Loss of Coolant Accident (LOCA) Analysis of the ARIES-ST Design

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ABSTRACT

Loss of coolant accident (LOCA) analysis is performed for ARIES-ST. ARIES-ST is a fusion power plant design based on the spherical tokamak concept to serve as a commercial power plant. It is assumed that the plasma is immediately quenched at the onset of the LOCA and the chamber components begin to increase in temperature due to the afterheat generated. This analysis examines the thermal behavior of the in-vessel components to determine the maximum temperature reached and addresses various schemes of afterheat removal. The thermal behavior of the reactor following a LOCA is simulated using a transient two-dimensional finite element model.

I. INTRODUCTION

This work investigates the consequences of a loss of coolant accident (LOCA) for ARIES-ST. ARIES-ST is a fusion power plant design based on the spherical tokamak concept to serve as a commercial power plant. The spherical tokamak concept has many attractive features, including high beta and power density, low magnetic field, high self-driven current fraction, and a compact power core.[1] Figure 1 shows an elevation view of the ARIES-ST power core. 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.

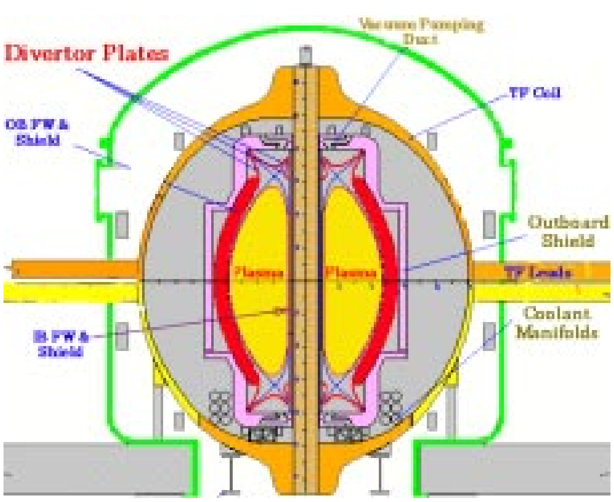

Figure 1. An elevation view of ARIES-ST power core.

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. It is assumed that the plasma is quenched simultaneously with the onset of a LOCA. 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 thermal response of the blanket and shield following a LOCA is determined by a cylindrical two-dimensional (R, Θ) finite element model at the midplane. For the LOCA analysis the central post (CP) is made of copper with empty coolant channels. The cross-sectional area of the empty coolant channels represents 15% of the total CP cross-sectional area. The same conditions are applicable for the rest of the reactor. Several cases are investigated using different values for partial thermal conduction in the gaps. The massive copper busbars are considered as ultimate heat sinks at a constant temperature of 35°C.

II. METHODOLOGY

In order to perform the ARIES-ST LOCA analysis, a number of assumptions have to be made. The assumptions for the accident conditions are:

1. All of the coolant is drained from all the blanket/shield sectors leaving the coolant channels empty and making it possible for coolant channel surfaces to radiate to each other.
2. The plasma is quenched instantaneously upon the onset of a LOCA. An appropriate shutdown mechanism must be in place for this to happen. If it takes 10 seconds for the plasma to be shut down, the heat generated amounts to 1% of the integrated afterheat in the first week after LOCA. Even though this does not appear to be very much, the immediate effect on the first wall could be significant.
3. All facing surfaces radiate to each other.
4. Both inboard and outboard (OB) blanket/shields are solved interactively and can therefore radiate to each other across the plasma space.
5. Heat transfer across the gaps is by thermal radiation and partially by thermal conduction. In the gaps a certain percent of the facing area is assumed to have connecting

structure for internal support and can, therefore, also conduct heat.
6. Thermal emissivity is taken as 0.5 for all surfaces.
7. The massive copper busbars are considered as ultimate heat sinks at a constant temperature of 35°C.
8. Temperature dependent thermo-physical properties are used for all the materials.
9. The material properties of the different zones in the radial build have been adjusted (linearly proportional to volumetric ratio) to preserve the density, heat capacitance and thermal conductivity of the actual composition.
10. The plant is assumed to operate for 40 full power years. Activation analysis assumed average neutron wall loadings of 3 MW/m^2 for the inboard and 5 MW/m^2 for the outboard.

