Brief Overview of APEX

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APEX Website: www.fusion.ucla.edu/APEX

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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.**

Chamber Technology Goals
Used in APEX to Calibrate Progress

1. **High Power Density Capability (main driver)**

   Neutron Wall Load > 10 MW/m^2

   Surface Heat Flux > 2 MW/m^2

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

3. **High Availability**

   -Lower Failure Rate

   MTBF > 43 MTTR

   -Faster Maintenance

4. **Simple Technological and Material Constraints**

APEX Phases

- **APEX was initiated in November 1997 as part of the U.S. Restructured Fusion Program Strategy to enhance innovation.**

- **The first phase of APEX (11/97 to 10/99) explored and screened many ideas.**
  - **The technical results of this phase are documented in an APEX Interim Report (November 99).**

- **The new phase of APEX (starting 11/99) focuses on more detailed exploration and critical R&D for two classes of concepts:**

  1. **Liquid Walls (many variations)**

  2. **EVOLVE (high-temperature refractory alloy with Lithium evaporation)**

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

   To obtain a copy:

   A. Complete copy is displayed on the APEX Website.
   B. Hard copies are being distributed

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>

Outline of APEX Presentations in this Workshop

- *This presentation will cover:*
  - Introduction to APEX
  - Introduction to Liquid Walls and EVOLVE
  - Brief description of FY 2000 Tasks

- Technical results will be covered in U.S. presentations as follows:

Safety	
• Safety & Environmental Issues	Dr. McCarthy
Liquid Walls	
• Scientific Exploration, Hydrodynamics, Heat Transfer, Modelling, Plasma-Bulk Interactions	Dr. Morley
• Engineering of CliFF, Divertor Integration, Flibe Chemistry, Tritium	Dr. Sze
• Liquid Walls in NSTX, Other Results on Liquid Walls	Dr. Ying
• Plasma-Edge Modelling	Dr. Wong
Solid Walls	
• EVOLVE Technical Progress	Dr. Wong

APEX TEAM

Organizations

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

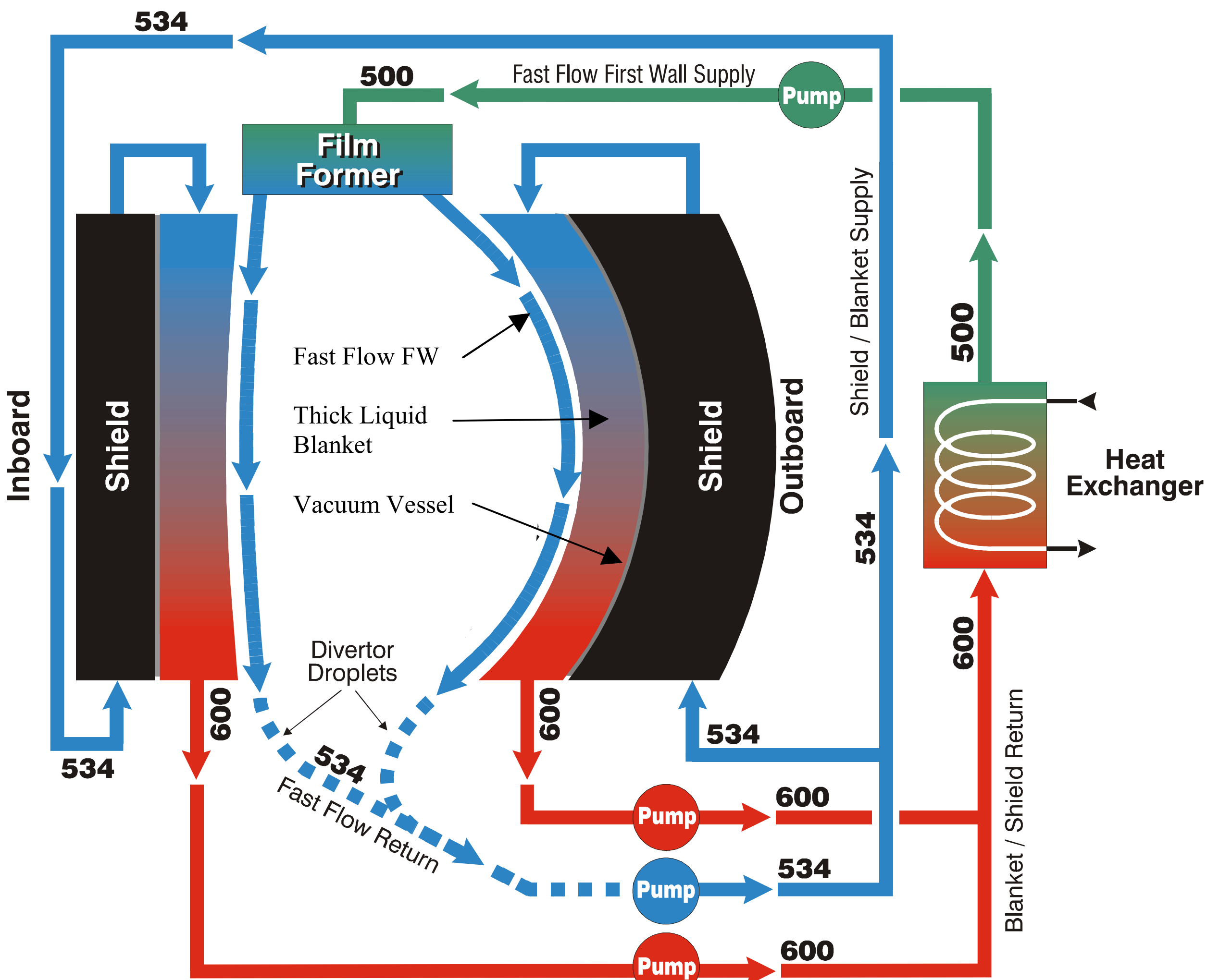
Contributions from International Organizations

