Summary of Thick Liquid FW/Blanket for High Power Density Fusion Devices

The replacement of the first wall with a flowing thick liquid offers the advantages of high power density, high reliability and availability due to simplicity and low failure rates, reduced volumes of radioactive waste, and increased lifetime. All these advantages render the thick liquid wall approach a strong candidate in the APEX study. Specifically, neutronics analyses showed that with ~42-cm layer thickness, about 2 orders of magnitude reduction in helium and hydrogen production is achieved with either Flibe or Sn-Li. With this thickness, and a 200 DPA damage limit for replacement, the use of Flibe can make the structure behind it a lifetime component. Furthermore, the radioactive hazard and waste from the FW/blanket system is reduced by about two to three orders of magnitude. The emphases of the Phase-I study include the exploration of design ideas, quantification of their high power density capabilities, and identification and analyses of the key feasibility issues of thick liquid wall configurations for various confinement schemes. The initial goal is to establish a free surface flow configuration. This involves: (1) an inlet nozzle and penetrations that pass flow without dripping or splashing, (2) a free surface flow section that allows liquid across temporally and spatially variable magnetic fields and provides full wall coverage, and (3) a head recovery nozzle system that accepts the flow and converts it from a free surface flow to a channel (pipe) flow.

There are three lithium-containing candidate liquids for the walls: 1) a good neutron absorber and low electrically conducting medium of molten salt Flibe, 2) a low Z material that is more likely compatible with the plasma operation of lithium, and 3) an extremely low vapor pressure fluid of tin-lithium. Both lithium and tin-lithium are good electric conductors. Utilization of these two materials will have to deal with MHD effects, not just in the surface flows, but in supply lines and feed systems, and it also would require electrical insulating coatings.

Design ideas of establishing thick liquid walls were addressed for Tokamak (such as ARIES-RS), Spherical Torus (ST), and Field Reverse Configuration (FRC). The fact that topologies are different in different confinement schemes requires different liquid wall design approaches. For example, as compared to the ARIES-RS, the ST confinement scheme tends to be highly elongated and uses a smaller radius as illustrated in Figure 1. Consequently, the centrifugal force carried by the fluid flowing across an ST configuration is higher than that in the ARIES-RS although it is flowing at the same velocity. Thus, one may expect a more stable hydrodynamics condition in the ST liquid blanket. However, being highly elongated, the fluid takes more time to travel through the reactor if only one coolant stream is used. This implies that the free surface side may be over heated from a long exposure time. A typical FRC reactor can be viewed as a long cylinder in which a football shape of plasma lies at the center of the reactor chamber (see Figure 2). The FRC confinement scheme appears more amenable to thick liquid walls due to its geometrical simplicity.

One of the most fundamental issues for thick liquid blanket is how to form, establish, and maintain such a thick liquid flow in a fusion reactor such as the ARIES-RS as shown in Figure 1. The simplest approach that can be conceived for a thick liquid blanket is free falling film under the effect of gravitational force. As illustrated in Figure 3, the thick liquid layer is injected at the top of reactor chamber with an angle tangential to the backing structural wall. Meanwhile the fluid adheres to the structural wall by means of centrifugal and inertial forces and is collected and drained at the bottom of the reactor. The hydrodynamics approach has been modeled with FLOW-3D: 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 FLOW-3D solutions, as shown in Figure 4, demonstrate that stable, thick fluid configurations can be established and maintained throughout a tokamak reactor configuration. Nevertheless the analyses indicate that some amount of thinning results from the gravitational acceleration and flow area expansions as the flow proceeds downstream. As shown, the fluid thickness is reduced by about a factor of 2 at the reactor midplane for an initial injecting velocity of 8 m/s. This thinning reduces liquid's potential for radiation protection of solid walls behind the liquid and creates an unfavorable situation for shielding. The jet thinning effect can be overcome by increasing the initial jet velocity; and a fairly uniform thick liquid film can be obtained throughout the plasma core if the jet is injected at velocities of 15 m/s or above.

The thinning effect due to the gravitational acceleration can be minimized by the MHD drag from the Hartmann velocity profile in a liquid metal flow. Numerical analyses are performed to determine whether the insulator is needed or not 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 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 liquid metal flow if a segmented toroidal liquid metal flow configuration is considered. As shown in Figure 5, 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. At this velocity, the total pressure (dynamic and static) exerted on the backplate is about 4800 N/m^2. This magnitude of pressure can be easily managed. In contrary, if the side-walls of the channel are submerged under the fluid a fast surface layer can form naturally. The liquid near the surface, above the submerged insulated side-walls, will be unfettered by MHD drag except in areas close to penetrations, and a thin, fast layer at the surface will result (see Figure 6).

The influence of the conducting backplate on the liquid metal flow characteristics is negligible in the presence of a purely toroidal magnetic field. But, 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 if the radial magnetic field is no more than 0.1-0.15 T in the presence of insulated side walls. This magnitude would drop to 0.015 T for the case of toroidally continous flow. Other 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, have yet to be addressed.

An alternate way to form a thick liquid flow is to utilize a rotating swirl flow, where again centrifugal forces keep the liquid against the wall. The scheme appears attractive for the FRC device because of its geometric simplicity. To create a rotational flow, the liquid carries both longitudinal and azimuthal velocity components. The flow spirals while it proceeds along the flow axis as illustrated in Figure 7. Numerical hydrodynamic analysis using FLOW-3D code with Flibe as the working fluid shows that a 0.6 m thick liquid first wall /blanket can be formed in a circular vacuum chamber of 2 m radius at an axial velocity of 7 m/s and an azimuthal velocity of 10 m/s. In this design, the fluid enters the main chamber zone through a convergent nozzle and is discharged to a divergent outlet after one turn rotation. The velocity field along the axial direction is shown in Figure 8. As noted in the FLOW-3D result, the fluid encounters different net forces along the circumferential direction due to different gravity effects, which result in non-uniform hydrodynamics characteristics along the flow axis. Studies indicate that an acceptable variation in liquid layer thickness in azimuthal and axial directions can be maintained for flowing Flibe with axial and azimuthal inlet velocities of 11 m/s and 13 m/s, respectively, in a cylindrical chamber with a 2 m radius and 12 m length.

The swirl flow concept can also be applied to the ST outboard FW/blanket region. In this case, a thick liquid carrying both vertical and azimuthal velocity components is injected at the top of the reactor. The centrifugal acceleration (> 35 m/s^2) pushes the fluid towards outward and prevents the flow from deflecting into the plasma core. The axial velocity increases as the flow proceeds downstream due to the gravitational acceleration and this leads to flow thinning. The thinning effect is further manifested in the ST because of the toroidal area expansion along the flow direction (the flow area increases by a factor of 2 as the flow approaches the mid-plane). Various numerical simulations were performed to identify “ways” to slow down the velocity and to reduce the thinning effect. Preliminary results, based on FLOW-3D calculations, indicate that the thinning effect can be mitigated by tailoring the back wall contour and by incorporating a step along the flow direction. The calculated “step” of about 0.2-m high, located at the reactor mid-plane, helps to maintain the liquid layer thickness greater than 0.3 m. In contrast to the rotational flow for the outboard blanket, a fast annular liquid flows along (no rotation) the central post forming the inboard FW/blanket zone, as shown in Figure 9.

