BRIEFING ON UCLA FUSION NUCLEAR TECHNOLOGY EFFORT

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UCLA Fusion Nuclear Technology Effort (1987)

I. Theory, Modelling and Analysis
   A. Liquid Metal Blankets
      1. Numerical Techniques and Code Development for Momentum and Heat Transfer (interface with ANL)
      2. Analysis of Experiments
      3. Material Interaction Modelling and Experiment (interface with ORNL)
   B. Nuclear Elements of In-Vessel Components
      1. Thermomechanical Design Window for Liquid Metal Cooled Divertors and Limiters (interface with Sandia)
   C. Solid Breeder Blankets
      1. Model and Code for Tritium Transport and Behavior (interface with ANL/HEDL)
      2. Helium Purge Fluid Flow, Heat Transfer and Tritium Convection
      3. Thermomechanical Behavior

II. "Current" Issues of Fusion Nuclear Technology
   A. Technical Analysis and Support on Short-Term Basis for Issues with Programmatic Implications (assist DOE, MFAC, community), e.g.:
      1. Neutron Source Evaluation
      2. New Experiment and Facility Initiatives
      3. MOTA/JMTR/BEATRIX

III. ITER (TIBER)
   A. Pulsing and Steady State
   B. Testing Requirements
   C. Test Module Design (2 blankets)
   D. Shield/Magnet Safety Factor

Neutronics Activities at UCLA

- Joint Effort with JAERI on Integral Experiments

  - Remarkable technical progress

  - Exemplary cooperation within U.S. organizations and with Japan

- Tritium Self-Sufficiency Modelling and Analysis

  a) Time-dependence analytic/formulation for tritium self-sufficiency conditions

  b) Modelling of Tritium: i) Flow Rates, ii) Inventories, iii) Other Losses (e.g., in physical/chemical tritium processes) for all reactor components

    - Tritium processing subsystems (in cooperation with LANL/TSTA)

    - Blanket Tritium Transport Model developed under solid breeder

  c) Input from neutronics and other studies

UCLA FNT Modelling and Analysis Effort (MOSAIC)

Objectives

1. Tools for analysis and interpretation of experimental results
2. Fundamental tools for design codes
3. Capabilities for use in planning experiments and facilities

Observations

- Very little resources were devoted to FNT modelling in the past. Vigorous modelling activities are necessary for further progress.
- Area particularly suitable for universities: ideas, theoretical/analytical formulation, numerical technique development, clearly identifiable technical areas suitable for "thesis-type" effort
- UCLA effort is interactive with and complementary to efforts in many organizations in the U.S. and other countries
- Area is difficult and often frustrating because a "visible pay-off" takes time. Scientists/engineers need encouragement for meaningful contributions.
- Effort on critical experimental and modelling areas of long-term R&D should be maintained in parallel to large projects such as ITER

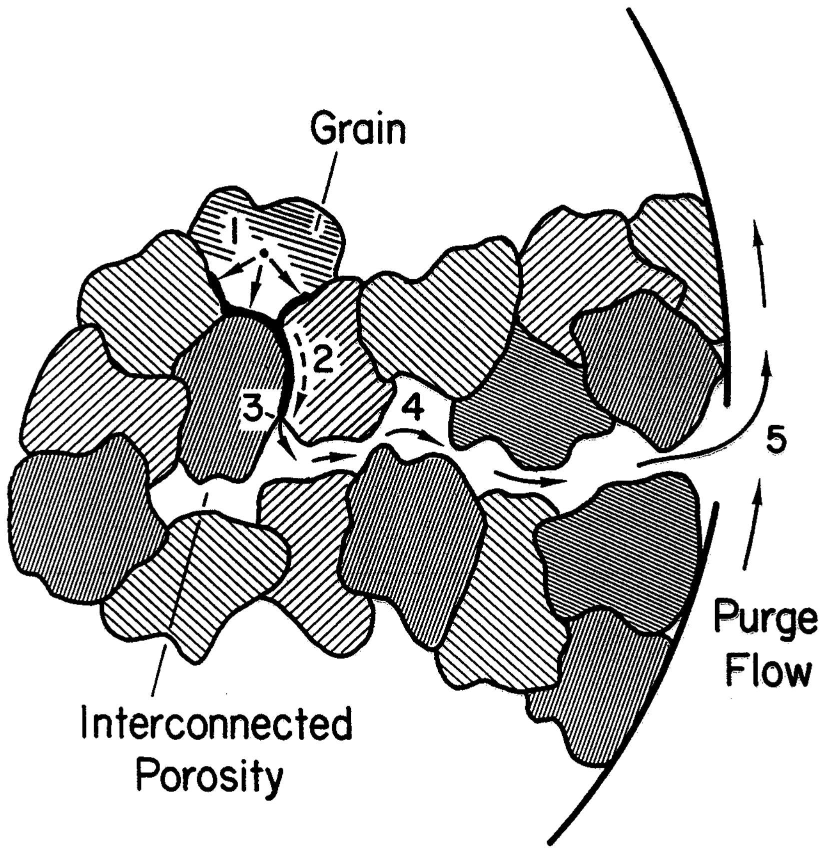
Modelling of Tritium Behavior in SB

Objectives

- Provide input to experiment planning
- Analyze and interpret experimental results
- Provide predictive capability for tritium self-sufficiency and safety analysis
- Provide a tool for design studies
- Provide a technical basis to help in the decision-making process for the selection of design and operating mode of ITER

Motivation

- Large uncertainties exist in predicting the tritium behavior in solid breeders. Large impact on:
  - assessing tritium self-sufficiency
  - selection of breeders
- The increase in the amount of experimental data requires vigorous complementary modelling effort
- Early effort may greatly influence ITER decisions



Mechanisms of Tritium Transport

1) Intragranular Diffusion
2) Grain Boundary Diffusion
3) Surface Adsorption / Desorption
4) Pore Diffusion
5) Purge Flow Convection

Modelling of Tritium Behavior in SB (UCLA Effort)

