MELCOR ACCIDENT ANALYSIS FOR ARIES-ACT

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We model a loss of flow accident (LOFA) in the ARIES-ACT1 tokamak design. ARIES-ACT1 features an advanced SiC blanket with LiPb as coolant and breeder, a helium cooled steel structural ring and tungsten divertors, a thin-walled, helium cooled vacuum vessel, and a room temperature water-cooled shield outside the vacuum vessel. The water heat transfer system is designed to remove heat by natural circulation during a LOFA. The MELCOR model uses time-dependent decay heats for each component determined by 1-D modeling. The MELCOR model shows that, despite periodic boiling of the water coolant, that structures are kept adequately cool by the passive safety system.

I. INTRODUCTION

The ARIES-ACT [1] design study will ultimately comprise four advanced tokamak designs representing the "four corners" of plasma physics and engineering/technology design space, in which each is either conservative or aggressive. Identification of these design points is made possible by the ARIES Systems Code [2], which is equipped with costing algorithms that allow for determination of the effect of various design parameters on the cost of electricity generated by the reactor. The first of these four design points, ARIES-ACT1, which features aggressive physics and engineering, is the subject of this paper.

As with previous ARIES designs [3-4], safety considerations play a role in the design, and safety analysis of the final design is an integral part of the project. As a first step, we consider here the implications of a loss of flow accident (LOFA) resulting from a loss of offsite power or long term station blackout. It is desired that ARIES-ACT withstand such an event by employing only passive safety systems.

ARIES-ACT1 resembles in some ways the previous ARIES-AT (advanced tokamak) design [5], and it uses a similar SiC blanket concept with LiPb as coolant and breeder. The LiPb flows upward through a thin outer annular shell in each blanket (one inboard and two outboard) at high velocity to provide sufficient cooling for the hot first wall, and then returns flowing downward at lower velocity through a larger center channel (Figure 1). Significant differences from ARIES-AT include a helium-cooled tungsten-alloy divertor, and a helium-cooled steel structural ring, which supports the in-vessel components and acts as a high temperature shield. These and other features of the ARIES-ACT1 design are described in [6].

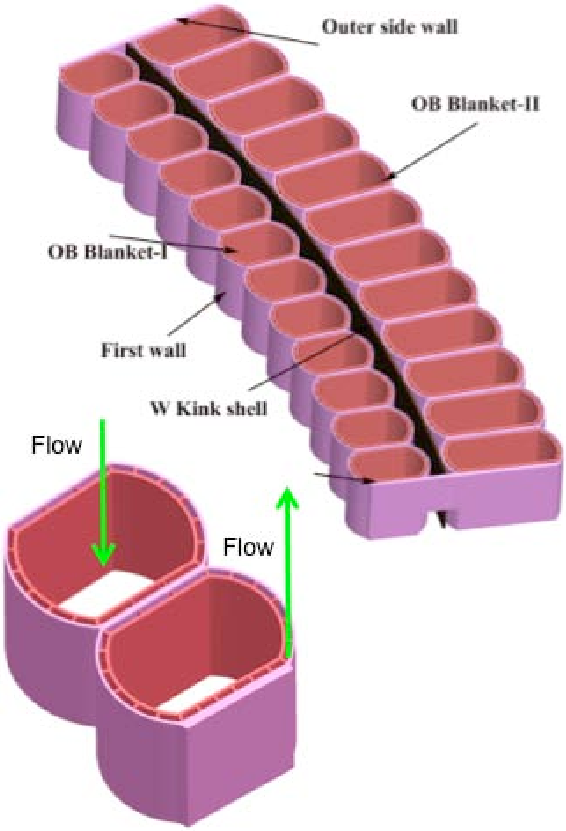


Fig. 1. ARIES-ACT1 outboard blanket and LiPb flow paths.

