Overview of APEX

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Seminar presented at ORNL

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APEX TEAM

Organizations

UCLA	ANL	PPPL
ORNL	LLNL	SNL
GA	UW	UCSD
INEL	LANL	U. Texas

Contributions from International Organizations

- FZK (Dr. S. Malang, Dr. L. Barleon)
- Japanese Universities
    - Profs. Kunugi, Satake, Uchimoto and others
    - Joint Workshops on APEX/HPD
- Russia
    - University of St. Petersburg (Prof. S. Smolentsev)
- Spain
    - Official proposal under review

APEX Steering Committee

Mohamed Abdou (UCLA)
Bob Kaita (PPPL)
Kathy McCarthy (INEEL)
Neil Morley (UCLA)
Brad Nelson (ORNL)
Tom Rognlien (LLNL)
Mohamed Sawan (UW)
Dai-Kai Sze (ANL)
Mike Ulrickson (SNL)
Clement Wong (GA)
Alice Ying (UCLA)
Steve Zinkle (ORNL)

How to Get APEX Documentation or Other Information

1. APEX Website has considerable information: meeting presentations, papers, interim report, study participants, etc.

   www.fusion.ucla.edu/APEX

2. APEX Interim Report (issued 11/99)
   Volume I: APEX Overview, ~90 pages
   Volume II: 17 Chapters, detailed, ~600 pages

   - Complete copy is displayed on the APEX Website.
   - Hard copies were distributed (1/2000)

3. If you wish to obtain a hard copy of the APEX Interim Report, or any other information on APEX, please send e-mail to the APEX Scientific Secretary, Dr. Mahmoud Youssef <youssef@fusion.ucla.edu>

Environment in 1997

- The prevailing mood in the technology community was dominated by "pessimism" and "frustration" (e.g. Chamber Technology in ISFNT-4 [April 1997, Tokyo]).

- The US developed a Restructuring Plan
  Emphasis on: Science and Innovation

- US Chamber Technology Discussions led by Mike Saltmarsh

- DOE and the Community agreed on initiating ALPS and APEX

- (Independently and about the same time frame)
  Letter from 23 Senior US Scientists to Dr. Anne Davies encouraging research on innovative high power density concepts ("we believe that it is timely for the technology side of OFES to consider a new focus to develop first wall/blanket schemes which can demonstrate high heat and neutron fluxes")

APEX Objectives

Identify and explore NOVEL, possibly revolutionary, concepts for the Chamber Technology that might:

1. **In the near-term: enable plasma experiments to more fully achieve their scientific research potential.**

2. **In the long-term: substantially improve the attractiveness of fusion as an energy source.**

3. **Lower the cost and time for R&D.**

APEX APPROACH

1) **Emphasize Innovation**

2) **Understand and Advance the underlying Engineering Sciences**

3) **Utilize a multidisciplinary, multi-institution integrated TEAM**

4) **Provide for Open Competitive Solicitations**

5) **Close Coupling to the Plasma Community**

6) **Direct Participation of Material Scientists and System Design Groups**

7) **Direct Coupling to IFE Chamber Technology Community**

8) **Encourage International Collaboration**

APEX Phases

1. Preparation Phase (early 98)

2. “Idea” Exploration Phase (98-99)

3. “Concept Exploration” Phase (Nov 99 – present)

1. <u>Preparation Phase</u> (early 98)

- Agree on goals for Chamber Technology

- Assess issues and status of current (conventional) Chamber Technology concepts

- Agree on technical approach and organizational structure for the team

<u>Documentation</u>:

- Presentations & Documents are preserved on the APEX website

- Assessment & approach published in Fusion Engineering & Design, vol. 45, pp. 145-167, May 1999.

Fundamentals of Economics Show That:

1. Attractive Vision Requires JOINT Physics and Technology Efforts
2. Advanced Technology (Power Extraction Technology) is Critical

Need High Power Density
- High-Performance Plasma
- Power Extraction Technology

Need Low Failure Rate

$$COE = \frac{C \cdot i + \text{replacement cost} + O\,\&\,M}{P_{fusion} \cdot \text{Availability} \cdot M \cdot \eta_{th}}$$

Energy Multiplication

Need High Temp. Energy Extraction

$$\frac{(1/\text{failure rate})}{1/\text{failure rate} + \text{replacement time}}$$

- **Need Low Failure Rate:**
  - Innovative Power Extraction Technology
- **Need Short Maintenance Time:**
  - Simple Configuration Confinement
  - Easier to Maintain In-Vessel Technology

Power Density and Heat Flux in Fission Reactors Compared To Fusion With Traditional Evolutionary Concepts

	PWR	BWR	HTGR	LMFBR	Fusion at 3MW/m^2
Equivalent Core Diameter (m) Core Length (m)	3.6 3.8	4.6 3.8	8.4 6.3	2.1 0.9	30 15
Average Core Power Density (MW/m^3)	**96**	**56**	**9**	**240**	**1.2**
Peak-to-Average Heat Flux at Coolant	2.8	2.6	12.8	1.43	50

Need Revolutionary Concepts with High Power Density Capability

i.e. **concepts capable of handling both high plasma heat flux and neutron wall load**

Peak Neutron Wall Load Limits for "Dry" First Wall

Material	Max. Temp (°C)	Wall-Coolant Interface Temp (°C)	Peak Neutron Wall Load Limit (MW/m^2)		
			Limited by Max. Temp	Limited by Stress Criterion	Max. Wall Load
Ferritic Steel	550	500	1.5	3.6	1.5
Ferritic Steel	550	450	2.9	4	2.9
V-Cr-Ti	700	600	3.2	5.4	3.2
V-Cr-Ti	700	550	4.7	5.4	4.7
SiC-SiC	1000	700	3.5	2.5	2.5
ODS	700	600	3	2.6	2.6
Nb-1Zr	1100	600	24.5	6.6	6.6
Tungsten	1500	600	>30	8.8	8.8
TZM	1200	600	>25	13	13
T 111	1300	600	22.3	11.6	11.6

Note: Average Neutron Wall Load is about a factor of 1.4 LOWER than the Peak Values shown in the Table.

Two Highly Interrelated Challenging Issues:
A) Failure Rate B) Maintainability

- A Practical Engineering System Must:
  A) Have Sufficient Reliability

  MTBF = Mean Time Between Failure

  B) Be Able to Recover From Failure in Short Time

  MTTR = Mean Time To Recover

- Two Key Questions Concerning MTBF & MTTR:
  1) What should be the goals for a practical fusion system?
  2) What values are achievable with current fusion designs?

Failure is Different From Design Lifetime

Definition

Failure is defined as the ending of the ability of a design element to meet its function before its allotted lifetime is achieved, i.e. failure before reaching the operating time for which the element is designed

Causes of Failures

- Errors in design, manufacturing, assembly and operation
- Lack of knowledge and experience
- Insufficient prior testing
- Random occurrence despite available knowledge and experience

Goals for MTBF & MTTR Can be Easily Derived

Availability = A
A (Plant) = 75%
A (BOP) = 85%
A (Reactor) = 88%

Reactor
Assume 6 major components with equal outage risk
An example of such a component is FW / Blanket
A (Blanket) = 97.8 %

A (FW / Blanket)

$$A = \frac{MTBF}{MTBF + MTTR}$$

$$\boxed{\frac{MTBF}{MTTR} = 43.8}$$

Note: It is the Mean Time Between Failure which is the issue.
It is NOT lifetime

Goals For MTBF & MTTR For First Wall/Blanket

MTBF = 43.8 MTTR

MTTR

- Estimated by many experts to be > 3 months
- By moving the vacuum vessel outside the blanket, we protect the vacuum vessel, but blanket removal takes longer and leaks represent failure

MTTR	**MTBF** **FW / B System**	**MTBF** **FW / B Module**
1 Month	**3.6** yr	**290** yr
3 Month	**11** yr	**877** yr

- First Wall/Blanket has typically 80 modules; each module is about 15 m^2 in surface area
- Such long MTBF requirement for such a large system is ALARMING

What MTBF Can Be Achieved?

Several Studies

- R. Bünde et al. (several articles, 1990-95)
- Abdou & Ying (1994)
- Detailed EU Blanket Evaluation (1994)

Methodology

- Compile Relevant Failure Rate from Mature Technologies (e.g. fission)
- Estimate Failure Frequency For the Best FW/Blanket Designs Available
  - ◊ Include Failures for Pipes and Welds
  - ◊ IGNORE (DO NOT Include) Fusion Specific Failure Modes

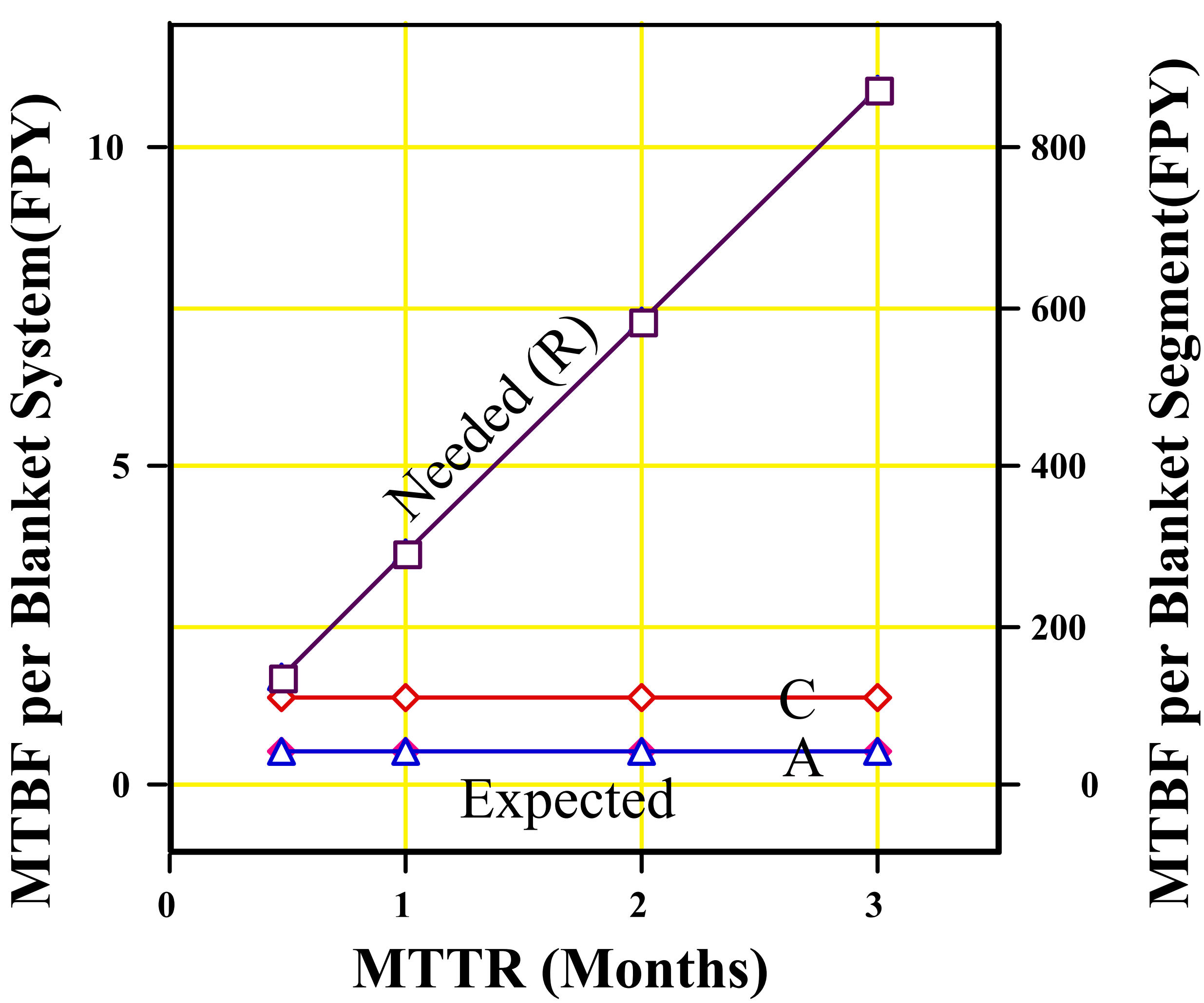
Failure Modes (FW)	**Failure Rate $hr^{-1}.m^{-1}$**	**Length**
Diffusion weld	1×10^{-9}	4.56 km
EB Weld	1×10^{-8}	2.93 km
Longitudinal weld	1×10^{-9}	19 km

Failure Modes (BLKT)	**Failure Rate $hr^{-1}.m^{-1}$**	**Length**
Longitudinal weld	1×10^{-9}	4.8 km
Butt weld	1×10^{-9}	2.58 km
Pipe bend (90°)	5×10^{-9}	1152 bends
Straight pipe	1×10^{-10}	2.9 km

R = Required

A = Expected with extensive R&D
(based on mature technology and no fusion-specific failure modes)

C = Potential improvements with aggressive R&D



Current FW / B Design Concepts are NOT Capable of Meeting the Challenging Reliability Requirements

Current FW/Blanket Design Concepts are NOT capable of Meeting the Challenging Reliability and Maintenance Requirements

Chart here.

