LOSS OF COOLANT ACCIDENT AND LOSS OF FLOW ACCIDENT ANALYSIS OF THE ARIES-AT DESIGN

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ABSTRACT

Loss of coolant accident (LOCA) and loss of flow accident (LOFA) analysis is performed for ARIES-AT, an advanced fusion power plant design (1000 MWe). ARIES-AT employs a high performance, high temperature blanket system. It uses the high temperature SiC/SiC for structural material and LiPb for coolant-breeder. Due to the large difference between the time scale of plasma shutdown and the coolant or power loss, it is assumed that the plasma is immediately quenched at the onset of the LOCA/LOFA and the chamber components' temperature begins to rise due to the decay heat generated. A 2-D transient finite element model is established to examine the thermal behavior of the in-vessel components to determine the maximum temperature reached, the time, and duration of the peak. The model is axisymmetric in (r-z) around the reactor axis to show the details of temperature distribution in the vertical direction. The vacuum vessel is assumed adiabatic in the inboard side and radiates to the maintenance port located on the outboard side. The maximum temperature of steel in the reactor is about (600 °C - 700°C) after about 4 days from the onset of the accident. The highest temperature in the reactor is in the divertor region and it reaches ≈1050°C after about 2-3 hours. The analysis indicates that the reactor does not need any special scheme for decay heat removal.

I. INTRODUCTION

The ARIES-AT blanket/shield has been developed with the overall objective of achieving high performance while maintaining attractive safety features, simple design geometry, credible maintenance and fabrication processes, and reasonable design margins as an indication of reliability. Figure 1 shows a cross section of ARIES-AT power core configuration. The design utilizes LiPb as breeder and coolant and low-activation SiC/SiC composite as structural material. The LiPb operating temperature is optimized to provide high power cycle efficiency while maintaining the SiC/SiC temperature under reasonable limits.[1] This analysis addresses the consequences of the rare events of loss of coolant accident and loss of flow accident. Accident histories werw calculated for the first week following the event.

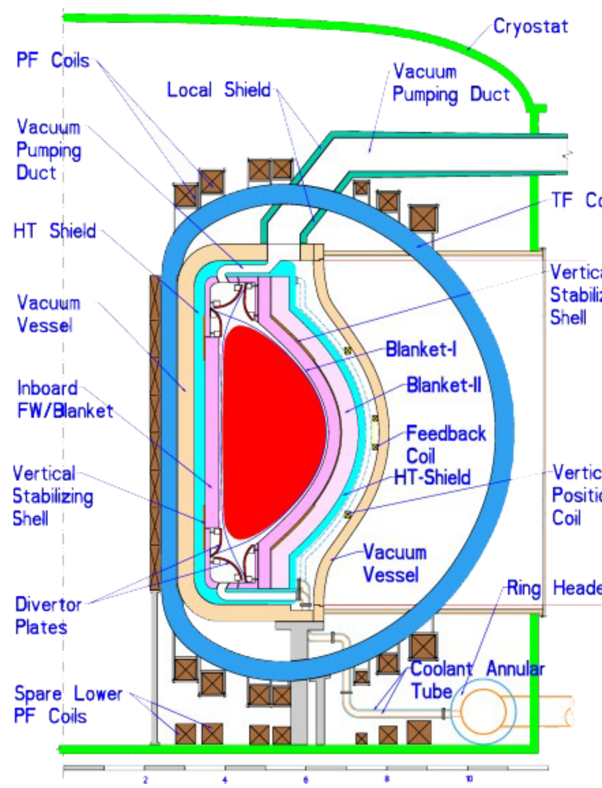

Figure 1. ARIES-AT cross section.

LOCA occurs when one or more supply tubes outside the reactor are damaged or ruptured, preventing the coolant from reaching the first wall or plasma facing components.

LOFA occurs when pumping power is lost and the coolant becomes stagnant (no flow). The goal of this investigation is to determine the temperature history of the different components as a function of time, and ultimately, the highest temperature reached, and its duration. This will aid in determining whether the first wall or any other component material will be damaged as a result of this temperature, and will have to be replaced before reactor operations can be resumed. Even though neutron heating is absent, the lack of coolant in the coolant channels causes the temperature to rise in various sections of the blanket and shield due to afterheat. The analysis is performed for a base configuration specific to ARIES-AT (see Fig. 1.). This paper describes the results of the thermal hydraulics study of this blanket/shield and divertor including a discussion of the ways of dissipating the decay heat resulting during normal operation.