These hydrodynamics (with or without the effect of magnetic field) calculations indicate that a fairly uniform thick liquid wall can be formed in the aforementioned fusion relevant configurations as long as the injected fluid carries an adequate inertial momentum (e.g., corresponding to a velocity of 10 m/s). Moreover, the pumping power requirement becomes less of a concern for higher power density confinement concepts (such as FRCs) as shown in Figure 10. However, for a thick liquid wall concept to work, there remain many design issues particularly in the areas of moving liquid in and out of the reactor, of spatially and temporally MHD effects, and of accommodation of penetrations. Certainly, designs and analyses of the inlet and exit head recovery systems are needed for all the aforementioned concepts. Regarding the accommodation of fluid passing penetrations, FLOW-3D simulations are performed to understand the underlying scientific phenomena and provide design guidance. The challenges for accommodating penetration include flow stagnation at the front point of the penetration resulting in discharge of the fluid towards the plasma, rising of the fluid level surrounding the penetration due to the obstruction of flow path, and wake formation that persists downstream of the penetration. Different means have been proposed to avoid fluid splashing and to minimize disturbance. These involve modification of penetration shapes, introduction of guiding grooves and fins, and alteration of the back wall topology such as shown in Figure 11. Preliminary analyses for CLIFF concepts (2-cm thick convective liquid layer) confirm the effectiveness of the proposed schemes. As illustrated in Figure 12, Flow3D results show a much reduced level rise, no splash occuring at the stagnation point, and no separation in the flow field. These results are encouraging and provide "mechanism" for solving penetration issues in thick liquid wall concepts (in which much more fluid has to be dealt with.) The problem associated with penetration accomodating is considered as one of the high prioty issues to be continously addressed.

The power emanating from the burning plasma striking the liquid will cause its surface temperature to rise as it passes along the walls of the chamber. The temperature of the free liquid surface facing the plasma is the crucial parameter, which governs the amount of liquid that evaporates into the plasma chamber. However, it can only be determined accurately if the heat transfer at the free surface/vacuum boundary is well understood.

Since a liquid metal wall will be highly laminarized by the magnetic field, the heat transfer at the free surface wall is determined by the laminar convection and conduction. Furthermore, the lithium surface temperature is reduced because the surface heat load is deposited into the bulk due to x-ray penetration. Calculations show that, under a surface heat flux of 2 MW/m^2, the lithium free surface temperature drop can be kept below 100 ^{o}C at a velocity of 20 m/s throughout the reactor, taking account of x-ray penetration (see Figure 13). This film temperature drop increases to 140 ^{o}C if the lithium velocity decreases to 10 m/s. Nevertheless, it appears that the lithium free surface temperature can be maintained below 400 ^{o}C, which may be acceptable to the plasma operation. The surface temperature rise for Sn-Li as it reaches the bottom of the reactor is higher than that of lithium flowing at the same velocity. This is due to a lower thermal conductivity and a higher z. However, because of its low vapor pressure, Sn-Li can flow at lower velocities for higher surface temperatures yet not jeopardize plasma operations. However, the potential of using Sn-Li for a non-structure-thick liquid wall design is limited by its high density. As shown in Figure 14, a velocity magnitude of about 7.5 m/s or more is needed to maintain the liquid adherence to the wall as well as the surface temperature to remain below 827 ^{o}C (vapor pressure corresponding to that of lithium at 400 C). The corresponding pumping power is about 6 % of a fusion power of 5480 MW for a 45 cm thick Sn-Li FW/blanket.

The molten salt Flibe, which conducts heat poorly but convects heat very well, is not fully laminarized by the presence of the magnetic field. The heat transfer at the Flibe free surface wall is dominated by the rapid surface renewal of the turbulent eddies generated either near the back wall or nozzle surfaces by frictional shear stress or near the free surface due to temperature driven viscosity variations. Accurate calculations of Flibe free surface temperature require the knowledge of the turbulent structures, eddy generation and dissipation, and the degree of damping by the magnetic field. In the attempt to calculate the Flibe free surface temperature and to examine the effects of the magnetic fields on turbulence suppressions, a κ–ε model of turbulence was developed.

Preliminary results based on the κ–ε model of the turbulence, including MHD effects and various boundary conditions, predict a range of temperatures that may be beyond the plasma compatible temperatures. As shown in Figure 15, if the Flibe flow is laminarized, the Flibe free surface can be over heated. The film temperature drop can reach 700 ^{o}C at the bottom of ARIES-RS under APEX 2 MW/m^2 surface heat load (curve 1) while turbulent heat transfer considerably reduces Flibe free-surface temperature drop (curve 2). On the other hand, accounting for Bremsstrahlung radiation penetration further reduces surface temperature by about 90 ^{o}C (curve 3). Furthermore, heat transfer at the vacuum/free surface interface can be significantly enhanced by the existence of surface turbulence (curve 4), while turbulence suppression due to MHD can be neglected at the current parameters of interest (curve 4). If the Flibe surface temperature is high relative to the plasma operation limit, further design modifications such as using 2 coolant streams may be required to accommodate this deficiency.

The challenges of the liquid wall designs go beyond achieving a low enough surface temperature compatible with the plasma operations, but also to maintain a mean bulk temperature of greater than 600 ^{o}C for high thermal efficiency (see Figure 16). This temperature can be higher than the maximum allowable free surface temperature. The consequence may imply a thick liquid wall design involving two different coolant streams: one for surface heat removal and the other for neutronics heat deposition in order to simultaneously achieve these two temperature requirements. A subsequent design option for power conversion would then include two cycles: one for the conversion of the thermal power in the first wall and divertor coolants, and the other for conversion of the thermal power in the blanket coolant, which has a much higher thermal conversion potential. Since thick liquid walls would result in decreases in both the neutron damage rate and helium transmutation rate, the choice of the structural material should be determined by the high temperature capability and liquid/structure compatibility. It appears that the use of tungsten alloys would achieve the highest thermal efficiency because of its high temperature operation capability. The ODFS can operate up to a temperature of 650 ^{o}C, which provides a thermal efficiency of about 41.2%.

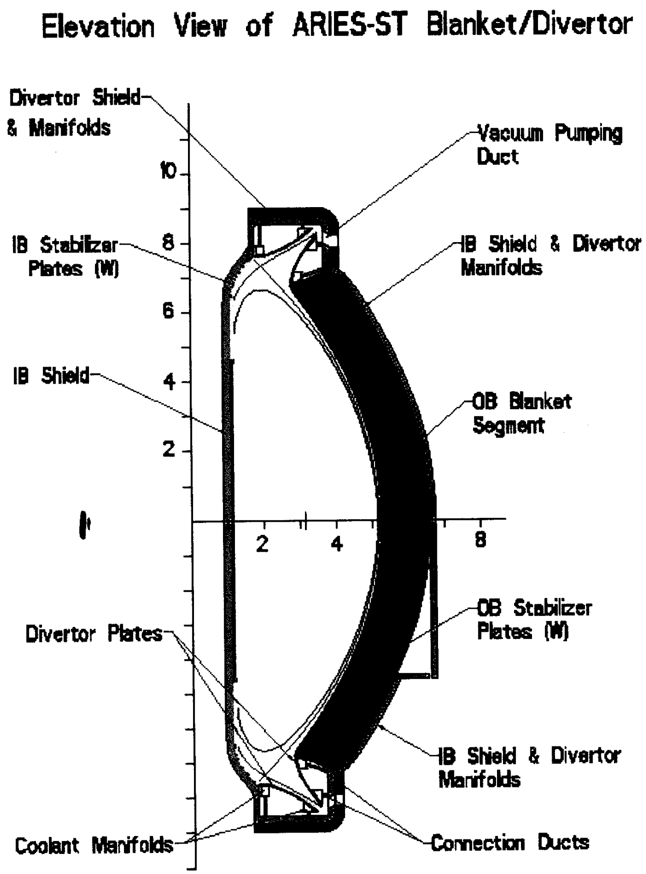
The present state of understanding of thick liquid blankets do not uncover any basic flaws in the underlying scientific and technical arguments for the concepts. Yet, there remain many issues for the implementation of this concept in any magnetic fusion configuration. Engineering innovations and analyses are required for the following numerous mechanical design issues, including:

- How to move mass quantities of liquid metal or salt in and out of the machine reliably
- How to provide sufficient access for supply piping and return ducts
- How to design the piping and nozzles for reliable operation at high fluid velocity
- How to start and stop the system safely
- How to keep the stream attached to the inboard wall (must prevent toroidal rotation of inboard stream)
- How to provide sufficient penetrations for heating and diagnostics
- How to account for image current effects from moving plasma

Near term R&D would focus on feasibility modeling and experiments and concept exploration. The critical issues to be addressed include:

(1) Liquid metal flow in 1/R toroidal field variation, effects of finite radial, polodial and vertical field components.
(2) Mechanisms of accommodation penetrations and experimental phenomena of flow around penetrations.
(3) Flibe free surface flow heat transfer and heat transfer enhancement.

