APEX Task IV The EVOLVE Design Evaluation

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Summary

To achieve high thermal performance at high power density, the EVOLVE W-alloy FW/blanket concept proposes to use transpiration cooling of the first wall and boiling or vaporizing lithium in the blanket zone leading to a lithium vapor outlet temperature of 1200° C. While maintaining at the saturation pressure of 0.028-0.17 MPa, this high lithium outlet temperature leads to a helium closed cycle gas turbine efficiency of ~57%. For this phase of the EVOLVE concept evaluation, we focused on addressing critical issues. For the transpiration cooled first wall design, we determined the characteristic dimensions of the lithium first wall flow channels and the capillary openings for lithium vaporization. The basic design criterion is that the capillary pressure must overcome the sum of all frictional and MHD pressure losses. We found that a reasonable design is to have a first wall tube diameter of about 6 cm, a lithium channel width of about 2 mm and a capillary opening of 0.5 mm. For the blanket design, two approaches were evaluated. The first approach is to hold the fluid lithium in horizontal trays. The lithium is allowed to boil and the vapor is routed with the first wall vapor to the lithium/helium heat exchanger. Using the drift flux model and considering the churn-turbulent boiling regime, the generation of Li-vapor was determined as a function of location in the lithium tray. Initial results show a large void fraction of up to 65%. The impact on the overall tritium breeding ratio and required radial build was found to be minimum. The second option is an extension of the FW transpiration-cooling concept. The lithium slabs in the blanket are held in walls with capillary openings. The characteristic dimensions are then determined based on the superheating of the lithium. There is no lithium boiling or bubble formation with this approach. We also evaluated the integrated and separated FW and blanket configuration options. With the separate FW option, welding between FW and the trays are minimized but the impact of the additional wall on afterheat removal has to be investigated. MHD experiments related to the boiling of liquid-metal were reviewed. The other critical areas of the EVOLVE concept are the fabrication of W-alloy components and the safety design to handle the very high afterheat from the W-alloy structure. These areas of work are summarized in the following.

Configurational Design

The original design of the trays in the EVOLVE configuration of the evaporative blanket, called for the first wall bank of transpiration cooled tubes act as the front surface of the trays. This meant that the trays and their associated reinforcing ribs are welded to the backside of the first wall tubes. At the present time, for the integrated FW option, we are assessing the boiling in the trays option to determine if there will be any vibrations set up which could impact the first wall tubes from stress concentrations at the welds. The results will determine if any modifications will be needed to the trays, such as the inclusion of a separate wall independent of the first wall to act as the front surface for the trays. If such a wall is needed, a careful evaluation will be made to determine how such a wall will be cooled, in particular during LOCA or downtime, when after-heat will have to be dissipated, and its impact to neutronics performance. With respect to vapor fraction in the trays, it has been suggested that reducing the height of the trays will decrease the vapor fraction. However, when the drift flux model was applied to trays of 10 cm and 15 cm height, it was found that the vapor fraction was essentially the same.

Transpiration First Wall Design Evaluation

During this period, Dr. Leopold Barleon from FZK, Germany, was stationed at General Atomics to work on the evaluation of the transpiration first wall design. The concept was evaluated with the goal of identifying and resolving critical issues. A potential solution for cooling the lithium supply channel of the first wall is to cool the channel with porous walls. This approach was then extended to the transpiration lithium blanket concept, which uses porous walls as the lithium container and also for the evaporation of the deposited thermal power in the lithium fluid and in the W-alloy walls. We started with a detailed review of the material properties of W-ally and vaporized lithium in the temperature range of interest. The first wall design was then reviewed based on the limiting condition that the capillary pressure head has to be able to overcome the sum of the frictional and MHD pressure drops. At a lithium vapor temperature of 1200°C, for the 6 cm diameter first wall tube and 3 mm thick wall design, in order to handle the surface heat flux of 2 MW/m^2, the first wall lithium channel was found to be 2 mm in width with capillaries of 0.5 mm in diameter. We continued on the evaluation of the transpiration blanket option. The same principle on the superheating of the fluid at the first wall was applied to the lithium slabs forming the blanket. Similar design principle of avoiding any bubble (boiling) formation was also applied. The vaporized lithium is extracted from the gaps between the slabs. Since the only requirement is the removal of the volumetric power in the lithium, the lithium radial slab was found to be 2 to 4 cm in thickness, depending on the radial position of the slab. Preliminary calculation indicated that the lithium, W-alloy and void volume fractions are 0.73, 0.15 and 0.12, respectively. For the next period we will continue to evaluate the following critical issues, first wall limitation of the lithium superheat, limitation on the volumetric superheating of the liquid metal along with the generation of helium in the fusion reaction, impacts from the wetting of the porous wall, initial lithium filling of the first wall and blanket structure and the systematic evaluation of various options of lithium delivery design to the first wall and blanket.

Lithium Tray Boiling Analysis

A generalized methodology was proposed for the determination of the void fraction profile in a boiling tray of liquid lithium. The formulation is based on isothermal experiments performed at the University of Wisconsin. A standard drift-flux model is utilized with data from liquid metal - nitrogen experiments. The boiling regime reviewed does not include MHD effects, which may significantly alter results. Two standard drift-flux correlations along with an analytical expression were compared giving reasonable agreement as to potential void fractions for the trays. The nominal system analyzed operated at 1200° C and 0.037 MPa, with 2 MW/m^2 surface heat flux and 10 MW/m^2 neutron wall loading. These preliminary studies have shown void fractions at the top of the pool ranging from 63% to 65 %.