III. MODELING THE INBOARD AND OUTBOARD BLANKET/SHIELD

A 2-D model in cylindrical coordinates is employed for finite element analysis at the reactor midplane. A cylindrical coordinate system is used to preserve the polar effect as the radius changes. The commercial finite element code ANSYS 5.2 is used in this analysis.[2] Tables I and II give the radial build and the material compositions, respectively, for the IB and OB sides. The finite element model used in the analysis is shown in Fig. 2. The only thermal loads considered in this analysis are those generated by afterheat following the onset of the LOCA. The afterheat loads are specific to each material, and are dependent on the degree of activation and are variable with respect to time. Various partial conduction in the gaps is used to determine how much thermal conduction is needed to maintain the maximum first wall temperature below the recommended temperature (up to the tempering temperature ≤ 750°C for a duration less than the tempering time of ≤ 2 hr).[3]

Table 1. Radial build in cm for the inboard/outboard sides of the blanket/shield used in LOCA analysis.

Radial Build	Inboard	Outboard
FW	1.4	4.1
Blanket	0	100
He Manifolds for Blanket	0	34
Assembly Gap	0	2
Shield:	20	25
HT Shield	20	0
Gap	0	2
LT Shield	0	25
He Manifolds for Shield	10	0
Assembly Gap	5	10
Center Post	80	---
Continuous TF Magnets	---	30

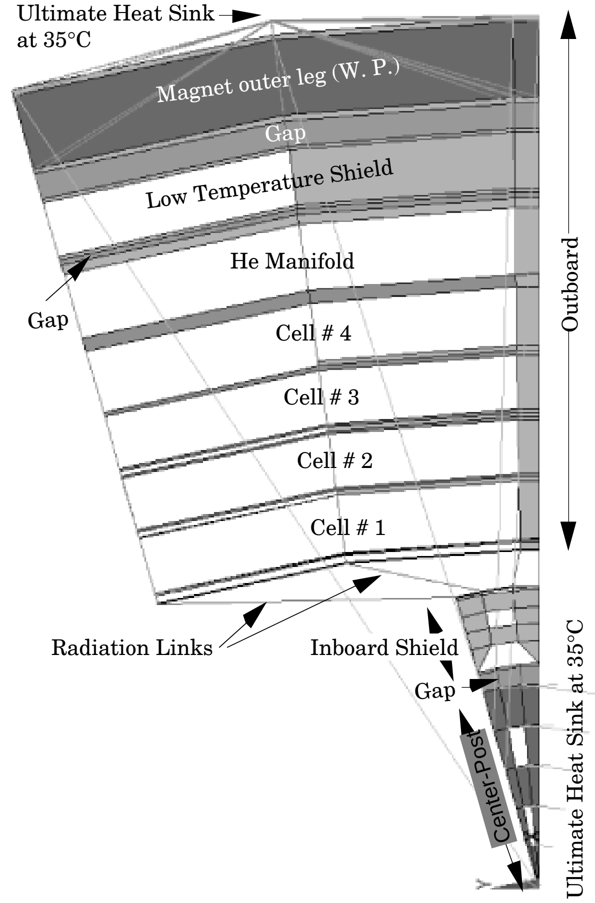

Figure 2. Finite element model for the inboard and outboard of ARIES-RS.

Table 2. The material compositions for the regions listed in Table 1.

Compositions	Inboard	Outboard
FW	30% FSS* 70% He Coolant	40% FSS* 60% He
Blanket	-----	6% FSS* 6% He coolant 12% SiC (75% dense) 76% $Li_{17}Pb_{83}$ (breeder/coolant)
He Manifolds	10% FSS* 90% He	30% FSS* 70% He
Replaceable HT shield	80% FSS* 20% He	------
LT Shield	------	15% FSS* 25% B-SS filler 60% H_2O coolant
TF Magnets	85% Cu alloy 15% H_2O	93% Cu alloy 7% H_2O

FSS* = Ferritic steel structural material.

Table 3. Initial thermal conditions (temperatures are in °C).

	T_{min} / T_{out} / T_{ave}		T_{min} / T_{max} / T_{ave}
Outboard FW			
He	300 / 425/ 362.5	FSS*	300/600/450
Outboard Blanket			
He in grid plates	425 / 500/462.5	FSS*	450/550/500
LiPb	500/ 700/ 600		
Inboard FW			
He	300/ 500/ 400	FSS*	300/600/450
Inboard Shield			
He	300/ 500/ 400	FSS*	300/550/475
Center Post			
H_2O	30/ 90/ 60	Cu	70/130/100

FSS* = Ferritic steel structural material.

IV. BOUNDARY CONDITIONS AND THERMAL LOADS

The sides of the model of the inboard and the outboard are reflecting boundaries (symmetry), i.e., they are adiabatic. The copper in the center post is thermally conducting to copper in the winding back of the TF coils. The center post and the TF winding pack are connected to the ultimate heat sink through a conduction bar that has a time constant of a copper bar 10 m long.

