ARIES-RS Loss of Coolant Accident (LOCA) Analysis

E.A. Mogahed, H.Y. Khater, I.N. Sviatoslavsky,
L.A. El-Guebaly and the ARIES Team

October 1997

UWFDM-1053

Presented at the 17th IEEE/NPSS Symposium on Fusion Engineering, 6–10 October 1997, San Diego CA.

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

ARIES-RS Loss of Coolant Accident (LOCA) Analysis*

E. A. Mogahed, H. Khater, I. N. Sviatoslavsky and L. El-Guebaly and the ARIES Team
Fusion Technology Institute
University of Wisconsin
1500 Engineering Dr., Madison, WI 53706

Abstract — Loss of Coolant Accident (LOCA) analysis has been performed for the ARIES-RS fusion power plant. LOCA occurs when one or more supply tubes outside the reactor are damaged or ruptured preventing the coolant from reaching the in-vessel components. For this analysis, it is assumed that the plasma is immediately quenched and the temperature of the chamber components begins to increase due to the generated afterheat. This work 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 2-D finite element model. The toroidal field (TF) magnets are perfectly thermally insulated from the rest of the reactor components and are not used as a heat sink. The analysis shows that the outboard first wall will reach a maximum temperature of 1174°C for a vanadium first wall and will remain at a temperature higher than 1100°C for about 10 hours. This means that a passive afterheat removal system should be incorporated in the design to protect the ARIES-RS plant in-vessel components from being damaged in case of LOCA.

I. INTRODUCTION

This work investigates the consequences of a loss of coolant accident (LOCA) in the rare event that a coolant tube ruptures and the coolant is drained from the reactor. 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. 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 the neutron heating is no longer there, the lack of coolant in the coolant channels causes the temperatures to rise in the 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 two-dimensional finite element model. Several cases are investigated using different shielding materials (Tenelon and vanadium) with different afterheat characteristics. Several alternate boundary conditions are also considered, primarily having to do with surface emissivities as well as location and availabilities of heat sinks.

A. Methodology

In order to perform the ARIES-RS 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. The TF coils on the inboard (IB) side of the plasma chamber are well insulated and are not available as a heat sink.
4. All parallel surfaces radiate to each other.
5. Both inboard and outboard (OB) blanket/shields are solved interactively and can, therefore, radiate to each other across the plasma space.
6. There is no heat transfer by conduction between the different zones. Within each zone, ten percent of the facing areas is assumed to have connecting structure for internal support and can, therefore, also conduct heat.
7. Thermal emissivity is taken as 0.5 for external surfaces and 0.8 for internal surfaces. The higher value for the internal surfaces is due to the effect of Li coolant on the channel internal coating.
8. The heat sink is located where the vacuum vessel is connected to the reactor support structure and to the access ports, and is assumed fixed at 100°C.
9. Temperature dependent thermo-physical properties are used for all the materials.
10. 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.

B. Modeling the Inboard and Outboard Blanket/Shield

A 2-D model in cylindrical coordinates (axisymmetric) 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 [1] is used in this analysis. 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 Figure 1 with the two sides appearing next to each other. In the actual case, the first walls for the IB and OB sides would be facing each other. Each separate zone is shown connected with a sidewall, which is the only thermally conducting member between the various materials in that zone.

*Support for this work was provided by th U. S. Department of Energy.

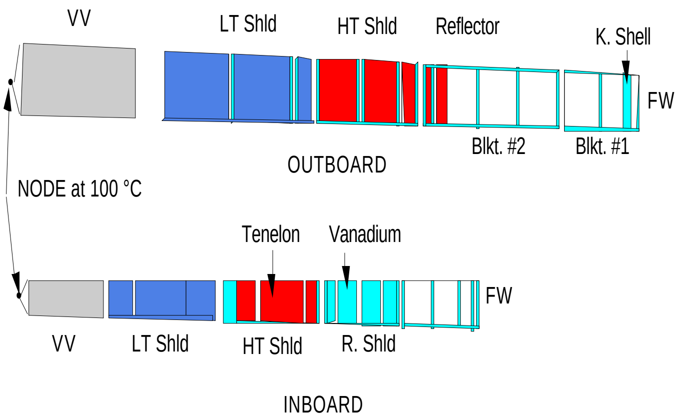

Figure 1. Finite element model for the inboard and the outboard of ARIES-RS.

