LOFA ANALYSIS FOR US ITER SOLID BREEDER BLANKET

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ABSTRACT

This paper addresses the thermal transport issues associated with a loss of flow accident (LOFA) for US ITER solid breeder blanket. Two LOFA scenarios were considered. For a LOFA due to a simultaneous catastrophic pump failure, the coolant temperature reaches its boiling point within only about 15 - 20 seconds. This scenario appears extremely unlikely and should be better characterized through a probability risk assessment study in order to determine to what extent corrective actions such as the use of backup pump should be taken. For a LOFA due to loss of power to the coolant pumps, the resulting flow transient is characterized by considering the effect of fluid inertia and pump inertia. Once a determination of the flow coastdown has been made, the temperature histories of blanket elements and coolant are analyzed using lumped parameter techniques. The results of the analyses indicate that the rate of coolant temperature rise due to the heat (generated and/or stored) transferred from the solid breeder area is strongly dependent on the transient flow behavior. If the coolant pump can be designed with a sufficiently large pump inertia (with an inertia time constants of about 1.5 s or more), the coolant temperature can stay under its boiling point for several minutes to allow for corrective action to be implemented. As an added safety measure, it seems prudent to include in the design a system of expansion volumes and/or safety valves for accommodating coolant pressure transients.

1. INTRODUCTION

The loss of flow accident (LOFA) considered in the present analysis is assumed to result from the simultaneous failure of all pumps due either to catastrophic mechanical failure or to loss of power. In postulating reactor accidents, loss of power is a less unlikely cause of LOFA since common mode failure could cause failure of the supply of power to all the coolant pumps. Note that in both cases, corrective action can be taken to avoid or limit damages, for example through the use of back-up pumps and back-up generators. The objective here is to assess the need for corrective action following a LOFA scenario and, if so, to characterize the time available for implementing the corrective action before irreversible damage could occur, caused by boiling water overpressurization, for example.

For the proposed ITER blanket design[1] (illustrated in Fig. 1), the coolant duct is laid in the toroidal-radial plane, and little benefit can be gained by natural convection when the pump becomes unavailable. The issues of LOFA then become whether the plasma can be shut down rapidly enough that the power flow mismatch during the transient does not lead to unacceptable temperatures and system pressure due to the thermal expansion of coolant or whether corrective measures are required for removal of afterheat (decay heat + energy stored inside the blanket module). The coolant temperature history following a LOFA is evaluated for both LOFA scenarios. For the scenario where LOFA is caused by loss of power, the effects of fluid inertia and pump inertia are included in the hydraulic model. Once a determination of the flow coastdown has been made, the transient heat transport between the coolant and blanket module is analyzed using lumped parameter techniques. Parametric studies are carried out to evaluate the required pump inertias to prevent the water from boiling inside the blanket module in the absence of corrective measures as a function of the time required for plasma shut down.

