Summary   Task III

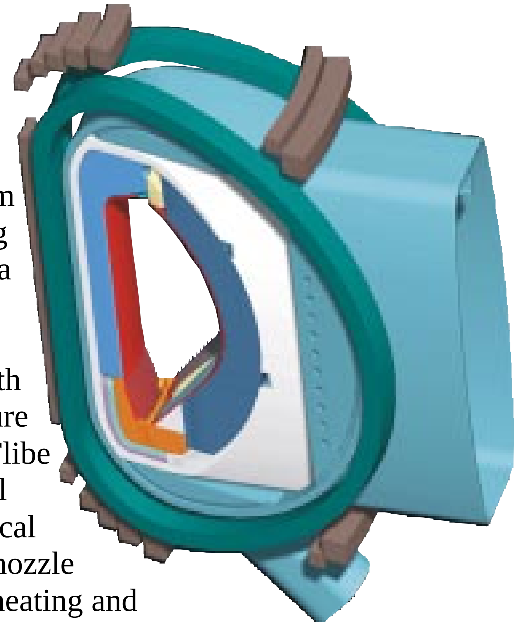
The progress of Task-III was summarized during the APEX Project Meeting hold at ANL, May 10-12, 2000. The mission of the Task-III is to assess the engineering issues associated on CLIFF, based on flibe design. The work can be divided into three parts, i.e.,

1. Reactor configuration *Brad Nelson*
2. Divertor integration *Richard Nygren*
3. Nuclear System *Dai-Kai Sze*

The key conclusion reached at this meeting, and was agreed by the APEX team, is that there no temperature window available to accommodate the temperature increase required for heat transport, heat transfer, heat exchanger design, while keeping the maximum flibe temperature below a limit for plasma considerations. For this reason, a recommendation was made, and approved by the team, that flibe CLIFF design work will terminate. Another coolant, either lithium or Sn-Li, will be selected for the next phase of design activities.

Since there are large uncertainties on both the plasma calculation to determine the maximum acceptable temperature, and the MHD effects on heat transfer, as well as possible methods to improve heat transfer, it is recommended that the effort on determine the maximum allowable flibe surface temperature, and the ways to improve heat transfer in flibe, will continue.

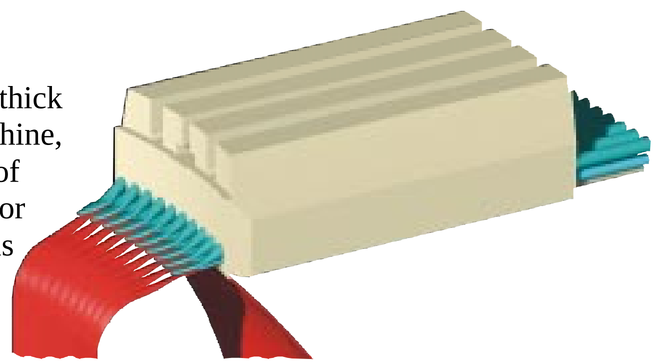
Cliff configuration summary for APEX Task III Study



A mechanical configuration for the CliFF concept was presented using the ARIES-RS reactor design for the basic size and geometry. The design and configuration are intended to satisfy the basic APEX design goals, including minimum limits on wall loading, shielding, tritium breeding, and availability as well as provisions for heating and diagnostic penetrations, vacuum pumping, and plasma exhaust (divertor).

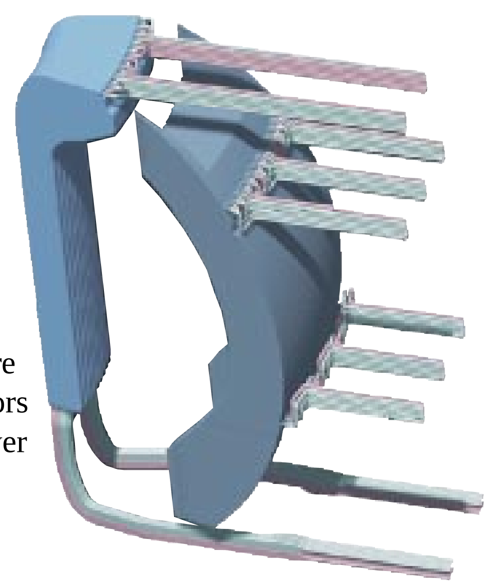
The CliFF concept replaces the conventional first wall with a thin, fast flowing convective layer of a low vapor pressure liquid. The liquids under consideration include lithium, Flibe or Sn-Li. This study began with the Flibe option, and will progress to other liquid options as required. The mechanical design must incorporate a thin film forming system (i.e., nozzle array), a fluid collecting system, a concept for providing heating and diagnostic penetrations, a vacuum pumping concept and a divertor concept.