PDF

Chamber Technology Goals
Used in APEX to Calibrate Progress

1. **High Power Density Capability***

   Peak Neutron Wall Load ~ 10 MW/m^2

   Peak Surface Heat Flux ~ 2 MW/m^2

2. **High Power Conversion Efficiency (> 40%)**

3. **High Availability (MTBF > 43 MTTR)**

4. **Simpler Technological and Material Constraints**

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* The APEX Steering Committee in May 2000 modified the goal as follows: "APEX will explore concepts with lower power density capabilities if they provide significant improvement in power conversion efficiency or other major features"

2. “Idea” Exploration Phase (98-99)

- Encouraged, solicited, and screened ideas
- Design “idea” formulation and analysis with existing tools
- Ideas were broad (solid walls, particulate bed, spray cooling, liquid walls, etc.)

External Events: Snowmass and its impact

- The physics community seemed to find important benefits in liquid metal walls (low recycling / improved confinement, increased elongations, increased Beta). These benefits were not on the list of technologists.
- The technology sessions concluded that liquid wall research should be pursued.
- The community was challenged to put liquid wall in NSTX (plasma physics device) in 5 years.
- Overall, Snowmass gave a very strong push to liquid wall research.

2. “Idea” Exploration Phase (cont’d)

Outcome:

A. Identified two classes of “ideas” as worth proceeding with to the “Concept Exploration” phase. These are:

   1) Liquid Walls (as a class that has many widely varying options yet to be explored and sorted out in the next phase: thin, thick, molten salt, LM’s, restraining forces, etc.)

   2) Advanced Solid Wall with High-Temperature Refractory Alloy and evaporative Li cooling (EVOLVE)

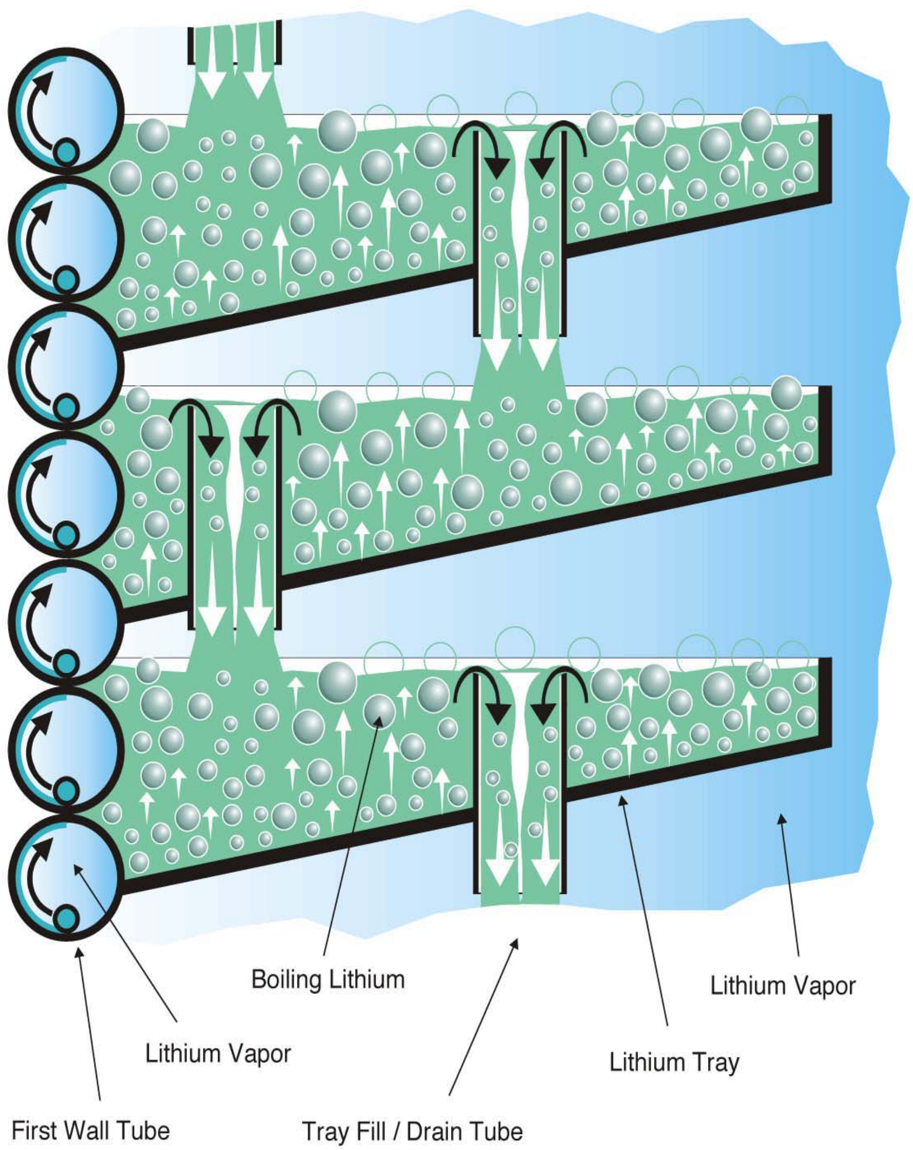
B. Identified key issues for the two classes of ideas. Identified deficiencies in tools and knowledge that are necessary for meaningful concept exploration

Documentation:

- All presentations, papers, communications are published on the APEX website.
- Many papers published by individual scientists in journals and conference proceedings.
- Comprehensive Interim Report issued November 99.

EVOLVE CONCEPT

Elevation Section of
Lithium Trays + First Wall Tubes



Characteristics of EVOLVE

1) The high operating temperature leads to a high power conversion efficiency.

2) The choices for structural materials are limited to high temperature refractory alloys.

3) The vapor operating pressure is very low (sub-atmospheric), resulting in a very low primary stress in the structure.

4) The temperature variation throughout the first wall and blanket is low, resulting in low structural distortion and thermal stresses.

5) The lithium flow rate is approximately a factor of ten slower than that required for self-cooled first wall and blanket. The low velocity means that an insulator coating is not required to avoid an excessive MHD pressure drop.

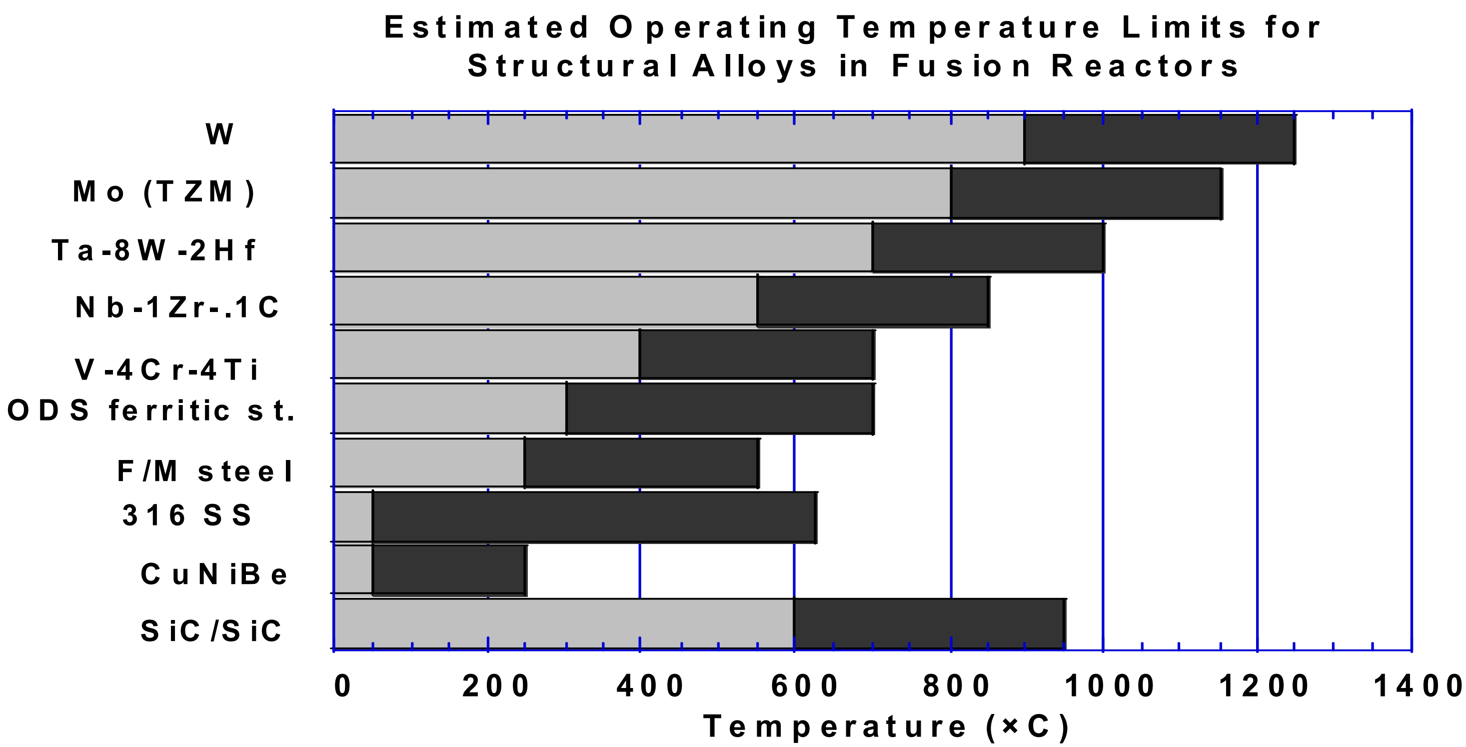
Key Issues for EVOLVE

1) 3-D heat transfer and transport modeling and analyses for the 2-phase flow including MHD effects.

2) Feasibility of fabricating entire blanket segments of W alloys.

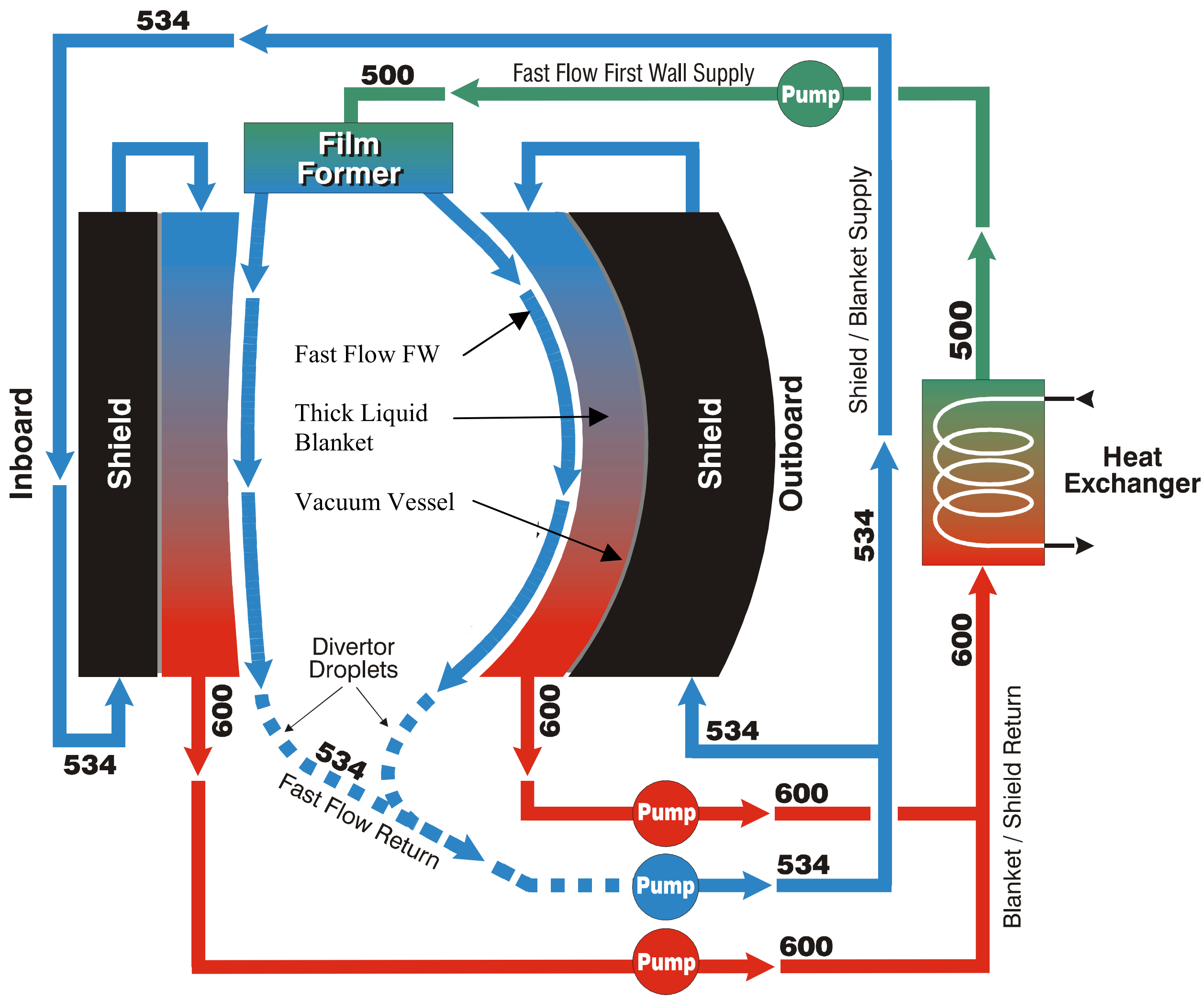
3) Effect of neutron irradiation on W alloys.

4) Analysis of safety issues associated with the high afterheat in tungsten in case of a LOCA.