Table I

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

Radial Build :	Inboard	Outboard
FW	0.3	0.3
Blanket-1	20	20
Gap	1	1
Blanket-2	-	30
RS/Reflector	20	7
Assembly gap	1	1

	Under Coils Inboard/Outboard	Between Coils Inboard/Outboard
Permanent shield	56 /70	90/82
HT shield	26/28	28 /35
Gap	2/2	2/2
LT shield	28/40	60 /45
Assembly gap	2 /2*	-- /2*
Vacuum vessel	20/30	-- /20
Total FW/B/R/S/VV/gaps	120/161	149 /130
VV management gap	5*/5*	5* /5*

* Minimum gap width

The only thermal loads considered in this analysis are those generated by afterheat following the onset of the LOCA. These afterheat loads are specific to each material, and are dependent on the degree of activation and are variable with respect to time. Two main options have been studied. The first is the baseline case which is described by the radial build given in Table I with the material compositon shown in Table II. The second is the same as the first case but with a change in the reflector material filler from Tenelon to vanadium. This change determines the effect of the reduced afterheat in vanadium relative to Tenelon. The lower maximum temperature using vanadium comes at an increase in cost of the material, ultimately reflected in the cost of electricity (COE). Various boundary and initial conditions are used to determine the best combination for maintaining the maximum first wall temperature below the recommended value of 1100°C.

Table II

The material compositions for the regions listed in Table I

Inboard	
First wall	100% V structure
Blanket	10% V structure + 90% Li
Replaceable shield	15% V structure + 10% Li + 75% V filler
<u>Permanent shield</u>	
HT shield	15% V structure + 76% Tenelon filler + 4% W structure + 5% Li
LT shield	15% Tenelon structure + 5% Li + 53% B_4 C filler (90% d.f.) + 27% WC filler (95% d.f.)
Vacuum vessel	35% Tenelon structure + 5% He coolant + 40% B_4 C filler + 20% WC filler

Outboard	
First wall	100% V structure
Blanket	10% V structure + 90% Li
Reflector	15% V structure + 10% Li + 75% Tenelon filler
<u>Permanent shield</u>	
HT shield	15% V structure + 5% Li + 73% Tenelon filler + 7% W structure
LT shield	15% Tenelon structure + 5% Li + 80% borated Tenelon filler
Vacuum vessel	2% Tenelon structure + 5% He coolant + 70% B-Tenelon filler

The initial conditions for the two options are as follows:

- The initial temperature of the first wall/blanket/reflector/HT shield is 600°C. It is 300°C for the LT shield.
- The initial temperature of the vacuum vessel is 150°C.

The boundary conditions are as follows:

- The sides of the model are reflecting boundaries, namely, they are adiabatic.
- The back of the vacuum vessel releases heat by radiation and by partial conduction through 10% of its facing area, to a heat sink at 100°C.

The afterheat variation in the OB and IB sides for the two cases considered is shown in Figure 2 and Figure 3.

II . RESULTS AND DISCUSSION

Two sets of thermal emissivities have been used for the two options with different reflector material fillers. In the first set, inner surfaces had an emissivity of 0.8 and the outer surfaces, 0.5. In the second set, both inner and outer surface

