Executive Summary

The objective of the APEX study has been to identify and explore novel, possibly revolutionary, concepts for Fusion Chamber Technology that can substantially improve the attractiveness of fusion energy systems. The first phase of the study was carried out in 1998-1999 by a multi-disciplinary integrated team of scientists and engineers from twelve U.S. organizations with participation of experts from Germany, Russia, and Japan. A set of goals for the Chamber Technology were adopted to calibrate new ideas and to measure progress. These goals include: 1 – high power density capability with neutron wall load >10 MW/m^2 and surface heat flux >2 MW/m^2, 2 – high power conversion efficiency (>40%), 3 – high availability (i.e. low failure rate and fast maintenance) and 4 – simple technological and material constraints.

A number of promising ideas for new innovative concepts have already emerged from the first phase of the APEX study. While these ideas need extensive research before they can be formulated into mature design concepts, some of them offer great promise for fundamental improvements in the vision for an attractive fusion energy system. These ideas fall into two categories. The first category seeks to totally eliminate the solid “bare” first wall. The most promising idea in this category is a flowing liquid wall concept. The liquid wall idea is “concept rich” and has many variations. The second category of ideas focuses on extending the capabilities, particularly the power density and temperature limits, of solid first walls. A promising example is the use of high temperature refractory alloys (e.g. tungsten) in the first wall together with an innovative heat transfer and heat transport scheme based on vaporization of lithium.

Liquid Walls

The liquid wall idea evolved during the APEX study into a number of concepts that have some common features but also have widely different issues and merits. These concepts can be classified according to: (a) the type of working liquid, (b) the thickness of the liquid flow, and (c) the type of restraining force used to control the liquid flow.

Basic Principles and Concepts

The practical candidates for the working liquid are the liquid metals lithium and Sn-Li (Sn-Li was introduced into APEX because it has very low vapor pressure), and the molten salt Flibe. The hydrodynamics and heat transfer characteristics of high conductivity, low Prandtl Number liquid metal flows will depend heavily on the interactions with the magnetic field and are considerably different from low-conductivity, high Prandtl Number Flibe flows which will be dominated by turbulence considerations. The Z number and ionization potential of any vapor generated from the liquid surface will affect significantly the plasma contamination levels. The relative hydrogen solubility in the working liquid will play a significant role in the structure of the edge and the stability of the plasma discharge.

In addition, high conductivity liquid metal (LM) flows have the potential to affect the local magnetic fields and the plasma stability in a potentially positive manner. LM walls appear capable of allowing stable tokamak operation with increased elongation under reactor conditions. Modeling results indicate that the magnitude of improvement can be large with up to a factor of three improvement in stable beta (from 5-7% to 20-22%) at aspect ratio 4 and 3, respectively. Flowing liquid metals can potentially stabilize resistive wall modes as well allowing higher beta steady state equilibria with very hollow current profiles. Steady state operation with such profiles enables high bootstrap fractions and thus low recirculating power. Also, hollow current profiles are theoretically predicted to give $\mathbf{E} \times \mathbf{B}$ shearing rates larger than instability growth rates for conventional drift instabilities, leading to transport barriers and high confinement.

The thickness selected for the liquid wall layer flow (directly facing the plasma and in front of a solid “backing wall”) leads to different concepts that have some common issues but many unique advantages and challenges. Both thin and thick liquid walls can adequately remove high surface heat flux. A primary difference between thin and thick liquid walls is the magnitude of attenuation of neutrons in the liquid before they reach the backing wall. The “thin” liquid wall concept is easier to attain, but “thick” liquid wall concepts greatly reduce radiation damage and activation of the structure. Assuming a 200 DPA damage limit for structure replacement, the use of about 40 cm Flibe or Sn-Li can make the structure behind it a lifetime component. Furthermore, the volume of the radioactive waste from the FW/blanket system is greatly reduced.

Widely different liquid wall concepts are also obtained by applying various forces to drive the liquid flow and restrain it against a backing wall. An example is the Gravity-Momentum Driven (GMD). In the GMD concept, the liquid is injected at the top of the chamber with an angle tangential to the curved backing wall. The fluid adheres to the backing wall by means of centrifugal force and is collected and drained at the bottom of the chamber. The criterion for the continuous attachment of the liquid layer is simply that the centrifugal force pushing the liquid layer towards the wall is greater than the gravitational force.