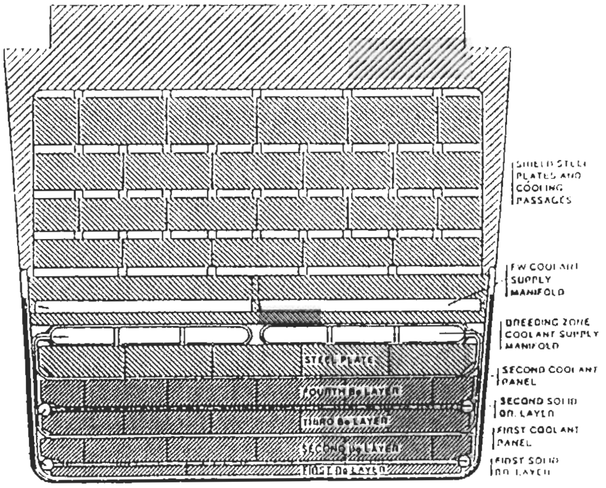

Figure 1: Illustration of U.S. ITER Mid-Plane Outboard Blanket Module

2. LOFA DUE TO CATASTROPHIC MECHANICAL PUMP FAILURE

For the case of catastrophic mechanical pump failure, it is assumed that the flow stops completely at the initiation of the LOFA. The heat transport mechanism within the blanket is mostly conduction due to the small Grashof number (<< 2000). The coolant temperature histories under this type of accident were estimated using the TOPAZ code[2] for different times following the initiation of the LOFA during which the plasma stays on. This is shown in Fig. 2. It indicates that the coolant reaches the boiling point (471 K at 15 atm) after about 16 seconds if the plasma stays on for 10 seconds after LOFA and after about 22 seconds if the plasma stays on for 1 second after LOFA assumming the coolant inlet temperature of 333 K. Boiling would lead to system overpressurization and possible catastrophic blanket failure. The results also show that the temperature increase rate varies with blanket location due to the different time constants.

From the results, even if the plasma is turned off quasi-instantaneously following such a LOFA, only about 20 seconds are available before the water coolant reaches its boiling point for corrective action to be taken, such as to put back-up pumps on line or to start an emergency cooling system or to allow for release (active or passive) of the water pressure.

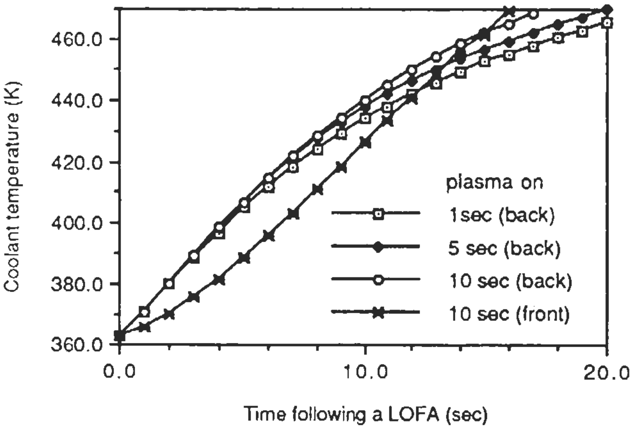

Figure 2 Coolant Temperature History Following a LOFA with Complete Flow Stoppage for Different Times During Which the Plasma Stays On

3. LOFA DUE TO LOSS OF POWER

3.1 FLOW TRANSIENT

To determine the flow transient, pressure drop flow relationships along with Kirchhoff's laws [3] are applied to the hydraulic systems, which include the blanket modules, inlet/outlet coolant pipes, and coolant pump. Kirchhoff's law states that the sum of the pressure drops around any channel loop is equal to zero. The resultant flow transient equation can be written as[3]:

$$t_l \frac{d}{dt}\left(\frac{W}{W_o}\right) + \left(\frac{W}{W_o}\right)^2 = \frac{1}{(1+t/t_p)^2} \qquad (1)$$

where t_l is the loop half-time, W is the mass flow rate, W_o is the mass flow rate prior to the LOFA and t_p is the pump half-time. The loop half-time is given by:

$$t_l = \frac{2\,\bar{m}}{W_o\,\tilde{k}_{pr}\,(A/L)_{sys}} \qquad (2)$$

where $\bar{m}$ is the average water density, $\tilde{k}_{pr}$ is the appropriate friction coefficient normalized to the second power of the flow area for the entire primary system, which accounts for the series and parallel flow paths within the blanket module and the loop, and $(A/L)_{sys}$ is the effective ratio of area to length for the system. A simple estimation of the loop half time for the first wall coolant within the blanket region based on the thermal-hydraulics parameters given in the US ITER report [1] gives about 0.18 seconds for L= 1.5 m. A real loop half time can only be obtained when the system (primary and secondary systems) design is completed.