The allowable operating temperature range for structural materials based on unirradiated/irradiated mechanical properties, void swelling and thermal conductivity degradation is denoted by the black boxes. Chemical compatibility issues may cause a further restriction in the operating temperature window

Illustration of Liquid Walls



* Temperatures shown in figure are for Flibe

Thin Liquid Wall

- Thin (1-2 cm) of liquid flowing on the plasma-side of the First Wall

Thick Liquid Wall

- Fast moving liquid as first wall
- Slowly moving thick liquid as the blanket

Several "Ideas" Have Been Proposed for Liquid Walls

Fluids

1) High-conductivity, low Pr fluids (liquid metals)
2) Low-conductivity, high Pr fluids (e.g. molten salts)

Hydrodynamics "Driving Forces"

- Gravity-Momentum Drive (GMD)
- GMD with Swirl Flow
- Electromagnetically Restrained
- Magnetic Propulsion

Plamsa-Liquid Interface

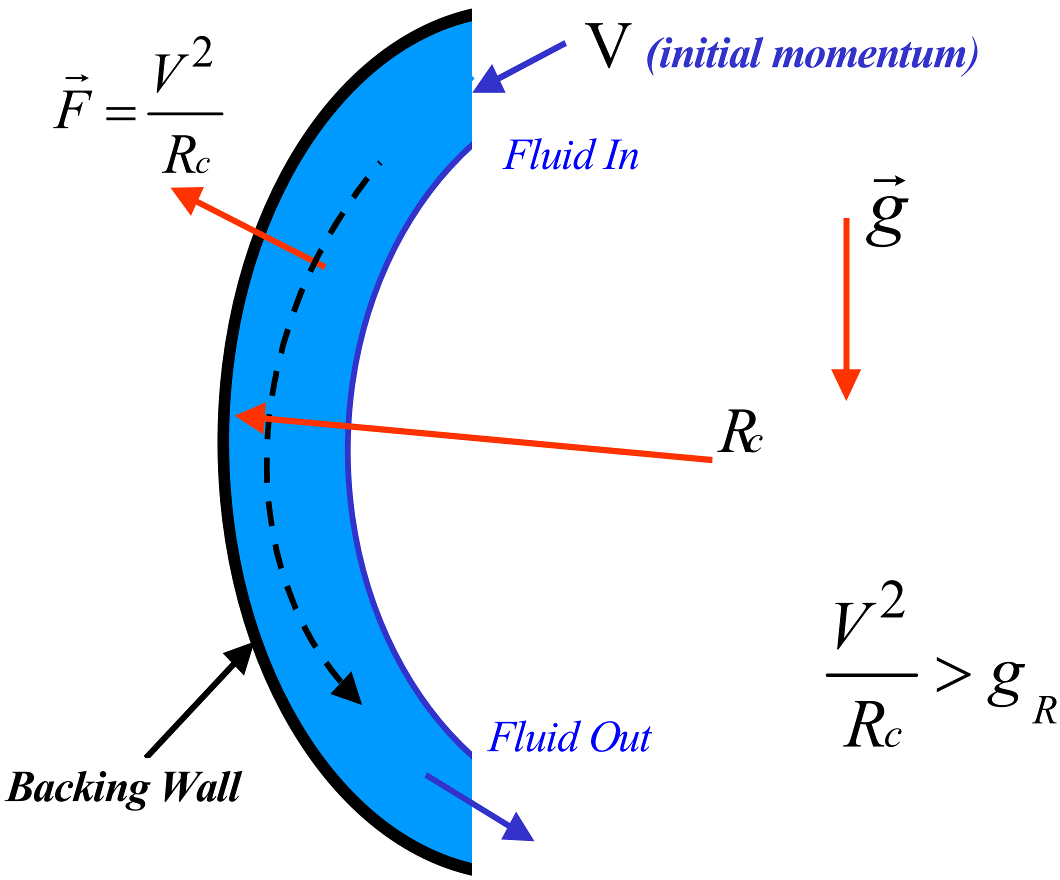
- Fluids with low vapor pressure at high temperature (e.g. Sn-Li discovered last year)
- Ideas for enhancing turbulence at the free surface
- Ideas for "two-stream flows"
- Etc.

Liquid Wall Options

Thickness	• Thin (~ 2cm) • Moderately Thick (~ 15 cm) • Thick (> 40 cm)
Working Liquid	• Lithium • Sn-Li • Flibe
Hydrodynamic Driving / Restraining Force	• Gravity-Momentum Driven (GMD) • GMD with Swirl Flow • Electromagnetically Restrained • Magnetic Propulsion
Liquid Structure	• Single, contiguous, stream • Two streams (fast flowing thin layer on the plasma side and slowly flowing bulk stream)

DIFFERENT MECHANISMS FOR ESTABLISHING LIQUID WALLS

- ***Gravity-Momentum Driven (GMD)***



- *Liquid adherence to back wall by centrifugal force.*
- *Applicable to liquid metals or molten salts.*

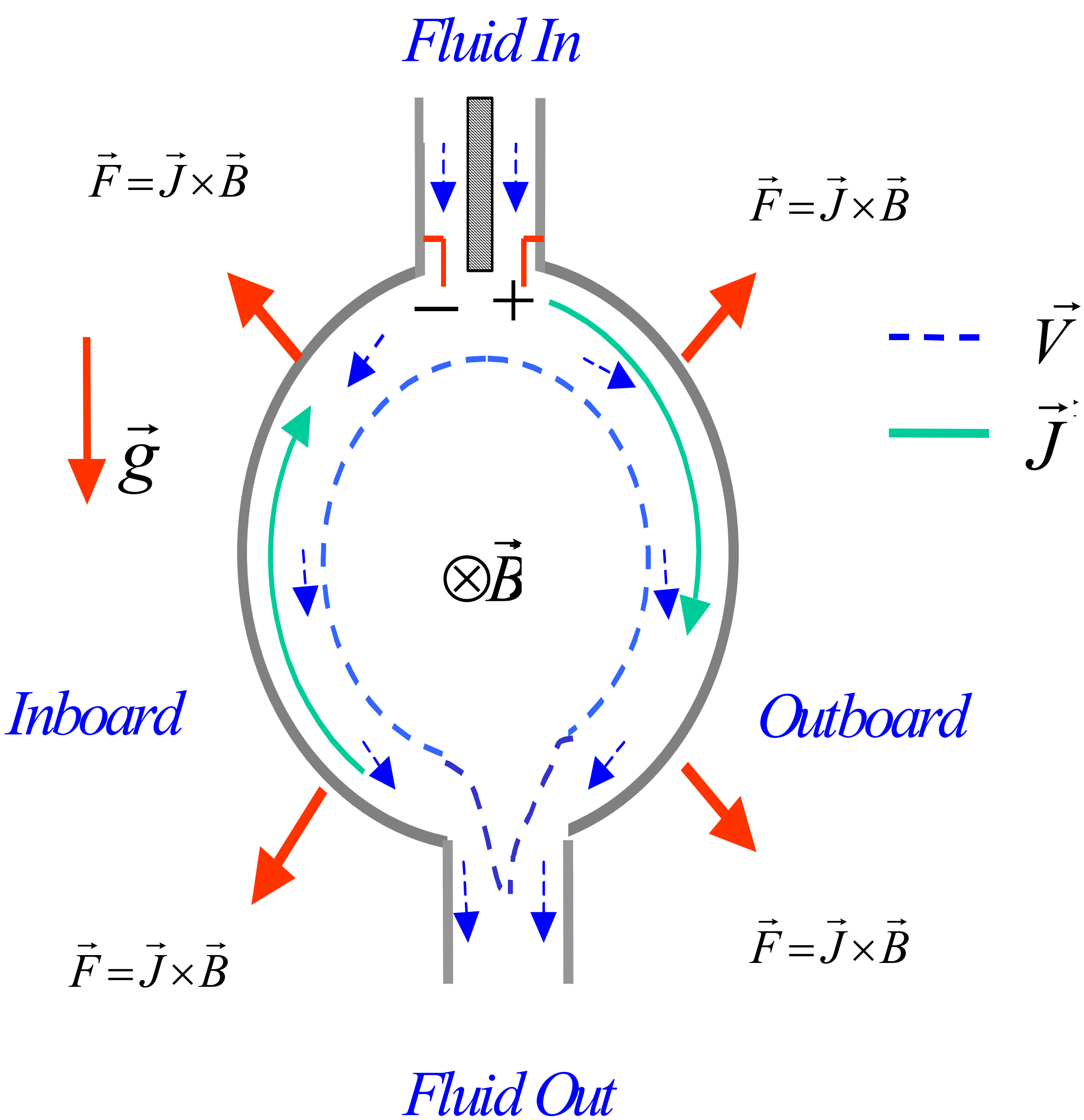
- ***GMD with Swirl Flow***

- *Add rotation.*

- ***Electromagnetically Restrained LM Wall***

- *Externally driven current* ($\vec{J}$) *through the liquid stream.*

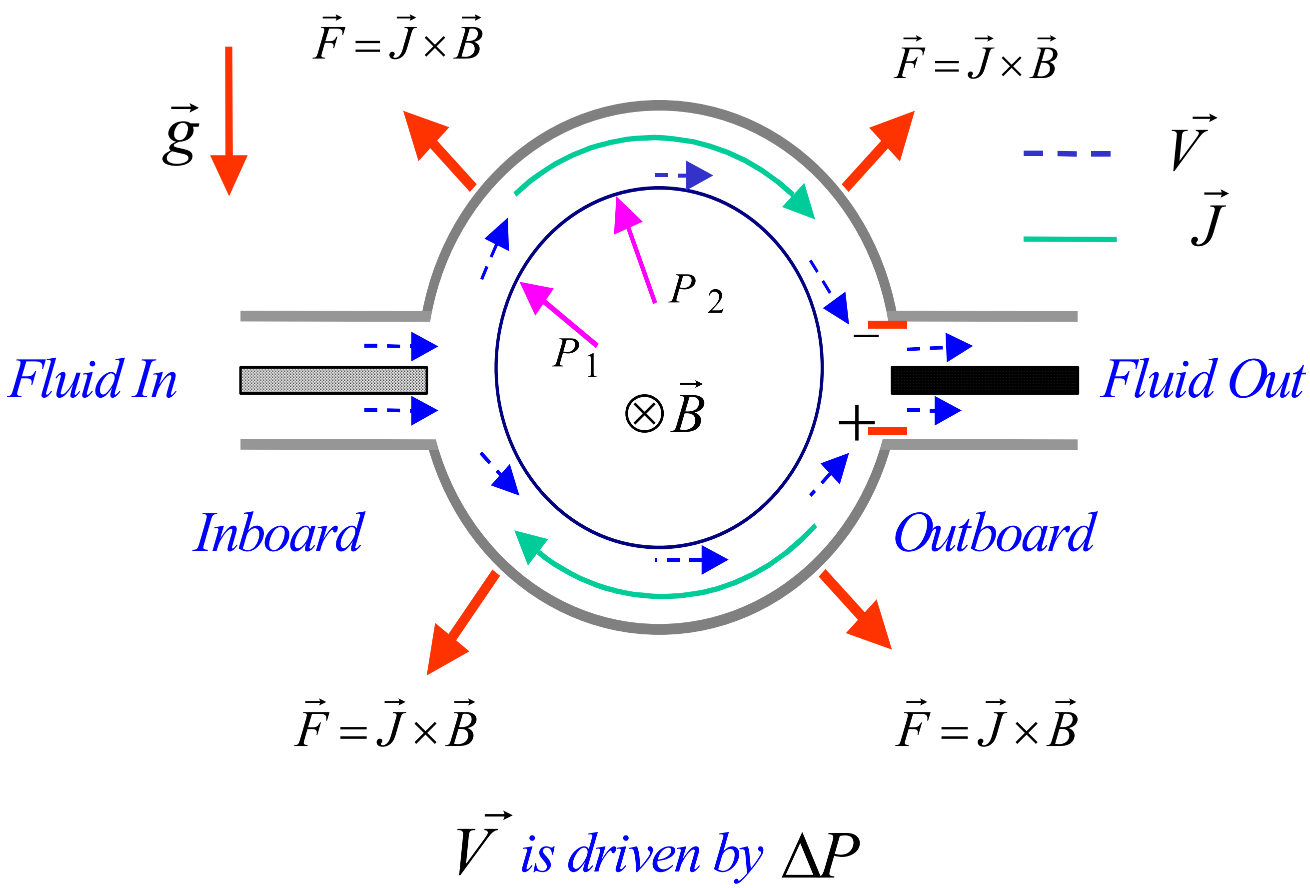
- *Liquid adheres to the wall by EM force* $\vec{F}=\vec{J}\times\vec{B}$



- ***Magnetic Propulsion Liquid Metal Wall (L. Zakharov)***

  - *Adheres to the wall by* $\vec{F} = \vec{J} \times \vec{B}$

  - *Utilizes 1/R variation in* $\vec{F} = \vec{J} \times \vec{B}$ *to drive the liquid metal from inboard to the outboard.*



Motivation for Liquid Wall Research

What may be realized if we can develop good liquid walls:

- Improvements in Plasma Stability and Confinement
  Enable high β, stable physics regimes if liquid metals are used

