Summary of ALPS Activities

R. F. Mattas
Argonne National Laboratory
Presented at APEX Meeting
May 6-8,1998, UCLA

The Use of Lithium in Fusion Applications May Create Unique Tritium Retention Problems

DFC980216

- Lithium has an exothermic heat of solution for hydrogen, and it is a hydride former
- To remove high heat fluxes, lithium will be exposed to intense particle fluxes of low energy tritium and deuterium
- The lithium may be converted into a combination of liquid lithium, liquid lithium with dissolved hydrogen, and liquid lithium with solid lithium hydride
- The different phases have different migration parameters for the hydrogen isotopes

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Phase diagram for H in Li:

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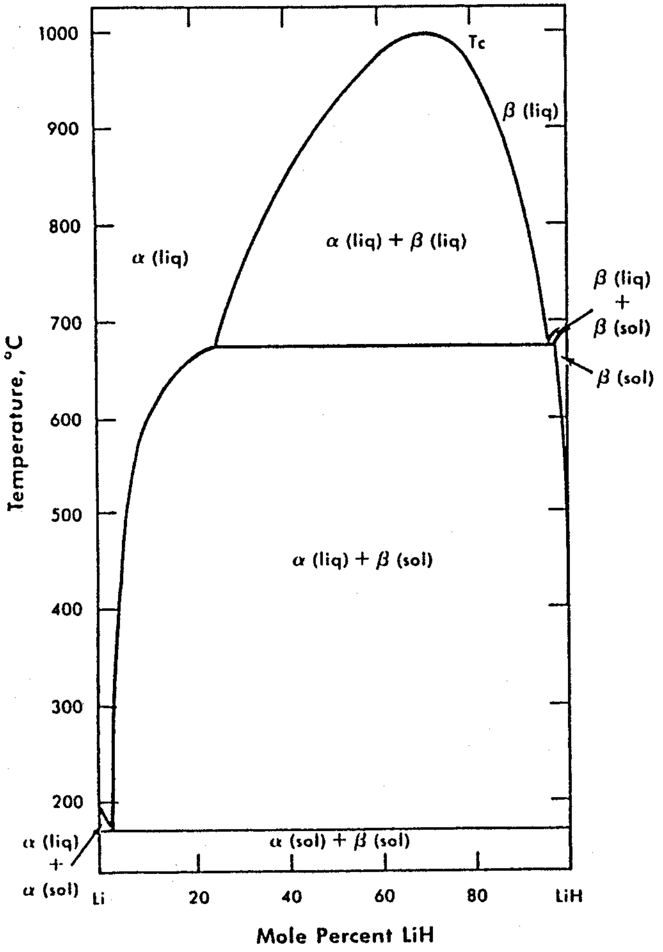

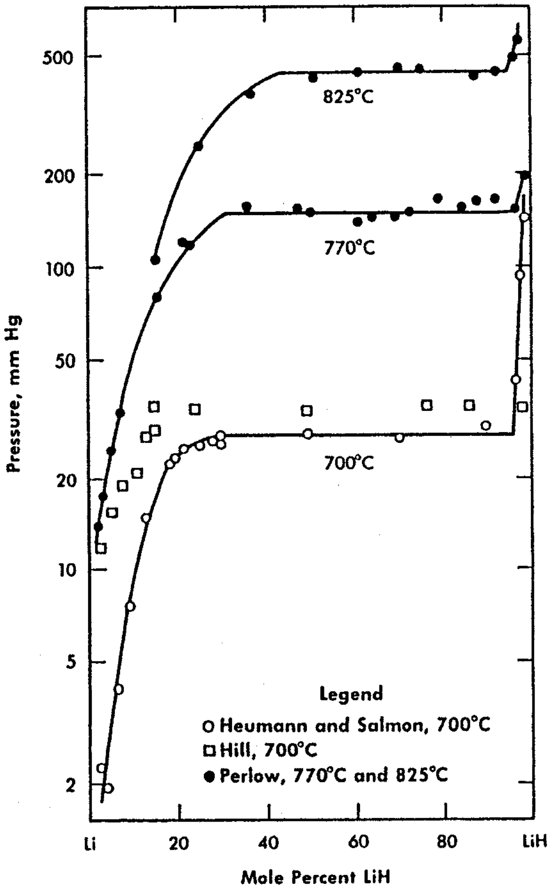

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Mueller, Blackledge & Libowitz, *Metal Hydrides*, 1968, Ch.6.

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Conclusions

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- A DIFFUSE model has been created for the study of tritium implantation of liquid lithium
- In all cases, the model predicts nearly complete retention of the incident flux
- Lithium tritide is unlikely to precipitate
- Experiments are proposed to benchmark the DIFFUSE model

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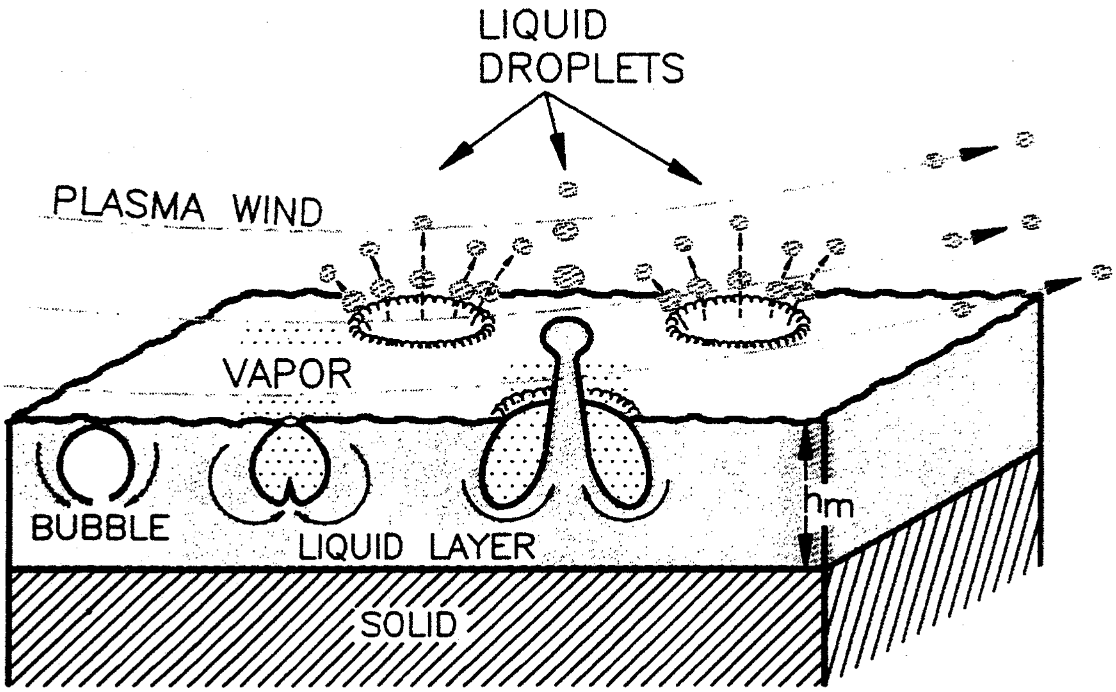
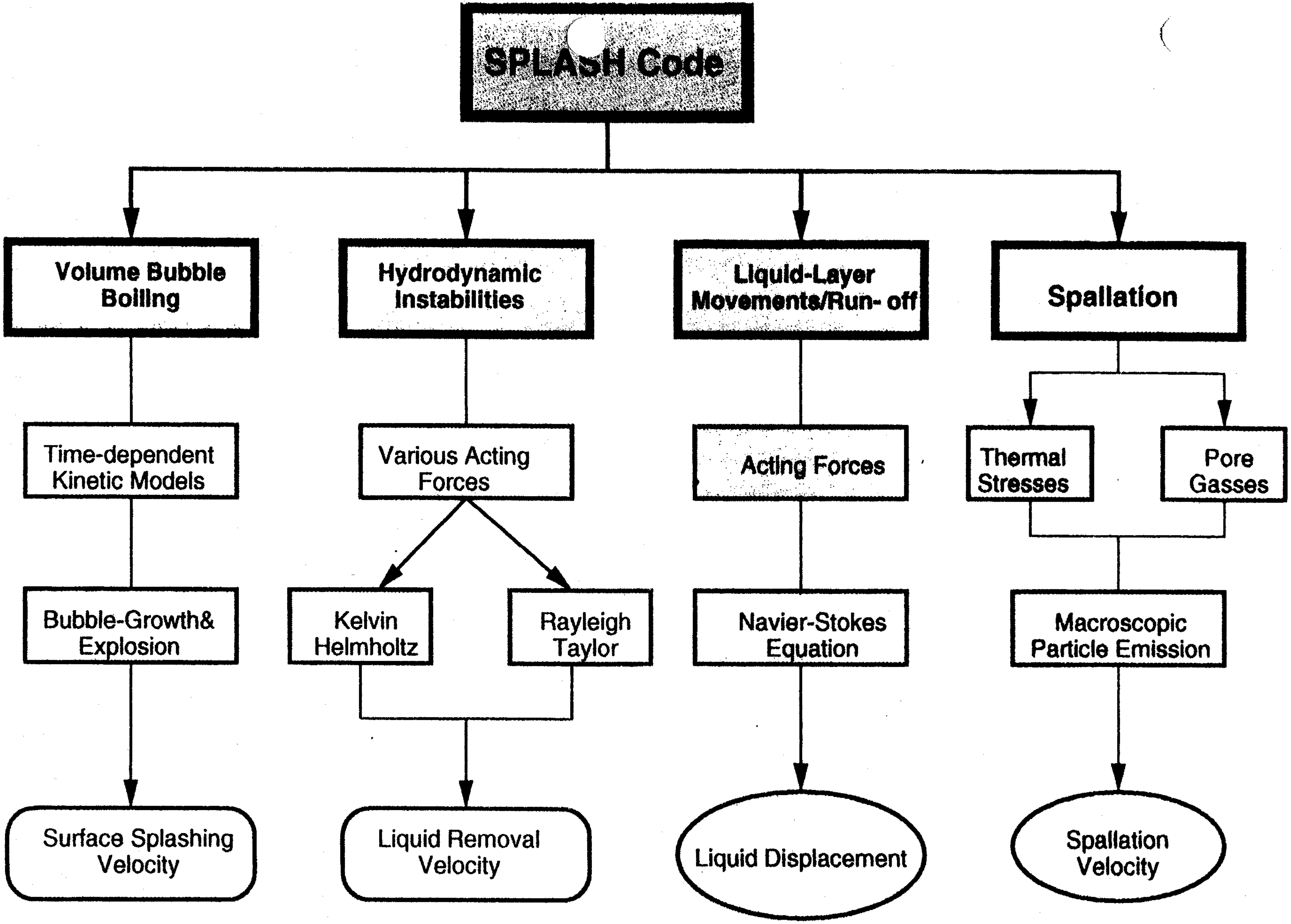