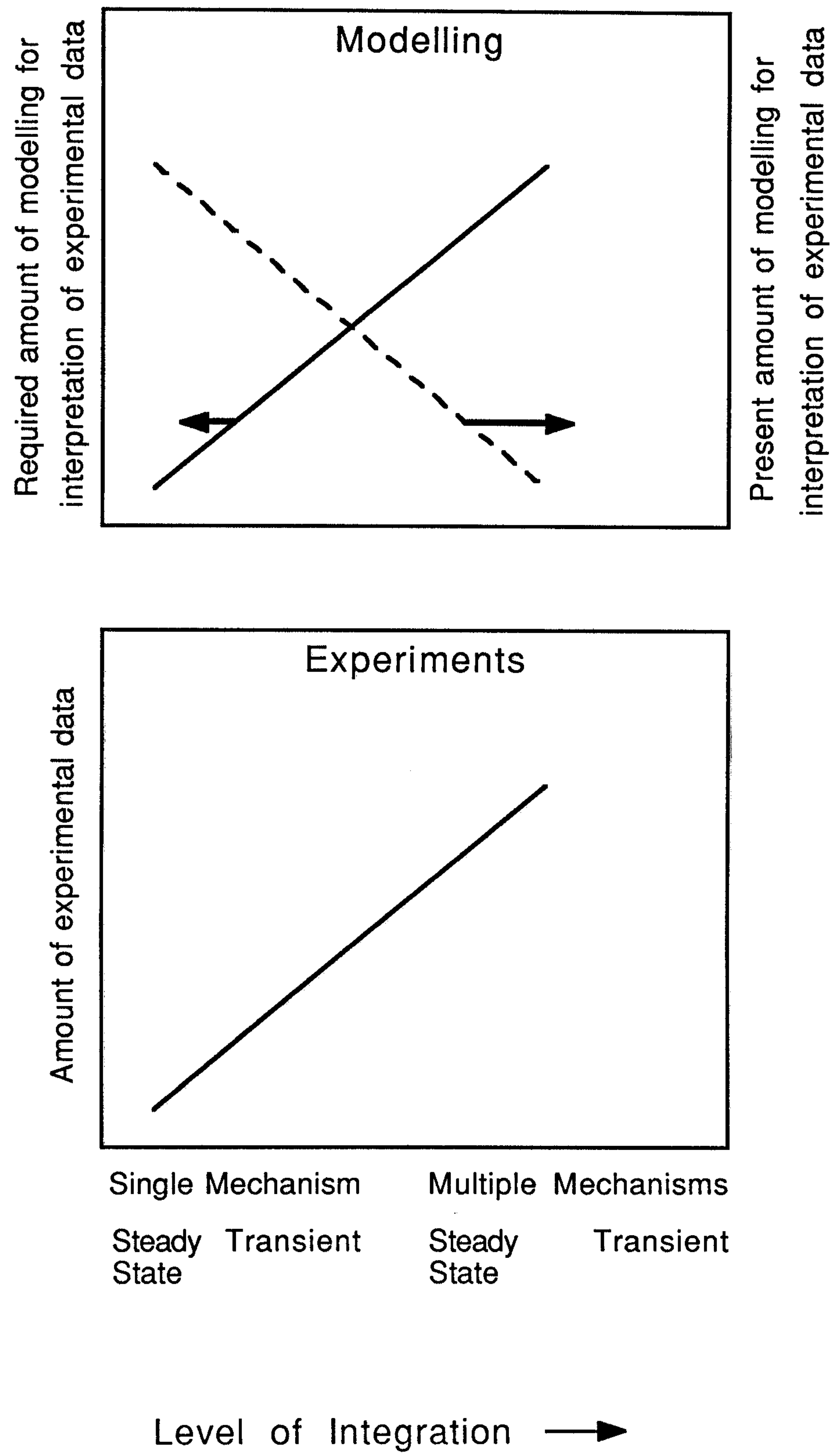
Areas of Emphasis

- Transient behavior
- Coupling of different transport mechanisms
- Surface adsorption/desorption
- Species (HT, H_2, T_2) diffusion in the pores
- Geometry
- Temperature dependence

Interaction with Other Organizations

Strong interactions exist with other groups performing tritium experiments and modelling, in particular with ANL and HEDL. Also, interacting with others in Japan and Europe.

Tritium Behavior in Solid Breeders: Status of Experiments and Modelling



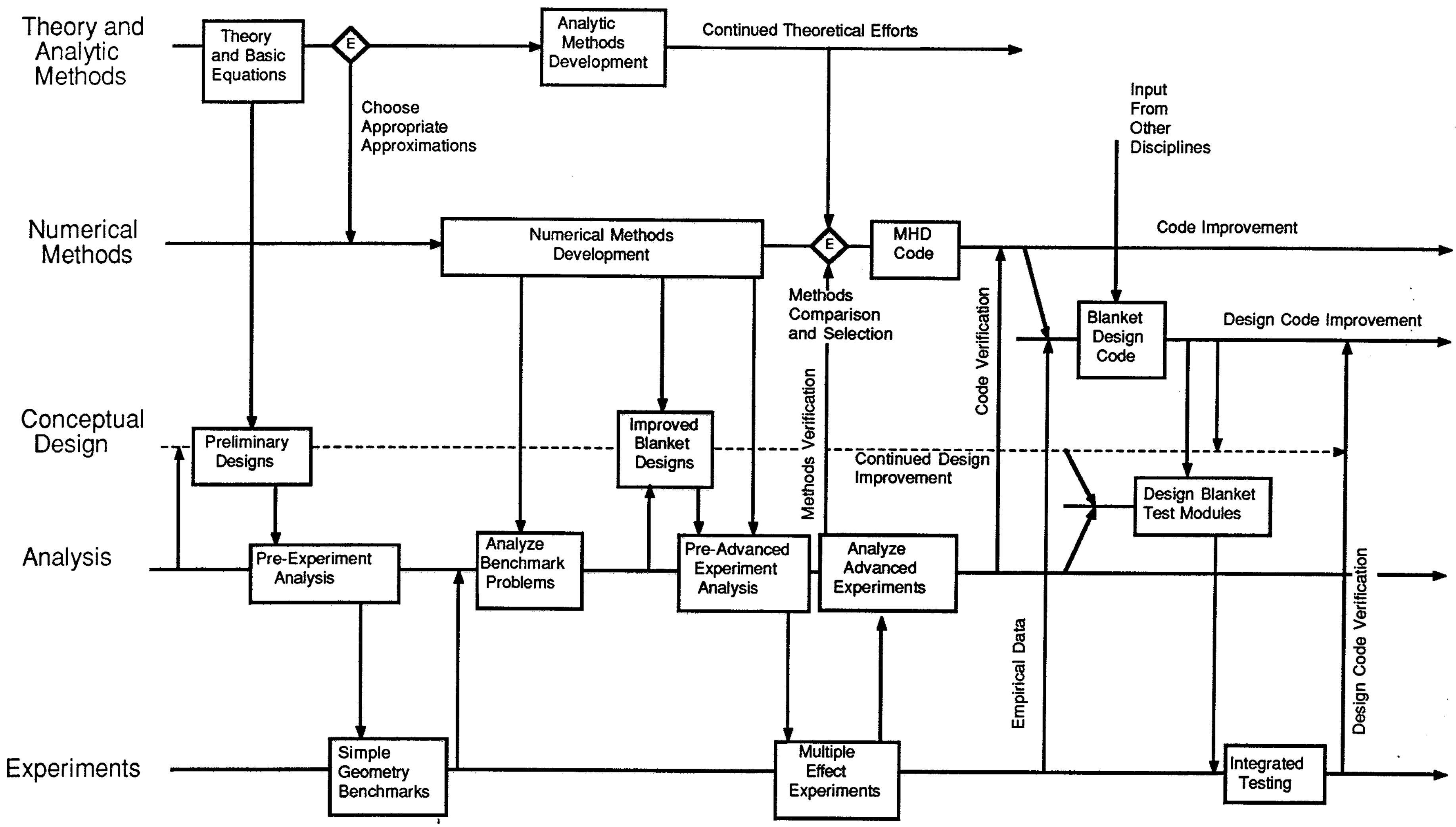
Solid Breeder Tritium Transport Mechanisms: Data and Modelling Deficiency*