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

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

Illustration of Liquid Walls



* Temperatures shown in figure are for Flibe

<u>Thin Liquid Wall</u>

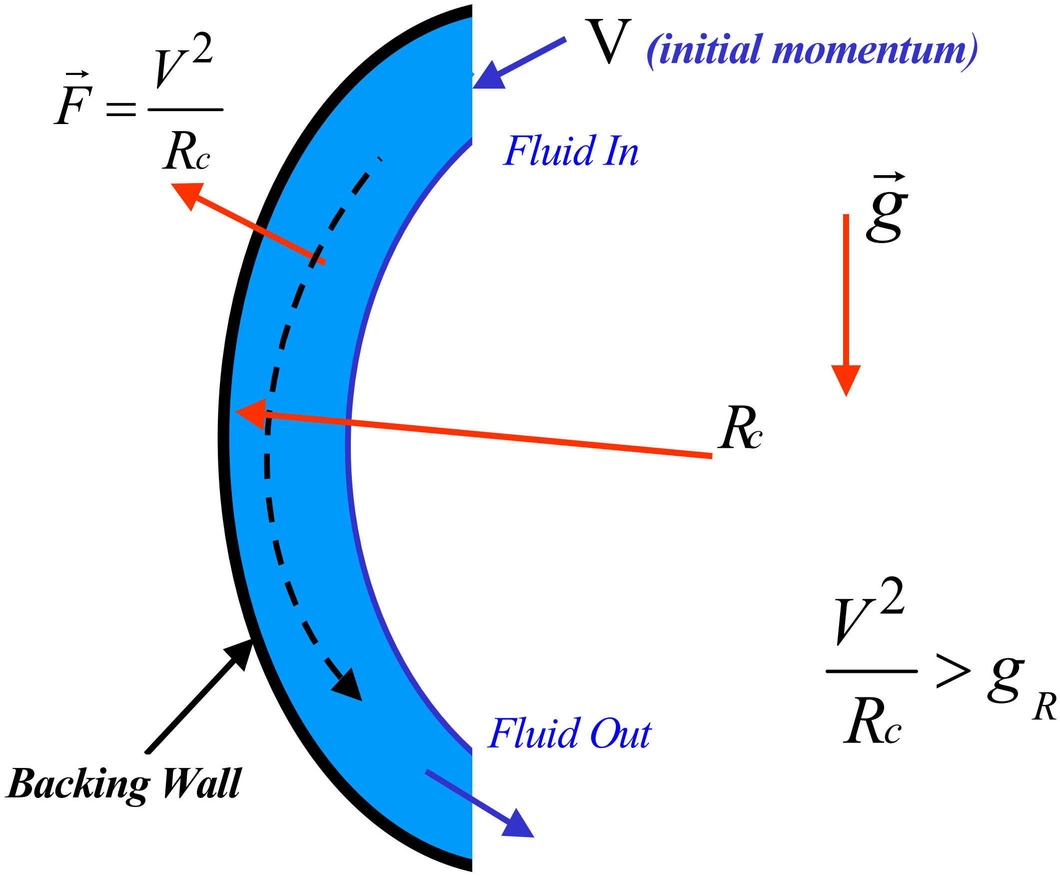
- **Thin (1-2 cm) of liquid flowing on the plasma-side of First Wall**