A. HASSANEIN

ARGONNE NATIONAL LABORATORY
UNIVERSITY OF CHICAGO



SPLASH Code

Volume Bubble Boiling

Time-dependent Kinetic Models

Bubble-Growth& Explosion

Surface Splashing Velocity

Hydrodynamic Instabilities

Various Acting Forces

Kelvin Helmholtz

Rayleigh Taylor

Liquid Removal Velocity

Liquid-Layer Movements/Run- off

Acting Forces

Navier-Stokes Equation

Liquid Displacement

Spallation

Thermal Stresses

Pore Gasses

Macroscopic Particle Emission

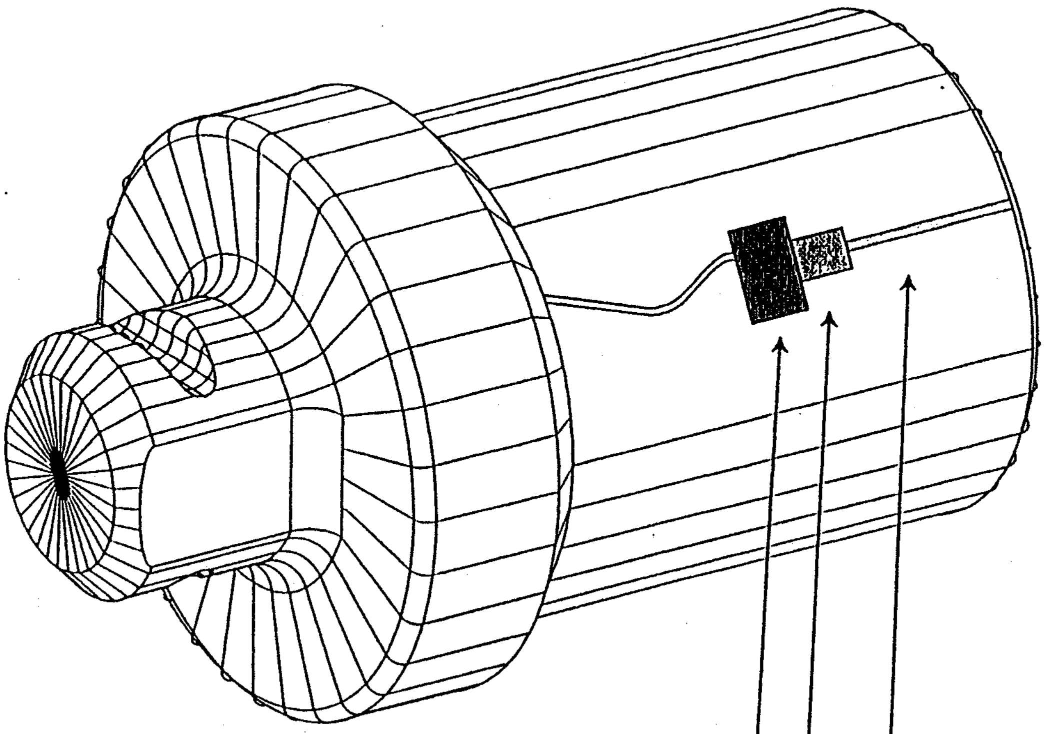
Spallation Velocity

Hassanein
IUIUC 12/97

PMI Experiments

- DiMES
- PISCES
- Laboratory
  - » SNL
    - Sputtering of liquid Li
    - Surface segregation effects
  - » UIUC
    - Sputtering of solid Li

DiMES can be used to test ALPS concept.



