 Local Study of Current and Flow Patterns

For large Hartmann numbers the momentum equation for the fluid reduces to

$$\Delta P = \vec{J} \times \vec{B} . \quad (50)$$

Viscous effects are limited to very thin layers, so the fluid may be considered ideal with flow conditions requiring the velocity component normal to the solid surfaces vanish. At those boundaries the longitudinal electric field and the component of the current normal to the surface will be preserved. From the momentum equation the following consequences follow immediately.

- a) Taking the cross product of Eq. (50) by $\vec{B}$, it follows that

$$\frac{\partial P}{\partial z} = 0 . \quad (51)$$

Consequently, P is only a function of x and y (or r and θ).

- b) Taking the curl of both sides of Eq. (50) it follows that

$$\Delta \times (\Delta P) = 0 = \nabla \times (\vec{J} \times \vec{B}) = (\vec{B} \cdot \nabla) \vec{J} + \frac{\partial \vec{J}}{\partial z} = 0 , \quad (52)$$

which implies that the current distribution is independent of z .

- c) Taking the curl of Ohm's Law we find

$$\nabla \times \vec{J} = \sigma B \frac{\partial \vec{U}}{\partial z} . \quad (53)$$

Consequently, $\nabla \times \vec{J} = 0$ if $\frac{\partial \vec{U}}{\partial z} = 0$. In general, as $\vec{J}$ and hence $\nabla \times \vec{J}$ are independent of z , Eq. (53) implies a linear local dependence of $\vec{U}$ on z ; i.e.,

$$\vec{U} = \vec{U}^*(x,y) + \frac{\nabla \times \vec{J}}{\sigma B} (z - z^*) \quad (54)$$

where the $*$ refers to a reference axial position.

- d) From the preceding it also follows that in the fluid the electric field is also a linear function of z :

$$\vec{E} = \vec{E}^*(x,y) + \frac{\nabla(\vec{J} \cdot \vec{B})}{\sigma B} (z - z^*) = \vec{E}^*(x,y) + \nabla \epsilon_z (z - z^*)^* . \quad (55)$$

If $\vec{J}$ is perpendicular to $\vec{B}$, $\vec{E}$ is independent of z .

- e) In general, if we let $\vec{J}_\perp$ be the current component perpendicular to $\vec{B}$, then from the preceding we have

$$\nabla \cdot \vec{J}_\perp = 0, \text{ but } \nabla \times \vec{J}_\perp \neq 0. \quad (56)$$

The preceding conclusions assume the magnetic field is locally constant as previously pointed out. There may, however, be discontinuities in the values of the velocity vector (slip boundaries). In particular, discontinuous jumps occurring over very thin layers in the velocity vector component U_z are possible.

The last consideration of interest relates to the jump condition across the shear layers at the surface of the pebbles. If we denote by the subscripts n and t , respectively, normal and tangential vectors to the surface of the pebble, then as previously pointed out

$$(\vec{U}_n)_f = 0 . \quad (57)$$

The subscript f refers to fluid properties outside the shear layer. As $\nabla \times (\nabla P) = 0$, it follows that $(\nabla P)_n = 0$; i.e., the free stream pressure is imposed through the shear layer. Consequently, the longitudinal velocity component satisfies the differential equation

$$[(\vec{J} \times \vec{B})_t]_f + \eta \frac{d^2 \vec{U}_t}{dn^2} = 0 .$$

As $(\vec{J} \times \vec{B})_t = \vec{J}_n \times \vec{B}_t + \vec{J}_t \times \vec{B}_n$, and as $\vec{J}_n$ is constant through the layer, it follows that

$$\frac{\eta}{\sigma} \frac{d^2 \vec{U}_t}{dn^2} = B_n^2 [\vec{U}_t - (\vec{U}_t)_f],$$

which integrates to

$$\vec{U}_t = (\vec{U}_t)_f \{ 1 - \exp [- (\frac{\sigma}{\eta})^{1/2} B_n n] \}. \quad (58)$$

In general the thickness of the layer is very small. Furthermore, the current component normal to the surface being constant, it follows that the electric field component normal to the surface satisfies

$$E_n = (E_n)_f + [(\vec{U}_t)_f \times \vec{B}_t] \exp [- (\frac{\sigma}{\eta})^{1/2} B_n n].$$

Hence, the voltage drop across the layer is

$$\Delta V = (\frac{\eta}{\sigma})^{1/2} \frac{(\vec{U}_t)_f \times \vec{B}_t}{B_n}. \quad (59)$$

Thus, for $(U_t)_f \approx 0.1$ m/sec and lithium ($\eta/\sigma = 10^{-10}$), the voltage drop is found to be of the order of microvolts only.