<u>Thick Liquid Wall</u>

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

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.*

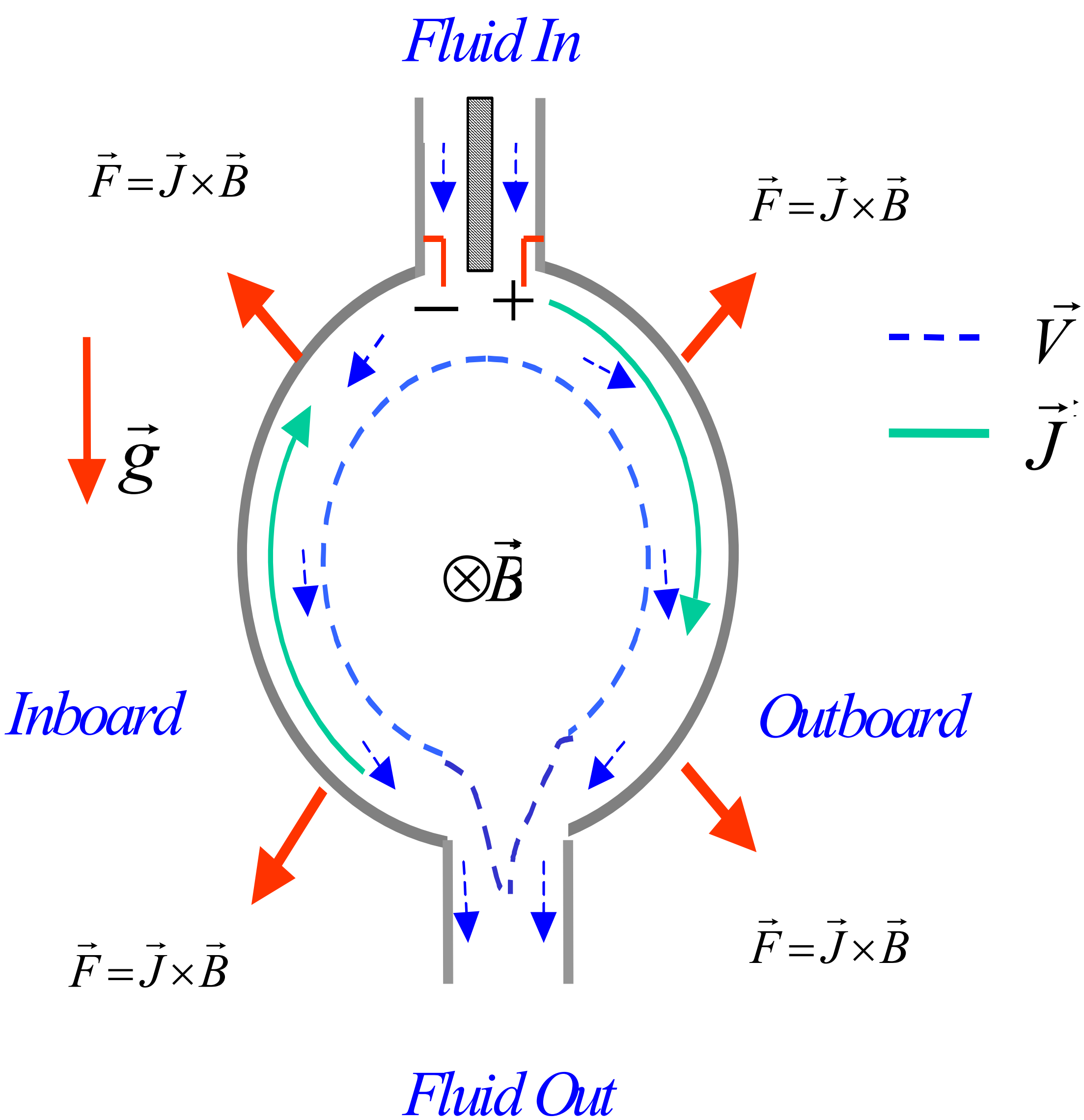
- ***GMD with Swirl Flow***

- *Add rotation.*

- ***Electromagnetically Restrained LM Wall***

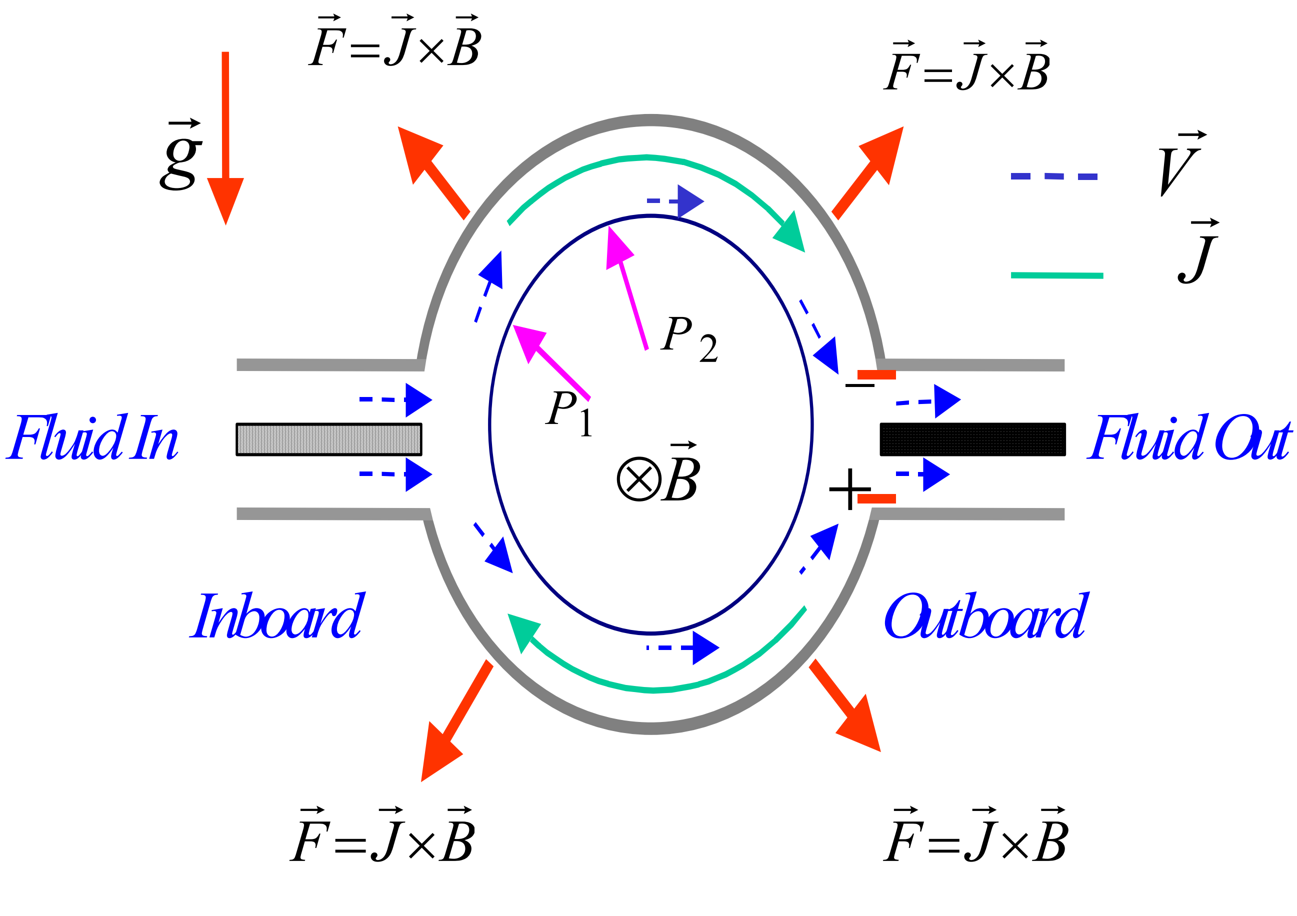
- *Externally driven current ($\vec{J}$) through the liquid stream.*