(S = small M = moderate L = large)

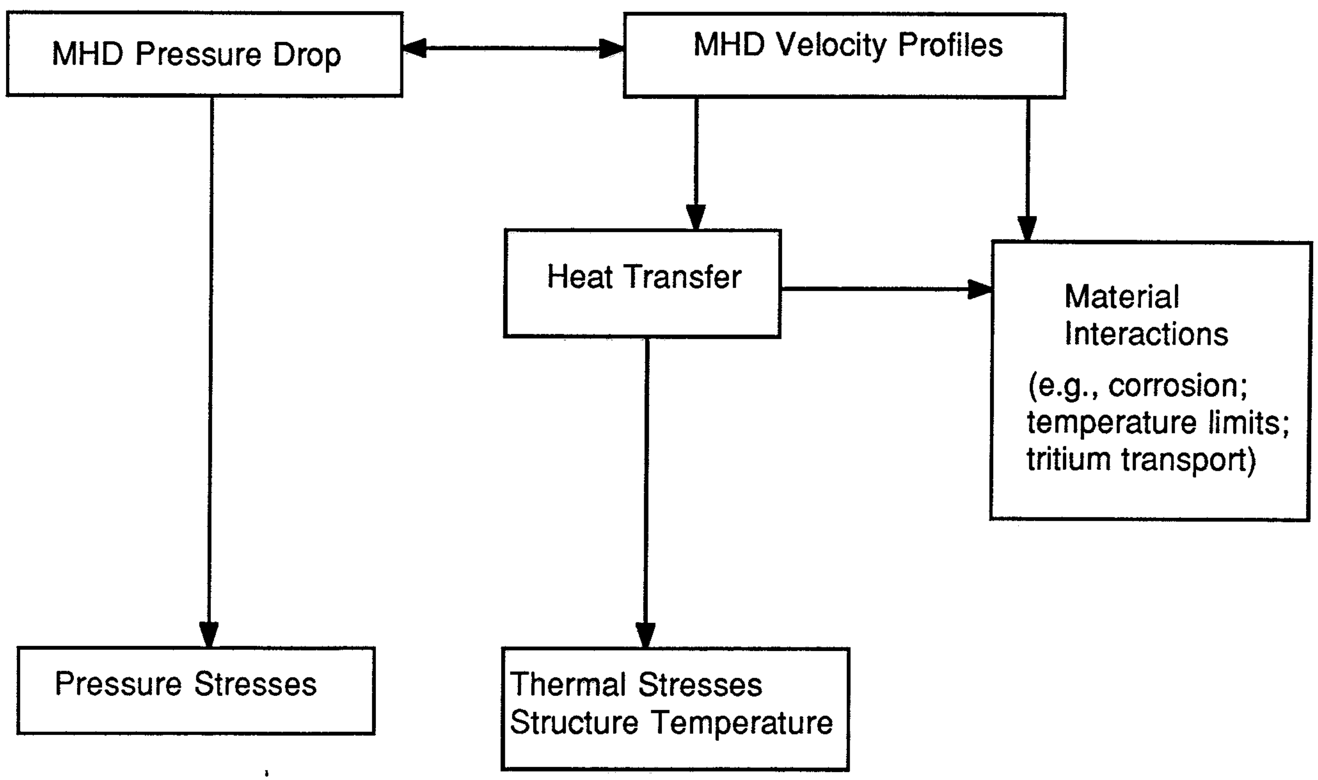
	Amount of Data Available	Data Base Uncertainty	Modelling Difficulty Steady State	Modelling Difficulty Transient
Intra Granular Diffusion	M	M-L	S	S
Grain Boundary Diffusion	M	L	M-L	M-L
Adsorption/ Desorption	S	L	M	L
Solubility	S	M	M	L
Pore Diffusion	M-L	M	L	L
Other Mechanisms	S	L	L	L