The pump half-time is the time required for the pump speed to be reduced to half its initial value, and is given by:

$$t_p = \frac{I\,\omega_o}{M_o} \qquad (3)$$

where I is the moment of inertia of the pump, ω_o is the initial pump speed and M_o is the pump steady state torque. The above relationship implies that the ratio of pump speed to flow velocity is a constant. If the coolant pumps for reactor applications are designed with sufficiently large flywheels, the pump inertia will be much larger than that of the fluid, i.e. $t_p \gg t_l$. In this case, it is reasonable to ignore the first term in eq. (1) and approximate the flow coastdown by:

$$W(t) = \frac{W_o}{1 + t/t_p} \qquad (4)$$

The flow histories following a LOFA based on eq. (4) are shown in Figure 3 for different pump half times. Increasing the pump half time from 1 s to 2 s has a propotional effect on the flow coastdown. After 5 s, for example, the flow rate is only about 15% of the original flow rate for tp=1 s, but is still about 30% of the original flow rate for tp=2 s. As an indication, the effective pump half-time for the NET water-cooled solid breeder blanket [5] based on eq. (3) would range from 0.35 to 1.32 s for pump inertias of 100 to 500 kg m^2, which can be achieved by a fly-wheel coaxial with the pump rotor.

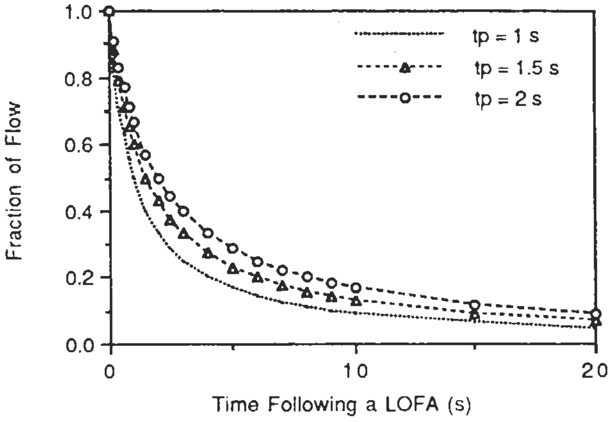

Figure 3 Transient Flow Behaviors Following a LOFA For Different Pump Half Times Assuming $t_p \gg t_l$.

In the intermediate range, where hydraulic and pump inertias are of the same order of magnitude, analytical and numerical solutions of flow coastdown behavior had been performed[5,6]. In general, the calculated results show fair agreement when compared with experimental data. Since the accuracy of the results would rely on the design parameters, further analyses could only be made when the design is completed. In the present analysis, the flow coastdown histories considered in Figure 3 are used for the transient heat transport analyses.

3.2 TRANSIENT HEAT TRANSPORT MODEL

Simplified Analytical Technique for Heat Transport Model

A sophisticated way to determine the thermal behavior of a blanket under transient/accident conditions is to solve numerically large systems of partial differential equations expressed in finite difference form for transient heat conduction, fluid flow, convection, and a host of other phenomena likely to occur during the course of a transient. This usually takes a large amount of computer times and requires all the system being designed completely to provide the meaningful information. A simple way to estimate the thermal behavior for a relatively slow transient such as LOFA is to use a lumped parameter technique,[3,7] which is illustrated in Figure 4. In this lumped parameter procedure, each component quantity is lumped at the middle of the physical geometry and axial conduction is neglected. The thermal resistances and the capacitances of the blanket module components are evaluated at their average condition in time and space. This method provides a rapid means for obtaining approximate estimates, yet accurate enough to understand the interaction of the various phenomena involved.

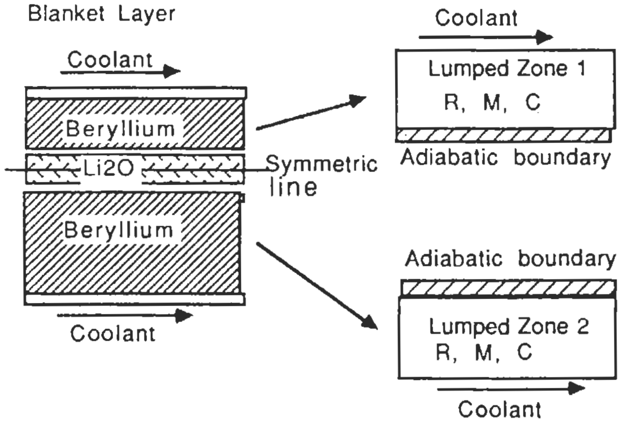

Figure 4: Illustration of a Lumped Parameter Technique for Transient Heat Transport Analyses