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



- ***Magnetic Propulsion Liquid Metal Wall***

  - *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.*



$\vec{V}$ *is driven by* ΔP

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)

Motivation for Liquid Wall Research

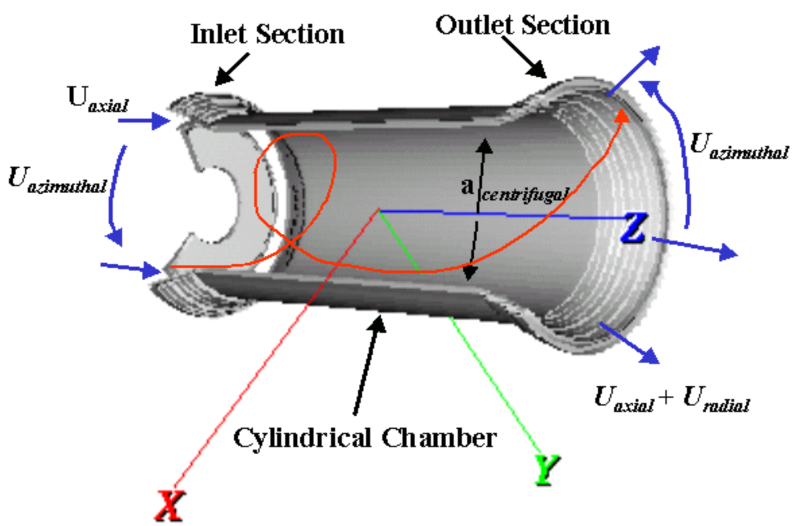
What may be realized if we can develop good liquid walls:

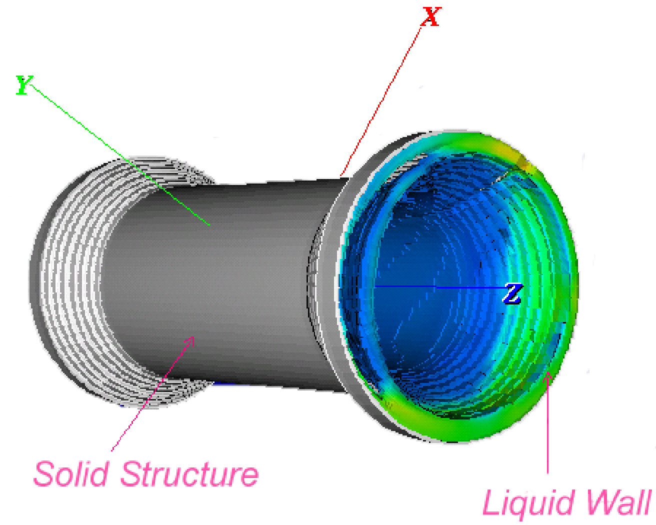
- Improvements in Plasma Stability and Confinement
  Enable high β, stable physics regimes if liquid metals are used
- High Power Density Capability
- Increased Potential for Disruption Survivability
- Reduced Volume of Radioactive Waste
- Reduced Radiation Damage in Structural Materials
  -Makes difficult structural materials more problems tractable
- Potential for Higher Availability
  -Increased lifetime and reduced failure rates
  -Faster maintenance

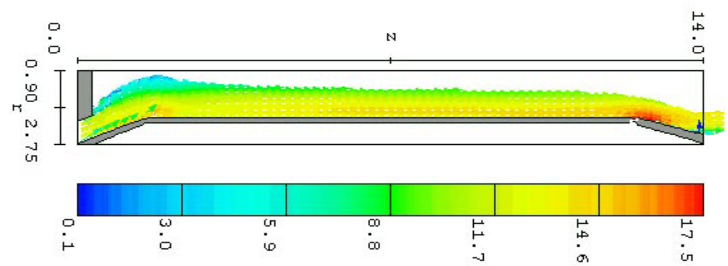
Scientific Issues for Liquid Walls

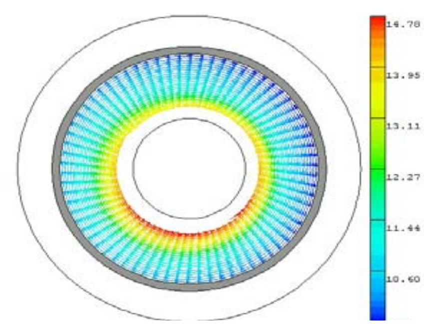
- Effects of Liquid Walls on Core Plasma including:
  - Discharge evolution (startup, fueling, transport, beneficial effects of low recycling)
  - Plasma stability including beneficial effects of conducting shell and flow
- Edge Plasma-Liquid Surface Interactions
- Turbulence Modifications At and Near 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