- High Power Density Capability

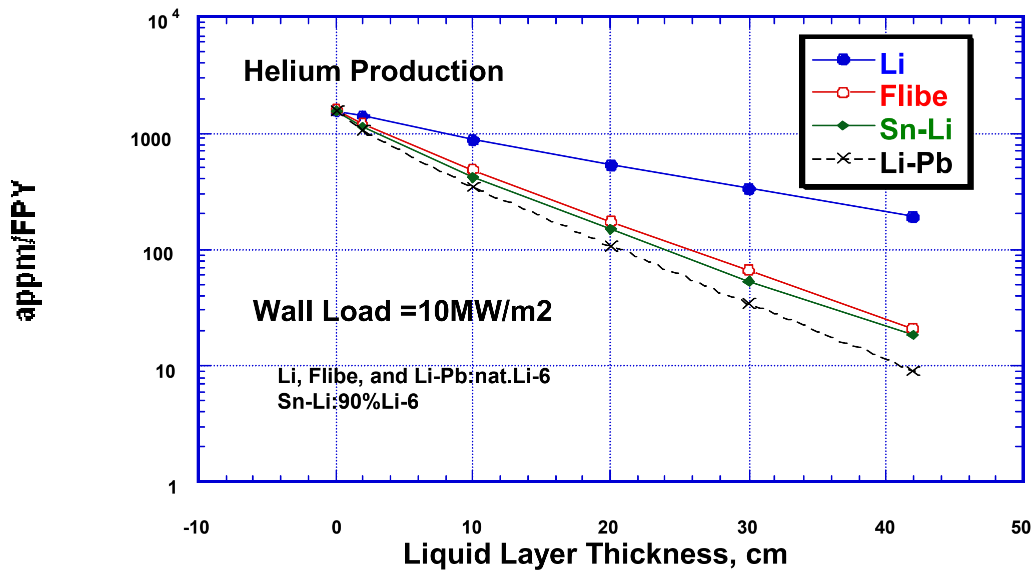
- Increased Potential for Disruption Survivability

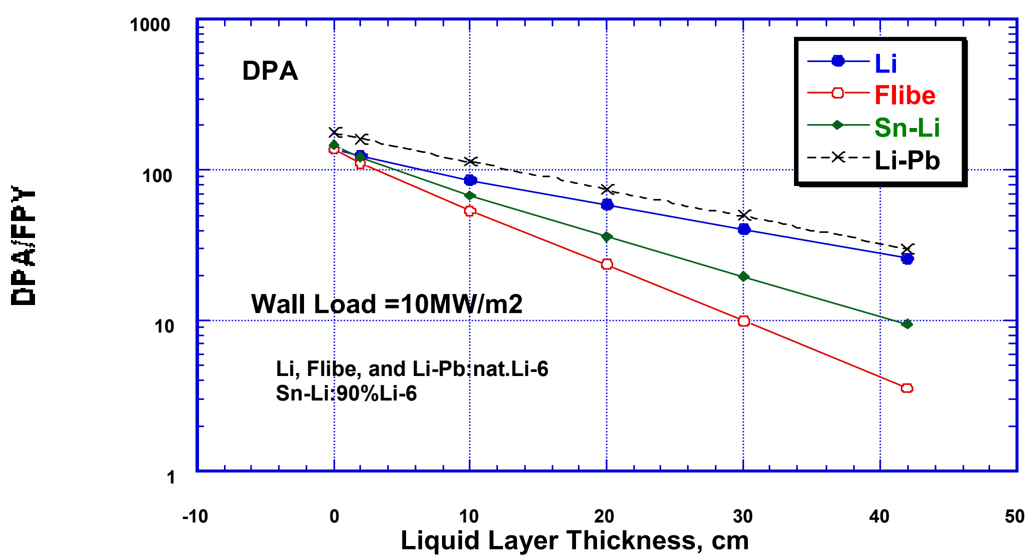
- Reduced Volume of Radioactive Waste

- Reduced Radiation Damage in Structural Materials
  -Makes difficult structural materials more problems tractable

- Potential for Higher Availability
  -Increased lifetime and reduced failure rates
  -Faster maintenance

Liquid Walls
Increase Lifetime of Structure





Conclusions

- An Order of Magnitude reduction in He for:
  - Flibe: 20 cm
  - Lithium: 45 cm
- For sufficiently thick liquid: Lifetime can be greater than plant lifetime

Liquid Walls Reduce the Volume of Radioactive Waste

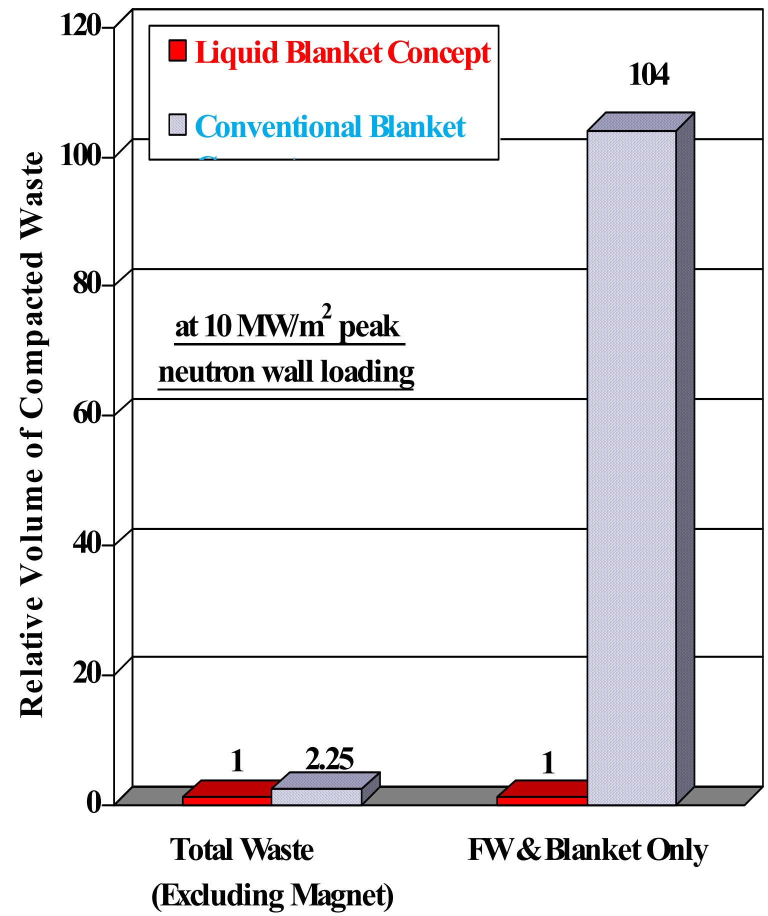
Basis of Calculations

- 30-yr plant lifetime
- Structure life = 20 MW• y/ m^2
- Liquid blanket is 52 cm of liquid followed by 4-cm backing wall
- Conventional blanket is self-cooled liquid with 2 cm FW, 48 cm of 90% liquid plus 10% structure
- Results are design-dependent

Conclusions

- **Relative to Conventional Blankets, Liquid Walls reduce the waste over the plant lifetime by:**
  - **Two orders of magnitude for FW/Blanket waste**
  - **More than a factor of 2 for total waste**

Waste Volume (Relative)



Low activation ferritic steel/Flibe systems

Flowing LM Walls may Improve Plasma Stability and Confinement

Several possible mechanisms identified at Snowmass…

Presence of conductor close to plasma boundary (Kotchenreuther)

- Plasma Elongation $\kappa > 3$ possible – with $\beta > 20\%$
- Ballooning modes stabilized
- VDE growth rates reduced, stabilized with existing technology
  (The closer the better, requires toroidal continuity, case considered 4 cm lithium with a SOL 20% of minor radius)

High Poloidal Flow Velocity (Kotchenreuther)

- LM transit time < resistive wall time, about ½ s, poloidal flux does not penetrate
- Hollow current profiles possible with large bootstrap fraction (reduced recirculating power) and $E \times B$ shearing rates (transport barriers)

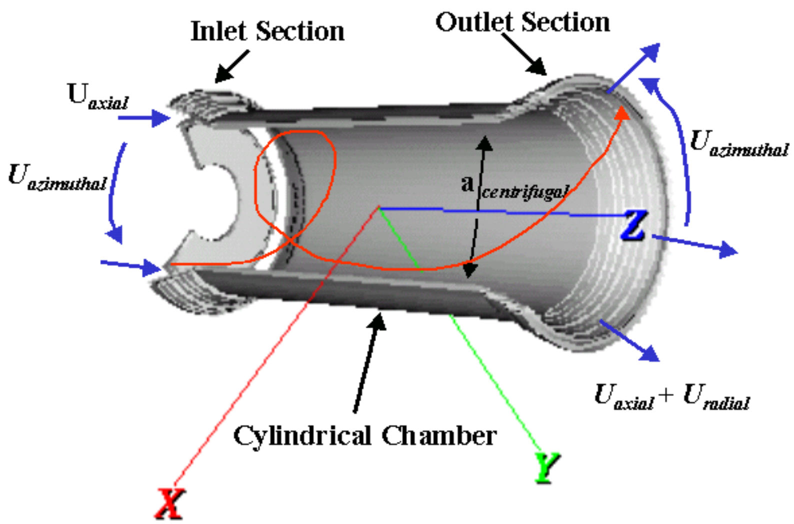
Hydroden Gettering at Plasma Edge (Zakharov)

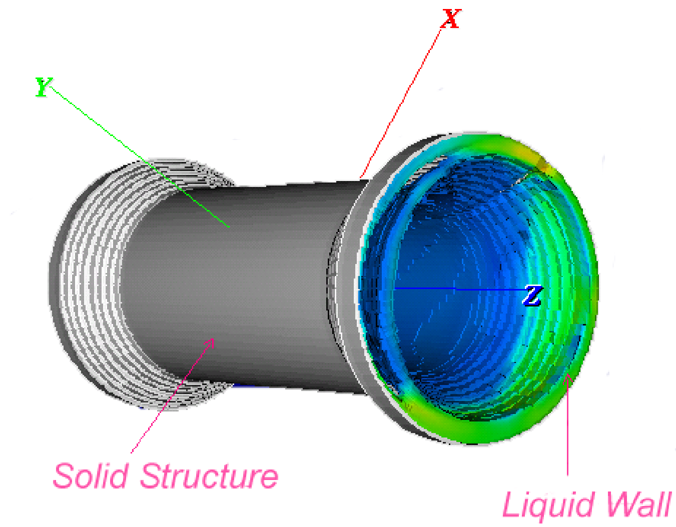
- Flattened average ion temperature profiles reducing anomalous energy transport
- Flattened or hollow current density reducing ballooning modes and allowing high β

Scientific Issues for Liquid Walls

- Effects of Liquid Walls on Core Plasma including:
  - Discharge evolution (startup, fueling, transport, beneficial effects of low recycling)
  - Plasma stability including beneficial effects of conducting shell and flow
- Edge Plasma-Liquid Surface Interactions
- Turbulence Modifications At and Near Free-Surfaces
- MHD Effects on Free-Surface Flow for Low- and High-Conductivity Fluids
- Hydrodynamic Control of Free-Surface Flow in Complex Geometries, including Penetrations, Submerged Walls, Inverted Surfaces, etc.

Swirling Thick Liquid Walls for High Power Density FRC

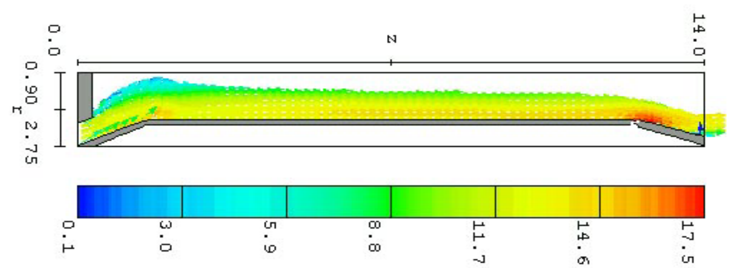


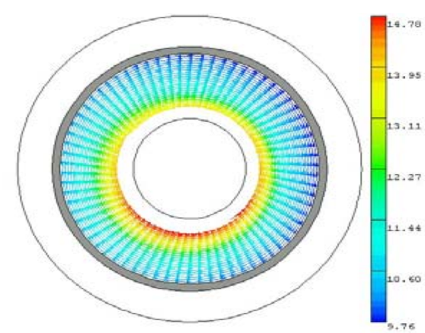


- **Design:** Horizontally-oriented structural cylinder with a liquid vortex flow covering the inside surface. Thick liquid blanket interposed between plasma and all structure

- **Computer Simulation:** 3-D time-dependent Navier-Stokes Equations solved with RNG turbulence model and Volume of Fluid algorithm for free surface tracking

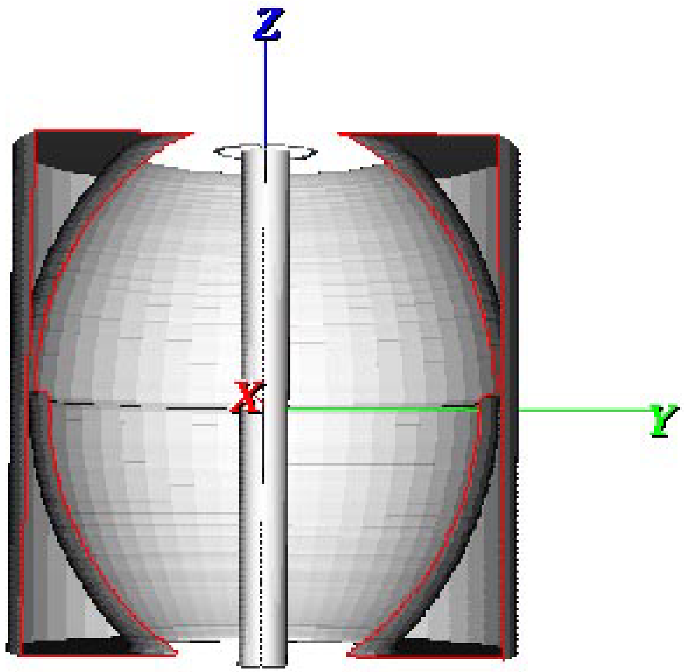
- **Results:** Adhesion and liquid thickness uniformity (> 50 cm) met with a flow of V_{axial} = 10 m/s, $V_{\theta,ave}$ = 11 m/s