II. ASSUMPTIONS, INITIAL AND BOUNDARY CONDITIONS

Due to the large difference between the time scale of plasma shutdown (≈1 ms) and the loss of coolant or loss of flow (several minutes-hours), it is assumed that the plasma is immediately quenched at the onset of the LOCA/LOFA and the chamber components' temperature begins to increase due to the decay heat generated (worst case scenario).
The base case assumptions are:

1. Adiabatic boundary conditions at the inner surface of the inboard vacuum vessel (I/B VV).
2. The outer surface of the outboard vacuum vesssel (O/B VV) radiates to the gate of the maintenance port.
3. The maintenance port convects (naturally) to the atmosphere at 20°C (ultimate heat sink).
4. Thermal radiation is allowed in the gaps between surfaces.
5. Emmissivity is 0.5.

The initial temperature of different reactor components used in this study are listed in Table 1.

III. FINITE-ELEMENT MODEL

An axisymmetric finite-element model in the r-z plane is constructed to study ARIES-AT LOCA/LOFA events. Assuming symmetry, the analysis was done for the upper half only: the divertor plates and 4 cm tungsten vertical stabilizing shells are included. This model assumes complete symmetry around the vertical z-axis. The ANSYS 5.4 code is used to perform this analysis.[3] Figure 2 shows the 2-D axisymmetric finite-element model used in this analysis.

An activation analysis is performed to determine the amount of thermal load to each component. The decay heat loads are specific to each material, depend on the degree of activation and vary with time after shutdown. The decayheat variation for the OB and IB sides is shown in Figures 3 and 4, respectively during the first month after shutdown. The FW-SiC decay heat drops after the first minute following shut down. Figure 5 shows the deacy heat in the divertor plate, manifold and the replaceable high temperature shield during the first month after shutdown. The activation calculations indicate that within one hour after shutdown the activity of the SiC structure drops by several orders of magnitude below the activity of the Table 1. Average temperature at onset of LOCA/LOFA. The analysis of the divertor and the ARIES-AT detailed activation analysis are presented elsewhere.[2]

Component	Coolant (°C)	Structure (°C)
Inboard Components:		
V.V.	75	100
HT shield	759	806
Blanket	968	925 for side SiC walls
First wall	800	960 for front wall
		925 for back wall
Outboard components:		
Blanket-I: Wall	787	950 for front wall
		925 for back wall
Blanket-I: Channel	965	925 for side SiC walls
Blanket-II: Wall	709	800 for front/back wall
Blanket-II: Channel	932	800 for side SiC walls
HT shield	725	800
V.V.	75	100

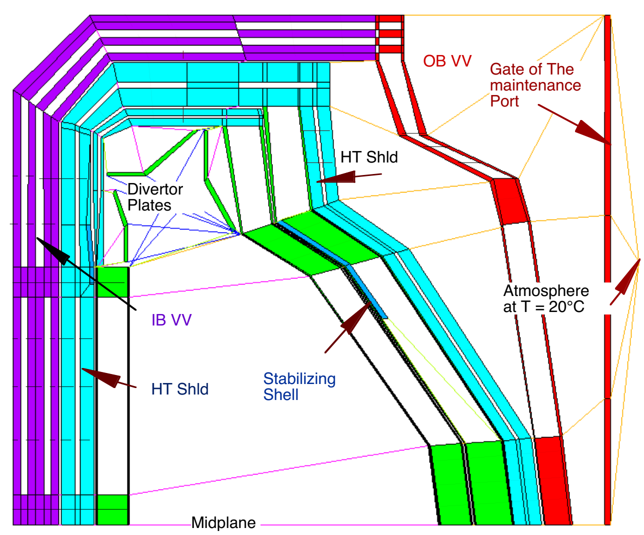

Figure 2. Finite-element model.

steel-based shielding components. The higher initial activity of the highly irradiated SiC components translates directly into higher initial decay heat for SiC. However, within an hour, the SiC decay heat drops by two decades to levels comparable to that of the well-protected steel-based shielding components.[2]

