Summary of Session VI, APEX meeting, November 14, 2000

Introduction and identified critical issues
Clement Wong

C. Wong outlined the presentations of the EVOLVE design. He also presented the list of critical issues that the team has identified. The key issues are the superheat of lithium for the capillary sheet concept, boiling stability under the magnetic field of the boiling blanket approach, and the robustness of the capillary sheet system.

Transpiration FW and blanket and experiment
Leopold Barleon /Clement Wong/Richard Nygren

C. Wong presented for L. Barleon the transpiration FW and blanket design and possible experiment. For the feeding of lithium to the toroidally oriented first wall tubes, using a thermally insulated double walled lithium feeding tube, Barleon showed that the pressure drop along the feeding tube fulfills the criteria for the MHD controlled feeding. He found that the overall pressure drop and the resulting capillary diameter of the toroidal flow FW concept are very sensitive to an increase of the B-poloidal B-toroidal ratio (Bp/Bt). The overall pressure drop of the poloidal flow FW concept is less sensitive to the thickness of the feeding gap than the toroidal flow FW concept. He also found that due to the shorter length of the vapor flow path the velocity at the corresponding outlet of the vapor is much lower for the poloidal design. Poloidal flow channel concept allows larger margin on the superheat uncertainty. It also allows more freedom on the selection of blanket tray geometric parameters. Barleon also proposed a hybride system with vertical vapor channels formed by capillary sheet structure, which may help to reduce the problem of high void fraction in the boiling blanket. In the presentation, Barleon also sketched a heat transfer experiment that could be used to study the superheat of lithium being heated from one side.

Boiling blanket and experiments
Michael Corradini/John Murphy/Mike Anderson

A generalized methodology was proposed for determination of the vapor fraction profile in a boiling tray of liquid lithium. A scenario with negligible magnetic interaction between the liquid lithium and the magnetic field is utilized with isothermal experiments performed at the University of Wisconsin. A standard drift-flux model is employed with data from liquid metal – nitrogen experiments. This boiling regime does not include MHD effects, which may significantly alter the results. Two standard drift-flux formulations along with an analytical expression were compared giving reasonable agreement. This preliminary study showed vapor fractions at the top of the pool ranging from 63% to 65%.

If MHD effects are included and utilized to inhibit the movement of the liquid lithium in the tray, smaller vapor fractions are predicted. It is assumed in this scenario that the magnetic effects retard liquid metal movement but do not effect the boiling curve for the liquid lithium. Combining mass, momentum and energy balances allow us to physically predict the presence of "thinner" vapor channels, initiated at preferred nucleation sites on the bottom of the tungsten tray. The overall vapor fraction is significantly reduced to less than 10% by these means. Flow regime experiments are needed to determine whether these channels can be maintained under the expected conditions in the EVOLVE design.

MHD effects may overwhelm the boiling process and essentially suppress boiling. We do not think this scenario is realistic but feel experiments to verify the behavior are necessary. Provided below is a discussion on proposed experiments to answer fundamental questions about the boiling thermal-hydraulics of liquid lithium in a magnetic field.

Evolve liquid boiling design.

There remain several open questions on the physics of boiling a liquid metal in the presence of a strong horizontal (perpendicular to gravity) magnet field. These issues are 1) flow regimes and the existence of a stable boiling regime 2) heat transfer reduction and 3) possible shift in the nucleate boiling curve. A literature review was conducted and found that there was some work in weak horizontal magnetic fields and some work in strong vertical magnetic fields with a heavy conductive liquid metal (Hg). This work (Lykoudis et al. 1981, 1998 and Takahashi et al. 1994) indicated that there was a decrease in the bubble rise frequency and there appeared to be the promotion of premature film boiling in a horizontal magnetic field. Also the nucleate boiling heat transfer was reduced by about 50%. There was some indication of a shift in the nucleate boiling curve, however the magnitude of the shift was small (~10's of K), although indications of the suppression of bubble departure was indicated at 0.7T and 100kW/m^2. After review of this work there are still open questions that need to be answered in order to determine if the EVOLVE concept is feasible. It was suggested that an experiment be conducted to answer some of these open questions. Considering the resources it was recommended to look at a more prototypic light liquid metal (NaK, Na, Li, etc.) and inject a light gas (He) into the liquid metal to simulate boiling. The flow regime would be studied with the use a high speed X-ray system during gas injection. This would allow us to understand the effects of the magnetic field on the flow regime and would answer the question of whether it is possible to create and maintain vapor channels. It would also give us insight on the promotion of the film boiling at low heat fluxes (which if present may cause an increase in temperature of the W beyond its limit). Further background search is to be conducted and a scaling analysis to determine the parameters of the experiment. Then an experiment will be conducted at the University of Wisconsin.