The afterheat variations in the OB and IB sides for this investigation are shown in Figs. 3 and 4 for the time of the first month after reactor shutdown. The afterheat of the inboard side is about half that of the outboard side, therefore the thermal response of the outboard will be paid more attention.[4]

V. RESULTS AND DISCUSSION

A parametric analysis is performed to study the effect of gaps on the thermal response of the in-vessel components to determine the maximum temperature and the duration of this temperature for different reactor components and to address various schemes of afterheat removal. The most critical component is the outboard first wall. The following is a description of the six cases investigated.

Case #1: There is no conduction in all the gaps, only thermal radiation is assumed. Cases #2 through #6: assume that there is partial conduction in the gaps. The conducting area is 0.05%, 1.0%, 2%, 5.0%, and 100% of the total facing area respectively.

Using the transient thermal loading due to the afterheat at times after LOCA onset of one second, one min, 10 min, one hr, six hr, one day, one week, and one month and the given boundary conditions and the initial temperatures for various components of ARIES-ST, the maximum outboard first wall temperature is about 765°C

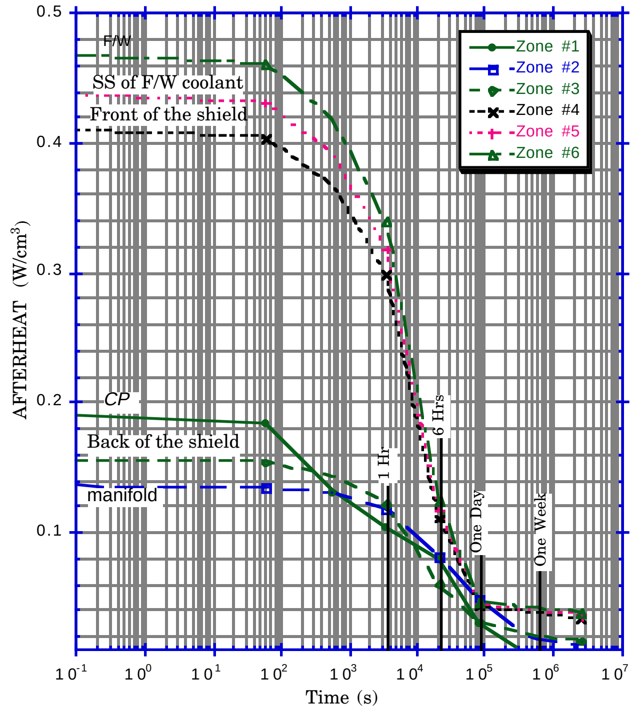

Figure 3. Inboard specific afterheat in a 100% dense material.

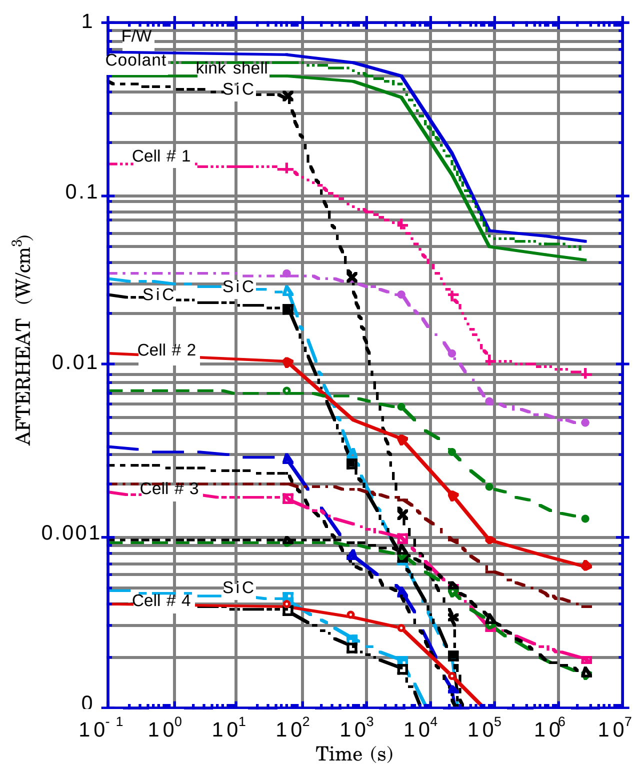

Figure 4. Outboard specific afterheat in a 100% dense material.

for the first five cases and 742°C for the sixth case investigated. This maximum temperature is reached after 6 hours from the reactor shutdown for all cases.

