A Complete Loss of Coolant Accident (LOCA) Analysis for the Inboard Component of ITER CDA

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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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Fusion Technology Institute
University of Wisconsin
1500 Johnson Drive, Madison, WI 53706

ABSTRACT

A two-dimensional thermal transient analysis, r-θ model, has been performed to study three cases of total LOCA in the inboard components for the ITER CDA design using realistic assumptions. The study shows that the first wall can withstand the surface heat flux without active cooling for an extended period of time longer than the 10 seconds normally assumed for the plasma to continue operation after the onset of LOCA. No melting at the first wall or at the blanket is expected, but the lead at the back of the vacuum vessel reaches the melting point within about two days after the onset of LOCA without active cooling. At this time, the front of the vacuum vessel will reach about 600°C. The temperature of the vacuum vessel will rise above 800°C in a week.

I. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) is a tokamak reactor that would be operating in two phases; a physics phase which is focused on demonstrating the controlled ignition for extended burn of the DT plasma, and a technology phase with the objective of demonstrating the reliability and maintainability of different reactor systems. Inherent safety is considered the ultimate design goal for ITER. The reactor is described as inherently safe if the design can demonstrate that the reactor can recover from a loss of coolant accident (LOCA), without imposing any hazard to the public, the operating personnel, and the equipment. It is ultimately desirable that this recovery be achieved with purely passive means.

The study of the thermal hydraulics transients and their serious effects on the performance of different reactor components during and after the loss of coolant accident is of paramount importance to insure the safety of the system, and integrity of the reactor structure. Without any active cooling and with the decay heat of the activated structural material, the temperature of some reactor components may rise to values higher than those permitted. This can cause considerable damage, even meltdown, of parts of the reactor structure. The purpose of this work is to assess whether structural integrity is maintained following a LOCA for the ITER design developed during the conceptual design activity (CDA) [1]. The effect of different boundary conditions on the temperature variation during a LOCA will also be studied. In the meantime, we will be able to evaluate the validity of using the approximate methods (lumped average temperature) to calculate the temperature response after LOCA. In this work, the post accident transient temperature distribution is predicted for a two dimensional (2-D) r-θ inboard sector at the midplane modeled for the finite element analysis code, ANSYS [2]. This sector covers the region from the inboard first wall to the central post of the magnet. The calculations performed utilize three different boundary conditions outside the vacuum vessel boundaries. Table I shows some of the key parameters of ITER.

Table I
ITER Parameters for Both Physics and Technology Phases

	Physics Phase	Technical Phase
Fusion power (MW)	1100	860
Average neutron wall loading (MW/m^2)	1	0.8
Breeder	sintered Li_2O (0.8 density factor DF))	
Multiplier	sintered beryllium (0.65-0.85 DF)	
Shield	steel/water	
Water coolant parameters		
Inlet temperature (°C)	60	
Outlet temperature (°C)	100	
Pressure (MPa)	1.5	
First wall coating	2 cm carbon	0.05 cm tungsten
Inboard FW	5 mm steel/4 mm	water/5 mm steel

II. HEAT SOURCE CALCULATIONS

A one-dimensional toroidal cylindrical model, in which the inboard and outboard regions are modeled simultaneously, has been used to determine the nuclear heat deposition in the different zones using the transport code ONEDANT [3]. The steady state temperature distribution in the inboard region is calculated using a surface heat flux of 28 W/cm^2 and the volumetric heating in the different zones of the inboard region shown in Fig. 1. The transient spatial distribution of the decay heat generation rate is calculated by the radioactivity code DKR-ICF [4] to represent the heat source following shutdown. Fig. 2 shows the decay heat generation rate after shutdown for the inboard region. The total integrated decay heat in the inboard zones is shown in Fig. 3. The heat source is normalized to the average inboard neutron wall loading of 0.88 MW/m^2 in the physics phase.