	ARIES-RS	ARIES-ST
Major Radius (m)	5.52	2.8
Minor Radius (m)	1.38	2
Plasma Aspect Ratio	4	1.4
Elongation		3.75
Fusion Power (MW)	5480	5470
(Modified for APEX)		
FW Surface Area (m^2)	438.8	541
Neutron Wall Load (MW/m^2)	10	8.085
Surface Heat Flux (MW/m^2)	2	2



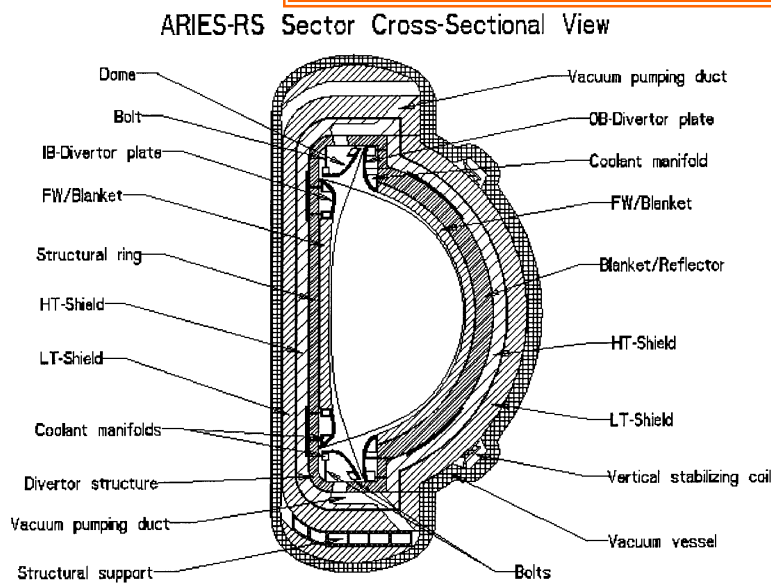


Figure 1 Hydrodynamics configurations of thick liquid walls may be very Different for ARIES-RS and ARIES-ST. Both configurations are converted to single null at the bottom of plasma compatible with the liquid wall configuration.

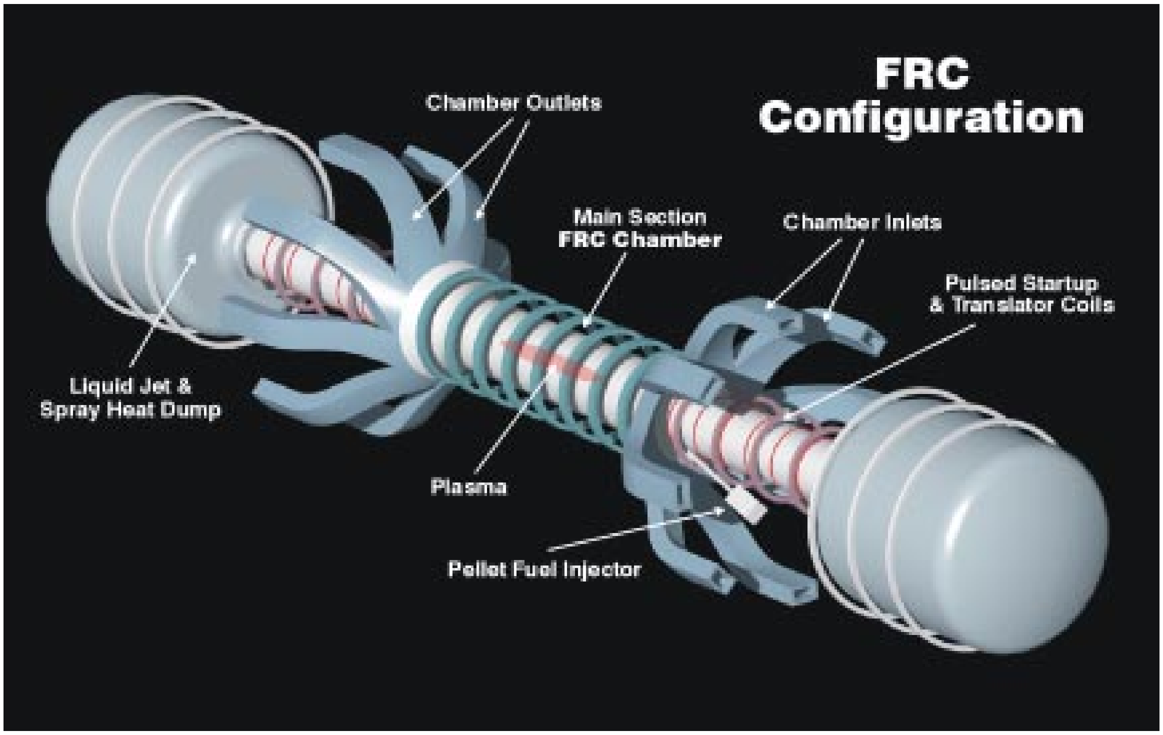


Figure 2 General layout of a FRC power plant design.