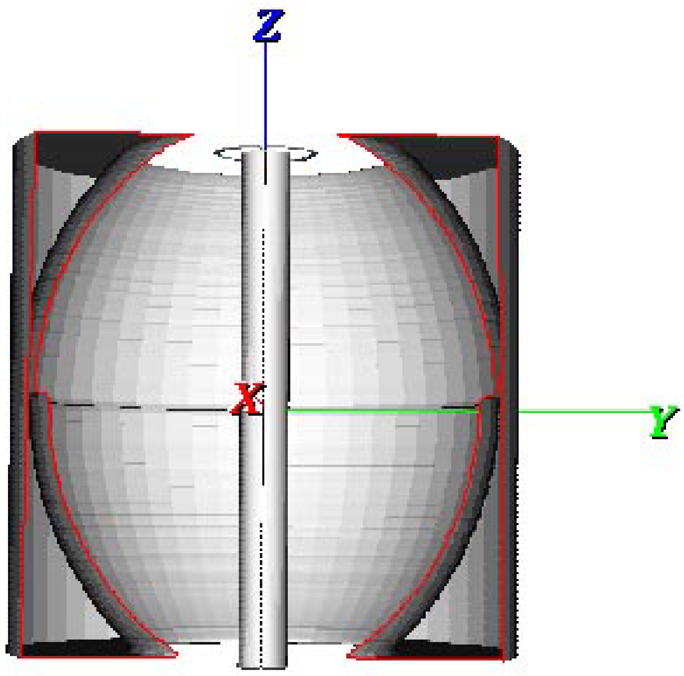
Calculated velocity and surface depth

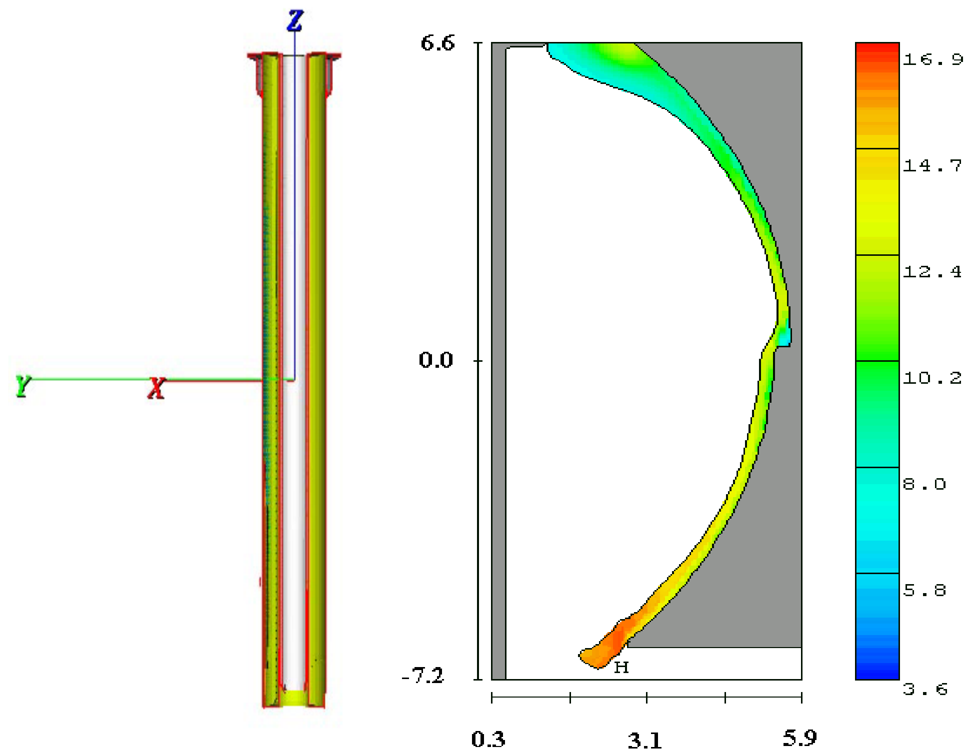
- **Design:** Horizontally-oriented structural cylinder with a liquid vortex flow covering the inside surface. Thick liquid blanket interposed between plasma and all structure

- **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

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:

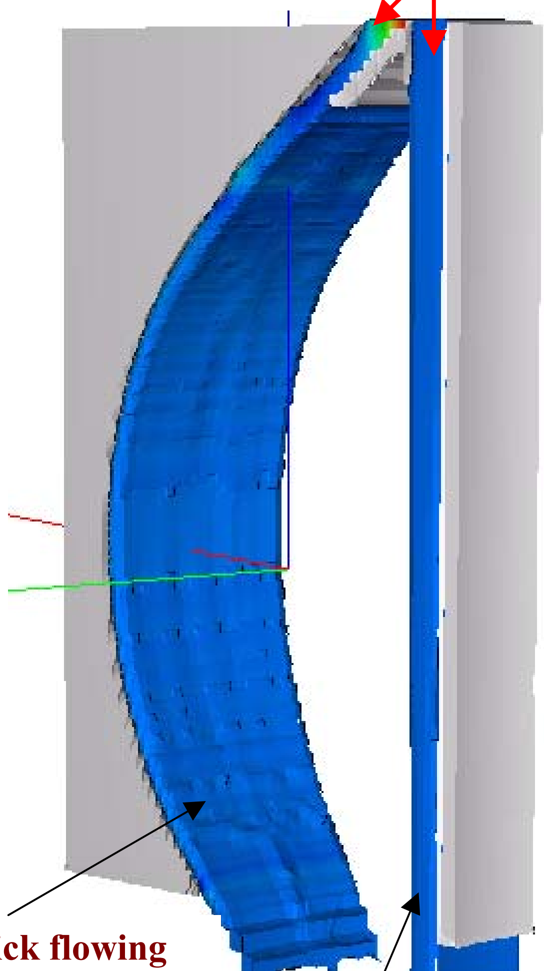
- Step in outboard vacuum vessel topology helps maintain liquid thickness > 30 cm
- Calculated outboard inlet velocity, $V_{poloidal}$ = 4.5 m/s, $V_{toroidal,ave}$ = 12 m/s
- Inboard jet V_z = 15 m/s is high to prevent excessive thinning, < 30%