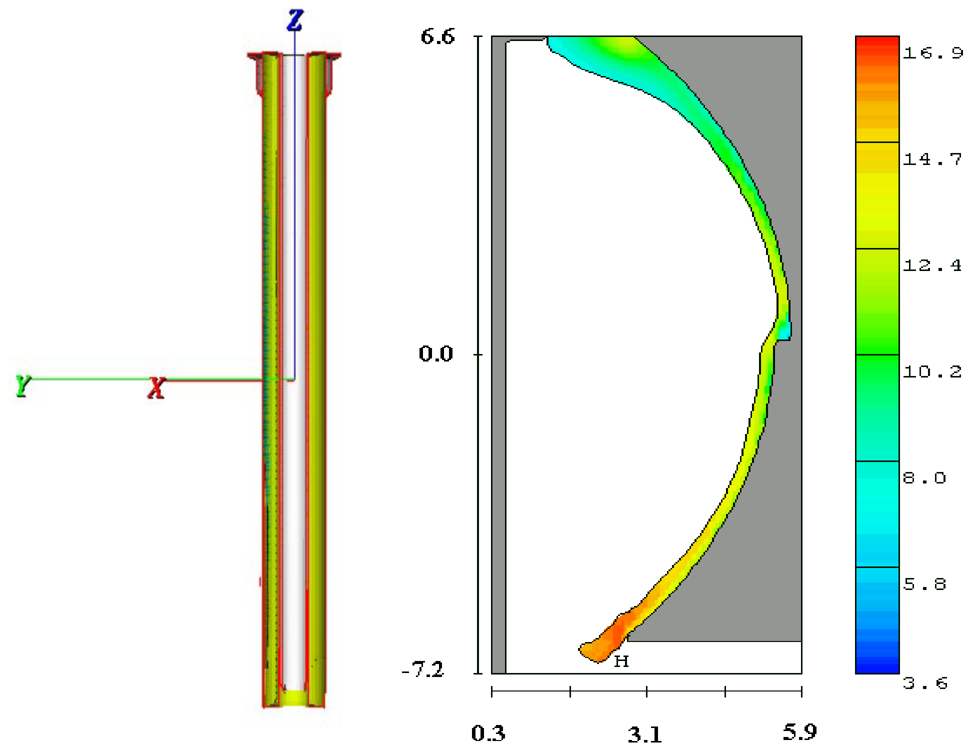




Calculated velocity and surface depth

Toroidally Rotating Thick Liquid Wall for the ST





Design Concept:

- Thick liquid flow from reactor top
- *Outboard:* Fluid remains attached to outer wall due to centrifugal acceleration from the toroidal liquid velocity
- *Inboard:* Fast annular liquid layer

Simulation Results:

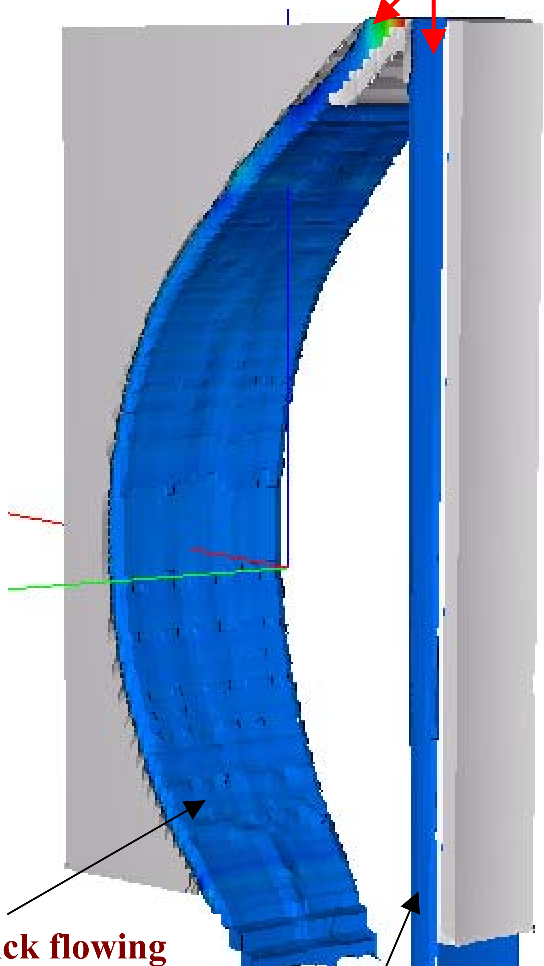
- Step in outboard vacuum vessel topology helps maintain liquid thickness > 30 cm
- Calculated outboard inlet velocity, $V_{poloidal} = 4.5$ m/s, $V_{toroidal,ave} = 12$ m/s
- Inboard jet $V_z = 15$ m/s is high to prevent excessive thinning, < 30%

Advanced Tokamak

3-D Hydrodynamics Calculation Indicates that a Stable Thick Flibe-Liquid Wall can be established in an Advanced Tokamak Configuration

ARIES-RS Geometric Configuration
(major radius 5.52 m)

Inlet velocity = 15 m/s;
Initial outboard and inboard thickness = 50 cm



Outboard thick flowing liquid wall

Inboard thick flowing liquid wall

- **Toroidal width = 61 cm Corresponding to 10° sector**
- **Area expansion included in the analysis**

The thick liquid layer:

- ***is injected at the top of the reactor chamber with an angle tangential to the structural wall***
- ***adheres to structural wall by means of centrifugal and inertial forces***
- ***is collected and drained at the bottom of the reactor (under design)***

Plasma-Liquid Surface Interaction and Temperature Control (Conflicting Requirements on Temperature and Velocity)

1. Plasma-Wall Interaction

   $T_S^{max} < T_S^p$ (Plasma allowable) T_S^p Uncertain

2. High Thermal Efficiency

   $T_b^{out} > T_b^e$ (for efficiency)

3. Newton's Law of Cooling

   $T_S - T_b = q/h$ Free Surface h Uncertain

4. Adheres to Wall

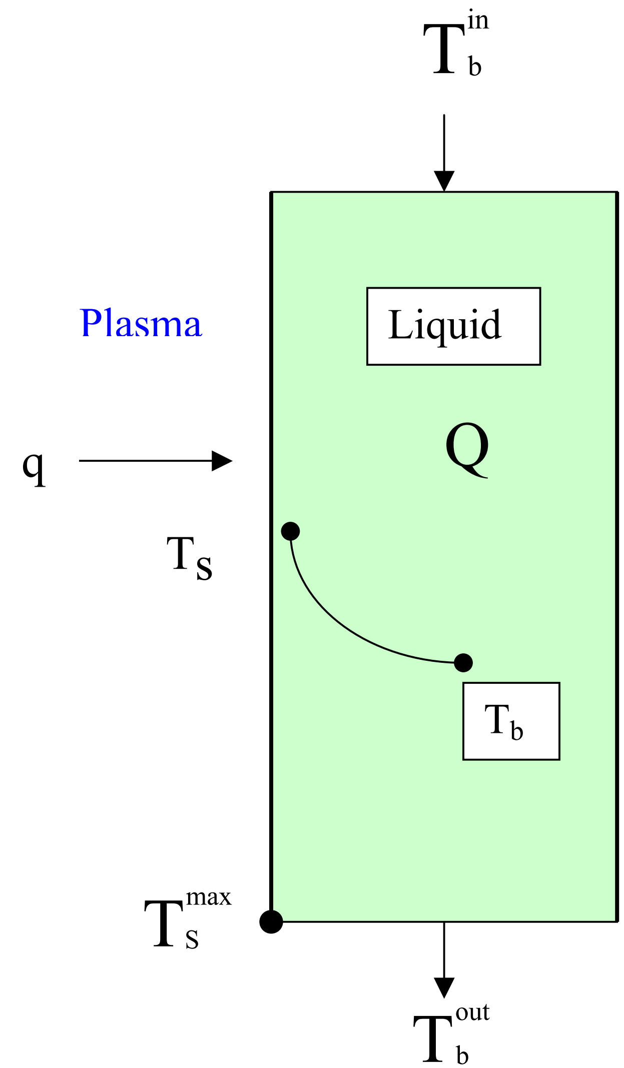
   $V^2/R > g$

5. Overcome Thinning

   $\dot{m} = \rho VA$ $V(t) = V_o + V_g(t)$ $V_o >> V_g(t)$

6. Higher V increases pumping power, reduces temp. rise

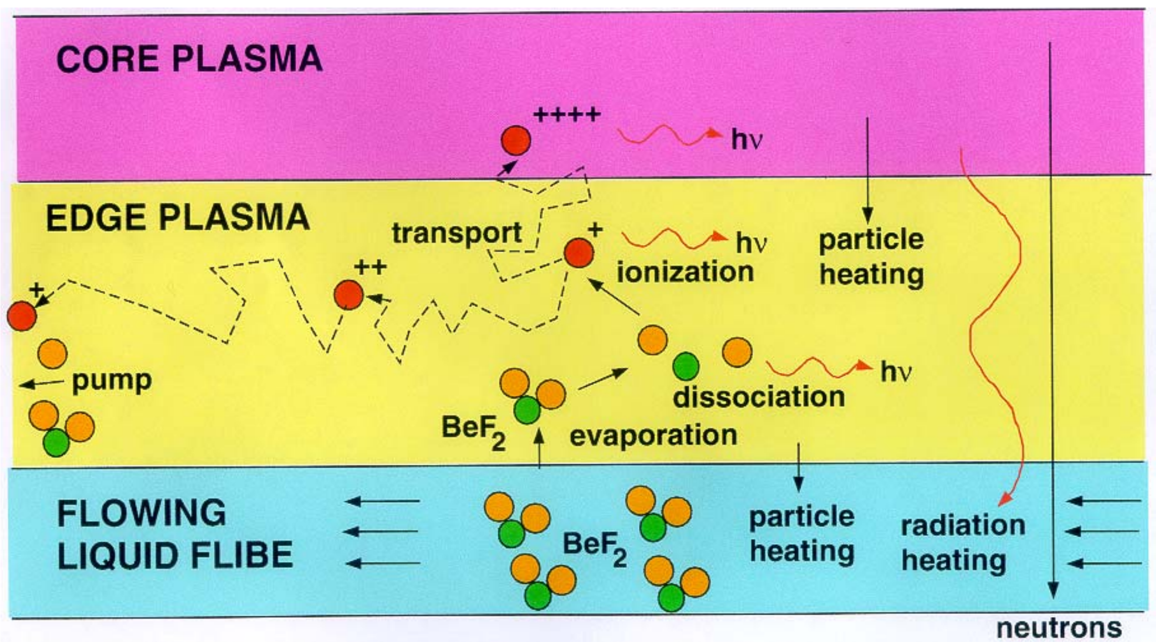
$\Delta P \sim \rho V^2$ $T_b^{out} - T_b^{in} = (Q + q) / \dot{m} C_p$

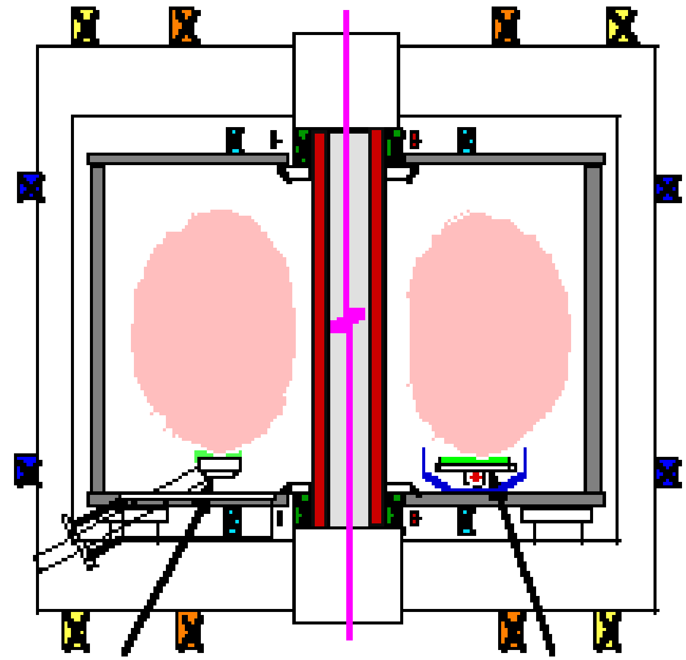


Plasma-Liquid Surface Interactions Affect both the Core Plasma and the Liquid Walls

- Multi-faceted plasma-edge modelling has started (Ronglien et al.)
- Experiments have started (in PISCES, DIII-D and CDX-U)