During the first six hours after shutdown, the gaps have no effect on the thermal response of the first wall temperature and the thermal response is mainly controlled by the immediate material in the zones between gaps. Figures 5 and 6 show a general temperature variation history of the outboard components for the cases of 0.5% and 5% conducting gaps during the first month after shutdown. The apparent sharp discontinuity in the temperature distribution is artificial, arising from sudden changes in heating due to use of heating values at specific times, as mentioned before in this section. The maximum temperature is the same for both cases and reached at the same time but the rate of cooling is greatly different as an efficient means of heat transport is provided through the conducting gaps.

The peak temperature during the first month after LOCA depends very little on the gap conductance, but the cooling rate of the first wall depends greatly on the gap conductance. Figure 6 also suggests that during the first six hours after shutdown, the gaps have no effect on the thermal response of the first wall temperature and the thermal response is mainly controlled by the immediate material in the zones between gaps. Figure 7 shows the cases of 0.0%, 5.0%, and 100% conducting gaps. For the case where there is no conduction in the gaps, the outboard first wall temperature starts to increase again after three days. This is due to the temperature equalization in the components between gaps and afterheat generation without an efficient heat path to the heat sink (thermal radiation plays a minor role in heat transport). Figure 6 shows that during the first three days the maximum outboard first wall temperature exceeds a temperature of 750°C only for 1.6 hours. The rest of the in-vessel components are well below that. Figure 8 shows the temperature of the outboard first wall after one month from LOCA as a function of the gap conductance. A small amount of conduction (0.5% to 5%) would reduce the temperature of the outboard first wall about 67°C to 125°C from that of the case of no conduction in the gaps at the end of the first month after LOCA.

VI. SUMMARY AND RECOMMENDATIONS

The maximum outboard first wall temperature is about 765°C for the first five cases and 742°C for the sixth case. This maximum temperature is reached after 6 hours from the reactor shutdown for all cases.

During the first 6 hours after shutdown, the gaps have no effect on the thermal response of the first wall temperature and the thermal response is mainly controlled by the immediate material in the zones between gaps.

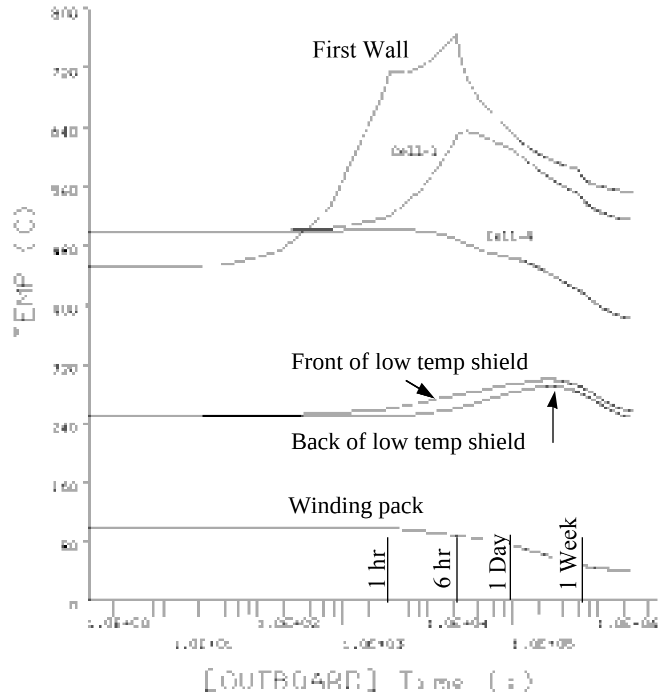

Figure 5. A general temperature variation history during the first month after shutdown of outboard components for the case of 0.5% conducting gaps.

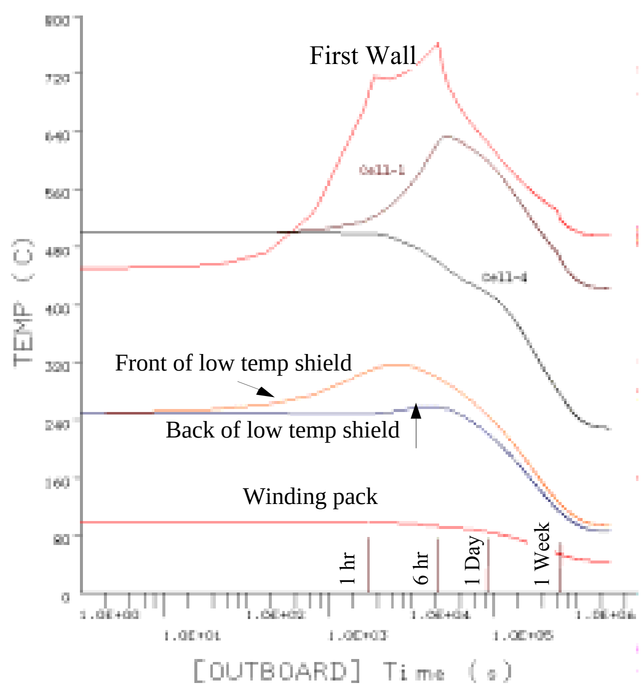

Figure 6. A general temperature variation history during the first month after shutdown of the outboard components for the case of 5% conducting gaps.