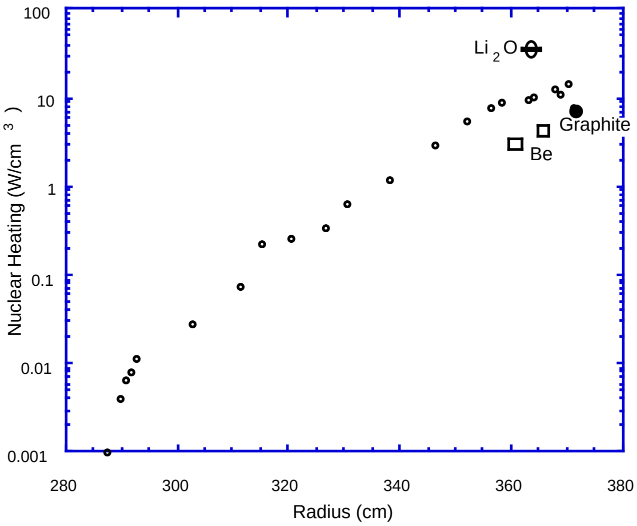

Fig. 1 . Nuclear heating distribution in the inboard zone.

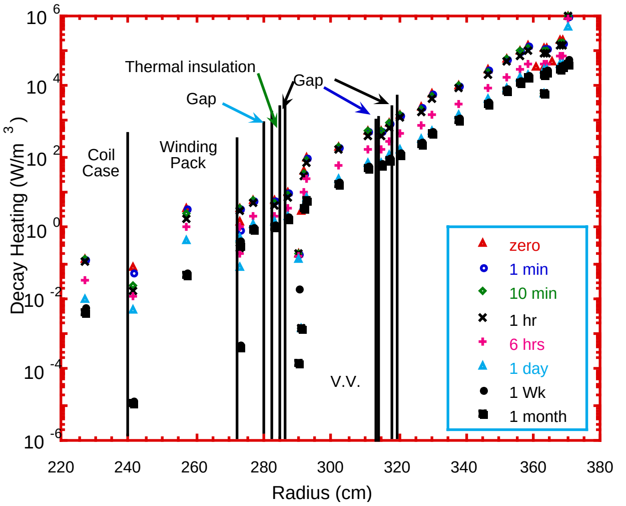

Fig. 2. Decay heat after shutdown for the inboard zones.

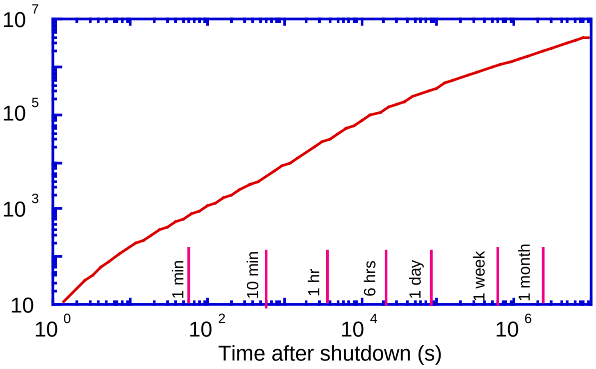

Fig. 3. The integrated decay heat variation after shutdown in the inboard zones.

III. ASSUMPTIONS AND MODELING

The scenario of a complete LOCA postulates that all active cooling of the reactor as well as the electric power to the magnet are lost at the same time while the plasma stays on for 10 seconds after the onset of LOCA. At the onset of LOCA all coolant tubes are completely empty and are considered to be radiating surfaces. Because of symmetry in the thermal loading, and symmetry in the geometry, only a small sector will be considered in the transient thermal calculations. A finite element model is prepared for a complete (from the inboard first wall to the magnet inner-leg and central post) inboard sector in the r-θ plane as shown in Fig. 4. The effect of thermal contact resistance between the steel/Be and steel/Li_2O in the blanket has been taken into consideration using a model for the thermomechanical contact between the ceramics (Be and Li_2O), and stainless steel plates [5,6]. In the model, a region of helium gas at a pressure of one atmosphere is assumed to fill the local zones around the tritium purging ducts. All the properties of the material used are temperature dependent.