Processes modeled for impurity shielding of core





Liquid lithium limiter in CDX-U

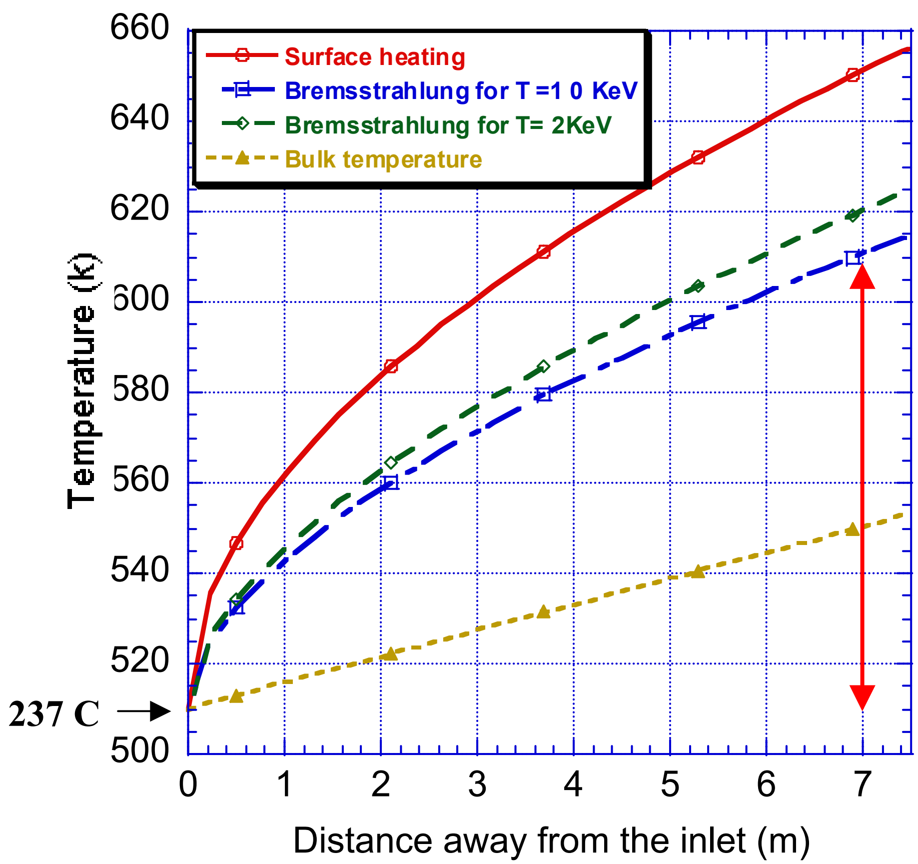
S. Luckhardt Viewgraph #1

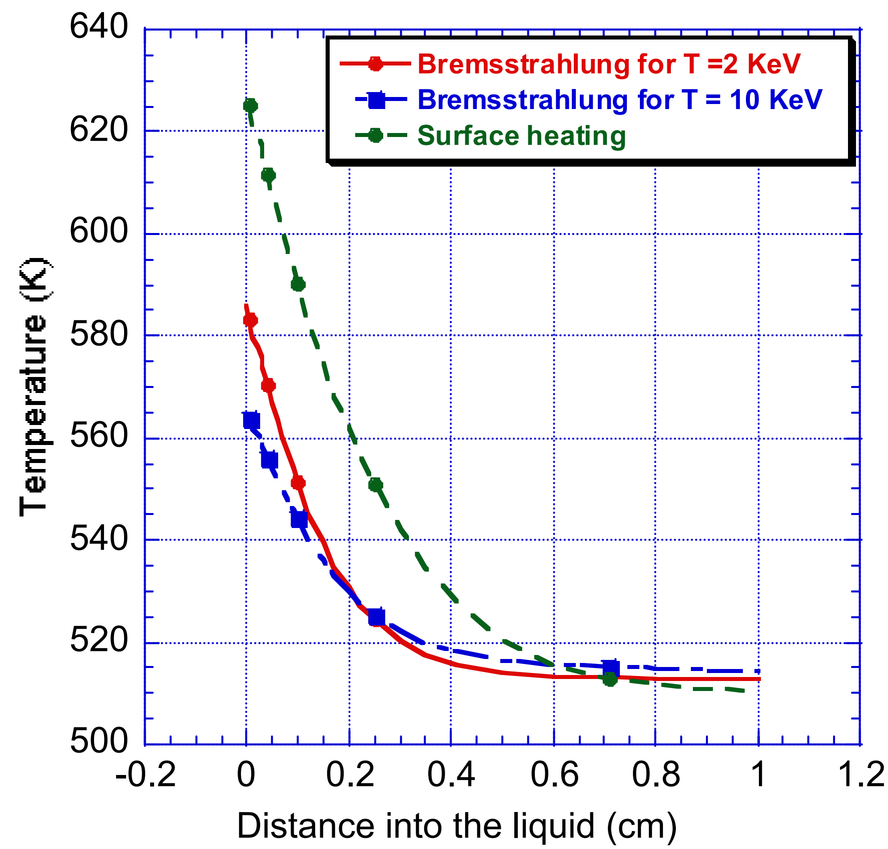
S. Luckhardt Viewgraph #2

Lithium Free Surface Temperature

- Predictable heat transfer (MHD-Laminarized Flow), but 2-D Turbulence may exist
- Laminarization reduces heat transfer
- But Lithium free surface appears to have reasonable surface temperatures due to its high thermal conductivity and long x-ray mean free path

Li velocity = 20 m/s
Surface heat load = 2 MW/m^2



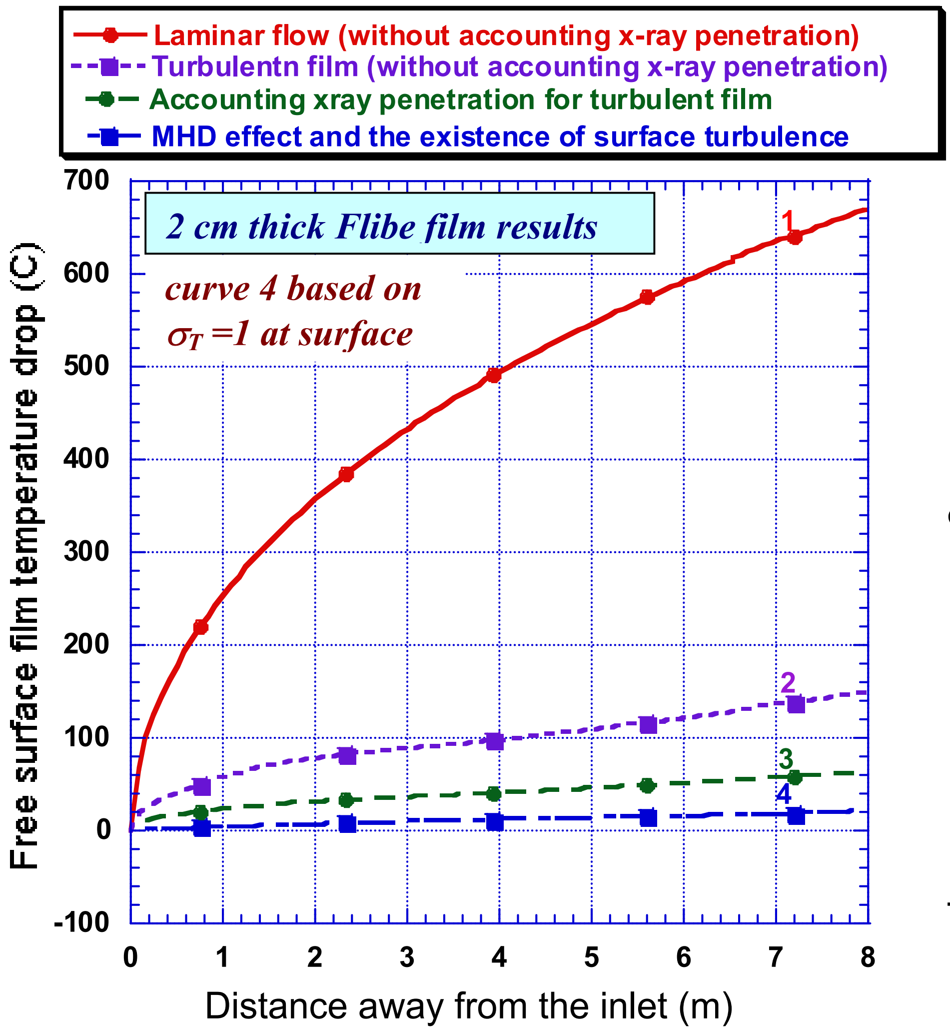


Flibe Free Surface Temperature Magnitude Highly Depends on the Turbulent Activities near the Surface

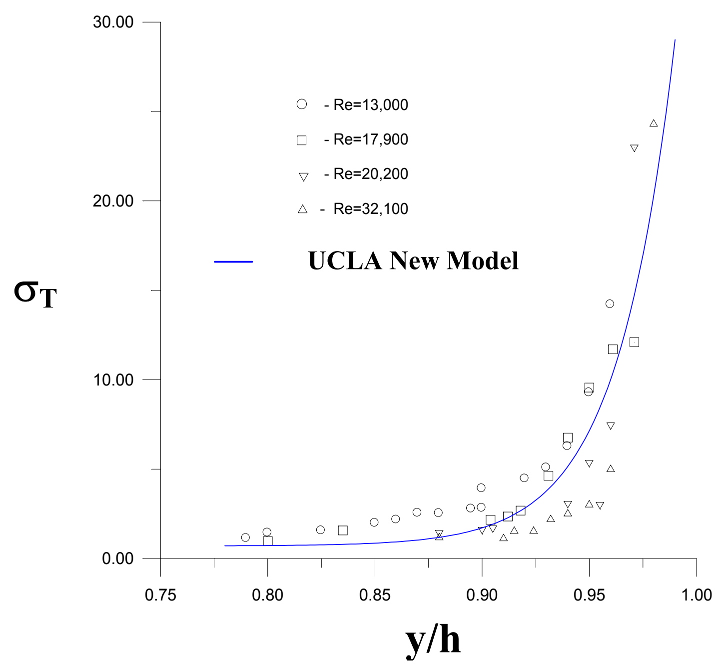
Heat transfer degradation at Flibe free surface results from both the damping of the normal velocity component at the free surface and suppression of turbulence by the field.

Energy Eq.

$$\rho C_p U \frac{\partial T}{\partial x} = \frac{\partial}{\partial y}[\lambda(1+\varepsilon_t \frac{\Pr}{\sigma_T})\frac{\partial T}{\partial y}]$$

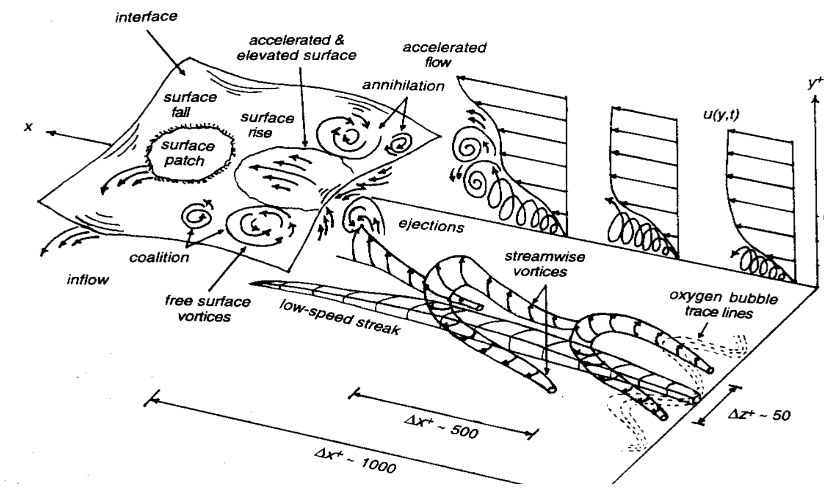


K–ε model update:
In the improved model, the empirical data obtained by Ueda et al. for the eddy diffusivity for heat was considered, which results in an increase in the turbulent Prandtl number near the free surface.

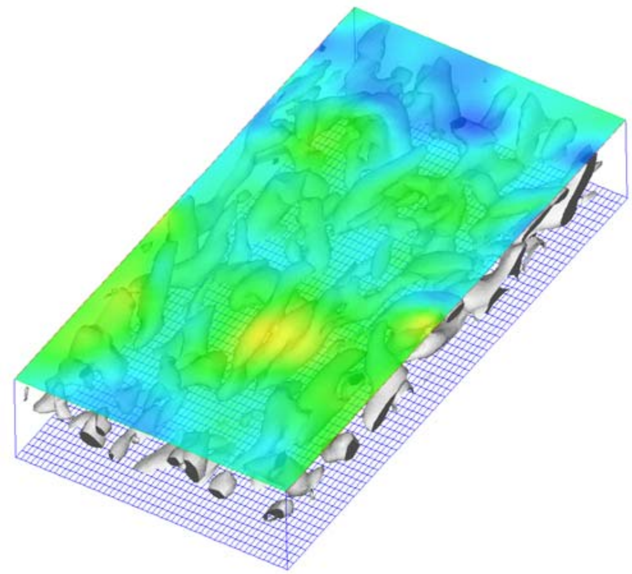


Turbulent Prandtl number growth near the free surface

TURBULENT FREE SURFACE FLOWS ARE COMPLEX



Conceptual illustration of experimental observation of burst-interface interactions



Vortex structure and free surface deformation (DNS calculation)

The flow is dominated by the generation of wall ejections, formation of spanwise "upsurging vortices", and interaction of such structures with the free surface. The spanwise "upsurging vortices" are seen to evolve near the wall, reach the free surface, form surface patches, roll back in form of spanwise "downswinging vortices", and mix into the bulk flow. There is evidence of "horseshoe" and "hockeystick" type vortices in relation to the bursting events. The ejection-inflow events are associated with the deformation of the free surface and a redistribution of near surface vorticity and velocity fields.