The peak temperature during the first month after LOCA depends very little on the gap conductance, and is not worth worrying about. The cooling rate of the first wall depends greatly on the gap conductance. A small amount of conduction (0.5% to 5%) would reduce the temperature of the outboard first wall about 67°C to 125°C from that of the case of no conduction in the gaps after one month from onset of LOCA.

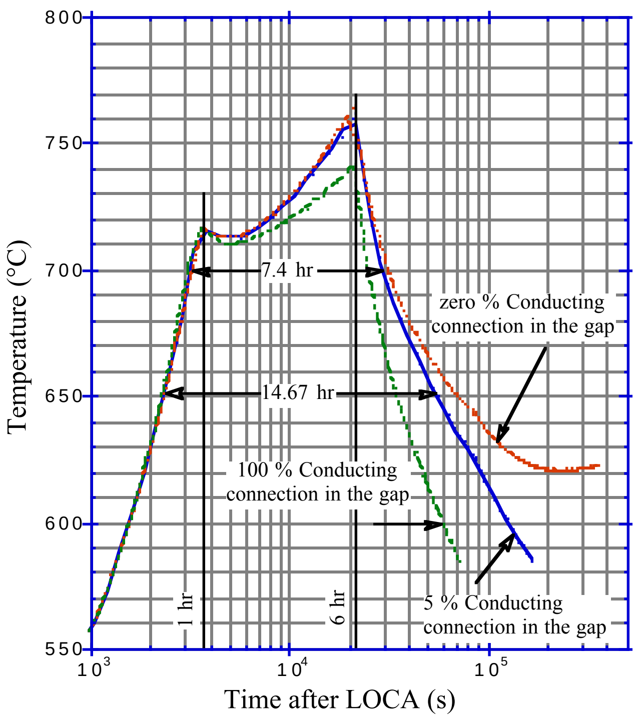

Figure 7. Temperature variation of the outboard first wall for three cases.

To understand how the long thermal path through the whole length of the center post and the TF coil would affect the general thermal response of ARIES-ST components, a vertical finite element thermal model for the inboard/outboard components with the heat sinks is needed.

To reduce the heat leakage during normal operation it has also been suggested that a passive method can be incorporated into the gaps. For example, a group of heat tubes that would be active only at certain temperatures and conduct heat in the gaps could be used. These heat tubes would be inactive during operation due to low temperature. However, during LOCA at a higher temperature, they would operate by melting of the heat transfer medium.

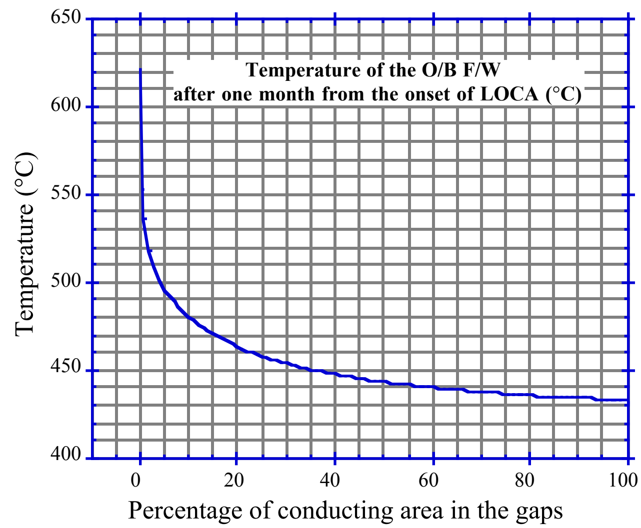

Figure 8. Temperature of the outboard first wall after one month as a function of percentage of thermal conduction in the gaps.

Although this is an interesting idea and should be explored further, it is not an entirely fail-safe system since the tubes could also rupture and themselves experience a LOCA. Also, a gas like He could be admitted to the vacuum vessel after the onset of LOCA and the gas can transport heat from hot parts to cold parts via natural convection.

ACKNOWLEDGMENT

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