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

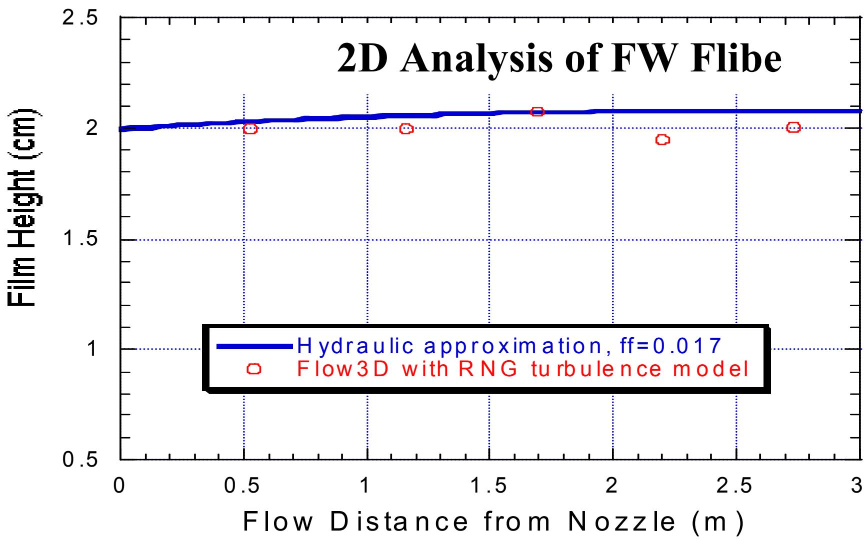
- **Toroidal width = 61 cm Corresponding to 10^{o} sector**
- **Area expansion included in the analysis**

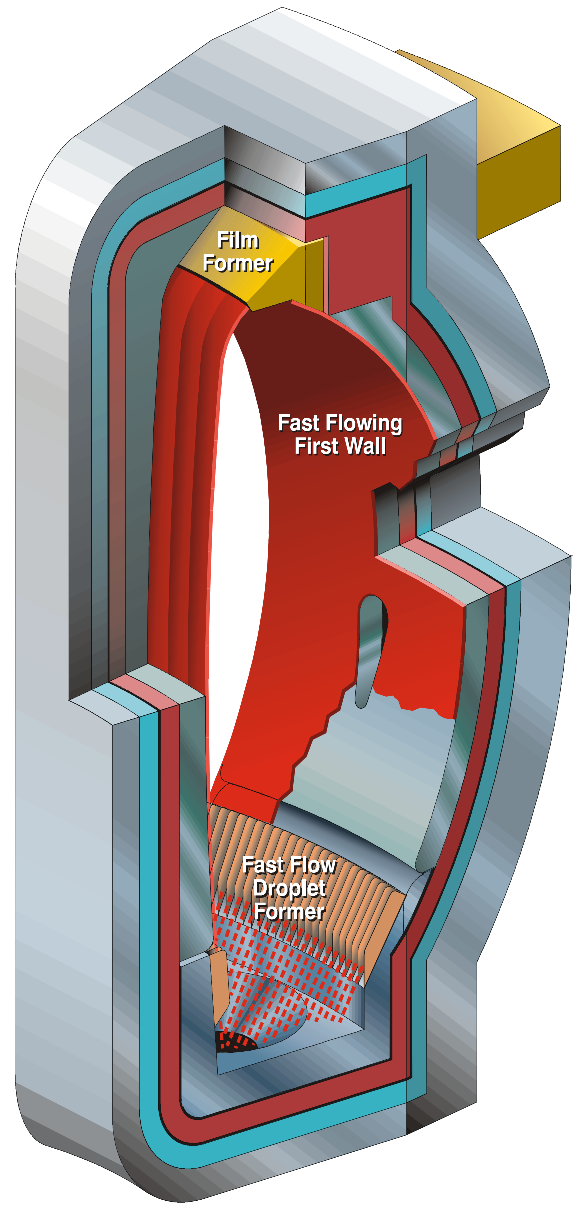
The thick liquid layer:

- ***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)***

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.