heater cartridge
Li reservoir
capillary

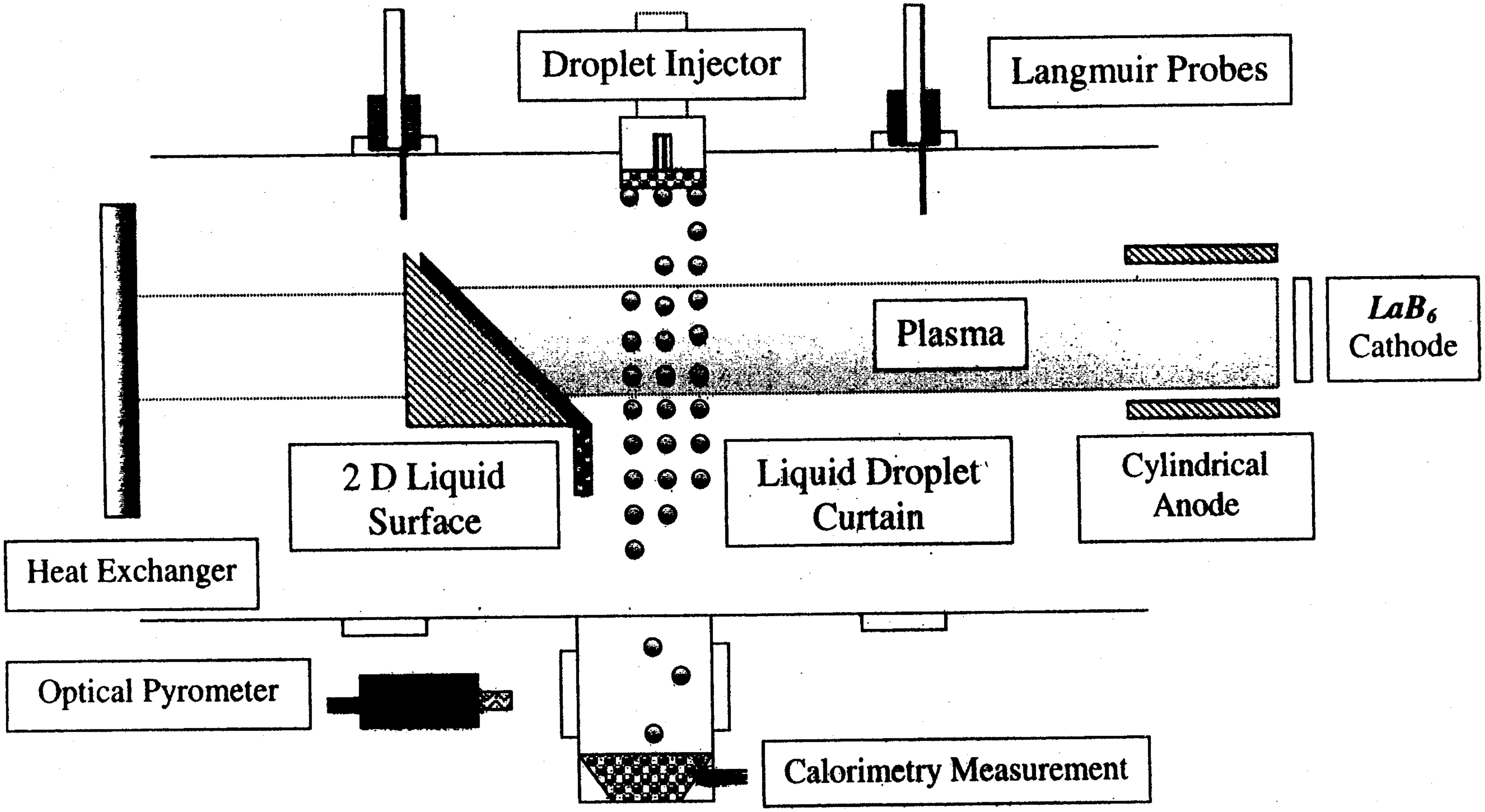
Concept of DiMES sample for ALPS test

Study:

- stability
- erosion
- transport

RB:SNL:8716:97091102 K. WILSON

PISCES-A Liquid Metal PMI Experiment



Droplet Injector

Langmuir Probes

Plasma

LaB_6 Cathode

2 D Liquid Surface

Liquid Droplet Curtain

Cylindrical Anode

Heat Exchanger

Optical Pyrometer

Calorimetry Measurement

S. LUCKHARDT

ALPS Engineering

- Heat transfer
- MHD modeling
- Evaporation limits
- Tritium systems
- Concepts

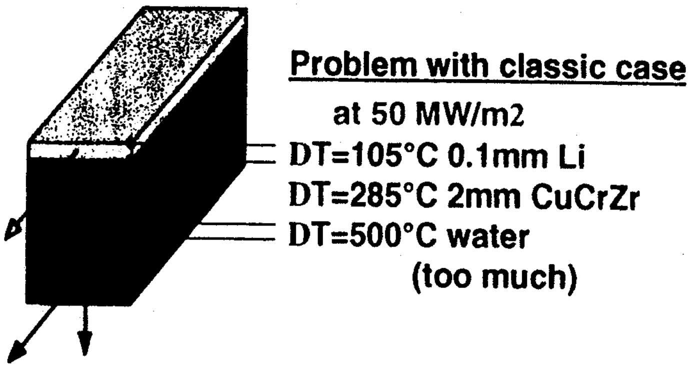
Liquid Surface High Heat Flux Technology

ALPS basic issue: What limits heat removal in liquid surface PFCs?

heat transfer
- near surface heat transfer limits heat removal capability
- MHD effects dominate heat transfer (for liquid metals)
- appropriate experiments (B + HHF) may be challenging

thermal-hydraulics
- MHD effects dominate heat transfer (for liquid metals)
- MHD effects control pressure drop

surface stability
- sputtering erosion
- plasma wind effects
- transients (disruptions)
- collection of open flow



Problem with classic case
at 50 MW/m2
DT=105°C 0.1mm Li
DT=285°C 2mm CuCrZr
DT=500°C water
(too much)

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R. NYGREN

ALPS Meeting - Feb. '98

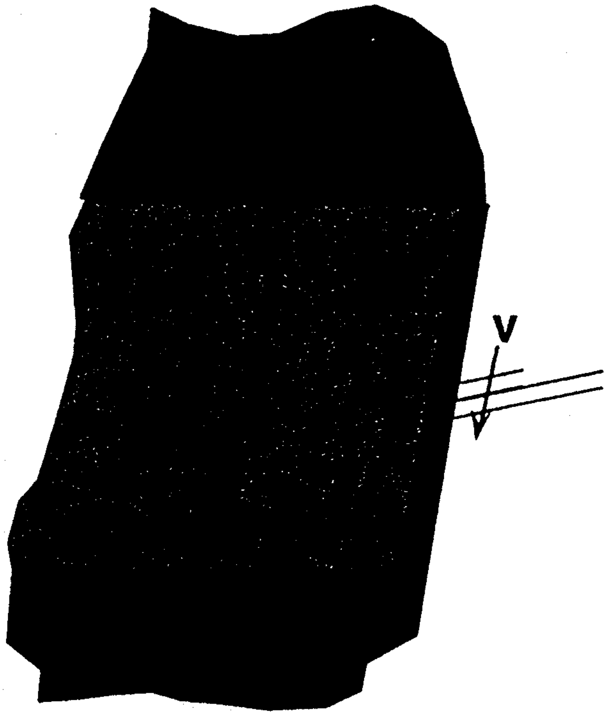
- Physics/PMI
  - Core considerations
  - Li experience in TFTR
  - Evaporation/sputtering
  - Tritium/helium containment
  - Experiments
  - High-z plasma effects
- Engineering
  - Heat transfer- thermalhydraulics
  - MHD modeling/experiments
  - Tritium processing system
  - Design concepts

Heat Acceptance Limit

laminar (MHD slug) flow has high temperature gradient

- limit is probably evaporation rate at the maximum surface temperature
- total power is more important than heat flux profile
- mixing is necessary for long flow paths