One of the lumped parameter techniques is based on two energy balances, one for the energy contained in all the blanket elements (such as, breeder, clad, multiplier) and a second one for the energy stored in the coolant within the coolant channel. This is the so-called singly lumped model. The energy balance for the blanket components may be written as:

$$M_b C_b \frac{d \tilde{T}_b}{d t} = P(t) - \frac{1}{R_{eq}} [\tilde{T}_b(t) - \tilde{T}_c(t)] \qquad (5)$$

Where M_b, C_b, $\tilde{T}_b$ denote the blanket total mass, specific heat per unit mass, and average temperature respectively. The first term on the right hand side of eq. (5), P(t), represents the nuclear heating power and the second term represents the rate at which energy is transported across the cladding surface into the coolant. The energy balance for the coolant within the coolant channel may be written as:

$$M_c C_p \frac{d \tilde{T}_c}{d t} = \frac{1}{R_{eq}} [\tilde{T}_b(t) - \tilde{T}_c(t)] - W(t) C_p [\tilde{T}_c(t) - \tilde{T}_i(t)] \qquad (6)$$

where M_c, C_p, $\tilde{T}_c$, W(t), and $\tilde{T}_i(t)$ are the coolant mass within the channel, specific heat per unit mass, average temperature, mass flow rate at time t, and inlet temperature at time t, respectively. The first term on the right hand side of eq. (6) represents the rate at which energy is transported from the blanket into the coolant, and the second term represents the net rate of convective heat transport out of the coolant channel. The parameter R_{eq} in eqs. (5) and (6) denotes the blanket equivalent thermal resistance and is expressed in terms of the material properties and dimensions of blanket elements. Under steady-state conditions, the temperature distribution in the solid breeder region can be written as:

$$T_{SB}(x) = T_{SB}(a) + q'''_{SB}\, a^2 \frac{\left[1 - \frac{x^2}{a^2}\right]}{2k_{SB}} \qquad (7)$$

where a and k_{SB} are the half width of the solid breeder region and the solid breeder thermal conductivity respectively. q'''_{SB} represents the average heat generation per unit volume of the solid breeder region, and x represents the distance away from the adiabatic center of the solid breeder region. The average breeder region temperature is obtained from integration of eq. (7) and is written as:

$$\tilde{T}_{SB} = T_{SB}(a) + \frac{q'''_{SB}\, a^2}{3k_{SB}} \qquad (8)$$

In general, it is likely that there will be a significant thermal resistance across the solid breeder and clad interface, which is expressed as a gap heat transfer coefficient, h_c. The temperature drop across this thin gap depends on the value of h_c and the difference between average solid breeder temperature and the inner surface clad temperature ($T_{SS}(a)$) may be written as:

$$\tilde{T}_{SB} - T_{SS}(a) = q'''_{SB} \left(\frac{a^2}{3k_{SB}} + \frac{a}{h_c}\right) \qquad (9)$$

Similarly, a steady state heat conduction equation can be written for the stainless steel (SS) clad region and the average clad temperature can be expressed as:

$$\tilde{T}_{SS} - T_{SS}(a) = -\left(\frac{q'''_{SB}\, a}{2k_{SB}} \delta_{SS} + \frac{q'''_{SS}}{6\, k_{SS}} \delta^2_{SS}\right) \qquad (10)$$

where q'''_{SS}, k_{SS}, and δ_{SS} are the clad average heat generation rate per unit volume, thermal conductivity, and thickness respectively. The difference between the average solid breeder and SS clad region temperatures may be written in term of an effective heat flux, $q'''_{SB,SS}$, between the two regions:

$$q'''_{SB,SS} = \frac{1}{R_{SB}} (\tilde{T}_{SB} - \tilde{T}_{SS}) \qquad (11)$$

where $q'''_{SB,SS}$ is defined as:

$$q'''_{SB,SS} = q'''_{SB}\, a + q'''_{SS}\, \delta_{SS} \qquad (12)$$

and $R_{SB,ss}$ is defined as:

$$R_{SB,ss} = \left[q'''_{SB} \left(\frac{a^2}{3k_{SB}} + \frac{a}{h_c} + \frac{\delta_{SS}\, a}{2k_{SS}}\right) + q'''_{SS} \frac{\delta^2_{SS}}{k_{SS}} \right] / q'''_{SB,SS} \qquad (13)$$