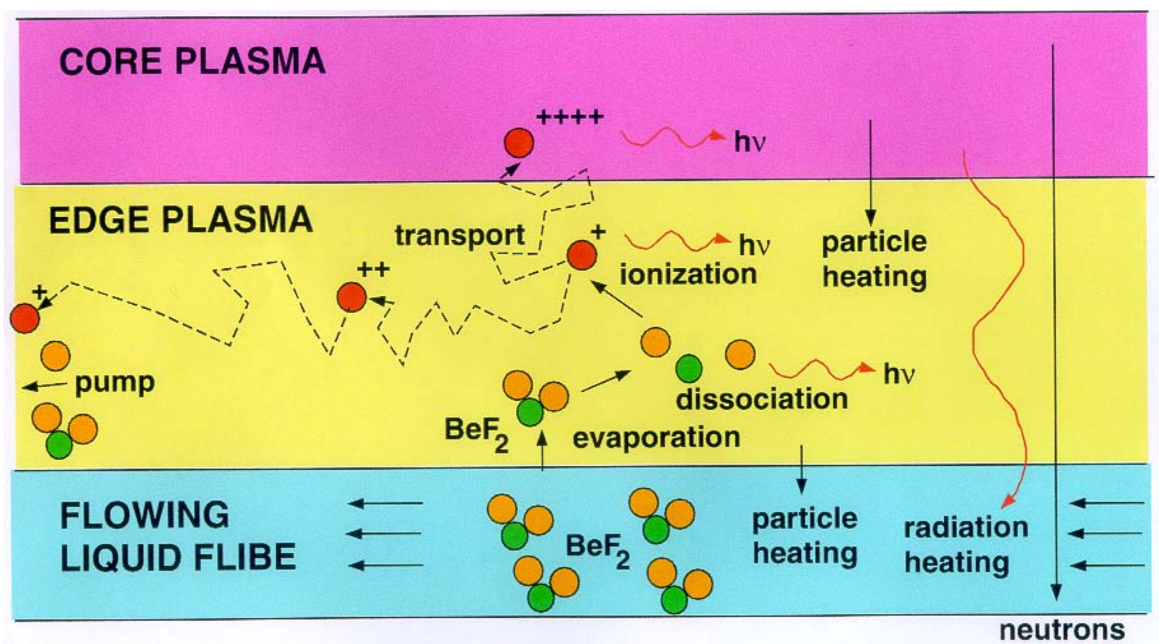


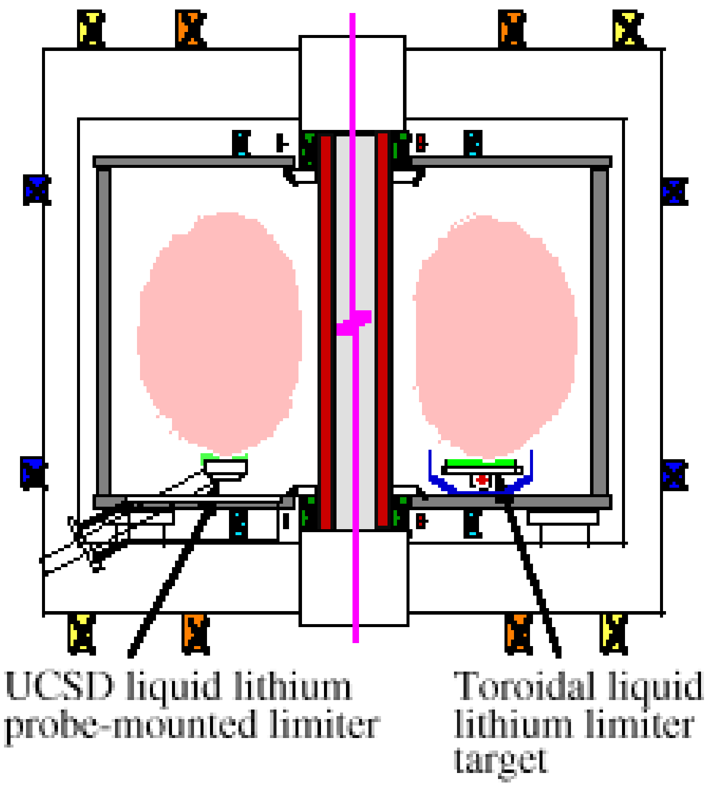


Plasma-Liquid Surface Interactions Affect both the Core Plasma and the Liquid Walls

- **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

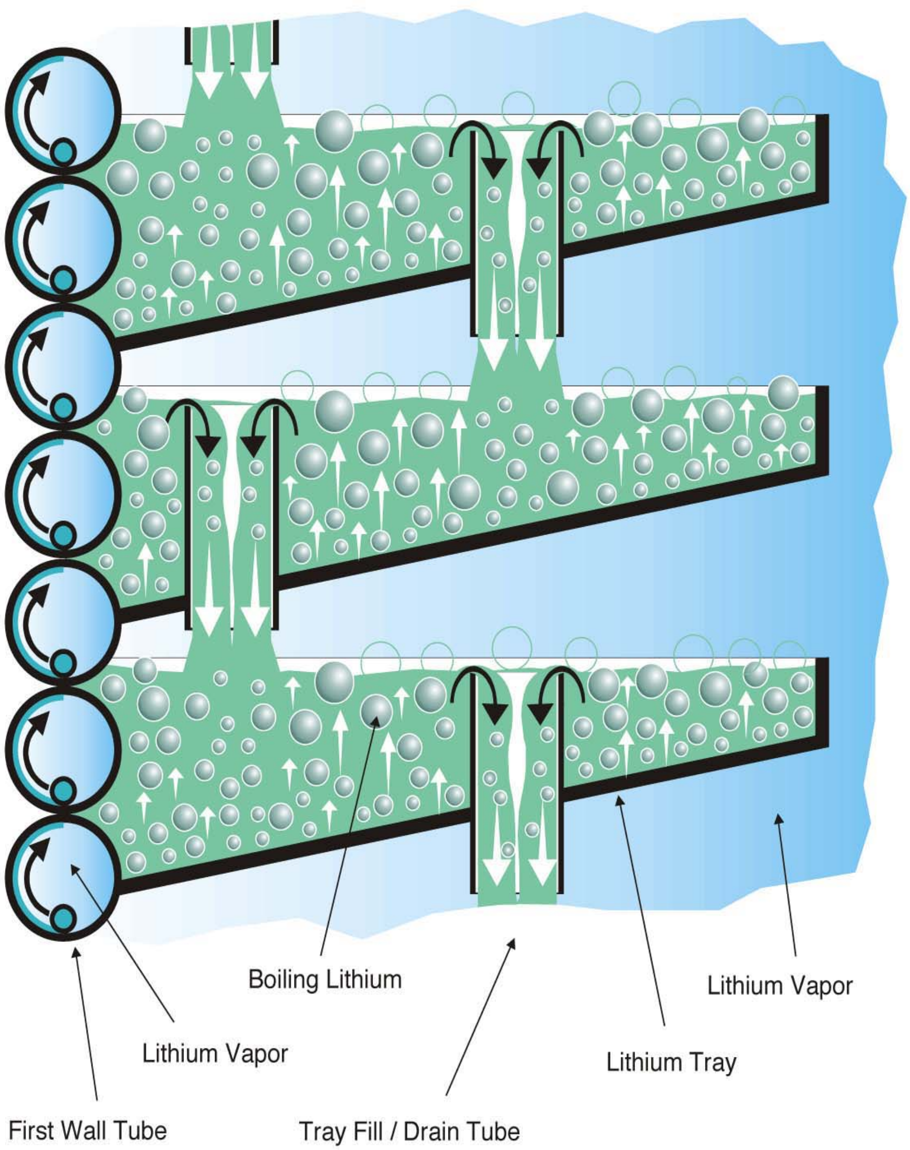




Liquid lithium limiter in CDX-U

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.