IV. RESULTS OF THERMAL HYDRAULICS CALCULATIONS

The transient thermal loads due to the decay heat with the given boundary conditions and the initial temperatures

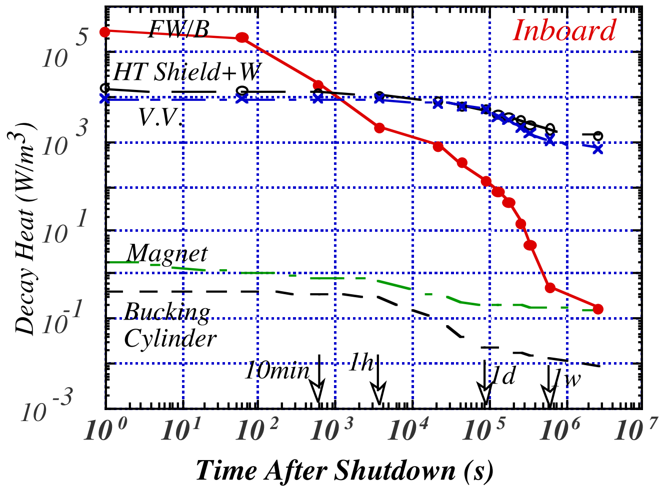

Figure 3. Decay heat of inboard major components.

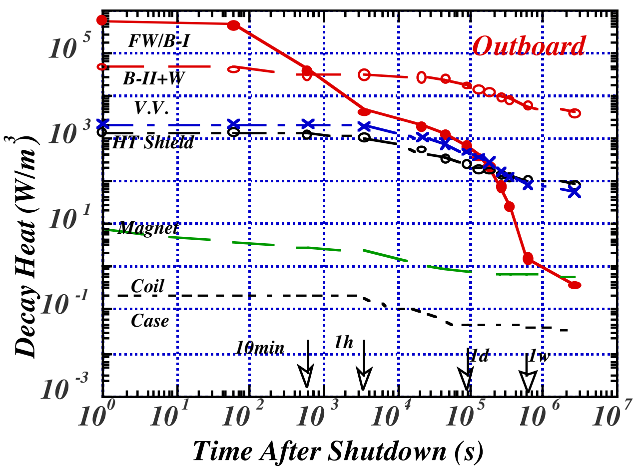

Figure 4. Decay heat of outboard major components.

for various ARIES-AT components are used to determine the thermal performance of the reactor.

The transient thermal analysis is performed for the upper half model of ARIES-AT for two major cases, namely LOCA and LOFA. Some detailed analysis is performed to examine a specific assumption like the effect of the vacuum vessel (VV) initial temperature on the maximum temperature of the rest of the reactor.

In a study of the thermal map of the reactor the following conclusions are reached. The inboard first wall (FW) would radiate a very small amount of heat to the outboard FW, because the temperature difference is small. That will leave the inboard VV as the only heat sink available in the inboard side. The VV massive steel structure acts as an immediate heat sink that heats up as time passes. The inboard side VV has no heat path except conduction to the top part of the reactor. Also there is no thermal radiation link between the VV and the magnet structural casing in the inboard side, to prevent thermal

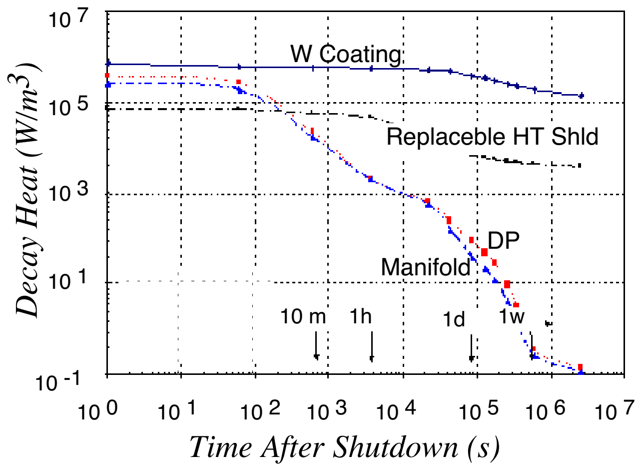

Figure 5. Decay heat of divertor, manifold and replaceable HT shield.

leakage during normal operation. This would, obviously, put a great deal of dependence on the thermal conduction performance of the inboard side of the VV.