The ARIES-AT vacuum vessel was a thick (25-40 cm), water-cooled, low activation ferritic steel structure that also served as a neutron shield for the magnets. For ARIES-ACT, concerns about tritium permeation through the vacuum vessel wall at high temperature and the resulting possibility of a large inventory of tritium in the vacuum vessel water coolant prompted an investigation of helium-cooled designs. These did not adequately shield the magnets, so the design was modified to serve each of these needs with a different component: a thin (5-10 cm) walled, high temperature, helium cooled vacuum vessel, and a room temperature water-cooled shield for the magnets outside the vacuum vessel. Both the vacuum vessel and water-cooled shield are constructed of a new reduced activation bainitic steel, 3Cr-3WV [7]. The arrangement of these structures is shown in Figure 2.

Similarly to previous ARIES designs [4], passive decay heat removal is achieved by natural circulation in the water coolant in the event of loss of flow. The heat exchanger for this system is located on the roof of the confinement building, and is thus able to transfer heat from the circulating water to ambient air.

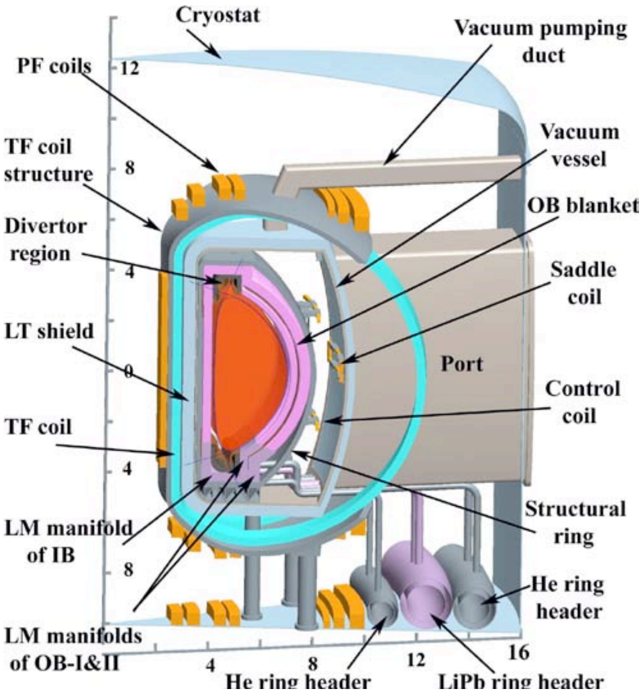


Fig. 2. Layout of ARIES-ACT1 inside the cryostat.

II. MELCOR MODEL

In order to determine whether natural circulation of the water is sufficient to remove decay heat during a LOFA, a MELCOR model of ARIES-ACT1 has been developed. MELCOR is a code developed at Sandia National Laboratories [8], originally for analysis of light water fission reactor accidents. A series of modified versions have been developed at INL for application to fusion accidents. MELCOR 1.8.5 [9] was unique among these in that the default water coolant could be replaced by a number of others relevant for fusion, including LiPb, a feature as yet unavailable in the other fusion versions of the code.

Though MELCOR 1.8.5 can use a variety of working fluids, as with all versions of MELCOR, only one such fluid may be used in a given problem (not including ideal gases). This presents some obvious challenges when modeling the present ARIES-ACT1 design, since there is no way to include both LiPb and water coolants. In order to overcome this, the present model is actually a scripted coupling of two separate MELCOR models, one containing the LiPb and helium cooled components and loops, and the other containing the water cooled shield and associated heat transfer system. The two models run concurrently and pass temperatures and heat fluxes through a common file. An additional benefit of this method is that it essentially parallelizes the problem, and a modest improvement in the wall clock time required to complete the simulation is realized.