liquid metal flowing film



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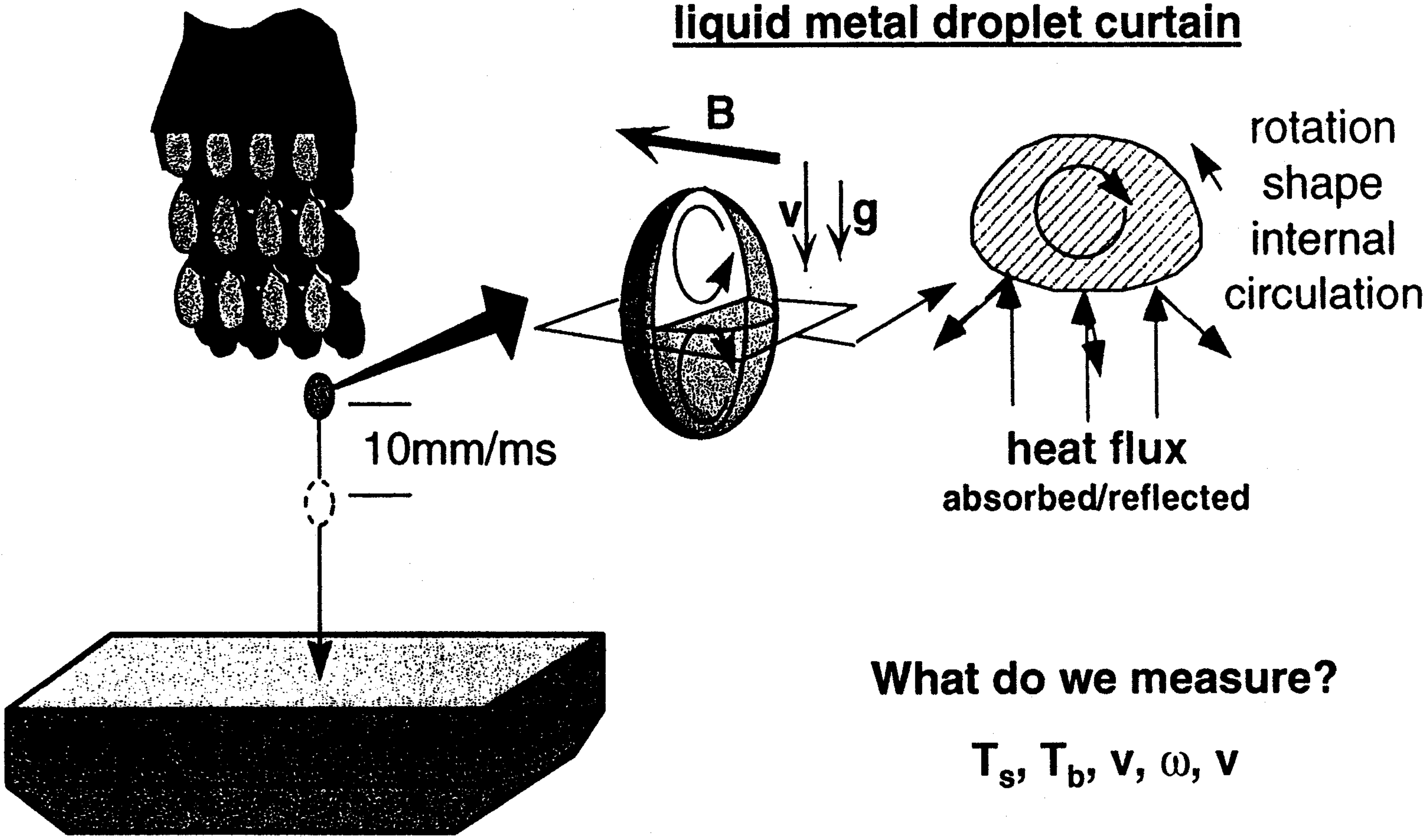
liquid metal droplet curtain



What do we measure?

T_s, T_b, v, ω, v

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Liquid Metal Film Flows in Magnetic Fields

Many factors come together to influence heat transfer at the free surface, all require modeling to assess their relative importance

- Laminarized velocity and depth profiles in spatially and temporally developing free surface flows (3D, unless axisymmetric)
  - ➢ Effect of nozzle design flow height and velocity profiles
  - ➢ Effect of 3D induced currents and variable fields on surface wave stability
- Plasma wind effect at free surface
  - ➢ Effect of 3D currents and variable fields on stabilization
- MHD turbulence in electrically insulated channels
- Plasma currents closing through film

Requires Unsteady, 3D, free-surface, turbulent, MHD flow analysis – very difficult

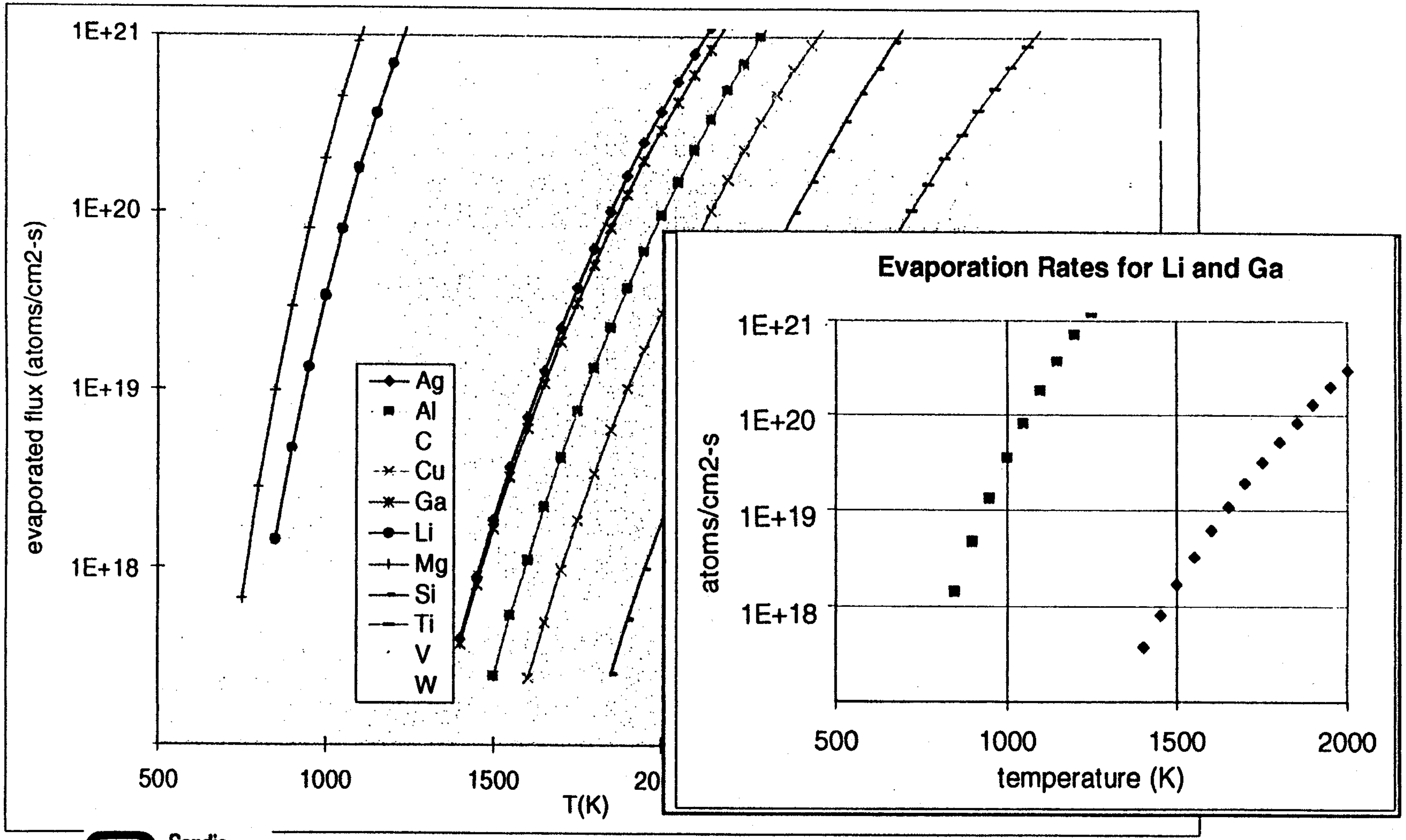
Liquid Metal Droplet Flows in Magnetic Fields

Some similar issues to films, but jet breakup must be modeled

- 3D jet breakup calculations giving droplet size and velocity profiles
  - ➢ Effect of nozzle design on breakup and
  - ➢ Effect of 3D induced currents and variable fields on jet breakup, droplet recirculation and surface stability
- Plasma wind effect at free surface
  - ➢ Droplet rotation and recirculation
- MHD turbulence in jets and droplets
- Effect of field variations on droplet stability