Using Flibe as the working fluid, the GMD concept has been modeled with a 3-D, time-dependent Navier-Stokes Solver that uses Reynolds Averaged Navier Stokes (RANS) equations for turbulence modeling and the volume of fluid (VOF) free surface tracking algorithm for free surface incompressible fluid flows. Example solutions at 8 m/s inlet velocity demonstrate that a stable, thick fluid configuration can be established and maintained throughout a tokamak reactor configuration. Nevertheless, gravitational acceleration and mass continuity lead to some amount of jet thinning as it proceeds from the top to the bottom of the reactor. Jet thinning can be overcome by increasing the initial jet velocity, and a fairly uniform thick liquid film can be obtained throughout the plasma chamber if the jet is injected at 15 m/s. The thinning can also be minimized by the MHD drag from the Hartmann velocity profile in a flow with conducting toroidal breaks. More analysis of this effect is needed for Flibe.

Numerical analyses were also performed for LM flows in GMD to determine whether or not an insulator is needed for free surface MHD flows, and to define lithium's initial velocity that enables a uniform thickness to be maintained throughout the plasma chamber in the presence of the toroidal magnetic field. The preliminary analysis based on simplified magnetic field geometries with only toroidal or radial fields shows that the MHD drag effect significantly increases the layer thickness and causes the associated reduction in the velocity. Thus, there is a need of insulators for a free-surface LM flow if a toroidally segmented poloidal liquid metal flow configuration is considered (other clever options may be possible that do not need an insulator). For an insulated open channel, calculations indicate that a uniform 40 cm-thick lithium layer can be maintained along the poloidal path at a velocity of 10 m/s.

Heat transfer calculations indicate that poloidal flow options like the GMD will have a surface temperature rise in the range of 150˚C for lithium, and from 25-150˚C for Flibe (depending on turbulence assumptions) when flowing at 10 m/s. A better understanding of free surface heat transfer (including the hydrodynamics near the free surface / plasma interface) is needed to more concretely determine these values.

Variations of the GMD for the low aspect ratio Spherical Torus (ST) and cylindrical FRC include adding an additional azimuthal (toroidal) velocity to produce rotation. The "swirl flow" results in a substantial increase in the centrifugal acceleration towards the back wall and better adherence to the wall, when the backing wall curvature in the poloidal direction is large and the toroidal curvature is comparable to poloidal curvature.

The thin wall analog of the GMD is the *C̲onvective L̲iquid F̲low F̲irst-Wall*, or CLiFF, concept, where the goal is to eliminate the presence of a solid FW facing the plasma through which the surface heat load must conduct. This goal is accomplished by means of a fast moving (convective), thin liquid layer flowing on the plasma side of the FW. Such a thin layer is easier to control than a thick liquid system, but still provides a renewable liquid surface immune to radiation damage and sputtering concerns, and largely eliminates thermal stresses and their associated problems in the first structural wall. The CLiFF class of liquid wall concepts is viewed as a more near-term application of liquid walls, and is suitable for some currently operating plasma devices.

MHD analysis for LM-CLiFF has shown that the MHD drag can be significant if there is a radial magnetic field component – one normal to the free surface. Analyses indicate that a metallic backplate is acceptable with insulated toroidal breaks if the radial magnetic field is no more than 0.1-0.15 T. The acceptable field magnitude would drop to 0.015 T for the case of toroidally continuous flow. Other important MHD issues such as flow across field gradients (1/R dependence of the toroidal field for example), temporal fluctuations during start-up and plasma control will be addressed in the next phase.

Penetrations will be required for plasma-support functions such as heating and fueling. Novel schemes for accommodating penetrations in liquid walls have been proposed. For example, modifications to the back wall topology to guide the flow around elongated penetrations are found to be effective. Computational 3-D fluid dynamic simulation results for the CLiFF concept with Flibe show significantly reduced liquid layer disturbance, no splash at the stagnation point, and no unwetted regions downstream the penetration. These results are encouraging and provide an excellent start for studying penetrations in thick liquid walls, where the volume of fluid is much larger.

The Electromagnetically Restrained (EMR), applicable only to liquid metals, is another example of liquid wall concepts. EMR utilizes a **J x B** force field to push the liquid against the backing wall. An injected poloidal current interacts with the main toroidal magnetic field to generate this force, resulting in liquid layer adherence to the back wall at potentially lower velocities than required for the GMD.

Other active control schemes with injected currents have been proposed as well, and will continue to be investigated with new modeling tools being developed for the task.

Motivation for Liquid Wall Research

There are many attractive features of liquid walls that have motivated this research:

- High Power Density Capability
    - -Eliminate thermal stress and wall erosion as limiting factors
    - -Smaller and lower cost components (chambers, shield, vacuum vessel, magnets)
- Improvements in Plasma Stability and Confinement
    - -Enable high β, stable physics regimes if liquid metals are used
- Increased Potential for Disruption Survivability
- Reduced Volume of Radioactive Waste
- Reduced Radiation Damage in Structural Materials
    - -Makes difficult structural material problems more tractable
- Potential for Higher Availability

It is not clear yet that all these advantages can be realized simultaneously in a single concept. However, the realization of only a subset of these advantages will result in remarkable progress toward the attractiveness of fusion energy systems.