* Due to geometry, irradiation, chemistry and time dependence effects

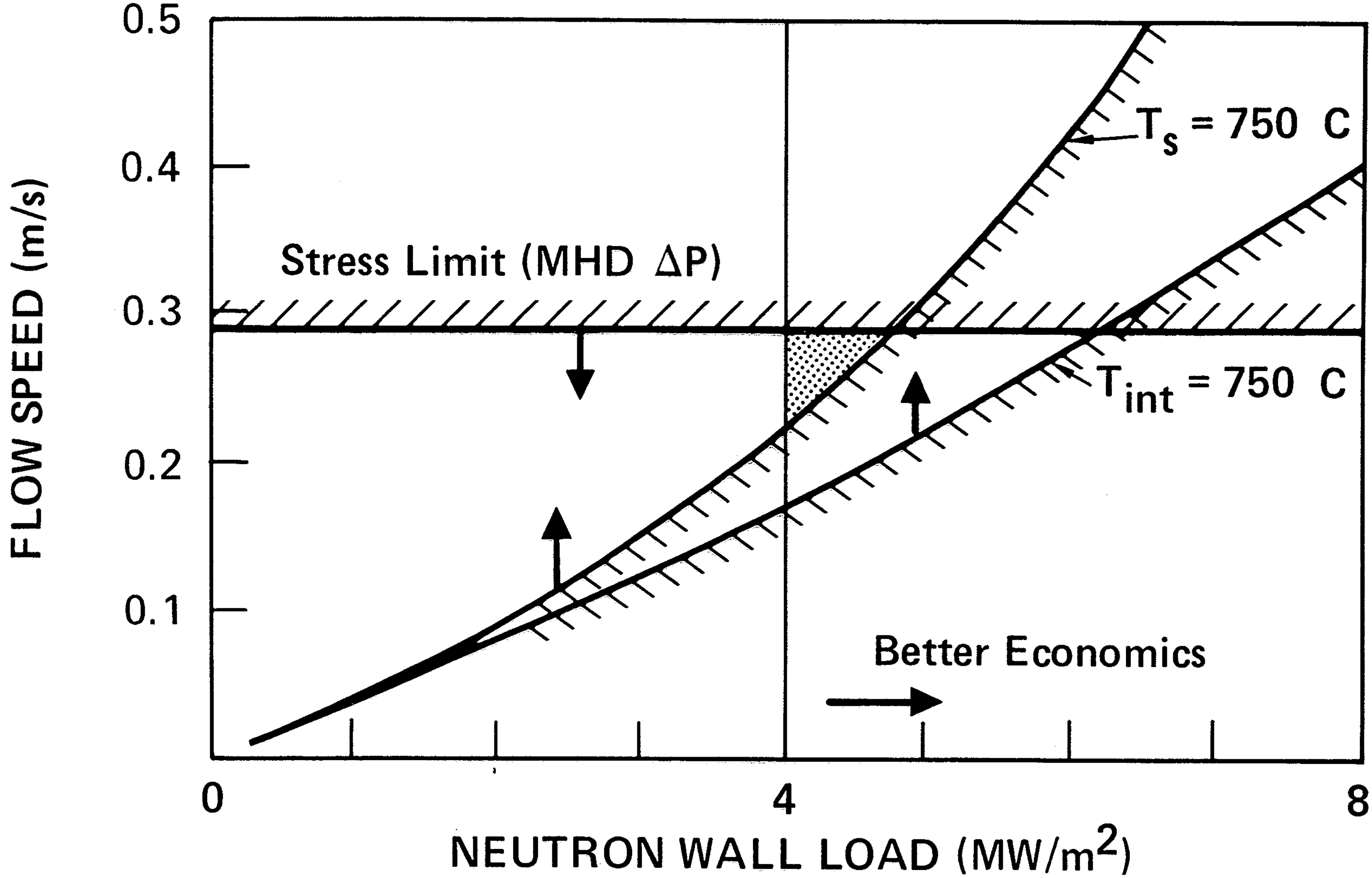
LIQUID METAL MHD MODELING LOGIC

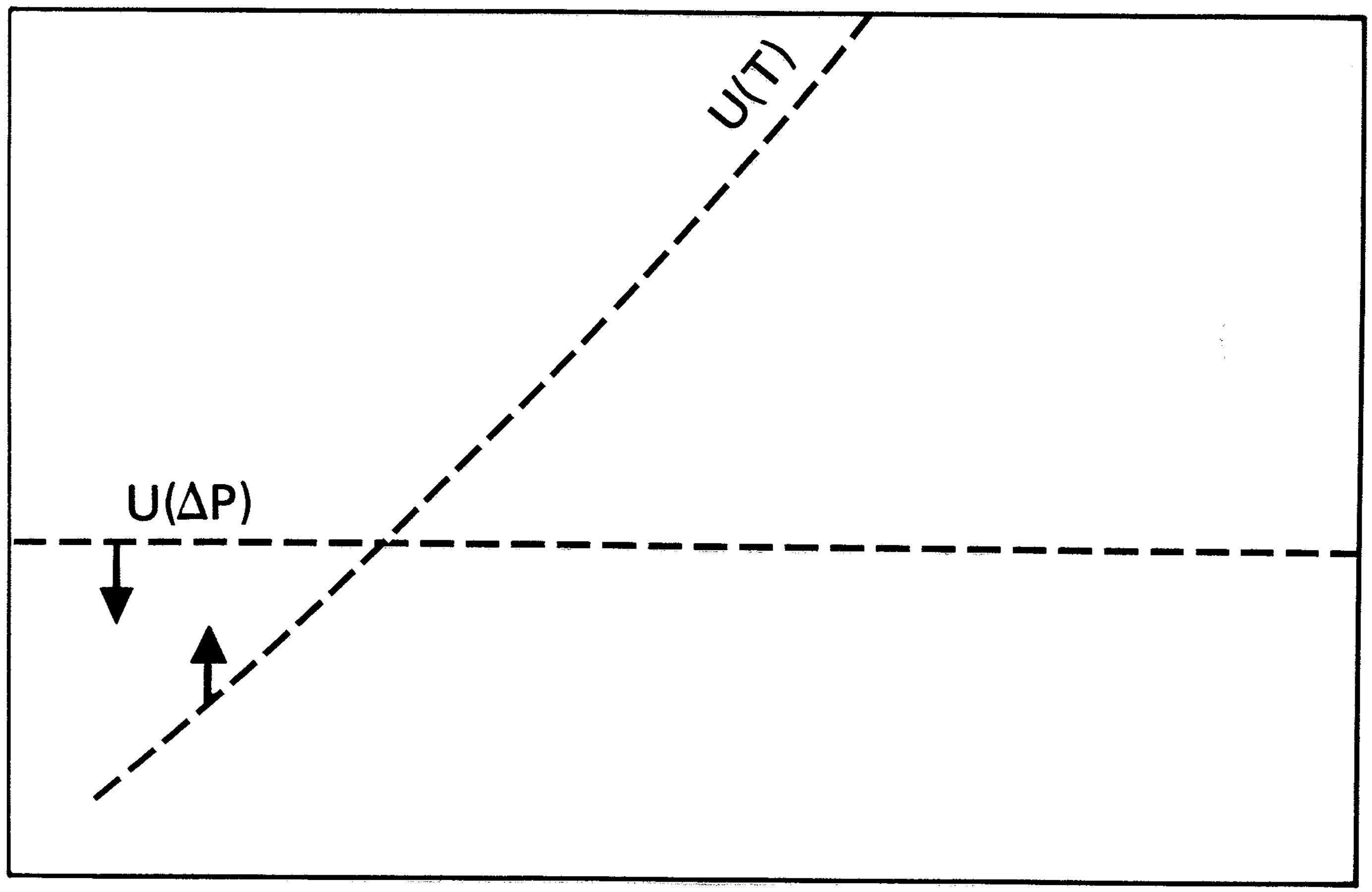


Accurate Prediction of MHD Effects is Fundamental to Quantifying the Performance (Attractiveness and Feasibility) of Liquid Metal Blankets