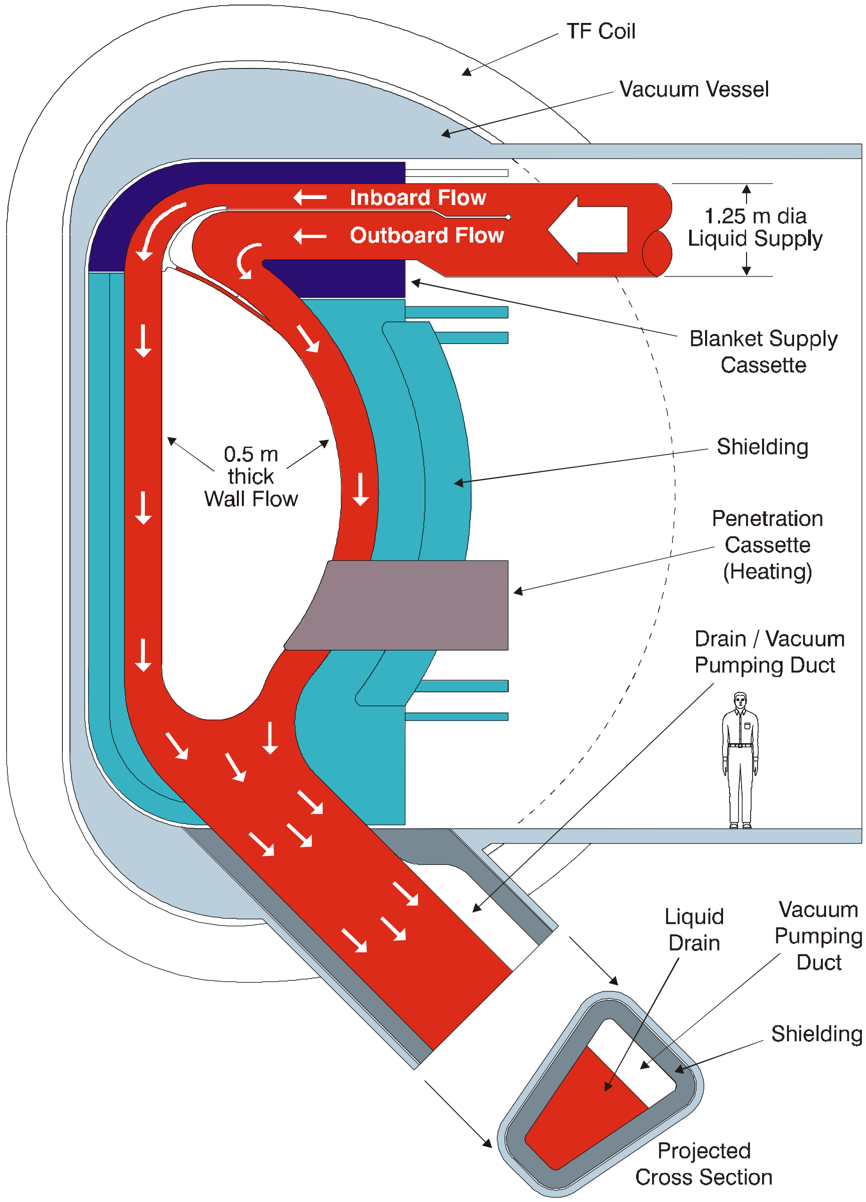


Figure 3 A thick FW/blanket design incorporated into the ARIES-RS configuration.

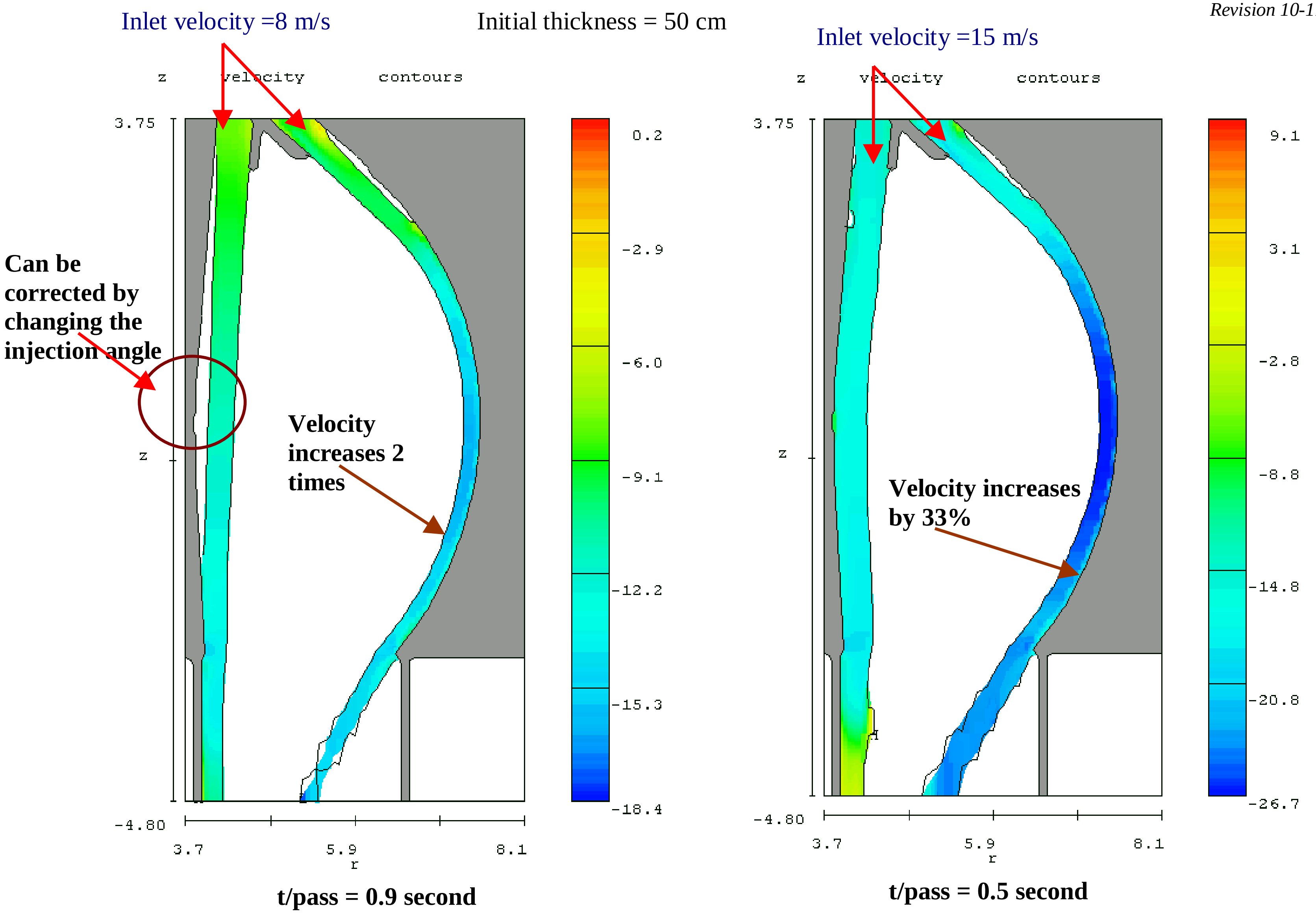


Figure 4 Some amount of thinning was observed along the poloidal path due to gravitational acceleration and toroidal area expansion (Z-velocity components increase along the structural inner walls from 3-D hydrodynamics calculations)