IV. TRANSIENT THERMAL ANALYSIS

Two-dimensional (2-D) finite-element thermal analysis has been performed for three different cases. The finite element analysis code, ANSYS [2], was used to model an inboard sector from the first wall to the central post. Some previous LOCA analysis for the inboard zones of ITER [7,8] proposed several boundary conditions. For instance, Attaya and Gohar, [7] assumed that the magnet will stay at 4 K and the back of the vacuum vessel will radiate to it all times. On the other hand Andritsos and Zucchetti [8] did not take into account the first 10 seconds where the plasma is still on at the beginning of LOCA. Both investigations have not taken into account the thermal contact resistance between different parts of the first wall and blanket and assumed uniform temperature for all the inboard zones as an initial condition. In this study, the effects of the different boundary conditions are assessed as well as the effect of the thermal contact resistance between different parts of the first wall and blanket. In the first of the three cases considered, the magnet is taken as a heat sink that heats up during LOCA. The magnet is assumed to lose operating power instantaneously at the time of the onset of LOCA. Heat is transferred only by radiation between the back of the shield and the front of the vacuum vessel. The inboard components radiate the heat generated after the plasma shutdown to the thermal shield, initially at 77 K. The thermal shield radiates heat to the superconducting magnet, initially at 4 K. Radiation heat transfer between the magnet, the central post, and the external environment at 300 K is taken into account. In the second case, the adiabatic boundary condition is at the outer side of the magnet and no radiation to the external environment is assumed. In the third case, which is the most pessimistic case and the most unlikely to happen, the outer side of the vacuum vessel is assumed as an adiabatic boundary and, hence, the magnet is not considered. For each material used in the different zones, the time dependent volumetric heat generation provided by the activation calculations has been utilized.

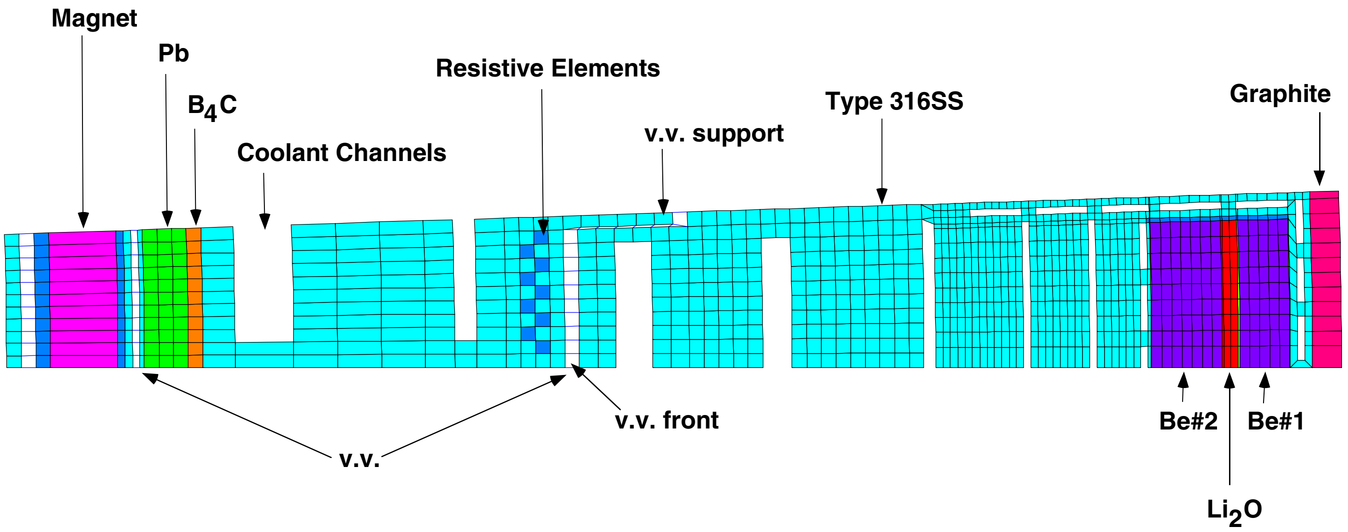

Fig. 4. 2-D finite-element model for the inboard zones.