Besides the preceding, we will have jump conditions at the fluid-solid interfaces. We have

$$(\vec{J}_n)_f = \sigma_f [(E_n)_f + (\vec{U}_t)_f \times \vec{B}_t] = \sigma_s (E_n)_s = (\vec{J}_n)_s, \quad (60)$$

and

$$(\vec{E}_t)_f = (\vec{E}_t)_s. \quad (61)$$

From which

$$(\vec{J}_t)_s = \sigma_s (\vec{E}_t)_s = S [(\vec{J}_t)_f - \sigma_f (\vec{U}_t)_f \times \vec{B}_n]. \quad (62)$$

From the preceding it also follows that on surfaces parallel to the z axis, $\vec{U}_t$ is zero.

B.3.a Flow Around One Cylinder

This is a very simple reference solution. If we take the x axis along the flow velocity at infinity and the z axis along the magnetic field at ∞ , as shown in Figure 2, the current is in the negative y direction. From Eq. (54) as the fluid is included and the velocity finite, it results that the velocity is independent of z and hence $\nabla \times \vec{J}_1 = 0$. As $\frac{\partial}{\partial y} = 0$ and both $\nabla \cdot \vec{J}_1$ and $\nabla \times \vec{J}_1$ are zero it follows that $\vec{J}_1$ is not only independent of z and y but also of x , and hence is constant throughout the fluid. Boundary conditions are selected so that $J_z = \sigma E_z = 0$ throughout. It follows that the electric field is independent of y and z . The current and electric field lie along y , and as $\nabla \times \vec{E} = 0$, E_x is also zero. Finally, from the fluid continuity equation it follows that $U_x = U_\infty = \text{constant}$. The flow stream lines are shown in Figure 2, the disturbance being felt at infinity. The electric field E_y is also constant in the fluid, and if we set $K = \frac{J_y}{U_\infty B}$ it follows that

$$(J_y)_f = -\sigma_f U_\infty B(1 - K).$$

The field E_y being the same in the cylinder and the fluid, if $\langle E_y \rangle = 0$ it follows that $K = 0$ independently of the conductivity of the cylinder. The preceding analysis remains valid for cylinders of arbitrary cross-section, the flow stream lines splitting on each side of the stagnation point and remaining parallel to the surface of the pebble.

B.3.b Flow Around an Array of Cylinders

The solution is an extension of the preceding pattern. With the same choice of axis, we find here again as a solution

$$J_x = J_z = E_z = E_y = U_y = 0$$

and

$$J_y = -\sigma U_x B.$$

This solution is a function of x only, whereas the z dependence of U_z is linear along the z axis and such that

$$\frac{\partial U_x}{\partial x} = -\frac{\partial U_z}{\partial z}.$$

Figure 2. High Hartmann Number Flow Around a Circular Cylinder With Axis Normal to the Magnetic Field.

Hence, the spacing between fluid stream lines is only a function of x and in the flow passages between two pebbles U_x is independent of z . The stream lines are shown in Figures 3.a and 3.b for two arrays of cylinders. The solution is also applicable to flow passages between cylindrical surfaces of arbitrary shape extending to infinity in the y direction as shown in Figure 3. If d is the width of the passage measured along z , the axial velocity U_x , uniform across the passage, is inversely proportional to d and proportional to the flow rate. For a given flow rate the pressure drop in the fluid is proportional to the effective l/d of the passage defined as

$$\left(\frac{l}{d}\right)_{\text{eff}} = \int \frac{dx}{d(x)} .$$

Thus, for passages of constant width the hydraulic impedance is proportional to the length l along the x direction and independent of the existence of turns in the x - z plane.

Figure 3.a. Flow Through Array of Cylinders.

Figure 3.b. Flow Through Array of Cylinders.

C EXISTING EXPERIMENTAL FACILITIES

C.1 Characteristic Parameters for MHD Flow Experiments

Before presenting a listing of existing MHD facilities, an introduction on the available liquid metals is warranted. The following is a tabulation of characteristic MHD parameters for different liquid metals that could be used to study the MHD effects for fusion reactor blankets.