Similar procedures are used for the beryllium and clad regions and the final equivalent thermal resistance R_{eq} of the blanket element can be estimated as:

$$R_{eq} = \frac{\sum_{i=1}^{4} \rho_i C_{pi} \delta_i \sum_{i}^{5-i} R_i}{\sum_{i=1}^{4} \rho_i C_{pi} \delta_i} \tag{14}$$

where i represents the four individual components (i.e., solid breeder, clad, beryllium and second clad regions) of the blanket element; ρ_i, C_{pi}, δ_i and R_i are the density, specific heat, thickness and thermal resistance of component i. The corresponding energy balance equation under steady state is written as:

$$\tilde{q}'' = \frac{1}{R_{eq}} (\tilde{T}_b - \tilde{T}_c) \tag{15}$$

where $\tilde{T}_b$, $\tilde{T}_c$ are the average blanket and coolant temperatures respectively. $\tilde{T}_b$ is defined as:

$$\tilde{T}_b = \frac{\sum_{i=1}^{4} \tilde{T}_i \rho_i C_{pi} \delta_i}{\sum_{i=1}^{4} \rho_i C_{pi} \delta_i} \tag{16}$$

A blanket time constant (τ_b) can be defined as:

$$\tau_b = R_{eq} M_b C_b \tag{17}$$

It is a measure of how much time is required for heat transport from the solid breeder to the coolant. The nuclear heating rates in each subregions obtained from Ref [8] and the maximum extreme temperature in the breeder region obtained from Ref [1] were used for the steady state calculations. For the calculations, a high solid-to-solid contact thermal resistance, h_c, of 15000 W/m^2K was assumed at all interfaces. The convective heat transfer coefficients were calculated from the following correlation for a thin rectangular channel based on the decreasing flow rate[9]:

$$h = \frac{k_c}{D_H} \left[0.116 \left(R_e^{2/3} - 125\right) \left(1 + \left(\frac{D_H}{L}\right)^{2/3}\right) P_r^{1/3}\right] \tag{18}$$

for Re > 10,000, where D_H is the hydraulic diameter, L the flow length, and k_c the thermal conductivity of the coolant. and, from[4]

$$h = \frac{k_c}{D_H} (0.0395\ Re^{0.75}\ Pr^{0.33}]$$

$$\text{for } 3 \times 10^3 < Re < 1 \times 10^4 \tag{19}$$

As the Reynolds number (Re) decreases to less than 3000, the Nusselt number ($Nu = hD_H/k_c$) can be linearly extrapolated to 2 , which means that the heat transfer mechanism is mostly conduction. The parameters used for temperature calculations are listed in Table 1 for the four zones into which the outboard blanket was divided. Each zone consists of a blanket element with four subregions (solid breeder, clad, multiplier, clad) between half of a solid breeder layer (whose center line is assumed to be a adiabatic boundary) and half of the corresponding coolant channel. The zone numbering is based on the distance from the first wall, Zone 1 being closest to the first wall. The time constants given in the table are for steady state conditions and vary from region to region based on local dimensions and properties. As the flow is reduced due to the pump failure, the convective heat transfer coefficient decreases, which results in increasing the time constant. It should be noted that when solving eqs (5) and (6), some quantities are approximated (i.e. initial mass flow rate) by making the preceding energy balances reduce to the steady state relationships(i. e.,the time derivatives are set equal to zero). The calculations start by the evaluation of $\tilde{T}_b$ from eq. 16. The transient calculations then proceed and eqs. (5) and (6) are solved based on a central difference scheme for time marching.