Lithium leakage assessment
Saurin Majumdar

Analysis of the toroidal flow EVOLVE first wall (tungsten) showed that fatigue crack growth data for tungsten are needed at low delta-K and high temperature to reliably predict the fatigue life of the first wall. Leakage analysis of through-wall cracks showed that lithium leakage through 1" long cracks into the plasma chamber will not adversely impact either first wall cooling or plasma performance.

Nuclear performance and activation analysis
Mohamed Sawan/Hesham Khater

The neutronics performance of the EVOLVE concept was analyzed using 2-D calculations. Preliminary results from lithium tray boiling analysis indicate that vapor fractions as high as 65% might be obtained. 2-D neutronics calculations showed that the higher vapor fraction in the Li trays has a minimal impact on the nuclear performance parameters. Based on the 2-D neutronics calculations for the worst-case conditions with the highest predicted vapor fraction distribution, all nuclear performance parameters are acceptable with a comfortable margin. Therefore, the EVOLVE boiling blanket is expected to perform adequately from the neutronics point of view for any of the boiling regimes considered. The neutronics parameters for the preliminary design of the transpiration blanket option were compared to those obtained for the boiling blanket with the largest predicted vapor fractions. The results indicate that with these assumptions, the transpiration blanket has larger Li and structure content resulting in slightly higher TBR and a factor of 2-5 better shielding performance. The nuclear performance parameters for both designs are acceptable with large margin implying that the choice between these two options should not be driven by differences in nuclear performance.

Activation calculations were performed for the W-La_2O_3 alloy using the 2-D model and results were compared with previous results for the W-5Re alloy. The W-La_2O_3 alloy generates slightly smaller level of decay heat than W-5Re during LOCA. W-La_2O_3 has twice the amount of Nb impurities resulting in higher WDR than the W-5Re alloy. The W-TiC alloy is expected to generate similar WDR results unless it contains much smaller level of Nb impurities. The main advantage of using the W-La_2O_3 alloy could be the production of lower level of off-site dose during an accident. Specific activity and decay heat data were provided to INEEL for use in updating the safety analysis

Configuration
Brad Nelson/Igor Sviatoslavsky/Brad Merrill/Seigfried Malang

B. Nelson presented the status of the boiling blanket design configuration. The design consists of large sector assemblies that include the first wall, tray system, breeding zone, and shielding. The heat exchangers are located inside the vacuum vessel duct and are also integrated with the sector assembly to form one module for maintenance.

Modifications to the original design include split (upper and lower) vapor exit paths, the addition of reinforcing ribs inside the modules, and a new natural convection heat removal system to accommodate a loss of cooling accident.

A study was performed by I. Sviatoslavsky to determine whether the first wall tubes should also form the front of the tray-boiling region (baseline design) or if the first wall tubes should be independent of the trays. A final decision has not been made, but no changes have been made to the baseline design.

The primary issues associated with the design remain the vapor evolution and behavior in the trays in a high magnetic field and the fabrication of large tungsten structures.

EVOLVE safety design and evaluation
Brad Merrill/Siegfried Malang

Brad Merrill updated the APEX teem on the status of the EVOLVE safety assessment. The MELCOR code was used to determine first wall temperature trends during a complete loss of cooling accident. This temperature dropped to 750 C in one day because of the EVOLVE natural convection decay heat removal system. Given the EVOLVE activation inventories predicted by Hesham Khater and tungsten oxidation data measured by the INEEL, the dose at the site boundary based on the aerosol mass mobilized during this accident was calculated. It was determined that this dose does not exceed 10 mSv as long as the EVOLVE facility is isolated within 2.4 hours. This means that EVOLVE can easily meet the no-evacuation goal required by the DOE Fusion Safety Standard.