From Mehdi Rashidi, *"Burst-interface interactions in free surface turbulent flows"*, Phys.Fluids 9 (11), November 1997

SIMULATION of TURBULENT FREE SURFACE FLOWS REQUIRES SEVERAL LEVELS of MODELING

- Direct Numerical Simulation (DNS) can model small sections of free surfaces and provide insight into the nature of turbulent flow phenomena
- Reynolds-Averaged models (*e.g.* k-ε models) can calculate flow and turbulence statistics at high Re and Ha numbers, if fundamental phenomena are accurately modeled in turbulence-closure equations

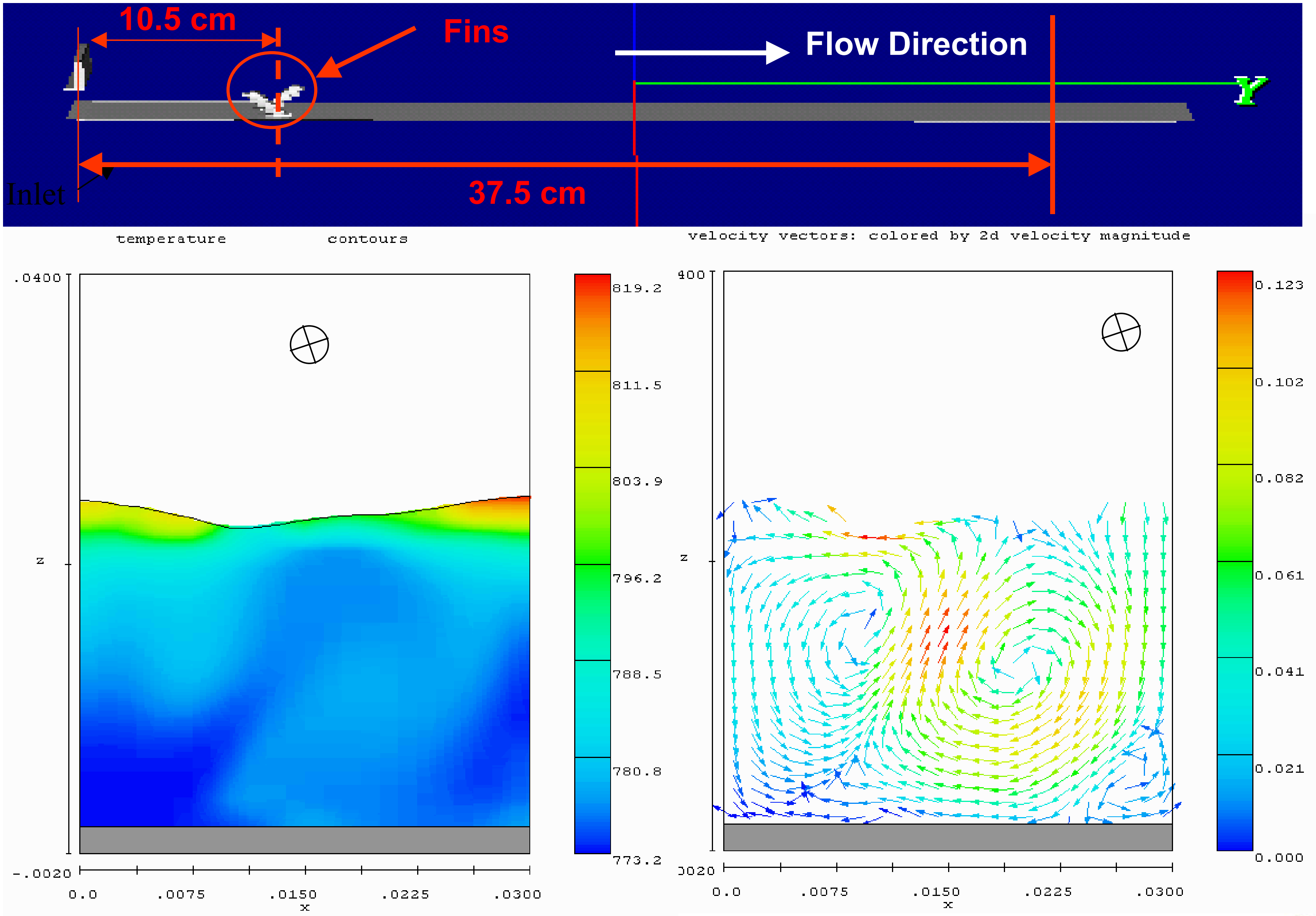
General Form of MHD k-ε equations developed at UCLA

(ε_{em} is a new term responsible for MHD effects)

$$\frac{\partial k}{\partial t} + \overline{V_1}\frac{\partial k}{\partial x_1} + \overline{V_2}\frac{\partial k}{\partial x_2} + \overline{V_3}\frac{\partial k}{\partial x_3} = \Pi + D - \varepsilon - \varepsilon_{em}$$

$$\varepsilon_{em} = \frac{\sigma}{\rho}(1-\gamma)\{2B_0^2 k - B_{01}^2\overline{V_1'^2} - B_{02}^2\overline{V_2'^2} - B_{03}^2\overline{V_3'^2} - 2B_{01}B_{03}\overline{V_1'V_3'} - 2B_{01}B_{02}\overline{V_1'V_2'} - 2B_{02}B_{03}\overline{V_2'V_3'}\}$$

3D Numerical Simulations Show Effectiveness of Surface Renewal Mechanism on Decreasing Free Surface Temperature of Flibe

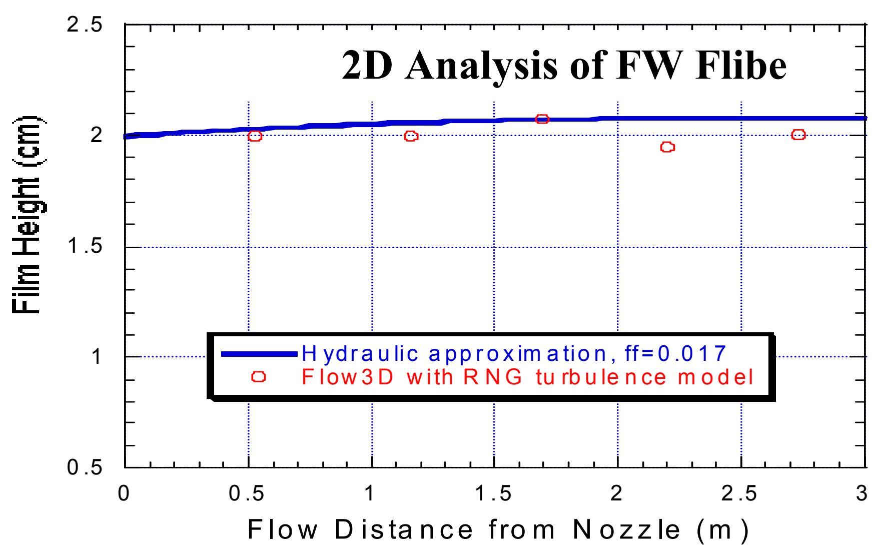


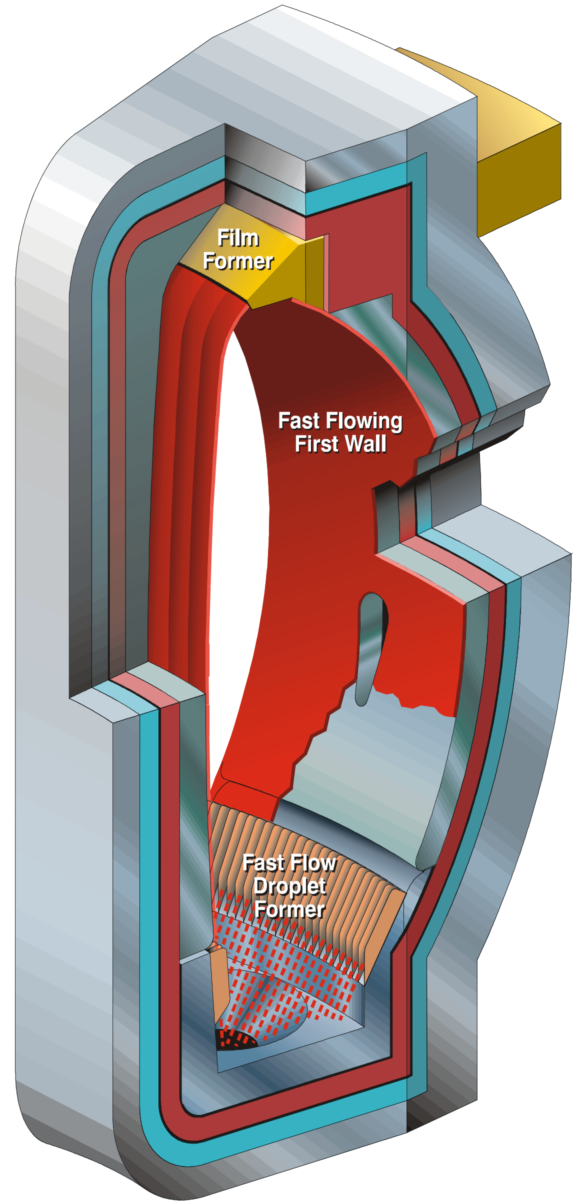
2-D Temperature Distribution 37.5 cm away from inlet

2-D Velocity Magnitude Distribution 37.5 cm away from inlet

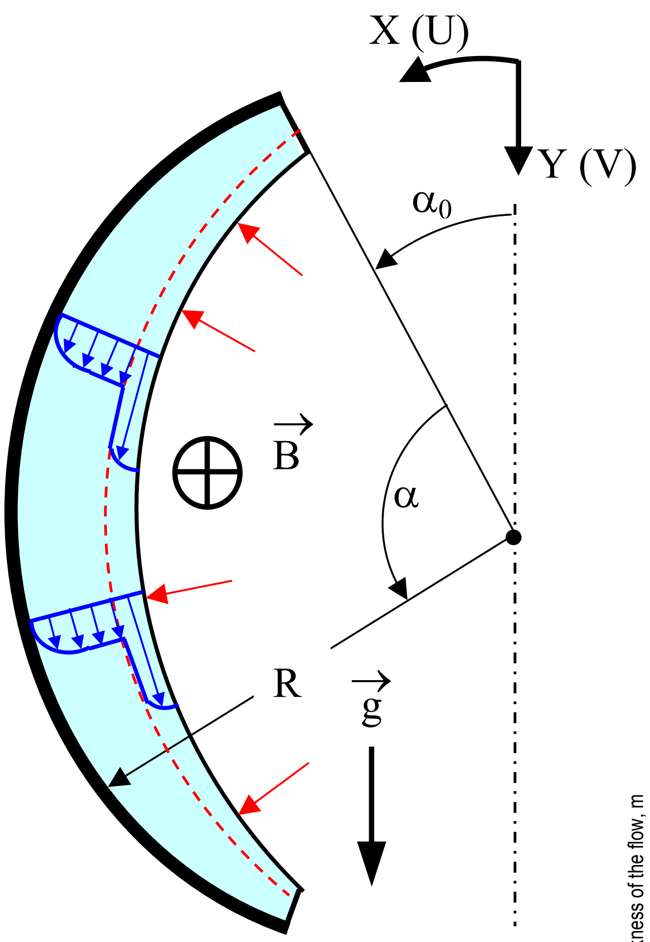
Convective Liquid Flow First Wall (CLIFF)

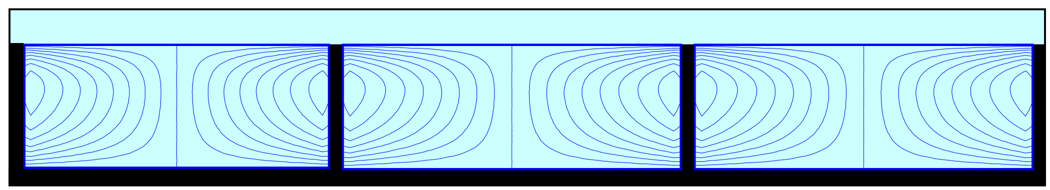
- **Underlying structure protected by a fast moving layer of liquid, typically 1 to 2 cm thick at 10 to 20 m/s.**
- **Liquid adheres to structural walls by means of centrifugal force**
- **Hydrodynamics calculations indicate near equilibrium flow for Flibe at 2 cm depth and 10 m/s velocity (below).** Some contradiction between different turbulence models needs to be resolved**.**



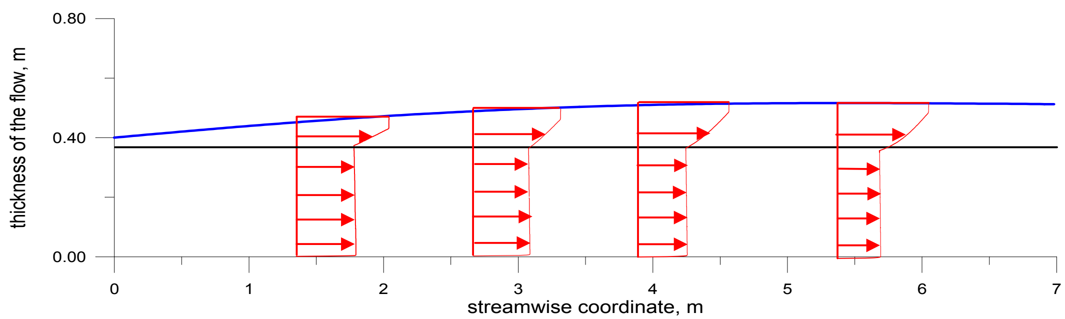


ESTABLISHING A TWO-STREAM FLOW USING SUBMERGED WALLS to IMPROVE HEAT TRANSFER





- MHD drag slows down liquid between submerged walls
- Free surface layer can accelerate to high velocity



UCLA Data

POTENTIAL CHALANGES IN LIQUID WALL BEHAVIOR AROUND PENETRATIONS

STAGNATION

- Minimizes the cooling of the front section of the penetration.
- Discharges fluid towards the plasma.