Requires Unsteady, 3D, free-surface, turbulent, MHD flow analysis – very difficult

Temperature Limit from Evaporation



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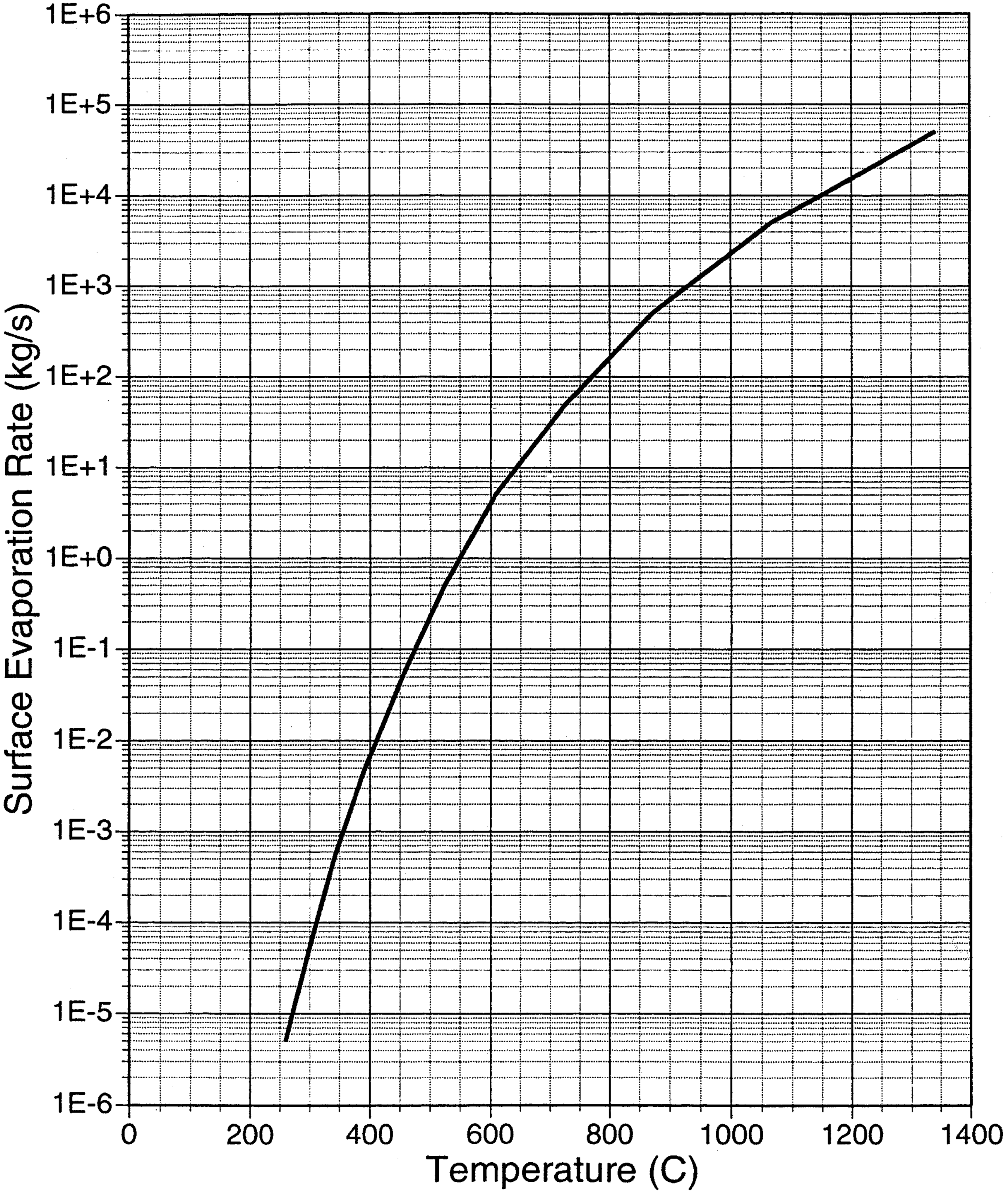
Lithium Vaporization Rate for 1000 m2 Wall area



R. MATTAS

Rough-Scaling:

for Fusion Power = 3000 MW

Alpha-Power = 600 MW

say Q = 300 MW to Divertor (or limiter, etc.)

No. of D-T ions in plasma = 1×10^{23} (for plasma volume = 1000 m^3, average core plasma density $N_{DT} = 1 \times 10^{20}\ m^{-3}$)

say we can "pump" 1/5 of plasma content per second, i.e. $I_{DT} = 2 \times 10^{22}$ /s (50 mg T/s)

then, edge temperature $T_i = T_e \approx Q/(8\ k\ I_{DT}) = 1170$ eV ≈ 1keV

(edge density ≈ $1 \times 10^{17}\ m^{-3}$, e.g. for 30 m^2 surface area, 1.5 deg. B-field incidence angle)

Helium Pumping:

for 5 % He/D-T in plasma; He current to divertor
$I_\alpha = .05 \times I_{DT} = 1 \times 10^{21}$ /s

Helium formation rate in plasma = 3000 MW/(17.6 MeV) = 1×10^{21} /s = helium "pumping" rate

Therefore, if the lithium traps all impinging helium (impact energy ≈ 10 KeV), then no vacuum pumping needed (or essentially possible anyway in this regime)

D. K. SZE, J. BROOKS

ALPS Low Recycling Regime

- The H-trapping "disadvantage" of a lithium plasma facing surface *may* be an advantage.

- High H-trapping leads naturally to a low-recycling, high edge temperature, low edge density plasma.

- A low-recycling regime offers these potential advantages:

1) no vacuum pumping needed (but He removal by Li is critically necessary)

2) higher non-inductive current drive efficiency (low-density effect)

3) low sputtering coefficients for D, T, He ,Li on Li (due to deep burial, but need data)

4) possibly better overall energy confinement (e.g. like TFTR "super shot" regime)

D. K. SZE, J. BROOKS

Approach - DT and He Pumping

- Use many individual Li jets/streams to capture He and DT
  - » Control number of jets on at any one time
  - » Control Li velocity
  - » With current flow in jet, it may be possible to control radial position
- Employ jets in divertor or limiter
- Use a high enough velocity to capture a reasonable percentage of He particles
  - » He reflection
  - » He residence time in liquid Li

Description of a Liquid Metal Spray Diverter Concept

- **Liquid metal (Li, LiPb or Ga) jet spray through a nozzle can produce a dense fine mist with very low transparency. Several rows of nozzles can be used to essentially give 100% coverage.**