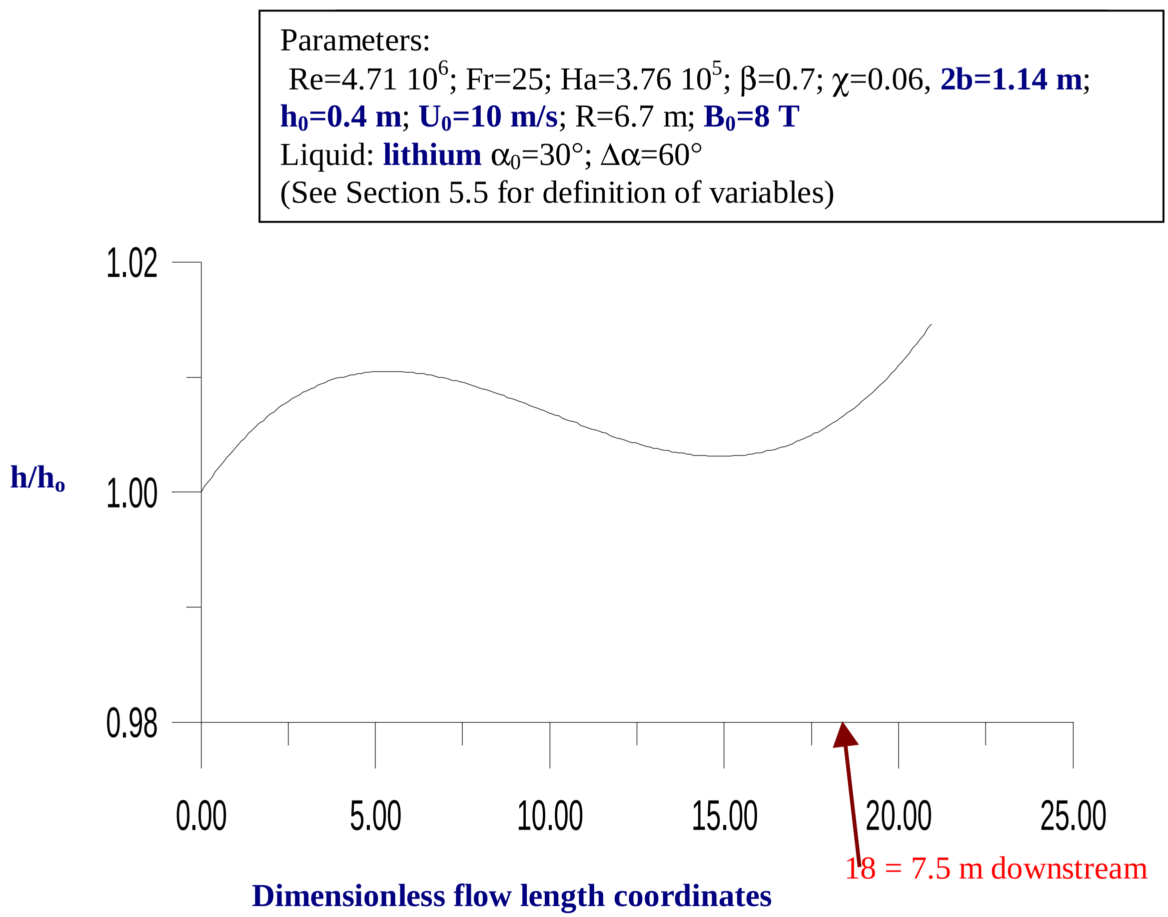
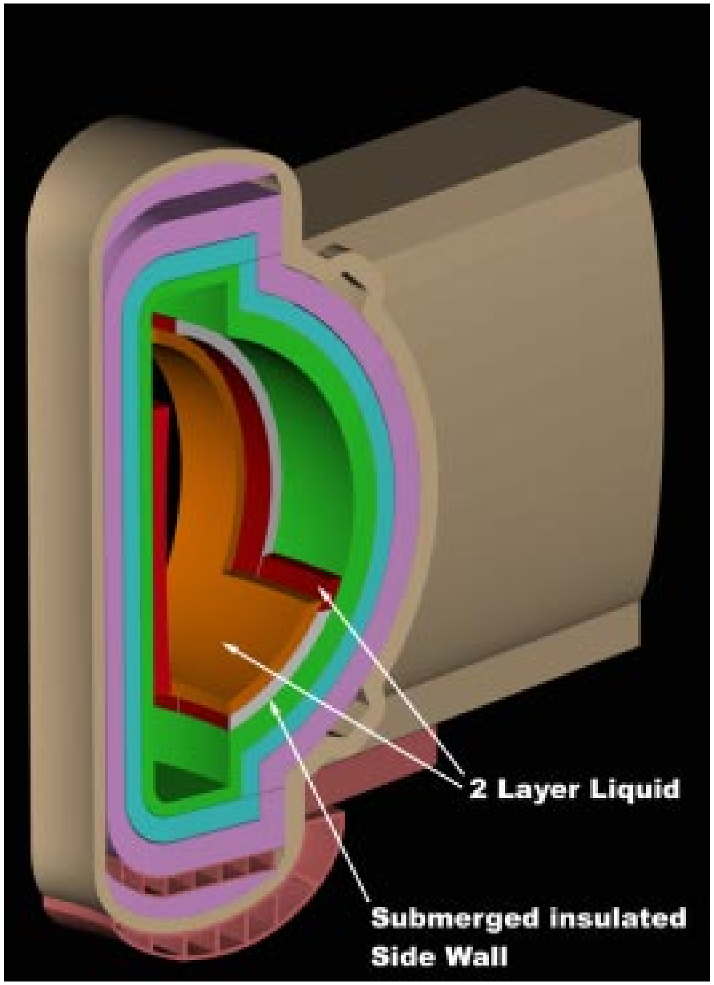


Figure 5 The thinning effect due to gravitational acceleration can be minimized by the drag from the M-shape velocity profile (A unifrom thickness of 40 cm can be establsihed fro 10 m/s lithium flow.)



<u>Lithium flow</u>: U_0=10 m/s; **h_0=40 cm; 2b=1.14 m**; B_0=8 T; R=6.7 m; α_0=30°; $\Delta\alpha$=60°; **h_w/h_0=0.5**; **c_w=0**
$X_{1\text{-}1}$=1.7 m; $X_{2\text{-}2}$=3.4 m; $X_{3\text{-}3}$=5.1 m; $X_{4\text{-}4}$=6.8 m; $X_{5\text{-}5}$=8.3 m
(See Section 5.5 for definition of variables)

Maximum velocity reaches 14 m/s at the bottom of plasma

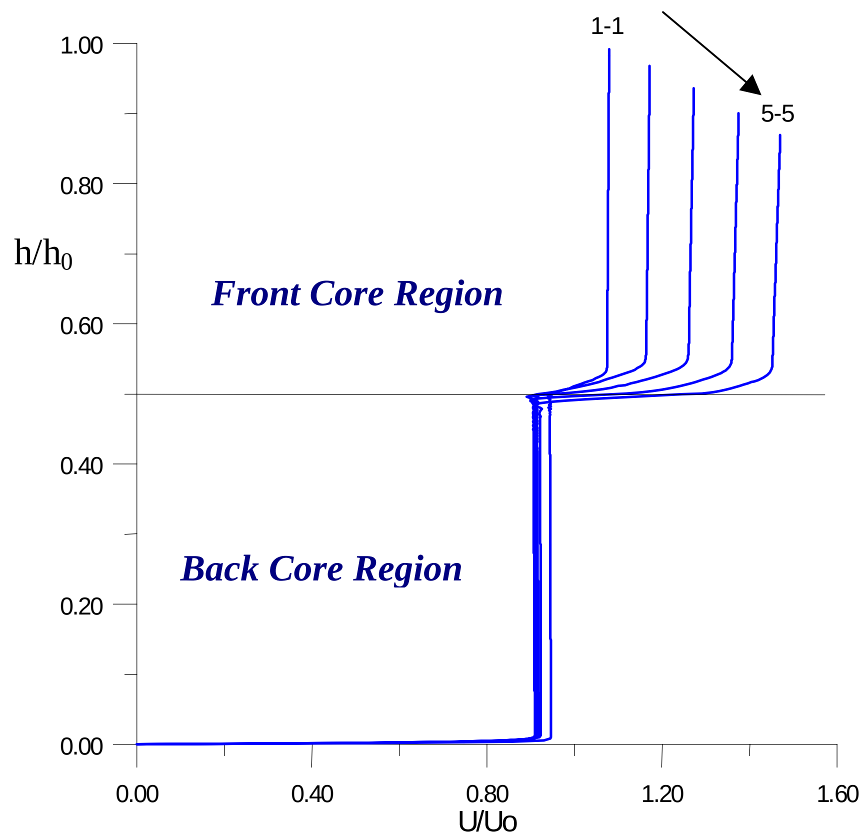


Figure 6 Two-Velocity Liquid Metal Streams can Be Established by Having Submerged Sidewalls.