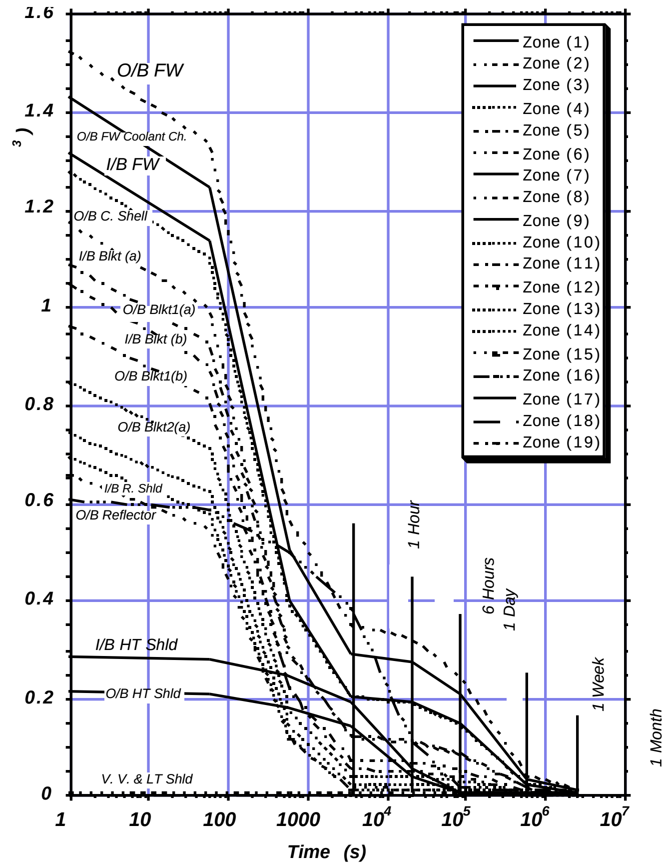

Figure 2. Specific afterheat in a 100% dense material (Tenelon in O/B reflector) (reference case).

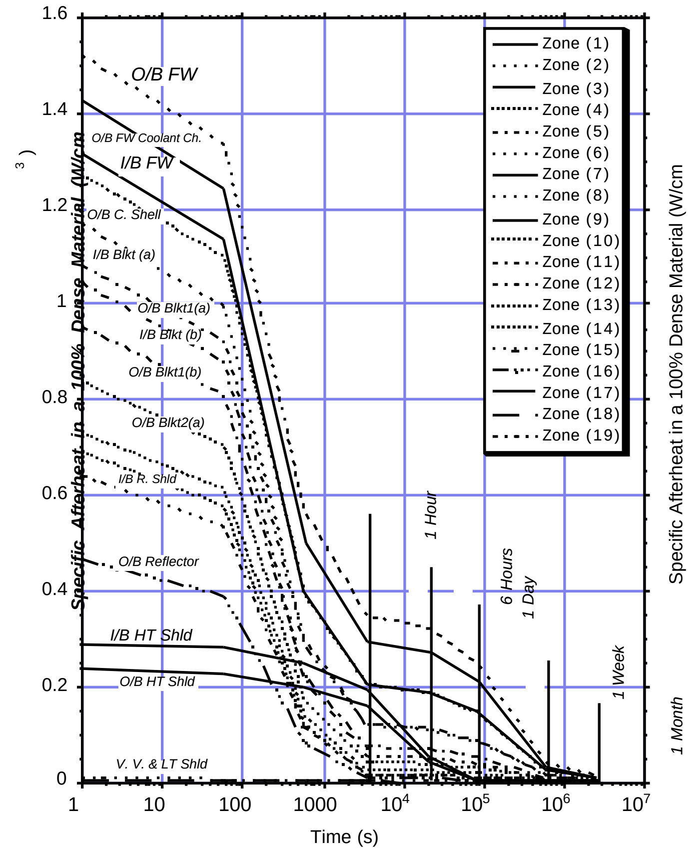

Figure 3. Specific afterheat in a 100% dense material (vanadium in O/B reflector).

surfaces had emissivities of 0.8. A maximum temperature of 1277°C occurs in Case #1 (Tenelon in the OB reflector, $\varepsilon_o/\varepsilon_i$ = 0.5/0.8) on the OB side. Its counterpart is Case #3 (vanadium in the OB reflector) where the temperature is 1176°C, or 101°C lower.