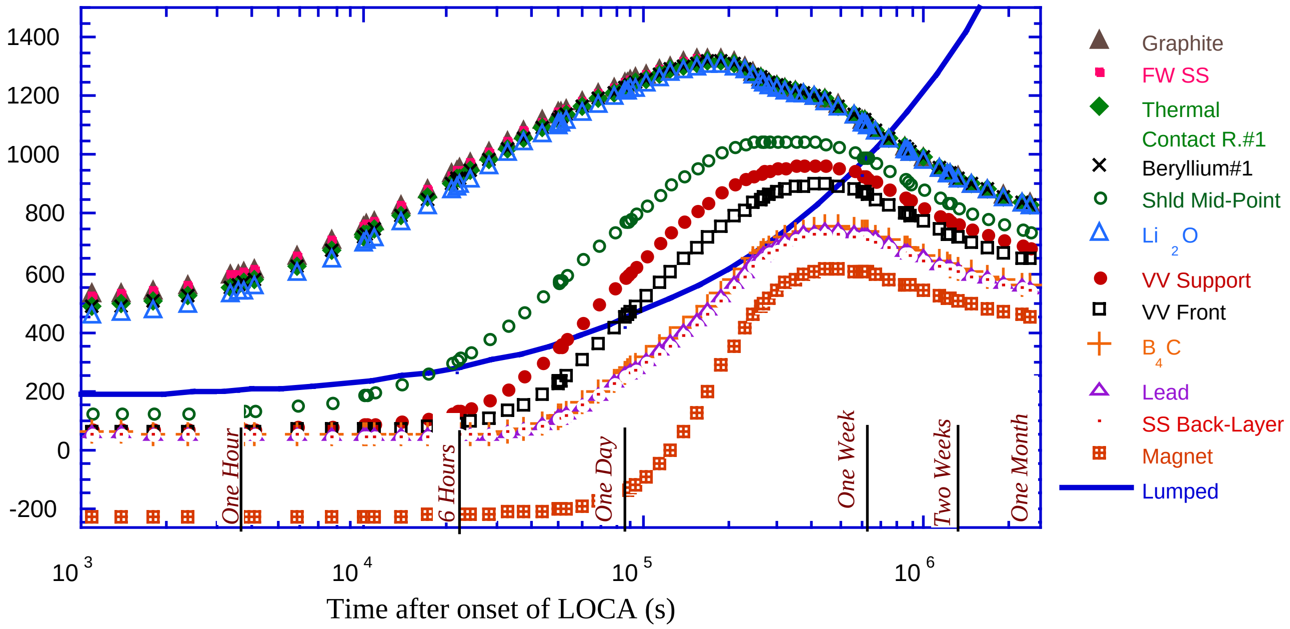

Fig. 5. Temperature distribution in inboard zones in the first case with the magnet as a heat sink and a radiative central post.

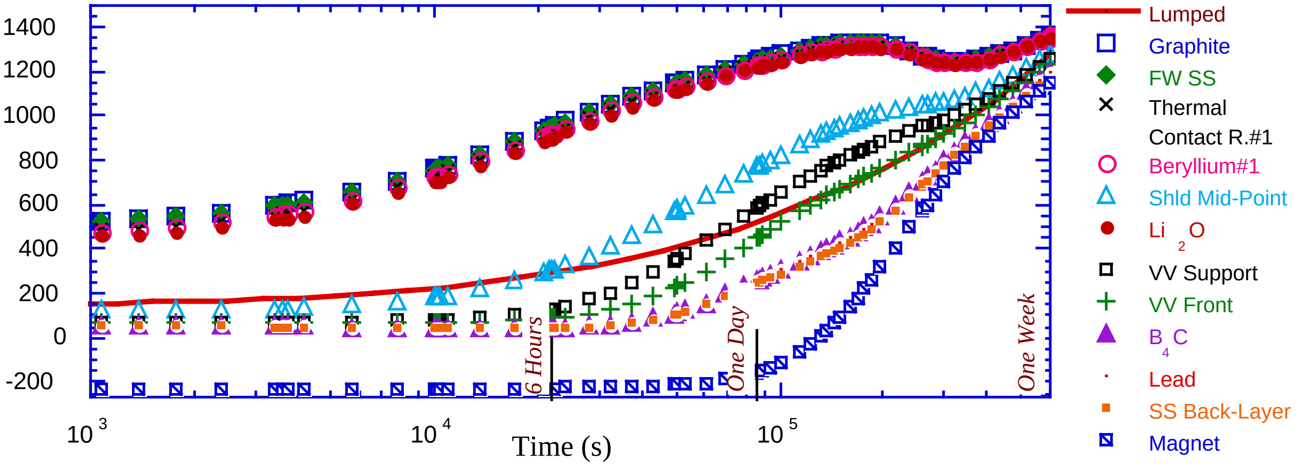

Fig. 6. Temperature distribution in the second case with the magnet as a heat sink and an insulated central post.