In order to make a consistent comparison of different liquid metals, a coolant velocity of 0.1 m/sec and a tube diameter of 1 cm was used. A low velocity was picked to simulate the packed bed flow conditions, to reduce the flow rate requirement, and to enhance the magnitude of the magnetic interaction parameter, $\frac{He_2}{Re} = \frac{(B_{ao})^2}{(2\rho V)}$ (which is a measure of the ratio of magnetic body force and fluid inertia force) and to provide reasonably high Reynolds number. A small pipe size was selected to indicate the usefulness of the possibility of doing small and inexpensive MHD experiments.

Table 1 presents the physical properties for NaK, Hg, Li, K, Na, and Pb. Their respective MHD parameters as a function of B-field strength are given in Table 2. These tables show that in order to simulate the effect of lithium with similar magnetic interaction parameters, NaK requires slightly higher magnetic fields while K and Na require slightly lower fields. A useful regime for testing results when the Hartmann number is high and the interaction parameter is greater than 1000. NaK has an advantage of Li, K, and Na because it is liquid at room temperature. Hg has the advantage of low melting point (-39°C), yet it has the disadvantages of having low electrical conductivity and high density. These results indicate that for simple channel flow experiments using a small channel diameter of 1 cm can provide meaningful results (for magnetic interaction parameter > 1000).

C.2 Survey of Liquid Metal MHD Experimental Facilities

With the purpose of identifying what can be done on MHD experiments, a survey was made of existing or potential MHD experimental facilities. This is by no means an exhaustive survey, but it does provide a sense of what type of facilities are available.

Table 1. Liquid Metal Physical Properties.

	Nak	Hg	Li	K	Na	Pb	
Melting point, °C		-11	-38.87	179	63.7	97.8	327.4
Boiling point, °C		784	357	1317	760	883	1737
Density, kg/m ³ (@ 100°C)		847 (@ 25°C)	13 645 (@ 400°C)	490 (@ 250°C)	783 (@ 200°C)	891 (@ 500°C)	10 390
Viscosity, kg/msec (@ 100°C)		0.47x10 ⁻³ (@ 20°C)	1.55x10 ⁻³ (@ 300°C)	0.44x10 ⁻³ (@ 300°C)	0.26x10 ⁻³ (@168°C)	0.50x10 ⁻³ (@ 500°C)	1.85x10 ⁻³
Electrical conductivity, (μohm · m) ⁻¹		2.4 (@ 100°C)	1.0 (@ 20°C)	3.1 (@ 400°C)	3.5 (@ 300°C)	7.6 (@ 200°C)	0.97 (@ 500°C)
Specific heat, J/kgm°C (@ 200°C)		908	138	4184	774	1339	152
Thermal conductivity, (@ 100°C)		24.4 (@ 20°C)	8.4 (@ 218°-233°C)	37.7 (@ 300°C)	42.0 (@ 200°C)	81.5 (@ 500°C)	15.5
Latent heat of fusion, cal/gm		--	2.8	158	14.6	27.1	5.89
Latent heat of vaporization Cal/gm		--	69.7	4680	496	1005	204.6

Table 2. Liquid Metal Parameters.

Parameter (B-Field Strength)	Nak (@ 100°C)	Hg (@ 25°C)	Li (@ 400°C)	K (@ 250°C)	Na (@ 200°C)	Pb (@ 500°C)
Re	1802	8803	1113	3011	1783	5616
He (1 T)	357	127	420	580	616	114
(4 T)	1428	508	1679	2320	2466	456
(8 T)	2858	1016	3357	4641	4932	915
He ² /Re (1 T)	70.7	1.8	158	1117	213	2.3
(4 T)	1131	29	2538	17 827	3408	36.8
(8 T)	4525	115	10 112	71 488	13 632	149

- Parameters calculated with a fluid velocity of 0.1 m/sec and a tube diameter of 1 cm.
- Re = Reynolds number = $\rho V D / \mu$: inertia force/viscous force.
- He = Hartmann number = $B a \sqrt{\sigma / \mu}$: body force/viscous force.
- He²/Re = interaction parameter = body force/inertia force.
- ρ = density, V = velocity, μ = viscosity, σ = electrical conductivity.
- B = magnetic field strength, D = hydraulic diameter, a = channel 1/2 width.

Table 3 provides a listing of facilities available at eight laboratories that could be used for fusion-related liquid metal experiments. It is obvious that some are better equipped than others. Some facilities, like GA Technologies and TRW, have only magnets and some, like ETEC, have only liquid metal loops. Other facilities have both. Westinghouse has both magnets and liquid metal equipment from their LMFBR program, and Purdue University has done many basic experimental and analytical studies, but mainly on mercury.