Film Forming Device



For the present design, the equivalent to a 2-cm thick layer of Flibe is introduced at the top of the machine, at 10 m/s through a set of nozzles. Three types of nozzles are used, one for the inboard flow, one for the main outboard flow, and a third type which is positioned to provide a spray that protects the other two nozzles, while being protected itself by the inboard spray. All the nozzles for a 1/16 sector of the machine are contained in a cassette for ease of maintenance.

Blanket Design



To take advantage of the thin film protecting the surface, an unconventional blanket concept is proposed that consists of a set of flexible woven structures, or “Bags” made from SiC. The “bag” concept has several advantages:

- The Flibe can be move slowly to provide a prescribed temperature rise of 70 to 100 C
- Low thermal stress
- Brittle, low activation material can be used for structure
- Bags are flexible and expand to fill gaps between sectors
- Hot liquid leaking from bags is cooled by fast flow layer
- Lower halo currents due to the low conductivity of the SiC/Flibe system

Summary: Divertor Integration
R.E. Nygren, Sandia National Laboratories

In the Divertor Integration Task, the objective has been to develop a configuration for divertor that would be fit with a CLIFF-type first wall and blanket design in a device with the shape of ARIES-RF. Three dimensional drawings of a divertor shape were developed by Nelson and Fogarty (ORNL) and the issues associated with the configuration were examined. Int this initial investigation, we tried to find a system in which the divertor flow was formed from the extension of the first wall flow rather than introducing a separate divertor stream.

The main issues regarding configuration are as follows. The flow from the outboard first wall stream must be redirected downward above the divertor strike point. The required structure may be exposed to plasma. With an extended flow system, the flux expansion possible is quite limited and there is relatively small incline of liquid surface off normal incidence. Together these provide only moderate reductions in heat flux. Conductance for He pumping appears adequate for tokamak-like hydrogen densities, but this requires a significant toroidal opening (roughly half the space) in each divertor sector. This opening must be kept free of liquid to provide adequate pumping (unless He entrainment is possible), and the cooling of the side surfaces of these ducts were not resolved in the initial design. (The side surface can likely be cooled by rerouting some of the first wall flow, but no design was developed for this purpose.)

To investigate heat flow and related thermal-hydraulic (TH) issues, TH modeling of Flibe was done by Smolensev (UCLA) and edge modeling of the shape of the divertor heat loads was done by Rognlein and Rensik (LLNL). These results were used in evaluating the power balance in the divertor.

Table 1 gives an example of one such analysis. The power to the divertor was 10% of the alpha power. Various combinations of conditions were evaluated such as scrape-off length, the power balance between the inner and outer divertor, the angle of inclination of the divertor and the flux expansion. The peak temperatures were found in the outer divertor. This was due to (a) greater power to the outer divertor and (b) partial toroidal coverage of the outer divertor to allow space for pumping. In the cases analyzed, the Flibe temperatures were excessive and the need for some type of thermal mixing was confirmed as expected.

The He pumping appeared to be adequate for a high recycling case where there would be a few milliTorr of hydrogen in the divertor. This does not address the case where recycling is lower. Recent results by Rognlein showed a regime in which the He pressure might boosted. The pumping for this case has not yet been analyzed.

The general issue is whether a Flibe concept is really feasible - is there an allowable temperature window? The initial results from the first wall and the divertor seem to indicate that a design solution is difficult. Were this design still pursued, then a design with a separate divertor stream would probably be necessary. Even with liquid metal wall designs, the integration of adequate space for pumping of He in the divertor will present a challenge unless some method for entrainment of He seems possible.

Table 1. Power and Heat Loads
(Example of Results)

ARIES-RS Fusion Power	2171	MW	
Pdiv (10% P-alpha)	43.3	MW	
	inner	*outer*	
R-div	4.1	4.9	m
f-rad-div	7.5%	7.5%	
fraction to outboard	40%	60%	
HF,100% toroidal div.	12.1	22.3	MW/m^2
toroidal coverage	100%	40%	
HFpeak-div, particles	12.1	55.8	MW/m^2
Pdiv-particles	16.0	24.0	MW/m^2
Prad-div	1.25	0.80	MW/m^2
Total Power, Divertor	42.10	---------	MW/m^2
Missing radiation	0.00	1.20	MW/m^2
incline, to flux surface	90	90	degrees
λ1a-target	0.029	0.021	m
λ 1b-target	0.130	0.200	m
λ 2-target	0.0073	0.0053	m
hot flow length	0.051	0.035	m
Adiv-footprint	1.32	0.43	m^2
rad div length	1	1.35	m
HFdiv, rad	0.05	0.05	MW/m^2
q1a/q-peak*	85%	95%	
q1b/qpeak*	15%	5%	

**These factors are the relative weighting of two exponential functions used to model the results of Rognlien and Rensik for the heat load to the divertor.*

Temperature design window:

The allowable first wall temperatures for different materials and with different divertor operating conditions was presented by Tom Rognlien and summarized on Figure 1.