Oxidation driven mobilization from a Ta alloy in air
Dave Petti

Oxidation driven mobilization tests were performed on Ta alloy T-222 in flowing air. T-222 contains 10 wt% W, w.5 wt% Hf and 0.01 wt% C. The mobilization of Ta and Hf was linked to oxide spalling. Particulate formation from oxide spalling was most abundant at 600 to 700C. The spalled oxide did not migrate out of the test chamber. Oxide spalling and volatilization mobilized the tungsten. Mobilization of W increased with temperature, but was inhibited by oxide scale formation. The mass flux of W was less than predicted based upon mass fraction in the alloy. Finally, it was shown that oxygen dissolved into the alloy causing hardening and embrittlement.

Comparison of the S&E characteristics of refractory alloys under consideration in APEX
Dave Petti

Dave Petti compared the safety and environmental characteristics of five refractory alloys: Ta (T-222), W, W-5Re, Mo (TZM), and V-5Cr-5Ti. All the alloys except TZM were assumed to include some impurities. The Ta alloy had the largest decay heat, while the V alloy had the lowest decay heat. Oxidation and mobilization characteristics based on a combination of experiment and calculations indicate that TZM and the W alloys could produce a site boundary dose of 400 times the no-evacuation limit, while the Ta and V alloys would produce several orders of magnitude lower site boundary dose. Waste disposal ratings for the W and Ta alloys are similar at around 30 (Fetter limits), while the TZM alloy was around 10,000 and the V alloy only 0.5.   .

W-alloy fabrication and testing
Dennis Youchison/Richard Nygren

It is possible to successfully fabricate a robust, all-refractory helium-cooled heat sink using existing porous metal technology. This high temperature heat sink removed substantial amounts of power even at low mass flow rates by taking advantage of large delta-Ts in the coolant. The heat sink survived over 500 thermal fatigue cycles at 3.5 MW/m^2 with only minimal micro-cracking of the faceplate. Existing tungsten rod armor may be incorporated into the tungsten faceplate in advanced pfc designs without the problems of joining dissimilar materials.

These heat exchangers exceeded design specifications and survived a maximum heat flux of almost 6 MW/m^2 and a maximum surface temperature near 1000 ^oC. However, the pressure drop across each module was relatively high, exceeding 55 kPa. The porosity difference between the two modules in these experiments was as high as 30%. Obviously, there remain problems with controlling porosity and clogging by contaminants.

No evidence of mass flow instabilities was observed for the two modules in parallel even for very high delta-Ts in the helium. Nearly the same thermal response was obtained on each module. However, for a worst-case scenario of an unrestricted flow bypass, a 39% reduction in mass flow occurred in the module resulting in a 37% reduction in power absorbed by the helium.

This level of thermal performance is more than adequate for 2 MW/m^2 first wall applications proposed for solid first walls in APEX and also for the Li-He heat exchanger in the Evaporation of Lithium and Vapor Extraction (EVOLVE) concept. However, better performance could be obtained if the porosity could be doubled. This would almost triple the mass flow and power handling capability. Such an innovation could open a design window into the divertor heat flux regime of 20 to 30 MW/m^2 and make high temperature, helium-cooled refractory heat sinks a desirable alternative to liquid metal pfcs.

Up-date on W-alloy and the potential for developing refractory alloys with improved ductility
Steve Zinkle, Shahram Sharafat, Nasr Ghoniem

Low-ductility refractory alloys such as Mo and W alloys apparently do not exhibit classical "Paris law" fatigue crack growth behavior. This produces a very high stress dependence on the fatigue crack growth rate. Further data are needed, since only one study on fatigue crack growth in W alloys was found in a literature search. There are several potentially promising ways to improve the ductility of W alloys, including controlled (~ppm) additions of Zr, C and B, and utilizing TiC additions to produced fine-grained material.

Task IV 2001 planning and solid wall concepts
Clement Wong/team

C. Wong led the discussion on the Task IV 2001 planning and solid wall concepts. The presented approaches were to continue to assess advanced first wall and blanket options or to find common critical items for different blanket designs and to focus the team effort to make advancement. After some discussions, the recommendation is to first assess the ARIES-AT design for seven months and then pick up the innovative first wall and blanket option of W-bag/mesh poloidal flow design cooled by FLiBe.