The MELCOR model of ARIES-ACT1 comprises 1/3 of the tokamak. The primary heat structures and fluid volumes included in the LiPb/helium system model include the SiC walls and LiPb flow channels of the three (one inboard and two outboard) blankets, the upper and lower divertors each with two plates and helium coolant, the steel structural ring (high temperature shield) and helium coolant, and the double walled vacuum vessel segments representing the inboard, outboard, top, and bottom of the vessel. These components are shown in the schematic in Figure 3. The ex-vessel heat transfer systems for LiPb and helium are included but not shown in the figure; neither does it include the water-cooled shield and associated heat transfer system, which are modeled by a separate input file as described above. The vacuum vessel, which operates at significantly lower temperature than the other helium cooled components (high temperature shield and divertor), is cooled by a separate helium loop as shown in figures 2 and 3. In the present model, the divertors and high temperature shield are cooled by the same loop. These may be split as the design evolves to allow for better control of the temperatures of these components.

After a short (1000 s) period that is modeled to establish the appropriate steady state temperatures of these components, forced cooling is lost in all loops. Beginning at this time, all the above-mentioned components generate decay heat. The decay heat

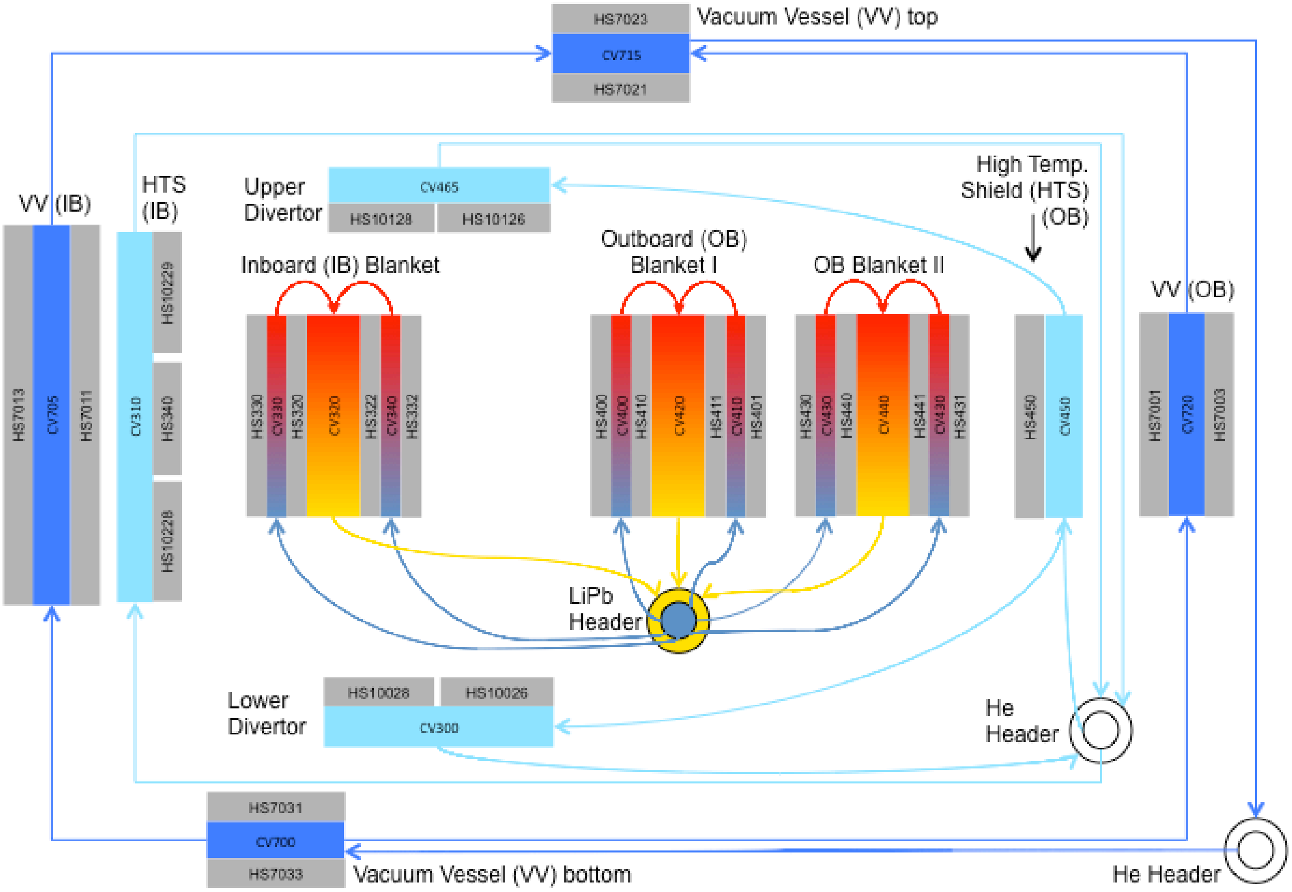


Fig. 3. A schematic of the primary components of the LiPb and He cooled systems in ARIES-ACT1 as modeled in MELCOR. Three coolant loops are present: two helium loops (one, light blue, for the highest temperature components, the divertors and structural ring, and one, dark blue, for the VV), and the LiPb loop through the blankets. The coloring of the LiPb flow illustrates the flow path and heating. Note that the ex-VV heat transfer systems and the water-cooled shield and associated water systems are not shown here.