Using the same conditions of Case #2 but with all the surfaces having emissivities of 0.8, except the outer surface of the first walls having emissivities of 0.5, the increase in the maximum temperature was only ≈ 4°C. During the study it was decided to reduce the temperature in the low temperature (LT) shield to 150°C in order to alleviate excessive heating in the access doors. This necessitated the use of He gas in a separate cooling loop. Two cases have been analyzed: Case #5 with a starting temperature of the LT shield of 150°C and allowing it to heat up and Case #6, also with a starting temperature of 150°C and allowing it to stay at that level. In both cases the reference configuration and other boundary condition are the same as in Case #1.

The results show that the gains are small, 16°C in Case #5 and 37°C in Case #6, both values still above T_{max} =1100°C. In Case # 7, we postulate that the initial temperature of the LT shield is 150°C and hold it there, while enhancing emissivity to 0.8 everywhere (same as Case #2). Case #7 produces a reduction in the OB side temperature of 35°C over Case #2, also a marginal improvement. None of the attempts tried so far have managed to achieve the goal of less than 1100°C. The lowest temperature of 1111°C is in Case #

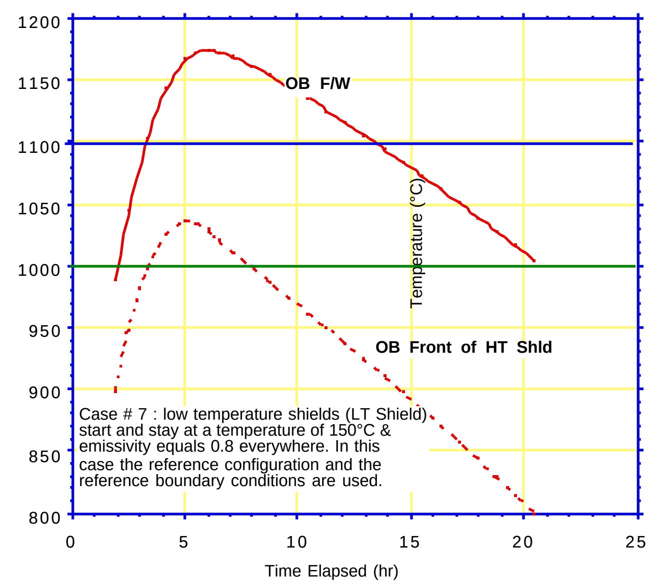

Figure 4. Temperature variation of the first wall and the front of the hot temperature shield for the final case (Case #7).

4, which has vanadium in the OB reflector and optimistic emissivities. Materials degrade from both high temperature and from time at that temperature. For example it is known that V-4Cr-4Ti shows no grain growth at 1000°C up to 600 hours, but exposure to 1100°C for more than two hours can cause excessive grain growth [2]. Typical short term temperature vs. time plots for Case #7 are shown in Fig. 4.

In Case #6 the OB first wall will be at a temperature > 1200°C for 10.5 hours and > 1100°C for ~ 20 hours. In Case #7 the OB first wall will be at a temperature > 1100°C for about 10 hours. These temperatures and durations do not comply with the recommended values; however, Case #7 is better than #6. A longer term temperature-time history for all the zones in Case #7 is shown in Figures 5 and 6 for the IB and OB sides respectively. These figures show that both IB and OB first walls cool down to less than 500°C after seven days with the remaining zones, well below that.

III. SUMMARY AND RECOMMENDATIONS

All the attempts to limit the first wall temperature during a LOCA to 1100°C for only several hours have failed, although some have come very close (see Case #4). It should be mentioned that these analyses have been made assuming that coolant is lost in all the sectors simultaneously. This is rather severe, since the survival of one coolant loop would provide a heat sink at the first wall, where the sectors with the LOCA loop would radiate to sectors which are still cooled, reducing the maximum temperature significantly. One of the primary reasons for this difficulty is the number of gaps between the zones in both the IB and OB radial builds necessitated by the desire to separate the zones and extend their lifetimes. Eliminating conduction between the zones severely limits heat transfer across the radial build to the heat sinks in the back.