Design Window Is Narrow For Best Liquid Metal Blanket (Li/V)





U(T): Any of:

T_s = 650 C

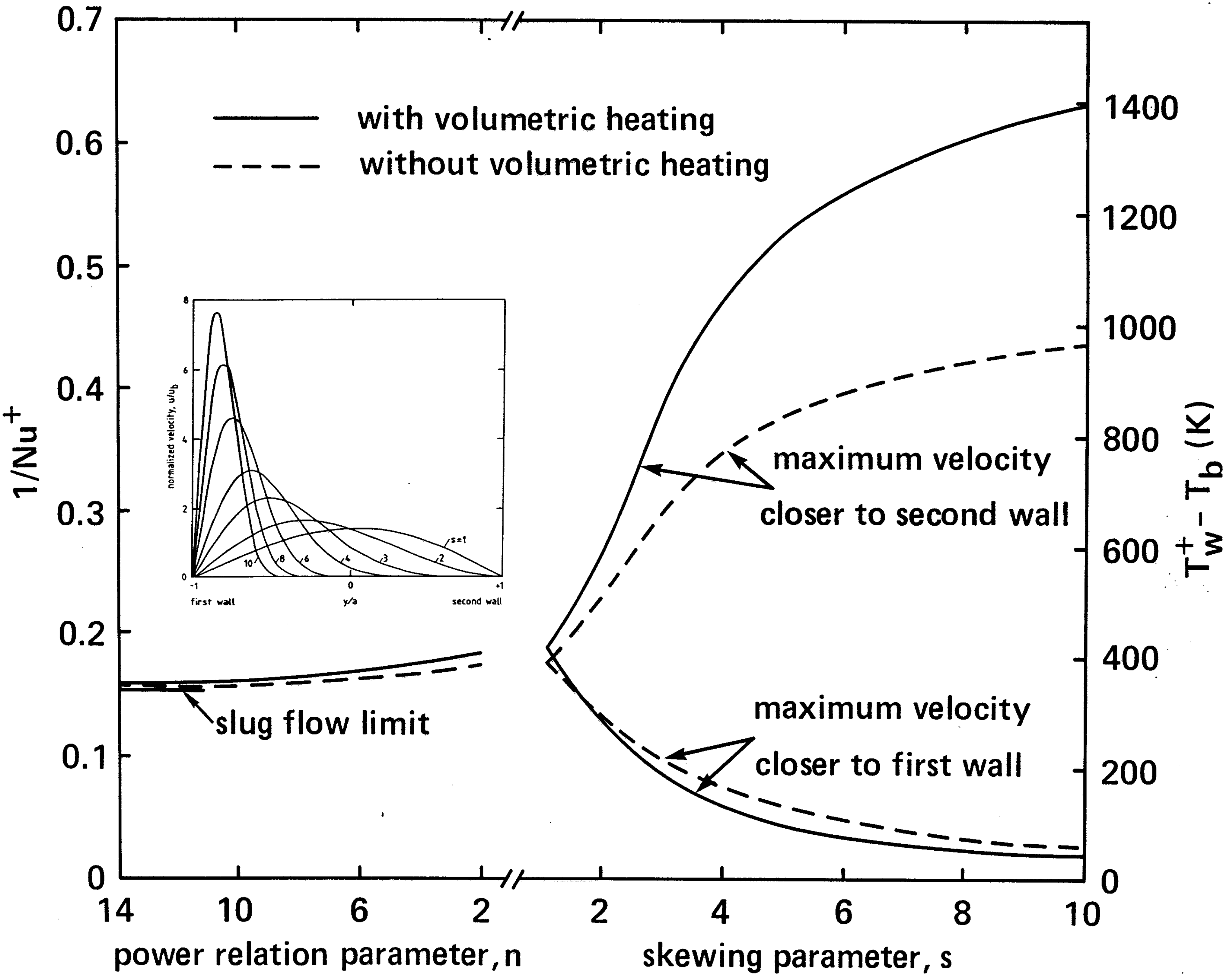
T_{int} = 550 C

h_m = 0.7h

Uncertainties in MHD, Corrosion, Heat Transfer, Radiation Effects Represent Major Issues