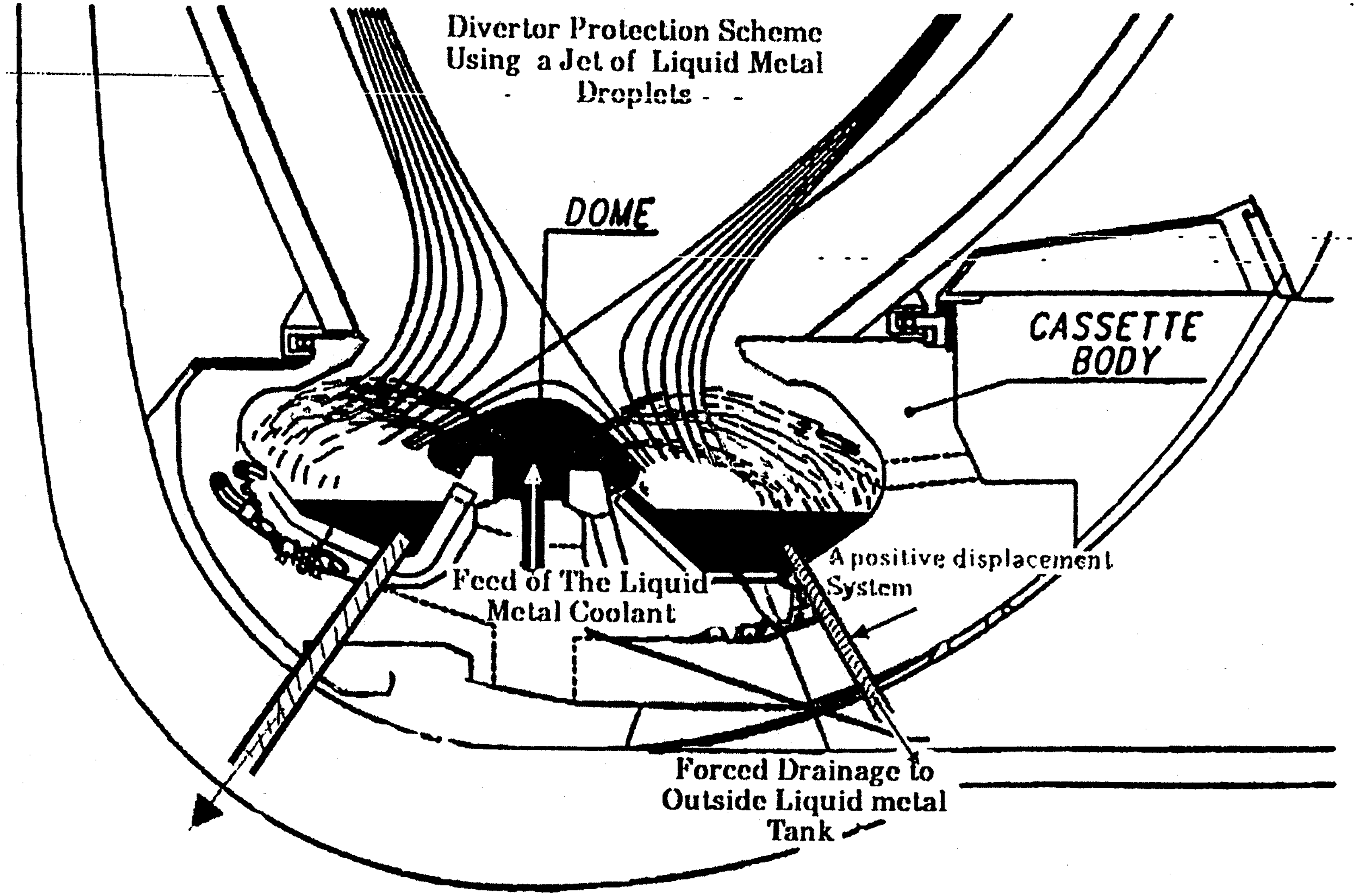
- **Since the droplets are not connected, they do not provide a continuous path for an electric current and thus, are not affected by MHD forces.**

- **The spray is directed to intercept magnetic field lines streaming to the diverter, neutralizing the ions, converting their kinetic energy into heat for useful availability in a power cycle.**

- **High heat flux can be dissipated with such a diverter concept with good control on the temperature rise in the liquid metal, to insure that the vapor pressure stays below a desired value (e.g. 10^{-5} torr).**

G. MOGAHED

Exposed Liquid Surfaces Will Significantly Affect Plasma Edge and Plasma Core Performance



Divertor Protection Scheme Using a Jet of Liquid Metal Droplets

E. MOGAHED

Next Steps

- Screening Criteria
- Approach
- Evaluation
- Plasma Edge Modeling

Evaluation Areas

- Safety/environment
  - Accident risk
  - Fault tolerance
  - Radiation emission, exposure, waste disposal
- Compatibility with Plasma Operation
  - Impact of impurities on plasma performance
  - DT, He pumping rate and capability
- Engineering feasibility (performance)
  - Power density
  - Power conversion efficiency
  - Lifetime
  - Ability to accommodate power variation
  - Maintenance and repair
- R&D requirements
  - Feasibility issues
  - Experiments/analytical capabilities required
  - Time needed for development

Suggested Screening Criteria

Criteria	Min/Max Value	Comments
Peak / Average Heat Flux	5/2 MW/m2	
Plasma operation	No degradation of plasma operation due to divertor. Potentially capable of pumping required levels of DT,He.	Net Power
Hydraulic system	Capable of circulating required levels of coolant (e.g. LM's).	MHD effects are the primary considerations.
Other in vessel systems	Shielding consistent with ITER guidelines for heating and damage in the SC coils. Allows for net breeding ratio > 1.05.	
Useful heat - Thermal Efficiency	> 20%	Divertor/limiter only
Safety	Tritium inventory < 500 g Reduced activation materials. No release of chemical energy during accident.	
Remote Maintenance	Show feasibility of clean-up and remote maintenance.	
Lifetime - Neutron	> 10 MW-y/m2	About the same as the blanket
Lifetime - Erosion	> 2 MW-y/m2	

Concept Evaluation

Concept Design & Analysis

- Concept 1
- Concept 2
- Concept 3

Technical Areas

Plasma Scrape-off & Core
- Core Response & Plasma Interface
- Scrape-off Modeling
- Erosion/ Redeposition
- Plasma Experiments

Surface Science
- Sputtering Behavior
- DT/He Trapping/ Release
- Liquid Surface Stability
- Laboratory Experiments

Heat Transfer
- Thermal Response
- MHD Free-surface Flow
- Coolant System Characteristics
- Laboratory Experiments

X-Vessel Components
- Tritium System
- Fuelling
- Heat Exchanger
- Vacuum Pumping

Safety
- Source Term
- Accident Response
- Waste Disposal Exposure Activation Recycle
- Laboratory Experiments

Data Base
- Surface Properties
- Solid Bulk Properties
- Liquid Bulk Properties
- Structural Properties