The allowable flibe temperature is only 400C. This is below the melting temperature of flibe (460C).

From heat transfer and heat transport considerations, here is the requirements:

1. The inlet flibe temperature to the blanket needs to be 50C higher than the flibe melting temperature to provide sufficient temperature for heat exchanger design.
2. The exit flibe temperature needs to be 50 to 100C higher than the inlet flibe temperature to limit the size, and cost, for the heat transport system.
3. The surface temperature of the flibe is 70C higher than the bulk flibe temperature for heat transfer reason.

Therefore, the minimum required surface temperature of flibe at the exit end is 630C. The 400C allowable temperature is far below this required temperature. With the calculation results presented by Rognlien, Smolentsev and Sze, the temperature window just does not exist.

The possibility of using a lower melting temperature BeF2/LiF mixture was also investigated. Due to the much higher viscosity, and its impact on heat transfer, it was determined that the larger heat transfer DT required due to the poor heat transfer, was more than offset the lower melting temperature.

Transmutation calculations:

Detailed transmutation calculation was performed by Sawan. The purpose of the calculation is to assess the mass balance of the transmutation of Li, Be and F in a fusion blanket. The ratio of transmutation of those materials determines the net ratio of production of free F or TF. The free F or TF will be important for chemical control process.

Table 1' summarizes the results from the transmutation calculation. The important results from this calculation is that the transmutation rate for F is more than double that of Be. Therefore, from mass balance point of view, free F will not exist. If the kinetics of the following reaction is fast enough, we will not have free F.

$$Be + 2F \rightarrow BeF2$$

We still have to worry about TF. However, free F is much more corrosive than TF. By remove free F, the chemical control process becomes easier.

Tritium recovery

If lithium is used for the first wall and the divertor, it is expected that tritium will be absorbed by lithium, and removed from the reactor. Therefore, the throughput of the tritium in the lithium stream will be much higher than a conventional blanket. The question is if the tritium can be recovered from lithium, with acceptable tritium inventory, and at a reasonable cost. This question was asked at Snowmass, as well as within the APEX team.

The tritium recovery process assumed is the cold trap system. The cold trap system was demonstrated to be able to recovery tritium to the saturation concentration, which is 440 appm at 200C. To lower the concentration to an acceptable level of 1 to 10 appm, Protium is added to the system. The addition of Protium to cold trap was demonstrated for both the LMFBR and from NaK.

The parameters of the cold trap system are summarized on *table 2*. There were three cases:

Case 1: The tritium throughput is 0.5 Kg/d. This is the case for a breeding blanket, with no additional tritium from the plasma.

Case 2: The tritium throughput is 5 Kg/d. This is the case with 10% plasma burn fraction, and all the tritium in the plasma will be deposited in the lithium.

Case 3: The tritium throughput for this case is 50 Kg/d. This case assumed that the plasma burn fraction is only 1%, and all the tritium will be deposited in the lithium.

The key logic for the design is that the lithium flow rate to the tritium recovery system is very small. Even for the third case, the lithium flow rate to the tritium recovery system is only 3% of the coolant flow to the divertor. Therefore, we will increase the lithium flow rate to the divertor, as the tritium throughput to the lithium system increases. With this option, the tritium concentration and inventory in the lithium coolant will not change, although the tritium throughput increases from 0.5 to 50 Kg/d. The tritium inventory, as well as the power requirement, for the tritium recovery systems is summarized on Table 2. The total tritium inventory and power requirements are reasonable.

The results from this calculation will be sent to TSTA to assess the impact on the ISS design from the increase of the tritium and hydrogen throughputs.

Summary of Neutronics Analysis under Task III

(M. Youssef 5/19/00)

I. Maximizing local TBR in CLiFF design:

In the CLiFF design, Flibe is use as the flowing liquid layer with a thickness of 2 cm. Last year, ferritic steel was used as the structural material. SiC has been adopted this year as the structural material and analysis was performed to assess the impact of this choice on the maximum attainable tritium breeding ration (TBR). Due to the narrow temperature operating window of Flibe, Sn-Li was also thought as the flowing liquid layer and breeder. In the following, the main findings from the TBR analysis is summarized:

(1) Without a beryllium multiplier, local TBR for either Flibe/FS or Flibe/SiC is *marginal.* Flibe/SiC combination gives lower TBR at all Li-6 enrichment. It decreases with Li-6 enrichment whereas it peaks around 25% Li-6 enrichment in the case of Flibe/FS.