The outboard side is in a better thermal situation, as it has the massive steel gate of the maintenance ports to conduct and radiate to. This is true for all cases studied. In the LOFA analysis we assume that the coolant channels are filled with LiPb that has higher activity than SiC and therefore generates a higher decay heat compared to the case of LOCA. Results show that LOFA is more critical than LOCA for that reason. Figure 6 shows the inboard LOFA temperature history of some key components at the midplane. The temperature of the steel inboard vacuum vessel reaches 686°C after 2.4 days and then decreases with time. The highest temperature in the reactor is at the divertor region and it reaches ≈1050°C after about 2-3 hours. Figure 7 shows the outboard LOFA temperature history of some key components. The temperature of the steel outboard vacuum vessel reaches 474°C after 14.7 hr and then decreases with time. It is clear from comparing the two figures that the inboard is the critical side and needs more attention.

The design offers the option of operaing the local shield located behind the divertor pumping ducts (not shown in Fig. 1) at the liquid nitrogen temperature (80 K) of the high-temperature TF magnet. In a series of investigations of the effects of the cryoshield on the thermal performance of the reactor components, we assumed that the initial shield temperature could be at the liquid nitrogen temperature (80 K). Figure 9 shows the transient thermal behavior of the inboard side during LOFA, of some key components. The temperature of the inboard vacuum vessel reaches 685°C after 2.4 days and then decreases with time. The temperature of the inboard vacuum vessel reaches 685°C after 2.4 days and then decreases with time.Those results proved that the cryoshield has an insignificant effect on the IB VV peak

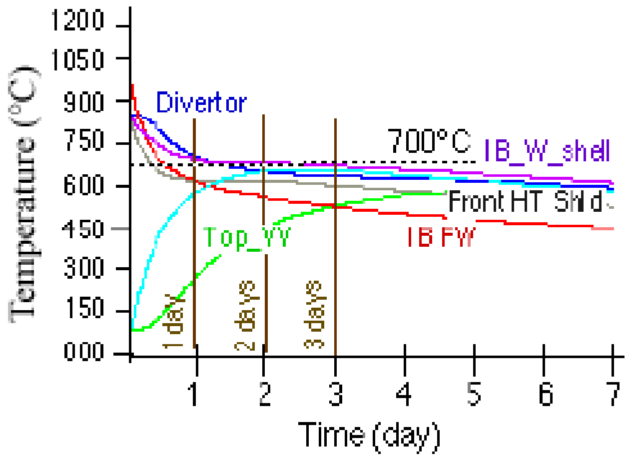

Figure 6. Inboard LOFA temperature history of some key components.

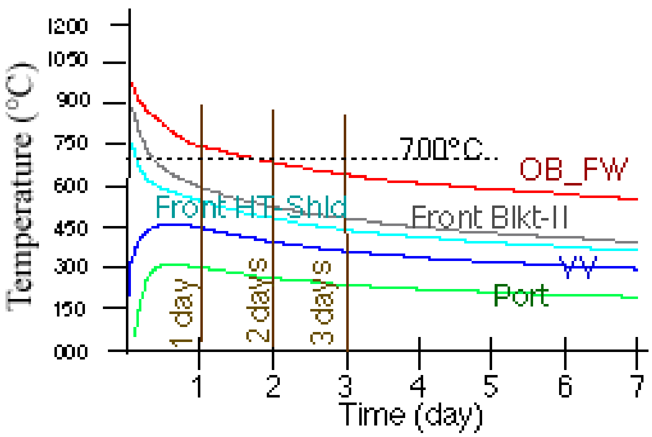

Figure 7. Outboard LOFA temperature history of some key components.

temperature at the midplane. Table 2 shows a summary of the results of LOCA/LOFA analysis assuming different initial conditions. Figure 8 illustrates the inboard LOCA