C.3 Observations and Recommendations

Considering the above discussions and facilities survey, the following observations and recommendations can be made:

1. Because of the importance of the MHD pressure drop information for self-cooled blanket designs and because of the large number of uncertainties presently associated with calculation of MHD effects in liquid metal fusion reactor blankets, the following phases of experimental work are recommended:

Phase 1. Small-scale experiments to quantify and bracket the questions of MHD pressure drop from channel flow of different configurations and packed-bed design.

Phase 2. Larger experiments to model contractions, expansions, and flow distributions.

Phase 3. Semi-scale module mock-up to simulate complex current flow paths in prototype configurations.

Phase 4. Full-scale module mock-up and testing.

2. NaK and B-field strength of $J \approx 4 \text{ T}$ are a good combination to simulate the MHD effects of Li in a commercial reactor.
3. In performing the MHD experiments, distinctions should be made between developed and undeveloped flow.

Table 3. Preliminary Survey of Liquid Metal MHD Test Facilities (Magnets and Loops).

Organizational/Facility	Fluid	Pipe Diameter (cm)	Maximum Flow Rate	B-Field Strength (T)	Characteristic Test Volume Dimension
1. Argonne National Laboratory					
- Ambient temperature liquid metal MHD loop	NaK	--	330 GPM	1.2	9 cm
- High temperature liquid metal MHD loop	Na	--	500 GPM	0.9	30 cm
- FELIX	Magnet only			0.8	1 m ³ (working volume)
- OCMHD-SC ^a	Magnet only			6	110 cm
- Split-Coil S/C	Magnet only			6	10 cm
2. Energy Technology Engineering Center					
- SPTF	Na	70	58 072 GPM	Loop only	
- SCT _L	Na	4 to 9	251 GPM	Loop only	
- Building 032	Na	4 to 9	211 GPM	Loop only	
- BLIP Loop	Li	2 to 4	17 GPM	Loop only	
3. GA Technologies, Inc					
- 8 T-S/C Magnet	Magnet only			8	40 cm (cold bore) 30 cm (warm bore)
- 5 T-S/C Magnet	Magnet only			5	21 cm (cold bore) 14 cm (warm bore)
- 10 T-S/C Magnet	Magnet only			10	26 cm (cold bore) 18 cm (warm bore)
4. Lawrence Livermore National Laboratory	Li	2	4.3 GPM	1.03	--

Table 3. Preliminary Survey of Liquid Metal MHD Test Facilities (Magnets and Loops) Cont'd.

Organizational/Facility	Fluid	Pipe Diameter (cm)	Maximum Flow Rate	B-Field Strength (T)	Characteristic Test Volume Dimension
5. Purdue University					
- Horizontal MFM ^b Loop	Hg	3.6	265 GPM	1.5	7.6 cm
- Small Vertical Loop	Hg				
- Large Vertical Loop	Hg	7.6	275 GPM	1.35	--
6. TRW Inc.					
- 2 m Long Solenoid	Magnet only			2	25 cm
- Pancake Helmholtz Coils	Magnet only			0.8	1 ft ² -area
7. University of Texas					
- NaK-Loop	NaK	2.54	30 GPM	1.5	~ 3 cm
8. Westinghouse Electric Corp.					
- GPL-1 ^c	Na	5.1	200 GPM	Loop only	
- GPL-2 ^c	Na/649°C	15.2	2000 GPM	Loop only	
- SCTF ^d	Na/400°C	--	100 GPM	Loop only	
. Proposed Possible Experiment (3)	NaK	Packed bed (13 cm dia.)	5 GPM	2.5	15.24 cm
. MFD ^e Test System (4)	NaK	1.8 x 4.6 cm cross-section	349 GPM	1.23	--
. ELMAG-II	NaK	3.8 x 4.5 cm cross-section	1000 GPM	0.35	14 cm
- EPRI Funded Program	Na	25.4	3500 GPM		

^a Open cycle MHD superconducting magnet.

^b MFM - magneto-fluid-mechanic channel.

^c GPL - general purpose loops (two loops are listed out of five available loops).

Other special purpose and material testing loops are available (Ref. 1).

^d SCTF - subcomponent test facility (Ref. 2).

^e MFD - magnetofluiddynamic.

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4. Besides basic MHD-pressure drop experiments, parallel efforts should be devoted to the design and development of electrically insulated walls.
5. MHD effects on heat transfer (turbulence suppression) and corrosion should be investigated, as well as MHD pressure drop effects.
6. Activities at different facilities should be coordinated and capabilities and experiences should be shared in order to gain the most information at reasonable cost for the Fusion Breeder Program.

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