(2) Local TBR for either Sn-Li/FS or Sn-Li/SiC increases drastically with increasing Li-6 enrichment (maximizes at 90%Li-6). TBR can reach values larger than Flibe/FS or Flibe/SiC cases.

(3) Local TBR with Li breeder is generally larger than with Flibe or Sn-Li (except Sn-Li with 90%Li-6).

(4) While beryllium improves TBR for either Sn-Li/SiC or Sn-Li/FS, local TBR is still marginal with natural Li, even with beryllium present in the entire blanket. (Max. TBR is 1.02 and 0.92, respectively). Lithium must be enriched (to 90%) to achieve reasonable TBR values. *(In this case, the effect of Be multiplier is comparable in Sn-Li/SiC and Sn-Li/FS designs. The rate of increase in TBR with Be zone thickness is not as steep as in the natural Li case.)*

(5) In the presence of Beryllium, the local TBR with Flibe (with either FS or SiC structure) is larger than TBR with Sn-Li (even at 90% Li6). Effect of Beryllium is more pronounced in the Flibe/SiC case than in the Flibe/F.S. case. Local TBR can be larger in with Flibe/SiC than with Flibe/F.S. (Contrary to the no Be case). Local TBR with Flibe(25%Li6)/FS is comparable to the values with Flibe (Nat. Li)/SiC.

(6) Maximum attainable local TBR are (Be presents in entire blanket):

Flibe (Nat. Li)/SiC ≈ 1.7 *Flibe (25%Li6)/FS ~ 1.68*
Sn-Li (90%Li6)/SiC ≈ 1.39 *Sn-Li (90%Li6)/FS ~ 1.39*

(7) Under practical condition (10 cm thick Be zone), local TBR are:

Flibe(25%Li6)/FS ~ 1.5 *Flibe (Nat. Li)/SiC ~ 1.5*
Sn-Li (90%Li6)/FS ~ 1.31 *Sn-Li (90%Li6)/SiC ~ 1.29*

(8) The Impact of using other structural material on TBR was also studied. The materials considered are: W, V-4Cr-4Ti, TZM, and Nb-1Zr. The presence of Beryllium in the Flibe Blanket has an adverse effect on Local TBR when the Tungsten structure is used everywhere. Likewise, the presence of Beryllium in the Sn-Li Blanket has an adverse effect on Local TBR when the structure is made of W, TZM, or Nb-1Z.

II. Effect of the conducting layer on TBR

In the Flibe/FS case, the effect of placing a solid conducting shell at the first wall on local TBR was studied (also part of Task II). The materials examined for the shell are: Cu, Al, ferritic steel, W, and V. One and two-cm thick shells were assumed. The following is the main findings:

(1) Removal of the liquid convective layer itself (2m thick) leads to an increase TBR by ~3% (from TBR=1.5 to 1.54).

(2) Placing W as a conducting shell at the FW in front of the beryllium multiplying zone gives the largest adverse impact on TBR (up to ~-30% for 2 cm shell). The least impact is with V and Al conductors (~-12% for 2 cm shell).

(3) Tritium Self-Sufficiency can't be guaranteed if local TBR falls below 1.2 when a conducting shell is used.

ACTIVATION

“Analyses are performed to assess the waste disposal of Flibe and the stabilizing shell. According to 10CFR61, Flibe waste needs to be solidified before qualifying for disposal as near surface low-level waste. The solidified waste would have an order of magnitude lower specific activity limits than an activated metal (corroded) waste. In addition, the solidification process must insure the structural integrity of the waste for 300 years. The waste disposal ratings are calculated for Flibe used in both thick liquid wall and thin liquid wall concepts. The analysis shows that a large amount of C-14 is generated in Flibe used in both concepts. The C-14 is generated by the high energy F-19(n,np) and (n,d) ----> O-18(n,na) reactions. Most of the C-14 is produced by neutrons with $E > 10$ MeV. Generation of C-14 is more of a problem for the thin liquid wall concepts. Due to the generation of high amount of C-14, Flibe from both concepts would not qualify for disposal as low-level waste.

The waste disposal ratings of the the stabilizing shells are performed assuming that the 2 cm stabilizing shell is placed immediately behind the liquid first wall or deep inside the blanket at 30 cm from the liquid first wall. The following materials are analyzed; ORNL (9Cr-2WVTa) ferritic steel, V-4Cr-4Ti, W-5Re, Al-606, and Glidcop-Al15-DS-Cu. The waste disposal ratings are calculated after 3 FPY. The analysis shows that only stabilizing shells made of ferritic steel and V-4Cr-4Ti alloys would qualify for disposal as low level waste".