Key Issues for Liquid Walls

The scientific and engineering issues for liquid walls are many. Of all the potential issues, a number of them stand out as the highest priority for near-term liquid wall research.

1. Plasma-liquid interactions including both plasma-liquid surface and liquid wall-bulk plasma interactions: plasma stability and transport may be seriously affected and potentially improved through various mechanisms including control field penetration, H/He pumping, passive stabilization, etc. More careful estimates for the allowable amount of liquid evaporation and sputtering need to be obtained and benchmarked.

2. Hydrodynamics flow feasibility in complex geometries including penetrations: the issue of establishing a viable hydrodynamic configuration threatens feasibility, while it differs significantly for thick versus thin and for molten salts versus liquid metals. The main issue facing liquid metals is of course that of MHD interactions. Without toroidal axi-symmetry of the flow and field, reliable insulator coatings will be required on all surfaces in contact with the LM layer. Eddy current forces perpendicular to the surface can pull the LM off the surface, even when complete axi-symmetry is assumed in the toroidal direction. Additionally, gradients in toroidal field can exert a significant drag on the free surface flow. For thick liquid walls, the main issues concern the formation and removal of the liquid flow in the plasma chamber, and the accommodation of penetrations.

3. Heat transfer at free surface and temperature control: liquid surface temperature and vaporization is a critical, tightly coupled problem between plasma edge and liquid free surface conditions including radiation spectrum, surface deformation, velocity and turbulent characteristics. Being a low thermally conducting medium**,** the Flibe surface temperature highly depends on the turbulent convection. However, the normal velocity at the free surface as well as the turbulent eddy near the surface can be greatly suppressed. The issue of heat transfer at free surfaces is a serious concern as the preliminary plasma-edge modelling estimate for the limit on the surface temperature for Flibe appears to be relatively low.

High-Temperature Solid Wall Concepts

APEX also explored ideas for extending the power density and operating temperature capabilities of solid walls. Achieving high power density means that the coolant heat removal capability must be high and the first wall material must have attractive thermophysical properties. Since materials operating at very high temperatures generally have limited strength, such concepts should operate at low primary stresses. This requires that the coolant pressure be as low as possible, and the temperatures throughout the first wall and blanket be as uniform as possible to reduce thermal stress.

Analysis of materials shows that the only structural materials suitable for high-power density, high-temperature operation are refractory alloys. A tungsten alloy, e.g. W – 5% Re, was selected as the primary candidate material, with tantalum alloys as the back-up. The minimum and maximum operating temperature for W and other structural materials were estimated. For W, the lower and upper operating temperature limits are about 900˚C and 1250˚C, respectively, depending on the choice of the coolant and the applied stress. The lower temperature limit is based on radiation hardening/fracture toughness embrittlement due to low temperature irradiation. There is a large uncertainty in the lower temperature limit for radiation embrittlement in W due to lack of mechanical properties data at irradiation temperatures above 700 ˚C. The upper temperature limit is based on thermal creep considerations and, depending on the coolant, could be further reduced due to corrosion issues.

Two coolant schemes were evaluated. The first uses helium with the motivation to explore the possibility of using high temperature helium for high-efficiency energy conversion in a gas turbine cycle. The key difficulties with helium cooling are the very high pressure (~12 Mpa) and large temperature rise, which push the requirements on the refractory alloy structural material to the range of uncertainty in available data.

A more promising idea is an innovative cooling scheme based on the use of the heat of vaporization of lithium (about 10 times higher than water) as the primary means for heat removal. This idea, called EVOLVE (Evaporation of Lithium and Vapor Extraction) was explored in APEX in some detail and will continue to be investigated.

Calculations indicate that an evaporative system with Li at ~1200˚C can remove a first wall surface heat flux of >2 MW/m^2 with an accompanying neutron wall load of >10 MW/m^2. The system has the following characteristics:

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.

A preliminary conceptual design was developed and analyzed for EVOLVE. Key issues that need to be addressed in the future in order to assess the potential of the concept include: 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, and 4) analysis of safety issues associated with the high afterheat in tungsten in case of a LOCA.

Future Work

The APEX team has already initiated its efforts for the next phase which will focus on more detailed exploration of liquid walls and EVOLVE. The effort will include modeling, analysis, laboratory experiments, as well as collaborating with the physics community to conduct liquid wall relevant experiments in existing plasma physics devices.