for each component is determined by a 1-D analysis [10]. Decay heats for outboard components are shown in Figure 4. These are input for each component, as a function of time, in the MELCOR model. Though the decay heat drops significantly in the first hour in the SiC structures, they continue to be heated by the decay heat from the LiPb, which does not. The kink shell, despite its comparatively small volume, contributes a larger amount of decay heat and therefore needs to be accounted for. More detailed 3D decay heat calculations are planned in support of the final ARIES-ACT1 design [10].

III. RESULTS AND DISCUSSION

At the initiation of the accident, decay heating of structures drives a continually increasing flow rate of water through the water-cooled shield by natural convection. About eight hours into the accident, when it has reached ~5 kg/s, water begins to boil. The boiling causes a large spike in the flow rate to the heat transfer system, but the steam condenses and returns through the same path to the shield, abruptly cooling the structures. This periodic (initially about every two hours; the period grows longer over time) boiling and condensing continues throughout the transient, with the flow rate remaining more or less constant in between boiling events at ~5 kg/s.

The periodic boiling does not detract from the ability of the system to passively cool in-vessel structures, as evidenced by their temperatures shown in Figure 6. Here it can be seen that the temperatures of the divertors, first wall (inboard and outboard), and structural ring (high temperature shield) do not increase significantly above