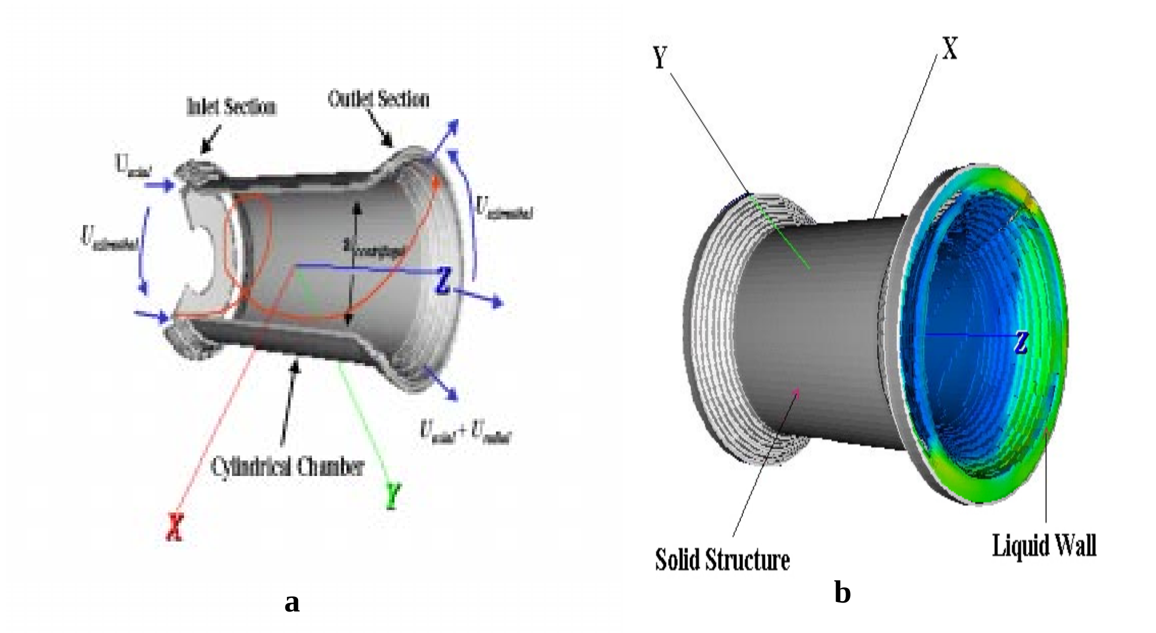


Figure 7 **a.** Illustration of the swirl flow mechanism in the main section with converging inlet and diverging outlet sections. **b.** The 3-D fluid distribution of FRC swirl flow. (Result of CFD simulation.)

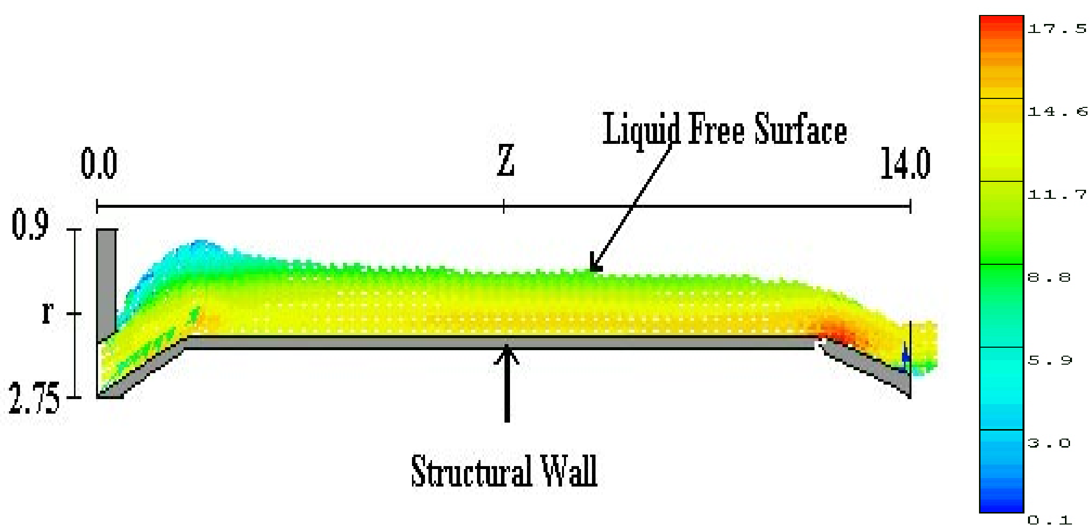
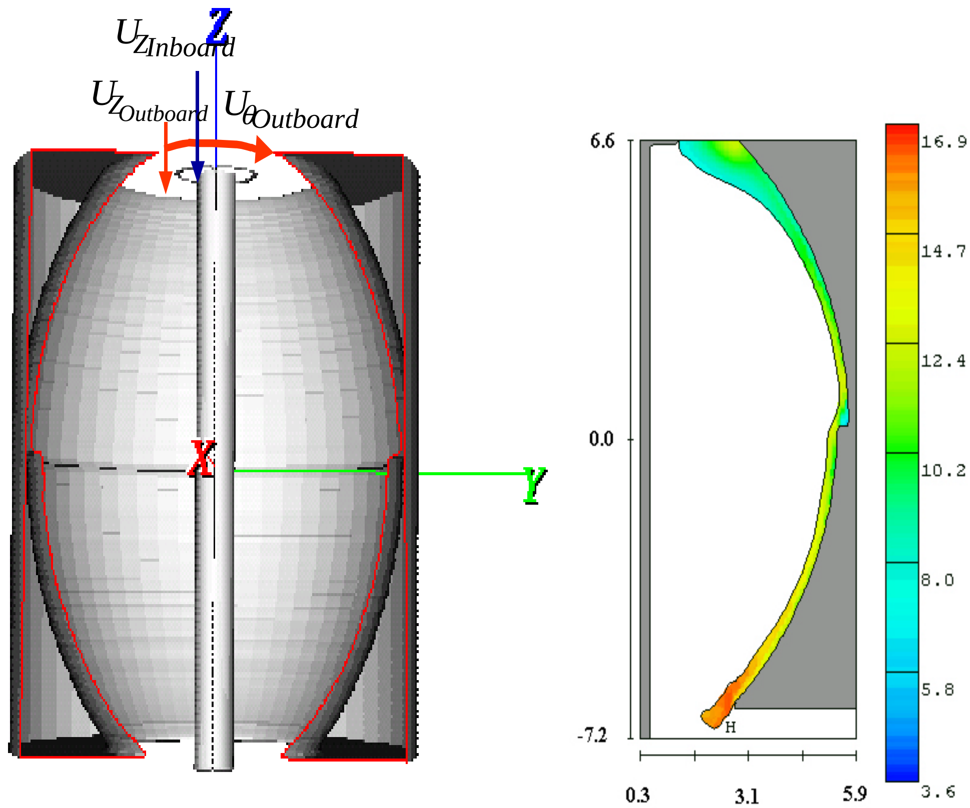


Figure 8 2-D (r-z) Velocity distribution and liquid layer height distribution in the axial direction at an arbitrary azimuthal location.



a **b**

Figure 9 **a** The structural modeling of ST geometry including the modification in the outboard topology. **b**. 2-D velocity magnitude contour at r-z plane at the outboard and liquid layer height distribution in the z-direction at an arbitrary azimuthal angle.