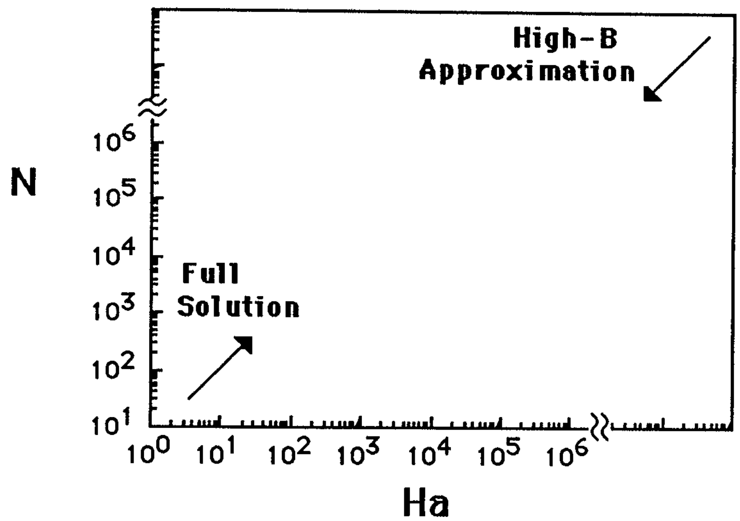
Contributors to MHD Pressure Drop

Type of Pressure Drop	Design Dependent	Well Understood	Some Work Done/More Work Needed	Not Yet Studied/Very Little Work
Global effects				
Intra-channel	X			X
Manifolding				X
Bends:				
In plane ⊥ to B				X
In plane || to B				X
Mixing vanes/ Helical flow paths	X			X
Mixed ||, ⊥ B components				X
Entrance and exit			X	
Varying B			X	
Contractions, expansions	X		X	
Non-uniform wall thickness	X		X	
Straight duct		X		
Turbulence enhancement				X
Flow tailoring			X	



with volumetric heating
without volumetric heating
1/Nu+
T+w − Tb (K)
maximum velocity
closer to second wall
maximum velocity
closer to first wall
slug flow limit
power relation parameter, n
skewing parameter, s
normalized velocity, u/ub
first wall
y/a
second wall
s=1

Two Complementary Approaches are Under Development (at UCLA) for Predicting MHD Effects:



high-B approximation

- easier to obtain solution
- provides Δp, heat transfer

full solution

- more difficult
- more complete:
  provides mass transfer capabilities (corrosion and tritium)

High-Field Approach to Solving MHD Equations (UCLA)

If B is sufficiently high, viscosity and inertia can be neglected

$$N \rightarrow \infty$$

$$Ha \rightarrow \infty$$

This reduces the MHD equations to a coupled set of *linear* equations

$$\nabla p = \underline{J} \times \underline{B}$$

$$\nabla \cdot \underline{v} = 0$$

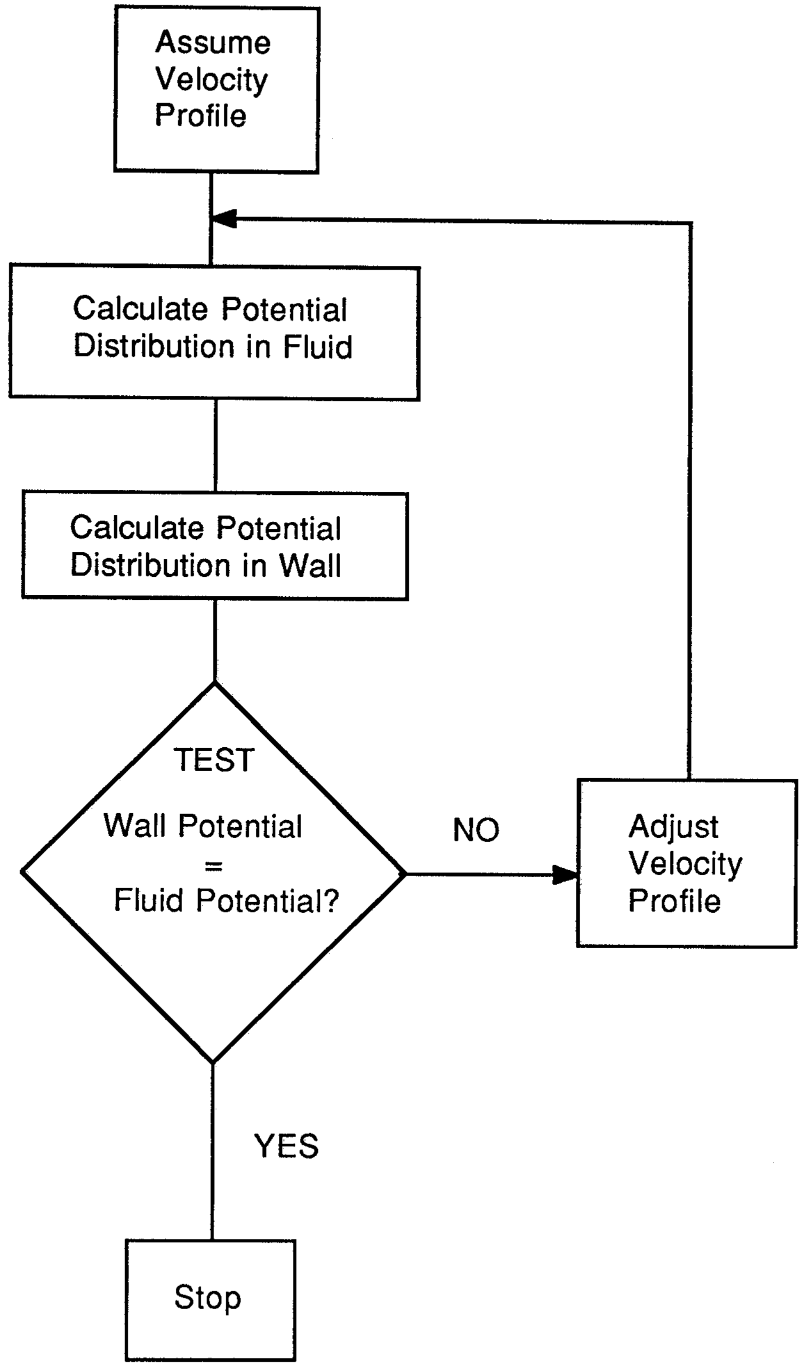
$$\underline{J} = \sigma(-\nabla\phi + \underline{v} \times \underline{B})$$

$$\nabla \cdot \underline{J} = 0$$

The solution to these is being attempted by 2 methods:

- iterative method
- direct method

Iterative Method for High-Field Approach to Solving MHD Equations



Direct Method for High-Field Approach to Solving MHD Equations

Integrate MHD equations

$$\nabla p = \underline{J} \times \underline{B}$$
$$\nabla \cdot \underline{v} = 0$$
$$\underline{J} = \sigma(-\nabla\phi + \underline{v} \times \underline{B})$$
$$\nabla \cdot \underline{J} = 0$$

along magnetic field lines, to obtain [Kulikouskii, 1968]:

$$j_\perp = \frac{\underline{B}}{B^2} \times \nabla\rho$$
$$j_{||} = B\,A_1$$
$$\sigma_f\phi = a\,A_1 + A_2$$
$$v_\perp = -\nabla p/\sigma_f B^2 + \frac{\underline{B}}{B^2} \times \nabla\phi$$
$$v_{||} = -\int(\nabla^2 p/\sigma_f B^3)da + B\,A_3$$

where $B = \nabla a$ = constant

and the four 2-D functions of integration (A_1,A_2,A_3,p) are determined by the boundary conditions

(1) $v \cdot \hat{n} = 0$

(2) $\sigma_w t\,\nabla_w{}^2\phi = \underline{j_f} \cdot \hat{n}$ or $(\sqrt{\sigma\mu}\,(\nabla \times \underline{v}) + \underline{j}) \cdot \hat{n} = 0$

thin conducting heat   non-conducting duct

MHD: "FULL SOLUTION" METHOD (UCLA)

OBJECTIVE

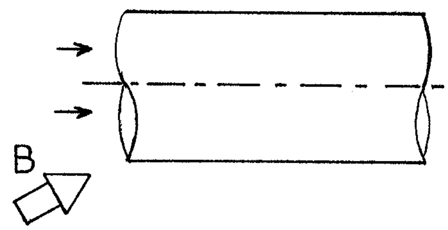
Numerical solutions of full MHD flows for liquid metal fusion blankets

FEATURES

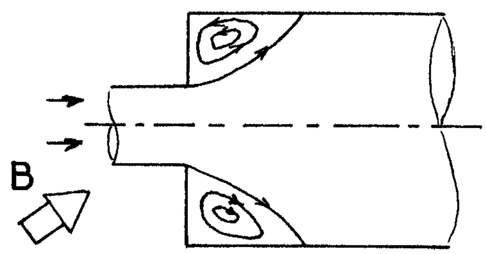
Solutions of coupled Navier-Stokes and Maxwell's equations in:

- 2-D geometry (with possible extension to 3-D)
- Steady (but transient processes are also soluble)
- Incompressible (but compressibility may be added)
- Viscous (laminar flow with viscous boundary layers)
- Low magnetic Reynolds number (i.e., ignoring induced magnetic fields)
- Solution method is applied to low and moderate values of Hartmann and interaction parameters (possible extension to higher Hartmann and interaction parameters)

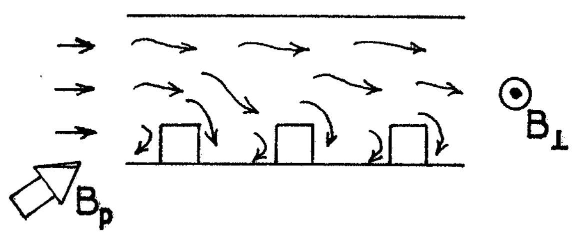
PRACTICAL RELEVANCE IN LIQUID METAL BLANKETS



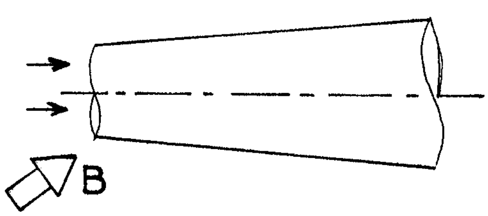
- Laminar pipe flow, effect of oblique applied field (2-D or 3-D MHD flow depending on orientation of B-field)



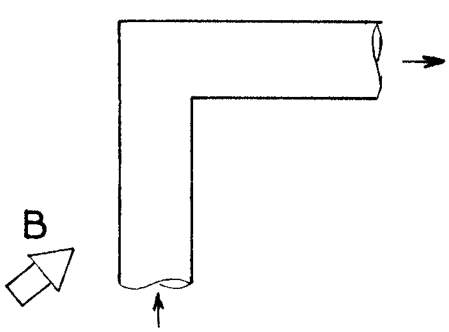
- Abrupt enlargement in pipe diameter with oblique B-field (2-D or 3-D MHD flow depending on orientation of B-field)



- Obstacles in ducts with an oblique B-field in plane of flow (B_p) or perpendicular to it ($B_\perp$) (2-D or 3-D MHD flow)



- Flow in a diffuser with an oblique B-field (3-D MHD flow)



- Flow through a sharp bend with oblique B-field (3-D MHD flow in circular X-section duct but 2-D MHD flow in plane channel)

PHYSICS

For 3-D, steady, incompressible and low Rm flows, there are generally five variables. These are:

u, v, w	velocities in x, y, and z coordinates
p	pressure
φ	electric potential

The electric currents can be obtained once the potential (φ) and velocities (u,v,w) are obtained through Ohm's law.

Other auxiliary variables can also be obtained once the velocity field is obtained, e.g., temperature (T) and species concentration (Ci).

EQUATIONS

The equations which describe the flow of an incompressible electrically conducting fluid in a constant applied magnetic field can be written victorially as:

Momentum: $\rho\vec{v}\cdot\vec{\nabla}\vec{v} = -\vec{\nabla}p + \mu\vec{\nabla}^2 v + \sigma(-\vec{\nabla}\varphi + \vec{v} \times \vec{B}) \times \vec{B}$

Continuity: $\vec{\nabla}\cdot\vec{v} = 0$

Scalar Potential: $\nabla^2\varphi = \vec{\nabla}\cdot(\vec{v} \times \vec{B})$

SOLUTION METHOD

- There are five unknowns and only four equations which explicitly describe them

- Pressure field is indirectly specified via the continuity equation

- Therefore, a method to link the pressure and velocity fields together is needed

- Once the velocity field is obtained, the Poisson type equation for the potential (φ) can be solved readily

- Consider a 2-D geometry. The differential equations are discretized over a rectangular staggered mesh, as:

$$a_e u_e = \sum a_{nb} u_{nb} + b + (P_p - P_E) A_e$$

$$a_n v_n = \sum a_{nb} v_{nb} + b + (P_p - P_N) A_n$$

- Coefficients a_e, a_n and neighbor coefficients a_{nb} account for the combined effect of convection and diffusion at the control volume faces