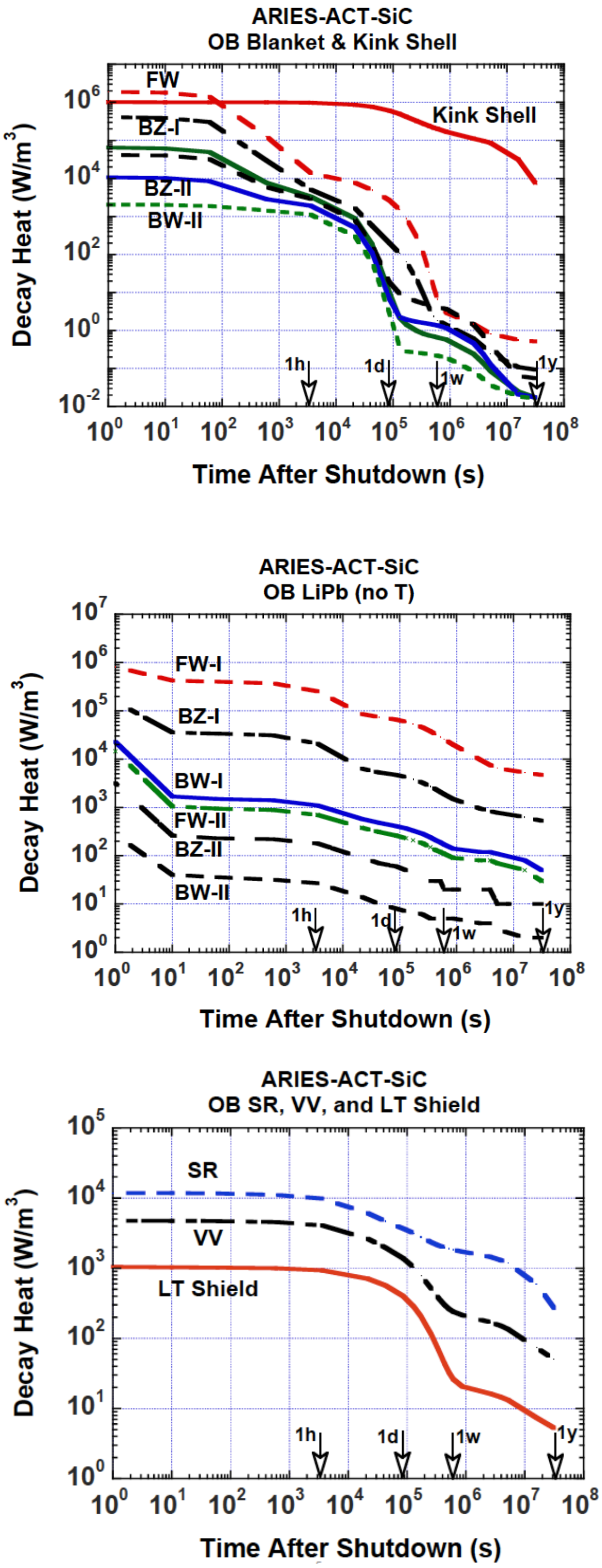


Fig. 4. Decay heat in ARIES-ACT1 outboard components as a function of time: blanket structure (SiC and kink shell, top), blanket LiPb (middle), and structural ring, vacuum vessel, and water cooled shield (bottom) [10].

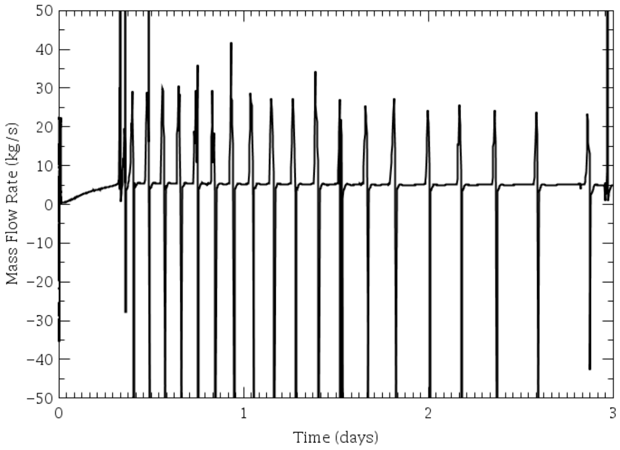
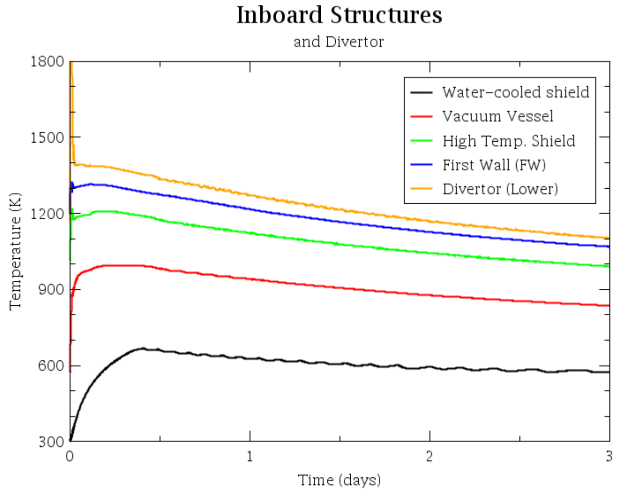


Fig. 5. Mass flow rate of water from the water-cooled shield outlet to the heat transfer system.