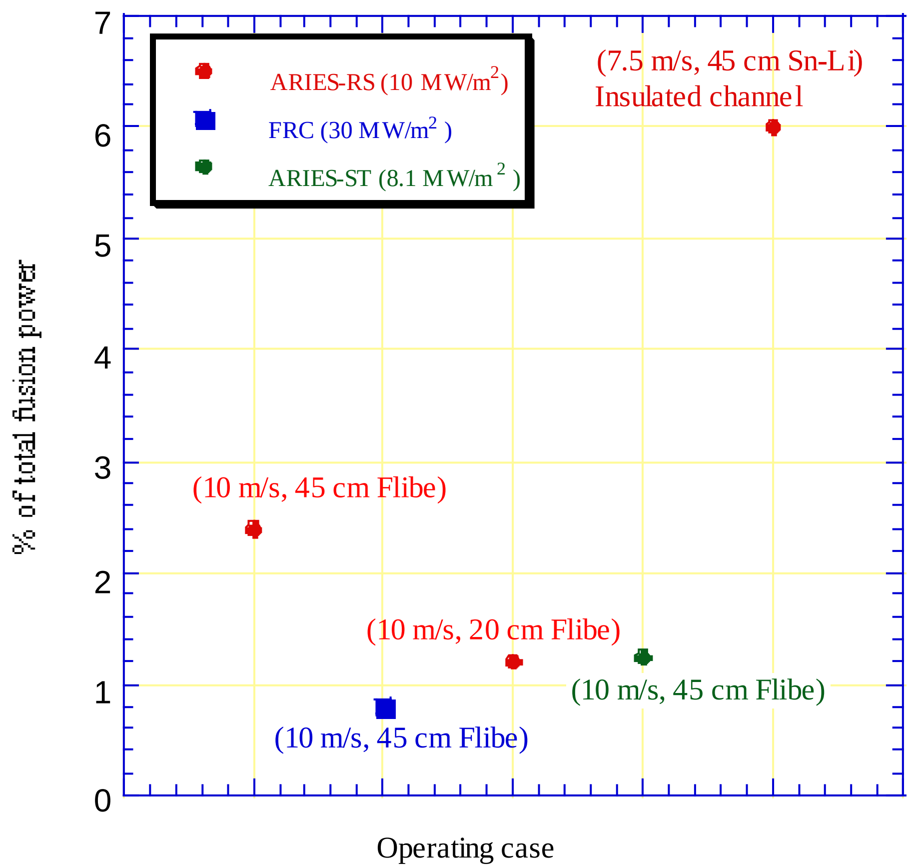


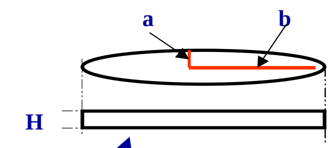
Figure 10 Pumping power requirement is less a concern for a high power density F

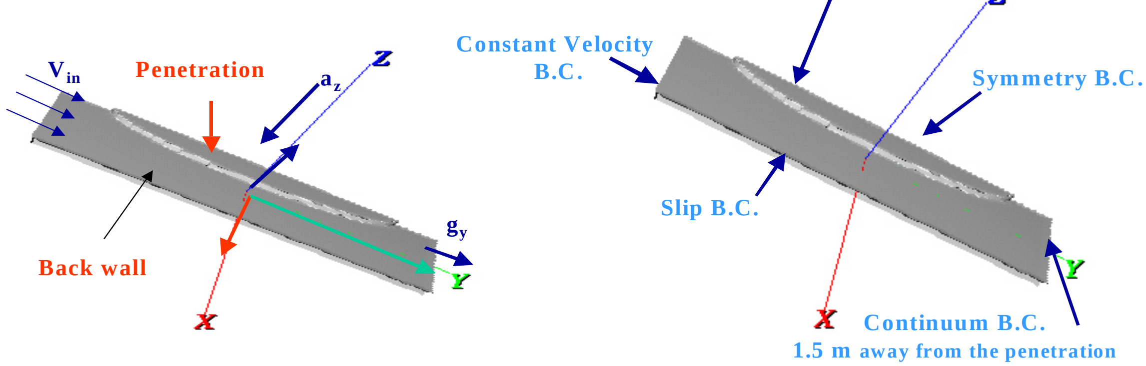
REFERENCE CASE PARAMTERS

V_{in} (m/s)	10.0		
a_z (m^2/s)	25.0		
g_y (m^2/s)	9.8		
Wall Roughness (m)	10^{-5}		
Fluid-Wall Contact Angle	0.0		
Penetration Dimensions (m)	a	b	H
	.1	.45	0.02

Flibe at 550 °C is used as a working fluid.

Fluid Wets the Structure.





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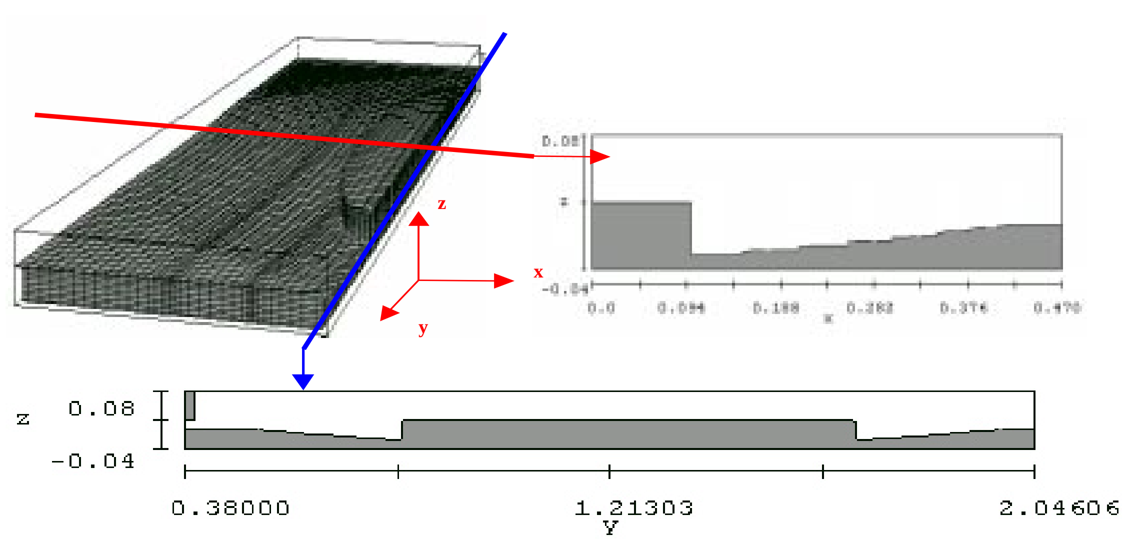


b

Figure 11 **a**. Reference penetration case operating conditions and dimensions.
b. Tailoring of the back-wall contour surrounding the reference penetration and related dimensions.

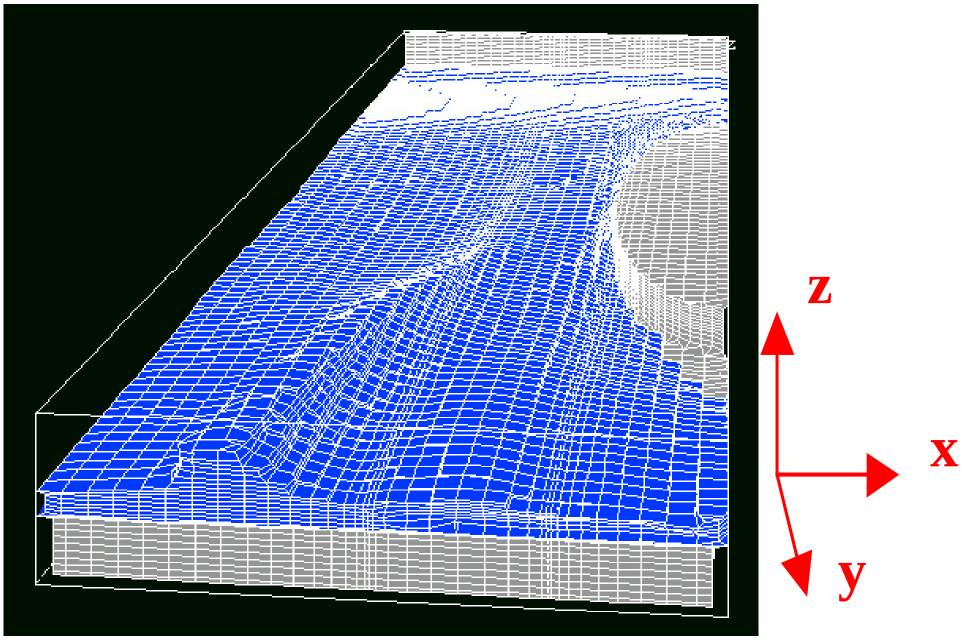


Figure 12 FLOW-3D results of Flibe flowing around a penetration surrounded by a tailored backwall as shown in Figure 11.