SPLASH OF THE FLUID AND DROPLET EJECTIONS

- Droplets may be generated and ejected into the plasma as the high velocity liquid layer hits the front section of the penetration.

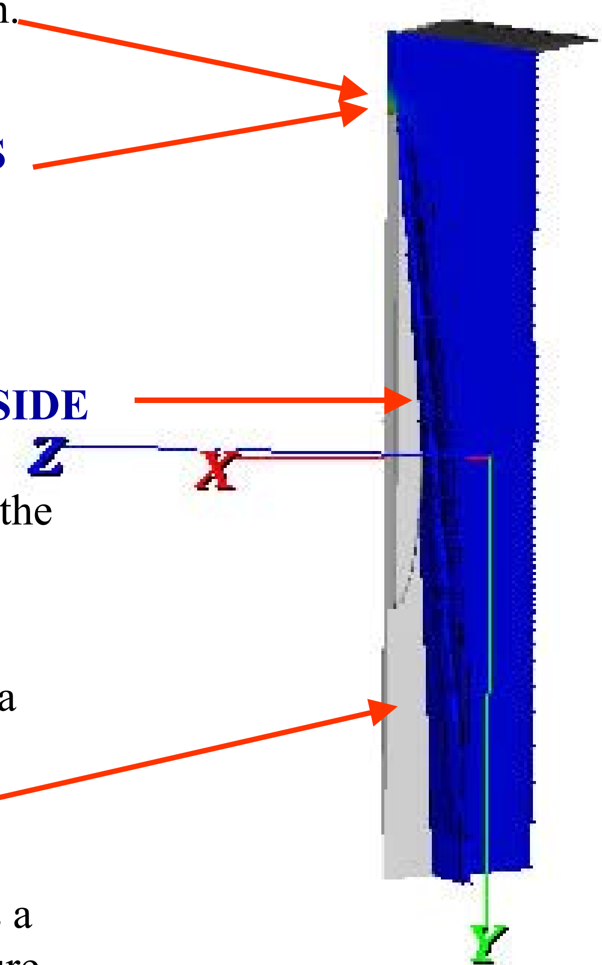
FLUID LEVEL RISE SURROUNDINDG THE FRONT SIDE OF THE PORT

- A stream of rising fluid is diverted to the sides surrounding the penetration due to the obstruction of flow path.

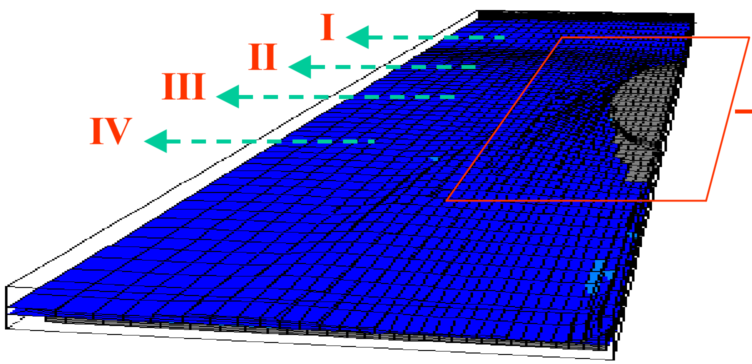
(144 m^3 of fluid per hour is displaced for a 20 cm wide (in the flow direction) penetration for the CLIFF concept with a base velocity of 10 m/s.)

WAKE FORMATION

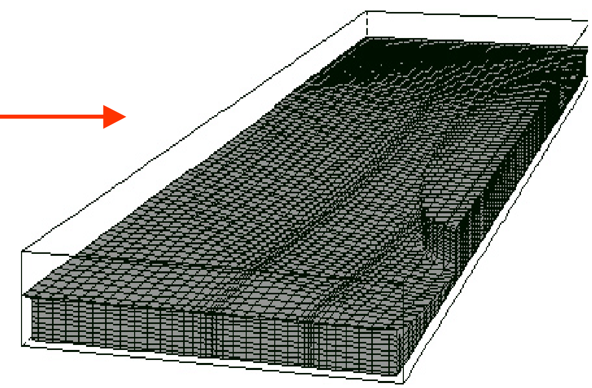
- The wake formation at the end section of the penetration, as a result of deflection of streamlines by the penetration structure.



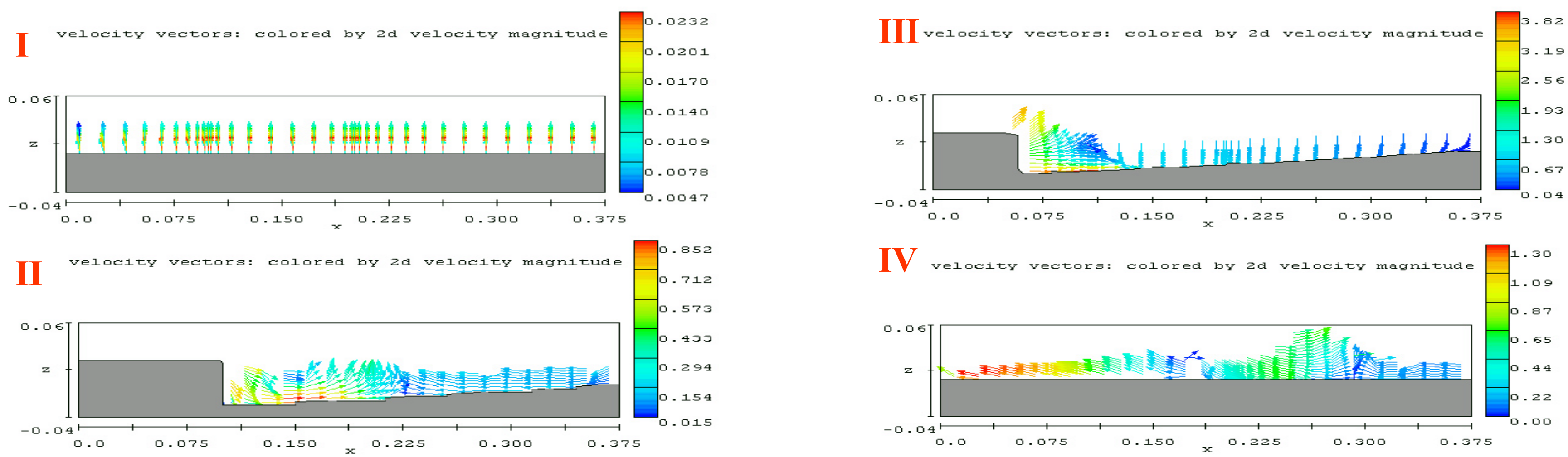
DESIGN SOLUTIONS, SUCH AS MODIFICATIONS TO BACK WALL TOPOLOGY RESULT IN MORE ATTRACTIVE FLUID FLOW CHARACTERISTICS AROUND PENETRATIONS



3-D Hydrodynamic simulation of penetration accommodation when the back wall topology surrounding the penetration is modified.



Modified back wall topology surrounding the penetration.



2-D Velocity magnitude in planes perpendicular to the flow direction

Photocopy (I think this was another one of S. Luckhardt's Viewgraphs)

Luckhardt's viewgraph

Luckhardt's viewgraph

Neil’s Huge Picture

Chamber Technology

5 – Year Goals

Liquid Walls (LW's)

1. Develop a more fundamental understanding of free surface fluid flow and plasma-liquid interactions
2. Operate flowing LW's in an experimental physics device (e.g. NSTX)
3. Initiate construction of an Integrated Thermofluid Research Facility for MFE/IFE
4. Understand advantages & implications of LW's in fusion systems.

Solid Walls

5. Advance novel concepts that can extend the capabilities and attractiveness of solid walls
6. Contribute to international effort on key feasibility issues where US has unique expertise

APEX Major Tasks for FY 00/01/02

Task I: Explore options and issues for implementing a flowing liquid wall in a major experimental physics device (NSTX is used as an example). Characterize the technical issues develop an R&D plan, initiate R&D.

(Lead Organizations: UCLA, PPPL, SNL) (Ying)

Task II: Explore high pay-off liquid wall options. Include: a) tokamaks and other confinement schemes, b) flibe and liquid metals (Li, SnLi), c) concepts with physics advantages, and d) concepts with engineering advantages. Include modelling and experiments R&D.

(Lead Organizations: UCLA, PPPL, Univ. of Texas) (Morley)

Task III: Investigate Practical Engineering Issues associated with the design of liquid walls in a high-power density fusion energy system

(Lead Organizations: ANL, SNL, ORNL, UCLA) (Sze/Nelson/Nygren)

Task IV: Investigate Key Issues and develop a practical design for high-temperature, high power density solid wall with primary focus on lithium vaporization scheme, EVOLVE

(Lead Organizations: GA, UW, FZK) (Wong)

APEX Major Tasks for FY 00/01/02 (cont'd)

Cross-Cutting Tasks (support Tasks I-IV)

Task A: Plasma-Liquid Surface Interactions and Plasma-Edge Modelling

(Lead Organizations: LLNL, ANL)

(Rognlien working with ALPS/APEX Edge Modelling Group led by Brooks)

Task B: Liquid-Wall Bulk Plasma Interactions

(Lead Organizations: PPPL, Univ. of Texas) (Kaita)

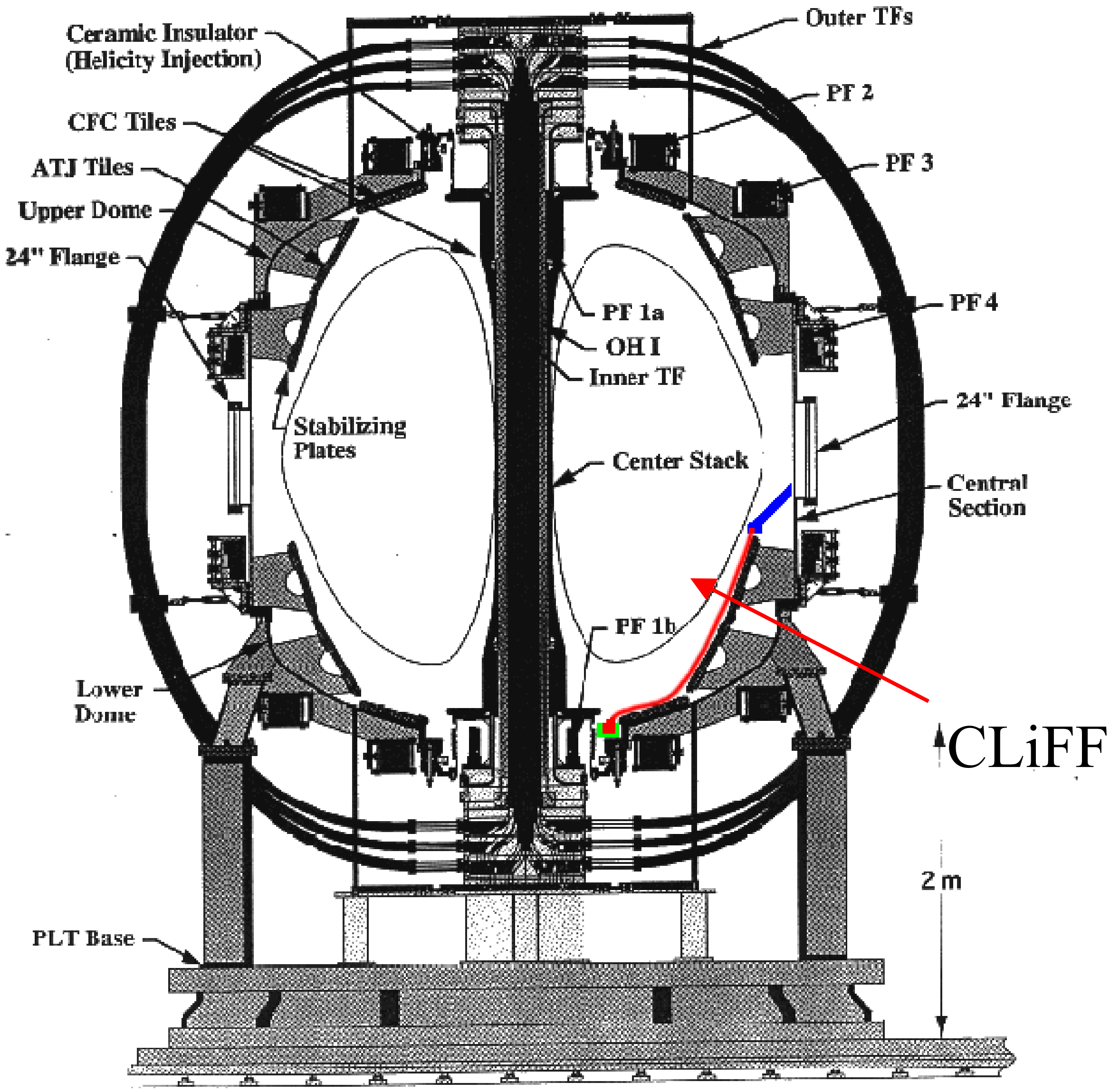
Task C: Materials

(Lead Organizations: ORNL, UCLA) (Zinkle)

Task D: Safety and Environment

(Lead Organizations: INEEL, UW) (McCarthy)

Liquid Wall in NSTX Provides Exciting Opportunities



- It helps NSTX remove high heat flux
- It provides excellent data on plasma liquid interactions

APEX

RELATED APPLICATIONS of NEAR SURFACE TURBULENCE MODIFICATION and MHD EFFECTS

- Melt and solid mircrostructure control in metallic casting and crystal growth
- Turbulent drag reduction and MHD ship propulsion
- Oceanography and atmospheric processes
- Droplet formation and fuel mixing for internal combustion and jet engines