ALPS

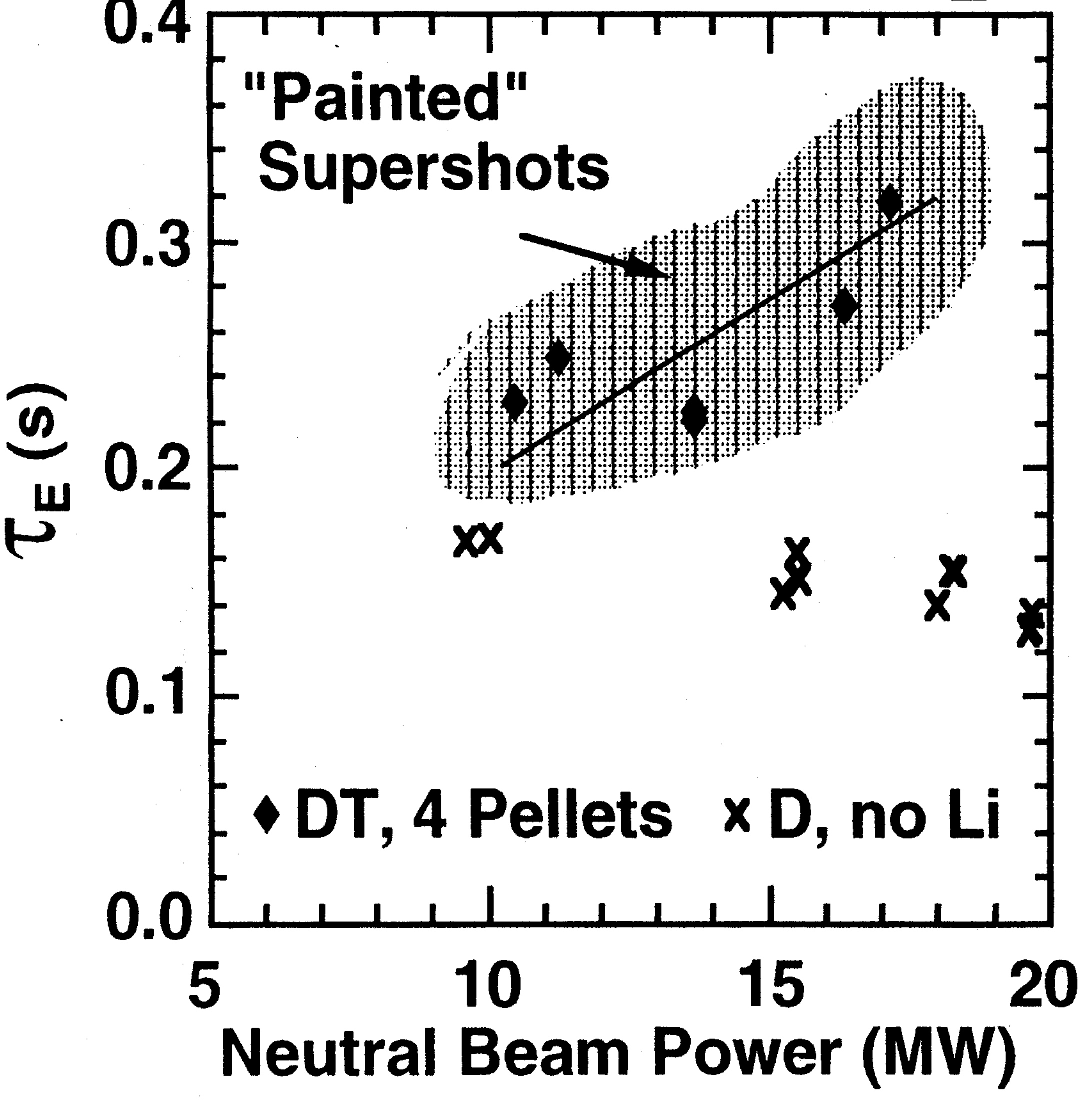
Plasma Effects

- Increased confinement with Li
- Enhanced DT fusion power with Li
- Little or no penetration into core by Li
- Enhanced radiation losses with high-z impurities
- Minimal effect on electron temperature
  - » Not well understood

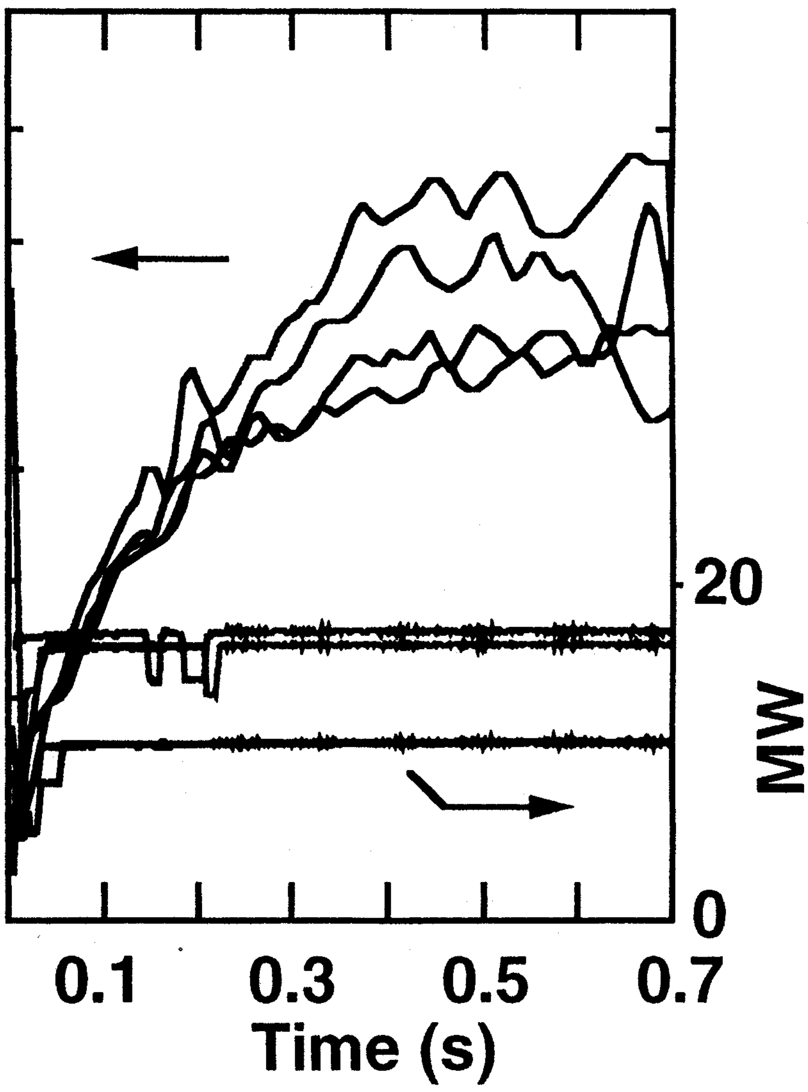
"Painting" → τ_E Increases With Beam Power