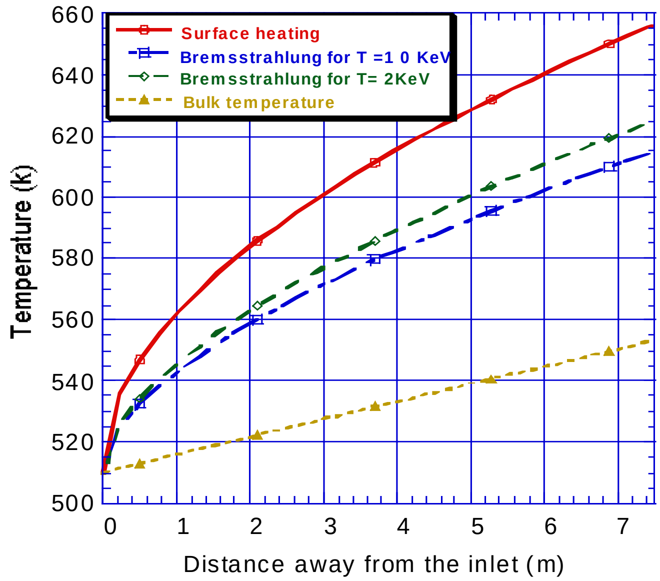


Figure 13 Lithium free surface appears to have reasonable surface temperatures due to its high thermal conductivity and long x-ray mean free path (Li velocity = 20 m/s Surface heat load = 2 MW/m^2)

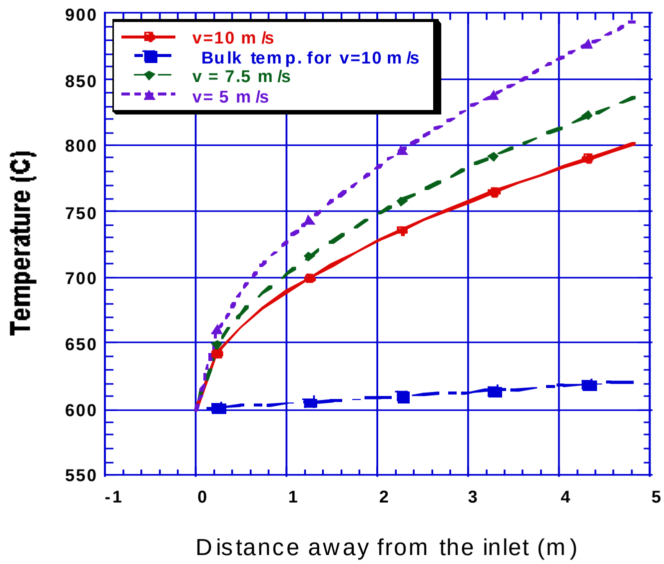


Figure 14 Sn-Li temperature increases due from surface heating as flow proceeds downstream for different velocity magnitudes.

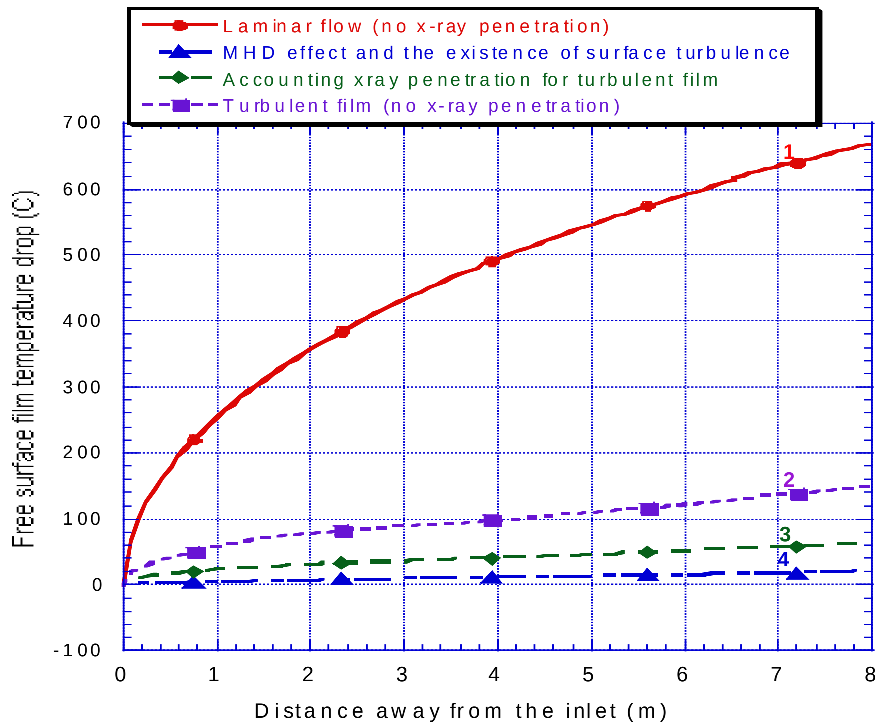
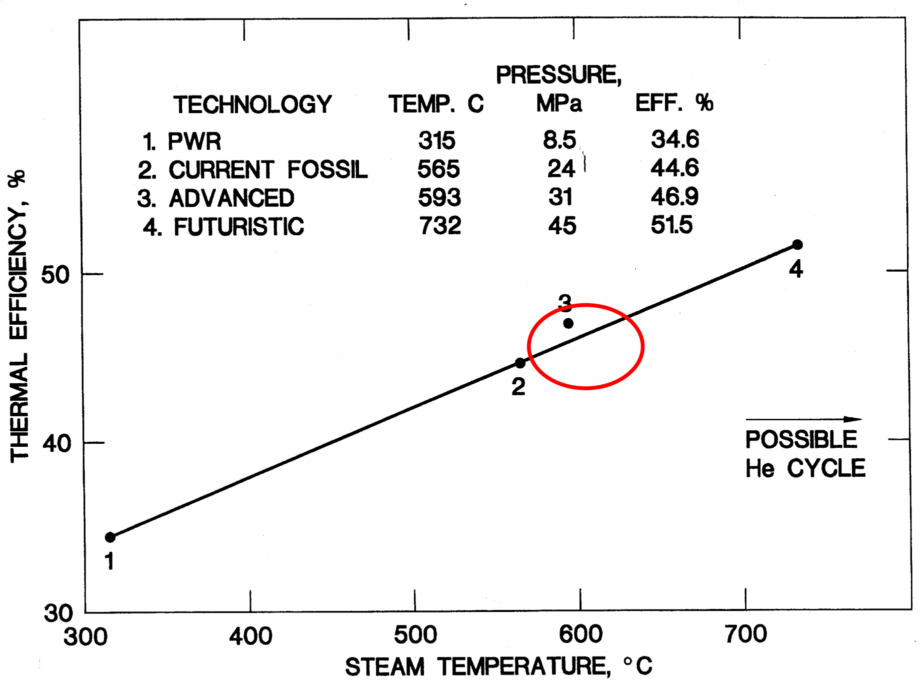


Figure 15 Effect of Different Heat Transfer Mechanisms on Flibe Free Surface Temperature (Initial velocity = 10 m/s and film thickness = 2 cm; Final velocity = 13.3 m/s and film thickness =1.5 cm)

Figure 16 Power Conversion Efficiency Determines Material Choice and Bulk Exit Temperature (Design Option: Two power cycles – *One for the conversion of the thermal power in the first wall and divertor coolants,* and the other for conversion of the thermal power in the blanket coolant, which has a much higher thermal conversion potential)



Taken from Dai-Kai Sze's APEX presentation

Material options for a thick liquid FW/blanket system

Material Choice	**Blanket In/out Temps**	η
ODFS	**600/650°C**	**41.2%**
V	**600/650°C**	**41.2%**
Nb-1Zr	**650/700°C**	**44.6~46.9%**
T-111	**750/800°C**	**46.9~51.5%**
TZM	**750/800°C**	**46.9~ 51.5%**
W	**800/850°C**	**~51.5%**