Attempts made to reduce the maximum temperature during LOCA were:

- Replace the filler material in the OB reflector (Tenelon) by vanadium.
- Use optimistic values of emissivity.
- Reduce the LT shield temperature from 300°C to 150°C.

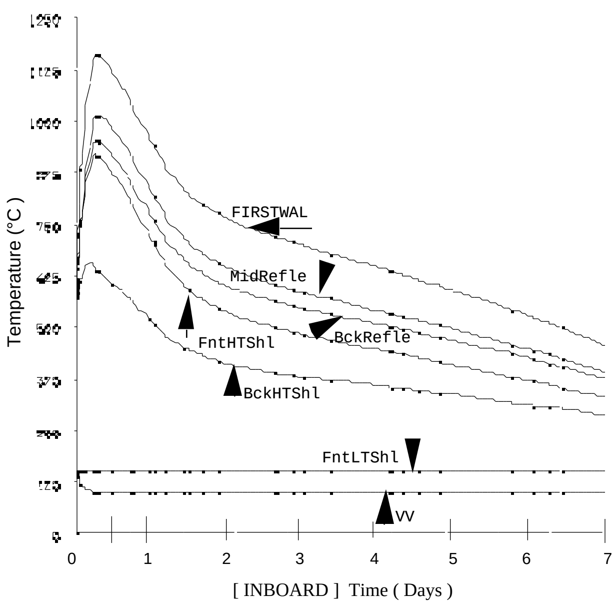

Figure 5. A general temperature variation history during the first week after shutdown of the inboard.

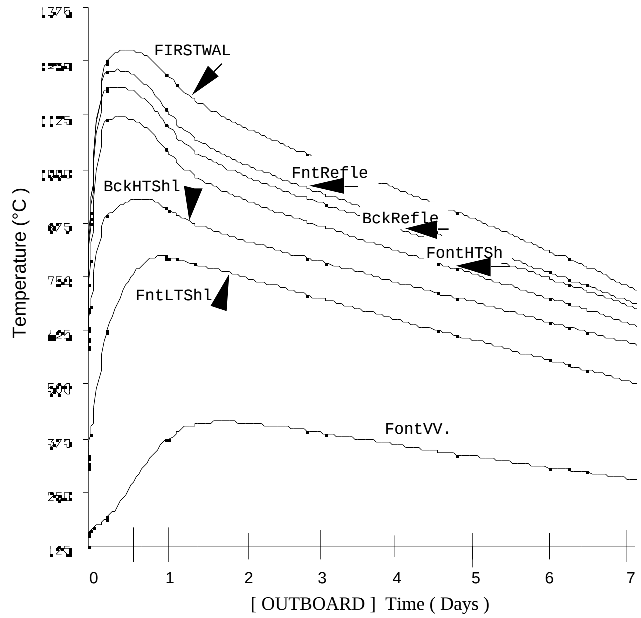

Figure 6. A general temperature variation history during the first week after shutdown of the outboard.

In the very best case (Case #4), which has a vanadium reflector and an emissivity of 0.8 everywhere, the maximum first wall temperature is 1111°C, and if the emissivity of the first wall is reduced to 0.5, it only rises to 1115°C. This case seems realistic and comes within 15°C of satisfying the requirement of 1100°C.

It has also been suggested [3] that a passive closed Li coolant loop can be incorporated into the back of the first wall segment connected to the back of the LT shield. This loop will be inactive during operation due to MHD effects. However, during LOCA with the magnetic field turned off, it will operate by natural convection with a temperature difference of only 50°C. Such a loop can limit the first wall temperature to 800°C. Although this is an interesting idea and should be explored further, it is not an entirely failsafe system since this loop could also rupture and itself experience a LOCA.

ACKNOWLEDGMENT

Support for this work was provided by the U. S. Department of Energy.

REFERENCES

[1] ANSYS 5.0 User's Manual, Updo, DN-R300:50-2 (1992).
[2] Mike Billone, private communication (Sept. 9, 1996).
[3] Siegfried Malang, private communication (1996).