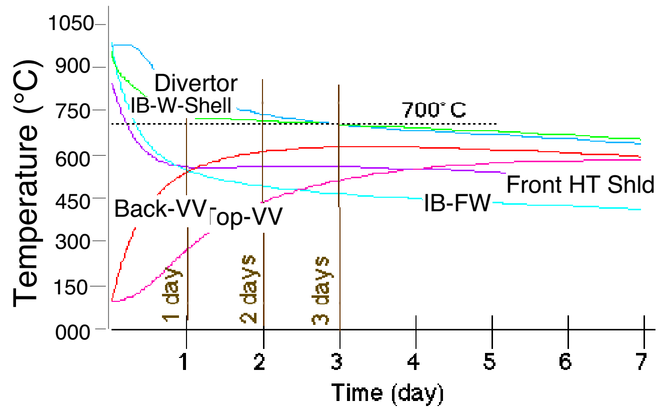

Figure 8. Inboard LOCA temperature history of some key components.

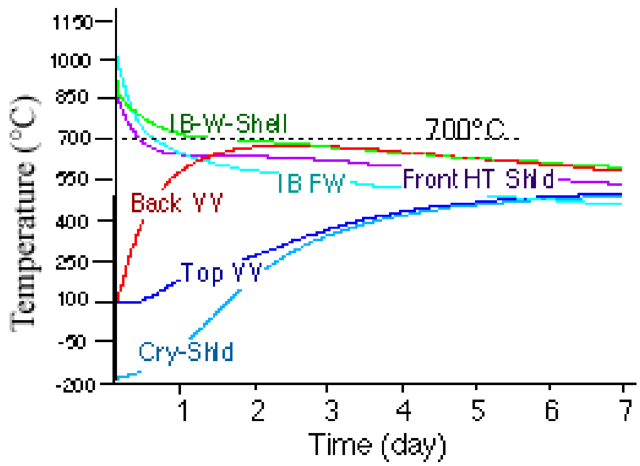

Figure 9. Inboard LOFA temperature history of some key components with cryogenic shield starts at 80 K.

performance. The temperature history of the key parts reveals that the temperature in the steel inboard vacuum vessel reaches 636°C after 3.4 days and then decreases very slowly with time.

Table 2. Summary of the Results

Case	1 day(°C)	2 days(°C)	3 days(°C)	7 days(°C)
a. Temperature in the I/B vacuum vessel at the midplane ($T_{initial}$ = 50°C).				
1 - Complete LOCA (in LiPb and water)	512.3	591.2	611.5	586.3
2 - LOFA in LiPb and LOCA in water	581°C	665.5	671.9	601.7
b. Temperature in the I/B vacuum vessel at the midplane ($T_{initial}$ = 100°C).				
1 - Complete LOCA (in LiPb and water)	543.8	617.4	634.6	601.5
2 - LOFA in LiPb and LOCA in water	608	683.9	685.9	669.4
3 - LOFA in LiPb and LOFA in water (with cryogenic shield)	607.9	682.2	680.9	590.5

V. SUMMARY AND CONCLUSIONS

• Worst case scenario is total LOFA in LiPb and total LOCA in water.
• SiC components have an acceptable temperature during full LOCA/LOFA (Tmax < 1100°C).
• IB VV exhibits the highest LOCA/LOFA temperature among all FS components (Tmax < 700°C).
• With no heat sink on the IB side, maximum IB VV LOCA/LOFA temperature reaches 689°C in ~ 2.5 days, which is acceptable.
• Partial LOCA/LOFA (in one loop or more) will result in lower temperatures.
• No need for a special procedure to deal with LOCA/LOFA because the heat redistributes in various components and the system get to thermal equilibrium.

Under different circumstances, if the temperature of ferritic steel (FS) components exceeds the limit, one or more of the following solutions could be considered:
- Take action before 2 days (e.g., flow helium gas into the chamber to remove decay heat).
- Install heat pipes that activate at 500°C on the IB VV.
- Drain the LiPb from the bottom immediately after the accident.
- Incorporate a LiPb heat removal loop (like that of ARIES-RS) using natural convection to transfer heat from the IB side to the OB side.[4]
- Provide a rupture disk mechanism that will release the water vapor from the VV during LOCA/LOFA.
- The water vapor released during LOCA/LOFA should be continuously collected, then condensed and returned back to the VV and LT shield. That could act as a passive heat sink (like a heat pipe).

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