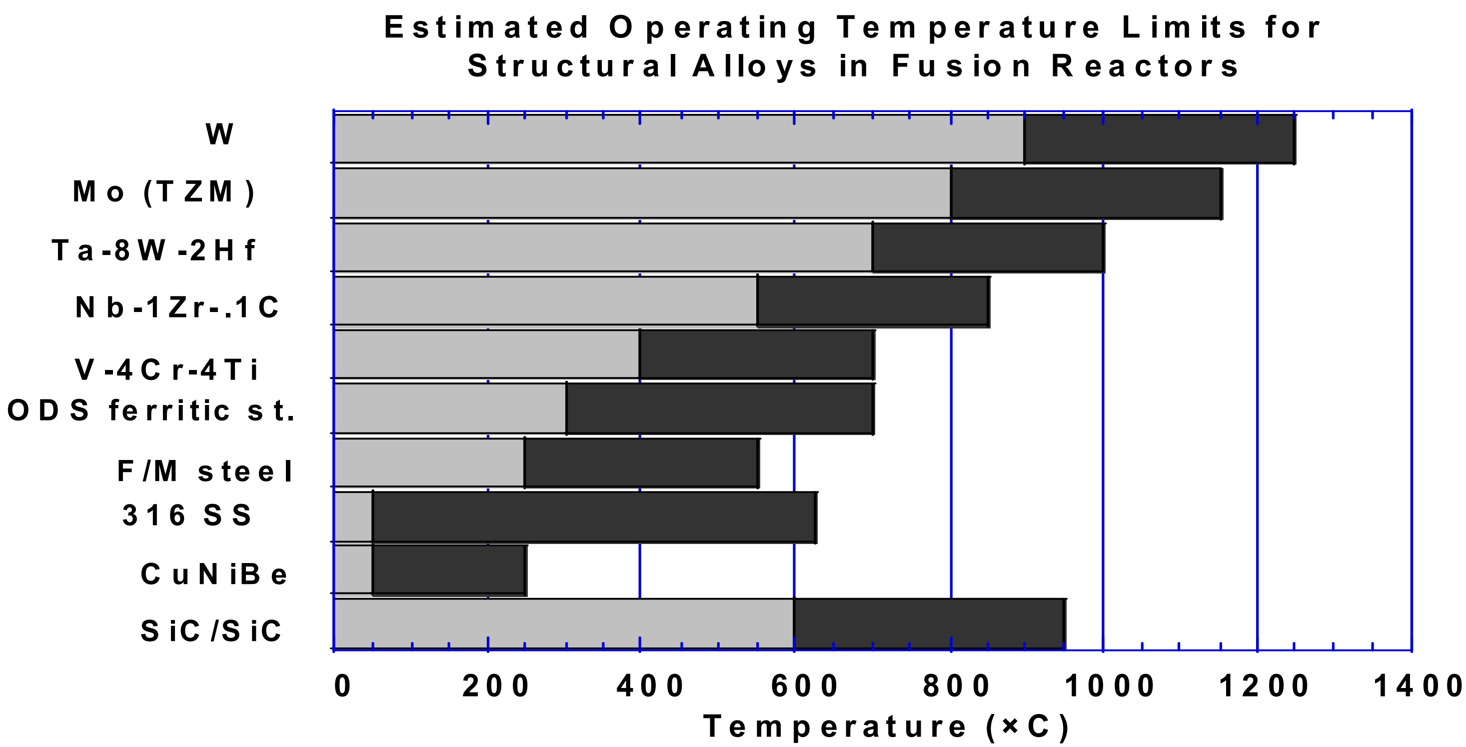
Key Issues for EVOLVE

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

APEX FY 2000 Activities
(started 11/99)

- In this new phase of APEX, the effort is focused on a more detailed exploration of two classes of concepts:

  1) Liquid Walls (several variations)

  2) EVOLVE (W with 2-phase Li)

- The effort includes:
  - Modelling
  - Analysis
  - Laboratory Experiments
  - Experiments in Plasma Devices

- There is a stronger involvement from the physics community in this new phase.

- The study is now organized around a number of Tasks. Each Task has a Leader and a Core Group.

5-Year Goals

Liquid Walls:

1. Fundamental understanding of free surface fluid flow phenomena and plasma-liquid interactions verified by theory and experiments

2. Operate flowing liquid walls in a major experimental physics device (e.g. NSTX).

3. Begin construction of an integrated Thermofluid Research Facility to simulate flowing liquid walls for both IFE and MFE.

4. Understand and document advantages and implications of using liquid walls in fusion energy systems.

Solid Walls:

5. Understanding of novel concepts that can extend the capabilities and attractiveness of solid walls.

APEX
FY 2000 Technical Tasks:

Study Leader: Mohamed A. Abdou

Task I: Explore options and issues for implementing a flowing liquid wall in a major experimental physics device. Characterize the technical issues and develop an R&D plan.

Task Leader: Alice Ying

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

Task Leader: Neil Morley

Task III: Investigate practical engineering issues associated with the design of a liquid wall in a high-power density fusion energy system (start with CLIFF-flibe because it is better understood and has more data available).

Task Leaders: Dai-Kai Sze and Brad Nelson

Task IV: Investigate key issues and develop a practical design for high-temperature refractory solid wall with primary focus on EVOLVE.

Task Leader: Clement Wong

Task V: Other tasks.

APEX Cross-Cutting Tasks for FY 2000

Task A: Plasma-Liquid Surface Interactions and Plasma Edge Modelling
Task Leader: Tom Rognlien

Task B: Liquid Wall-Bulk Plasma Interactions
Task Leader: Bob Kaita

Task C: Materials
Task Leader: Steve Zinkle

Task D: Safety and Environment
Task Leader: Kathy McCarthy