Based on the drift-flux methodology void fractions were very much driven by the low operating pressure (small vapor density of lithium). Raising the saturated operating conditions from 1200° C to 1500° C would drop the voids in half. An alternative-boiling regime was proposed by S. Malang that may allow significant reduction of the trays void fraction. By utilizing MHD effects in lithium we may be able to produce smaller vapor channels for heat removal. This concept will be reviewed in the next phase of work (first principle balances). Other future work involves: performing MHD analyses on the drift-flux boiling analyses, support the analysis of thermal-hydraulic effects of blanket capillary cooling, determining dynamic vibration loads to trays (during boiling) and first wall welds, and showing that a large oscillatory bubble effect will not propagate through the tray during boiling.

Neutronics Analysis

The Li tray boiling analysis indicates that high vapor fractions up to 65% could exist in the Li pool. Several 1-D calculations were performed for poloidal sections going through the trays to assess the impact of the higher vapor fraction on the nuclear performance parameters. The results of the calculations with 60% average vapor fraction were compared to previous results with 17% vapor fraction. The drop in local tritium breeding ratio (TBR) at poloidal locations where the trays are located is only ~4%. More neutrons go through the front of the tray producing more breeding at the back of the tray, secondary blanket, and shield resulting in relatively small drop in TBR. The overall TBR with 17% vapor fraction was 1.37 (assuming no breeding in the divertor region) implying that adequate tritium-breeding margin still exists. The results for sections through and between trays were combined to determine the fraction of energy carried by the vapor. With 60% vapor fraction in trays, ~54% of total energy is carried by the Li vapor compared to 66% obtained using the same analysis with 17% vapor fraction. The impact on the power conversion efficiency remains to be determined. The peak damage (dpa and He production) in the structural material behind the trays is increased by a factor of 1.78. This is not a concern since enough margins existed for these parameters (peak dpa rate in back manifold plate was 7 dpa/FPY and peak end-of-life He in VV was 0.3 appm). The peak fast neutron fluence and insulator dose in the magnet increase by a factor of 1.77. To keep magnet radiation effects at the same level we need to increase the radial build of the W-5Re/WC/Li shield by about 4 cm. However, this is not needed since magnet radiation effects are much lower than the limits of 10^{19} n/cm^2 and 10^{10} Rads. It is concluded that the higher vapor fraction in the Li trays will have a minimal impact on the nuclear performance parameters.

Separating the FW tubes from the Li trays requires adding a separate wall to which the trays are attached. Several calculations were performed to assess the impact of the added structure (W-5Re) on the TBR. Small enhancement in TBR results due to the neutron multiplication in W coupled with the Li enrichment (40% ^{6}Li). Two-dimensional neutronics calculations were performed to determine the nuclear heating distribution in both the tray's structure and the Li pool. The results were used in the Li tray boiling calculations to determine the void fraction distribution. The neutronics calculations were then repeated using the new void fraction distribution. The results of the iterated 2-D neutronics and Li tray boiling calculations converged after three iterations yielding detailed distribution of nuclear heating and vapor fraction. The overall nuclear performance parameters will be determined by performing detailed 2-D calculations for the whole system including FW, trays, secondary blanket, shield, vacuum vessel, and magnet using the vapor fraction profile determined from iterations with the Li tray boiling analysis.

MELCOR Safety Calculations

Loss of lithium flow calculations have been performed with the MELCOR code to evaluate after-heat removal options for the EVOLVE design. Three loss of cooling accidents were examined: a complete loss of cooling, the low temperature shield (LTS) cooling maintained, and high temperature shield (HTS) cooling maintained. A MELCOR model was developed that divides the EVOLVE design into inboard (IB) and outboard (OB) one-dimensional heat conduction segments. These segments simulate conduction, boiling, and thermal radiation heat transfer radially through the EVOLVE design. The thermal boundary conditions are an adiabatic inner surface for IB LTS, and thermal radiation and convection to the ambient at the outer surface of the OB primary vacuum boundary (PVB). Hesham Khater supplied the decay heat for this study based on a two-dimensional neutronics calculation performed 4/99.

During a complete loss of cooling event, the blanket lithium boils off after 11 hours and the HTS lithium boils off after one day. Beyond these times, the first wall (FW) and blanket/shield tungsten reach temperatures above 2500° C. In addition, the temperature of the IB LTS exceeds that at which structural failure would occur. While maintaining the LTS and HTS cooling systems on during this event eliminates problems for the LTS, temperatures of the interior of the reactor remain in excess of the 800° C (the tungsten oxidation guideline limit), because gaps between EVOLVE components restrict radial heat flow to these cooling systems. Increasing the heat conductance of these gaps by adding 10% structure in the gaps improves this problem slightly, but unless more structure is added to the exhaust plenum of the primary blanket FW temperatures will remain above 800° C. Because 80% of the decay heat resides in the FW and blanket, a removal system that operates within these regions of the reactor would be a preferred solution in handling the decay heat. With this in mind, two options will be examined in the future: (1) a natural convection removal system proposed by S. Malang (May 1998), and (2) a forced convection removal system by way of the tritium extraction system as adopted by the Helium Cooled Refractory Alloy APEX design.