PPPL

Confinement Time - τ_E



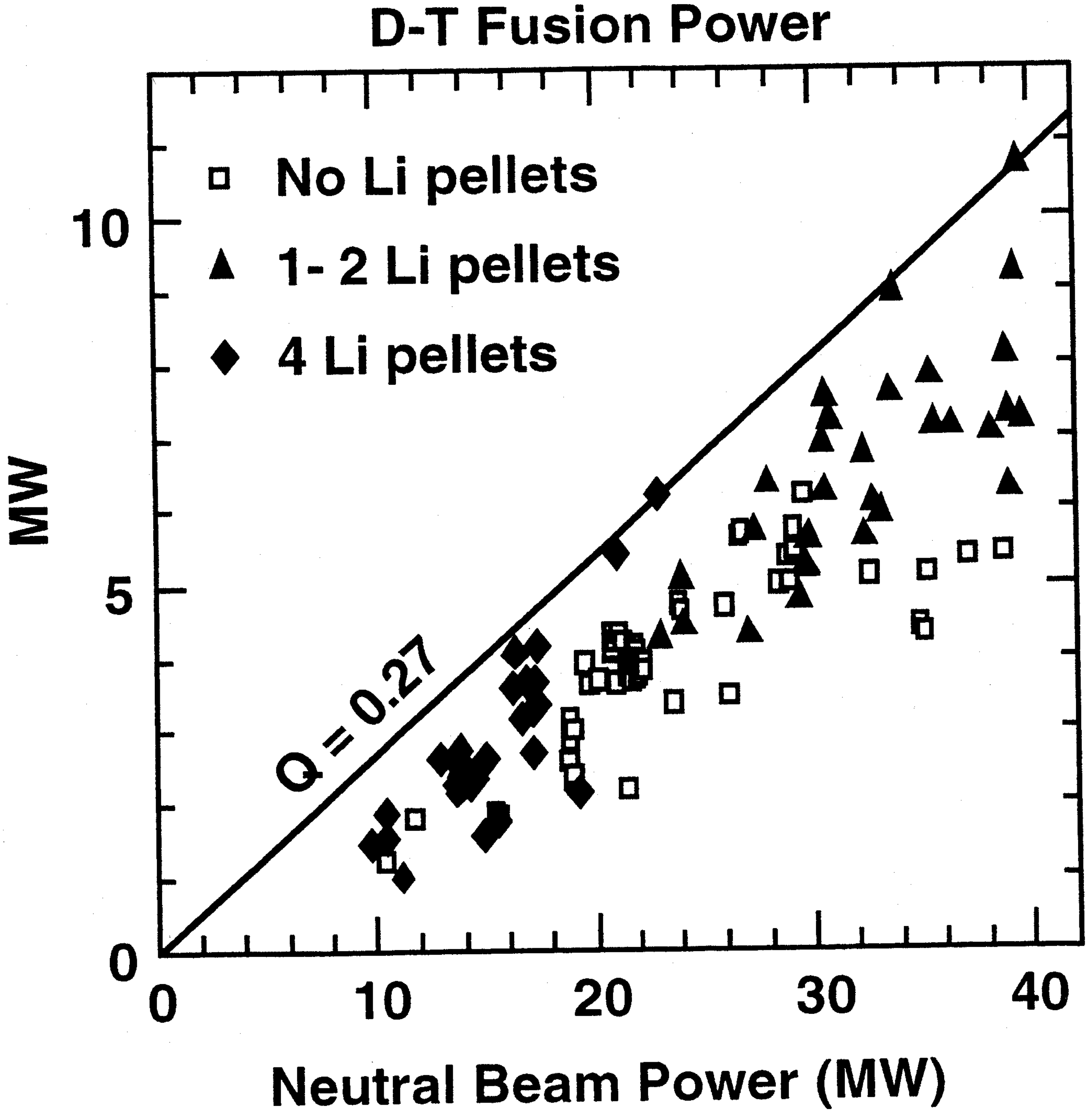
τ_E & NBI Power



D. MANSFIELD

Li → Enhanced D-T Fusion Power

PPPL



- D-T Discharges, $R_p = 2.52$ m, $I_p > 2.0$ MA

D. MANSFIELD

EXPERIMENTAL OBSERVATIONS

AS ANTICIPATED, RADIATIVE LOSSES FROM THE PLASMA INCREASED FROM THEIR NORMAL 25% TO AS HIGH AS APPROXIMATELY 90% (PERHAPS ALMOST 100%, DEPENDING ON ERROR BARS) OF THE INPUT HEATING POWER.

BUT SURPRISINGLY, INSTEAD OF THE PLASMA COOLING IN RESPONSE TO THIS ADDITIONAL RADIATIVE POWER LOSSES, THE ELECTRON TEMPERATURE STAYED APPROXIMATELY THE SAME, WHILE THE ION TEMPERATURE INCREASED. TOTAL STORED PLASMA ENERGY ACTUALLY INCREASED.

R. WOOLEY

MYSTERIOUS

IT SEEMS THAT WHEN THE ADDITIONAL PLASMA COOLING CHANNEL THROUGH RADIATION IS TURNED ON BY INJECTING THE HIGH-Z IMPURITY, SOME UNKNOWN PROCESS MUST SOMEHOW BE TURNING OFF THE NORMAL PLASMA COOLING CHANNELS (E.G CONDUCTION AND CONVECTION).

THESE NONINTUITIVE BUT REPEATABLE EXPERIMENTAL RESULTS ARE NOT PRESENTLY UNDERSTOOD THEORETICALLY. EXISTING PLASMA TRANSPORT MODELS PREDICT IMPURITIES BOOST PLASMA COOLING, WHICH IS NOT OBSERVED.

SIMILAR RESULTS HAVE BEEN SEEN ON OTHER TOKAMAKS
- ISX (ZMODE)
- TEXTOR (RIMODE)

R. WOOLEY

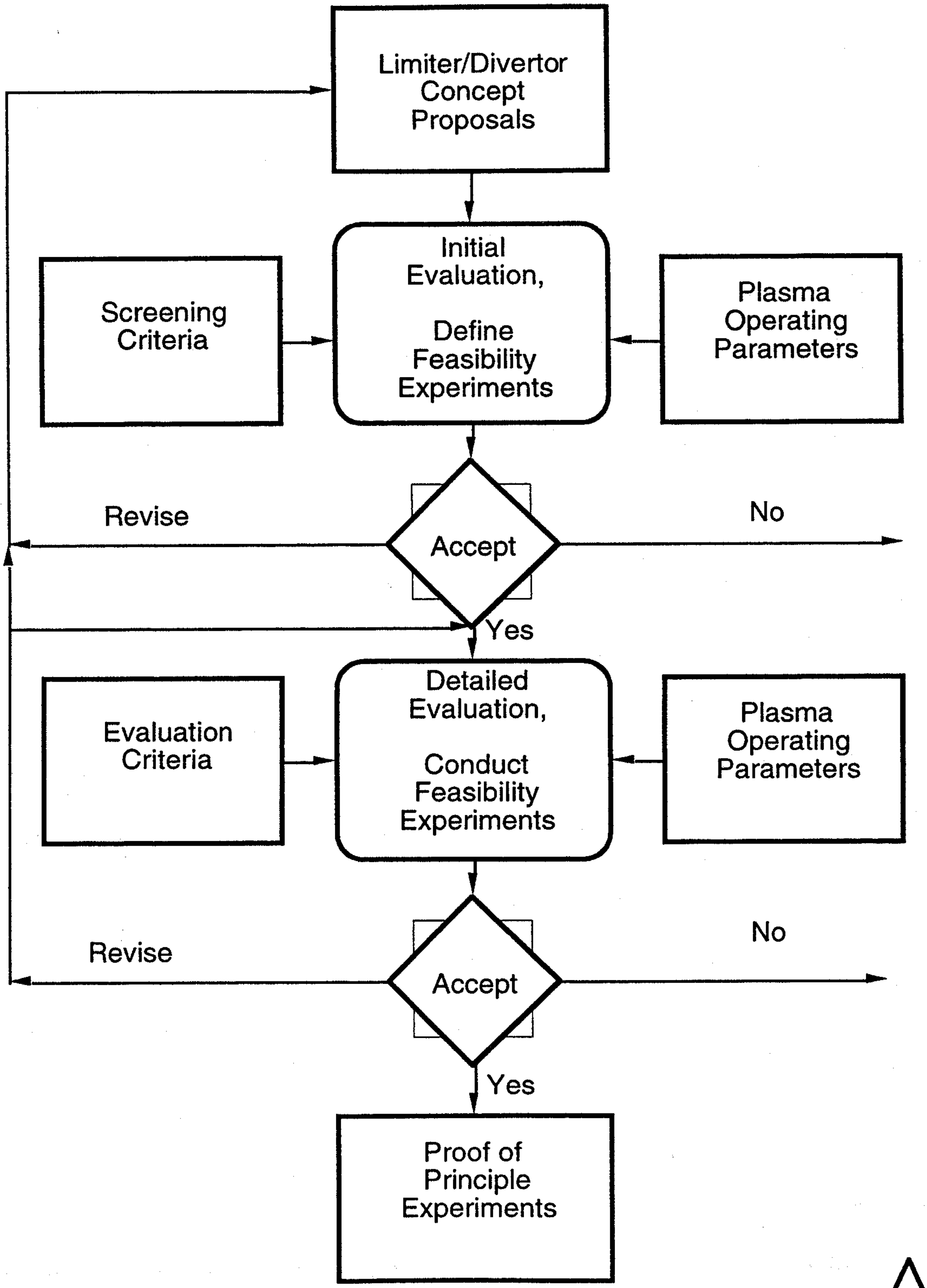
Plasma-Materials Interactions

- Li will trap essentially all DT particles striking the surface
- He may be trapped
  - No solubility
  - Kinetics
- There could be enhanced sputtering of liquid surfaces due to bubble/droplet formation
- There are models available to analyze these effects

Plasma Edge Modeling

- A self-consistent set of plasma parameters with liquid surfaces is needed to establish operating conditions.
- A high barrier efficiency is required to keep liquid impurities in the core to acceptable levels.
- Limits on tritium systems will restrict the tritium thruput to < 100mg/s
- An effort to analyze the tokamak plasma edge with Li is being started by J. Brooks.
- This area requires a significant effort
- Assistance by the plasma physics community is welcome.

Concept Evaluation Process



Limiter/Divertor Concept Proposals

Screening Criteria

Initial Evaluation,

Define Feasibility Experiments

Plasma Operating Parameters

Revise

Accept

No

Yes

Evaluation Criteria

Detailed Evaluation,

Conduct Feasibility Experiments

Plasma Operating Parameters

Revise

Accept

No

Yes

Proof of Principle Experiments