- Term b is part of the linearized source and may include the influence of the electric potential

- The last term represents the influence of the pressure gradient

PRESSURE AND VELOCITY CORRECTION

SIMPLE Method
(Semi Implicit Method of Pressure Linked Equations)

- Momentum equations can only be solved once the pressure field is known or estimated

- u^*, v^* denote velocity field based on a guessed pressure field P^*

$$a_e u^*_e = \sum a_{nb} u^*_{nb} + b + (P^*_p - P^*_E) A_e$$

$$a_n v^*_n = \sum a_{nb} v^*_{nb} + b + (P^*_p - P^*_N) A_n$$

- Aim is to improve the guessed pressure (P^*) such that the resulting u^*, v^* will get closer to satisfying the continuity equation

- Let $P = P^* + P'$, $P' \equiv$ pressure correction

- Corresponding velocities $u = u^* + u'$, $v = v^* + v'$

- Subtracting discretized equations

$$a_e u'_e = \sum a_{nb} u'_{nb} + (P'_p - P'_E) A_e$$

$$a_n v'_n = \sum a_{nb} v'_{nb} + (P'_p - P'_N) A_n$$

SIMPLE Method
(Semi Implicit Method of Pressure Linked Equations)

(continued)

- In SIMPLE, $\sum a_{nb} u'_{nb}$ and $\sum a_{nb} v'_{nb}$ are ignored

$$u'_e = d_e (P'_p - P'_E) \text{ and } v'_n = d_n (P'_p - P'_N)$$

- To obtain P'-equation, substitute for u'_e, v'_n in the continuity equation to obtain

$$a_p P'_p = \sum a_{nb} P'_{nb} + b^*$$

where b^* contains starred velocities and is the $-v_e$ of the continuity equation and must be driven to small value

- The term $\sum a_{nb} u'_{nb}$ represents indirect or implicit influence of the pressure correction on velocity. In SIMPLE, this term is not included and the scheme is partially implicit.

SIMPLER (SIMPLE Revised) Method

In MHD flows at high Hartmann number and interaction parameter, the omission of $\sum a_{nb} u_{nb}$ deletes the effects of neighboring velocities and thus reduces the rate of convergence

In SIMPLER, the effects of neighboring velocities are retained

$$u_e = \frac{\sum a_{nb} u_{nb} + b}{a_e} + d_e (P_p - P_E)$$

or similarly

$$u_e = \hat{u}_e + d_e (P_p - P_E)$$

$$v_n = \hat{v}_n + d_n (P_p - P_N)$$

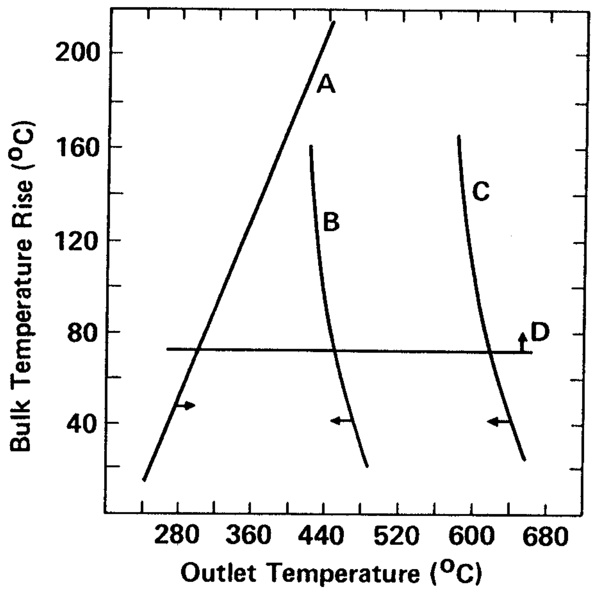
- Substituting for u_e, v_e in the continuity equation, we obtain an equation for the pressure

$$a_p P_p = \sum a_{nb} P_{nb} + \hat{b}$$

where $\hat{b}$ contains $\hat{u}$ and $\hat{v}$

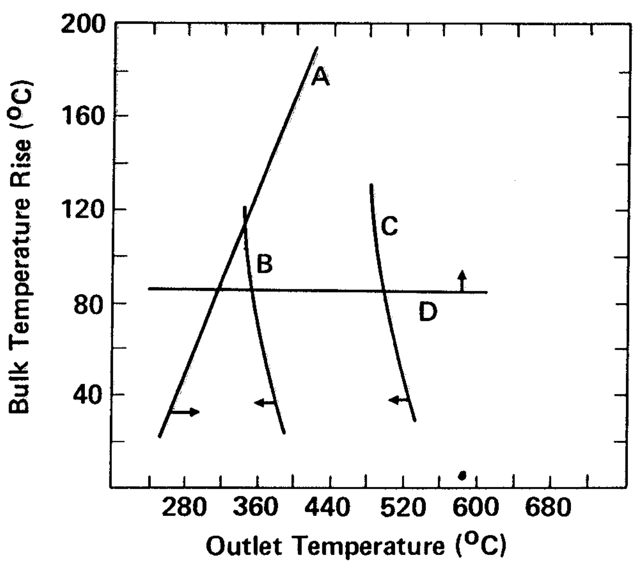
SIMPLER (SIMPLE Revised) Method
(continued)

- Solving the pressure equation, we treat this as (P^*) and solve the momentum equation for u^*, v^*
- Calculate (b^*) and solve P'-equation and then correct velocity field
- Repeat process until convergence
- SIMPLER method is supposed to give faster convergence at high Hartmann numbers and interaction parameters



A - Minimum inlet temperature limit
B - Maximum structure temperature limit
C - Maximum interface temperature limit
D - Maximum primary stress limit

Figure 4.8-26 Design window with insulated conduit at 4 MW/m^2 heat flux



A - Minimum inlet temperature limit
B - Maximum structure temperature limit
C - Maximum interface temperature limit
D - Maximum primary stress limit

Figure 4.8-27 Design window with insulated conduit at 5 MW/m^2 heat flux