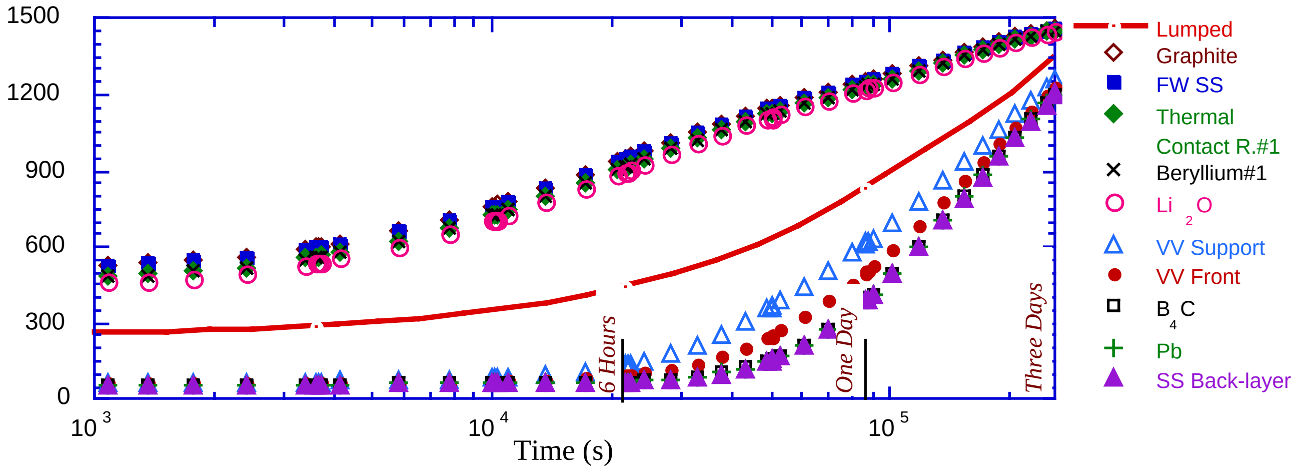

Fig. 7. Temperature distribution in the third case with the magnet not considered as a heat sink.

V. RESULTS AND DISCUSSION

The initial temperature at the onset of LOCA was obtained by calculating the steady state operating temperature distribution, using the nuclear heating distribution during operation given in Fig. 1, as well as the surface heat flux. During the first 10 seconds of the transient calculations the plasma is assumed to be on and the full operational heat source is considered. During this 10 second period no coolant is assumed to be active. The transient calculations were carried out up to one month after the onset of LOCA. The results of the first case are given in Fig. 5. The results of the second case are given in Fig. 6 for up to one week after the onset of LOCA. For the third case, the results up to three days following the onset of LOCA are given in Fig. 7. These figures show the temperature history of selected key points in the inboard zones of ITER for the three cases considered. It is found that the effect of the thermal contact resistance between the steel of the first wall and the Be#1 zone is to raise the temperature about 50°C. The same effect occurs between the Be#1 and the clad of the Li_2O layer, the clad and the Li_2O layer, the Li_2O layer and its clad, and finally between the Be#2 and the clad of the Li_2O layer. That results in about 150°C rise in the Li_2O temperature above that obtained when the effect of the thermal contact resistance is not considered. No melting at the first wall or at the blanket is expected in the first case but the lead at the back of the vacuum vessel reaches the melting point within about two days after the onset of LOCA without active cooling. At this time the front of the vacuum vessel structure will reach about 600°C. The temperature of the vacuum vessel will rise above 800°C in a week. These results are very conservative since the model doesn't account for the thermal coupling between inboard and outboard regions and doesn't allow for heat conduction to the massive colder structure at the top and bottom of the machine and to the ground through the machine base.

VI. CONCLUSIONS

Examining the results, one observes that the lumped calculation may produce deceiving results for the temperature to be used in calculating release fractions and off-pile dose levels. After one day from onset of LOCA the difference temperature between the FW and blanket zones is about 800°C for the first and second cases, and is about 350°C for the third case. Considering the magnet as a heat sink with a radiative central post is the most optimistic safety scenario because of the huge thermal inertia of the magnet that is at cryogenic temperatures. On the other hand, for the third and most pessimistic case, the first wall will start to melt after only three days, while the lead at the back of the vacuum vessel reaches the melting point within one day after the onset of LOCA without active cooling.

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