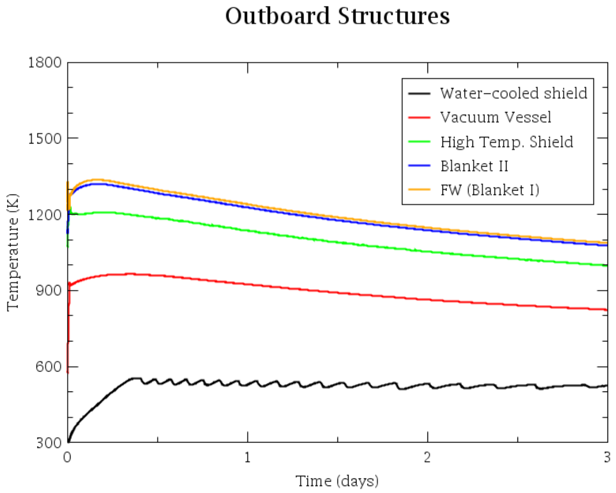


Fig. 6. Inboard (above) and outboard (below) structure temperatures during LOFA.

their normal operating temperatures. The vacuum vessel temperature does not rise enough to cause concern. All structure temperatures have peaked and begin decreasing again within the first half-day after loss of flow.

The effect of the periodic boiling of the water coolant is evident in the oscillating temperature of the inboard and outboard water-cooled shield after this time. These structures are more distant from the top of the vessel where the boiling occurs, so these oscillations are smoothed somewhat. Though the temperatures themselves are not a concern for 3Cr-3WV steel, it should be noted that the normal operating temperature of the water-cooled shield in this design is 300 K, at which it may be affected by shifts in the ductile-to-brittle transition temperature under irradiation. This may be acceptable since it is not intended to serve as a vacuum or pressure vessel; however, the assumption that stresses occurring in the shield are ignorable may warrant some further investigation in light of the fact that there are temperature differences of several hundred degrees K across it, and the fact that it must contain water that boils during the LOFA, which also creates some cyclic changes in temperature. An increase in the volume of water in this system to avoid boiling altogether will also be investigated.

IV. FUTURE WORK

A more comprehensive safety analysis is planned for ARIES-ACT1 and the other ARIES-ACT design variants, which will be detailed in a subsequent publication. These may include analysis of a loss of coolant accident (LOCA), in which release of the release of radioactive materials including tritium must be considered. The multiple coolants and coolant loops present in ARIES-ACT imply a number of different possible LOCA scenarios. The most challenging of these is a water LOCA in which the LiPb system remains intact; in this case, the passive heat removal provided by the water is lost, but the LiPb continues to heat surrounding structures. Some additional modifications to the MELCOR model will be necessary to consider this case. As a simplification and measure of conservatism in the present model, the outside of the water-cooled shield is treated as an adiabatic boundary. In a water LOCA, which disables the passive heat removal mechanism, heat transfer through this boundary is the only way to transfer it away from in-vessel components. In ARIES-ACT, the surface is covered with a multi-layer superinsulation. The superinsulation consists of multiple layers (e.g. 10-15, [11]) across which heat must radiate. Heat transfer is reduced depending on the number of layers N according to:

$$q'' = \frac{\varepsilon}{N+1}\sigma\left(T_H^4 - T_L^4\right) \qquad (1)$$

In the absence of water cooling, it is not clear whether sufficient heat would be transferred across the superinsulation to sufficiently cool structures. It might also act as a barrier to conductive and convective heat transfer that may not be easily overcome by other strategies for heat removal by these mechanisms, such as gas injection inot the cryostat.

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