3.3 RESULTS

The average blanket and coolant temperature histories for different transient flow behaviors are shown in Fig.5 for the mid-plane of the outboard blanket region 1. For this example, the plasma was assumed to stay on for 10 seconds following the LOFA. The figure shows that the average blanket temperature increases while the plasma stays on and then falls when the plasma is off. 1% of the nuclear heat generation inside the individual breeding region is assumed as afterheat when the plasma is turned off. This is based on the estimation of the decay heat generation rate at the time of shutdown for US ITER blanket and shield is about 1.5% of total thermal power at the fluence of 3 MWa/m^2. However, for all cases, the coolant temperature rises continuously and reaches the boiling point of 470 K at about 30 seconds after LOFA for the given pump half time of 1 second and after about 85 seconds for a given pump half time of 1.5 seconds. It is interesting to see that if the pumps can be designed with sufficiently large flywheels with corresponding pump half-times of the order of 2 seconds or more, it is possible to remove the heat stored inside the blanket element using the decreasing flow and to prevent the coolant from boiling over a period of several minutes. These results are obtained under the assumption of a constant inlet coolant temperature. This is reasonable as long as that the heat exchanger is intact and removes heat at the same rate as it is produced.

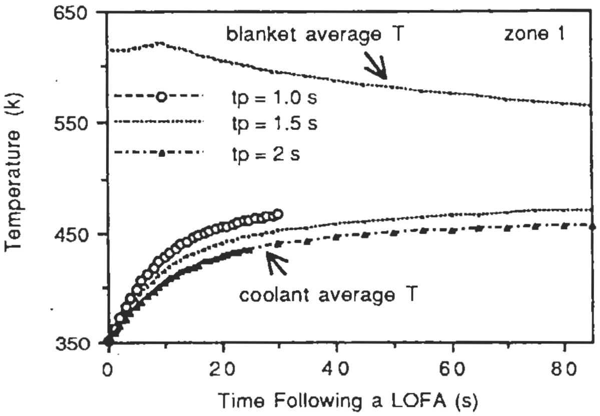

Figure 5 Breeder and Coolant Average Temperature Histories Following a LOFA For Different Pump Half-Time Constants

The average coolant temperature histories for different mid-plane outboard blanket zones (see Table 1 for individual zone information) are shown in Fig. 6 . The blanket zone time constant ranges from 85 seconds for zone 1 to 236 seconds for zone 4. For all cases, the plasma was assumed to stay on for 10 seconds following the LOFA. The figure shows that the average coolant temperature reaches the boiling point after about 85 seconds following the LOFA for zone 1 and after about 40 to 50 seconds following the LOFA for other zones for an assumed pump half time of 1.5 seconds The time requires to reach the boiling point depends not only on the rate of heat transfer to the coolant but also on the coolant capacitance inside the coolant channel. A larger coolant channel is used in zone 1 which results in a longer time for the coolant to reach the boiling point.

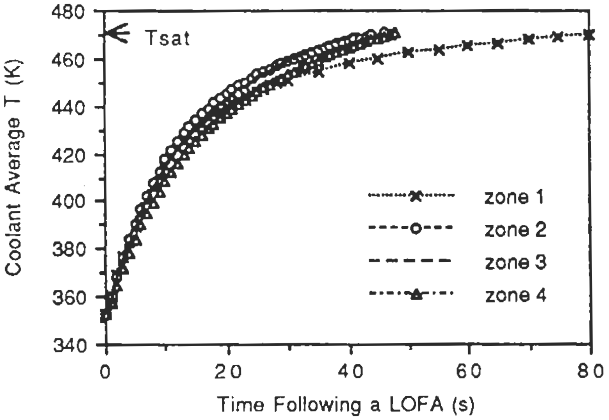

Figure 6 Coolant Average Temperature Histories Following a LOFA For Different Blanket Zones

Table 1: Parameters Used for Transient Thermal-Hydraulic Calculations

	Zone 1	Zone 2	Zone 3	Zone 4
coolant (cm) clad (cm)	0.2 0.5	0.1 0.2	0.1 0.2	0.1 0.2
Multiplier (cm) Clad (cm) Breeder Li$_2$O (cm)	3.4 Be (0.85) 0.1 0.4 (0.8)	5.7 Be (0.85) 0.1 0.4 (0.8)	5.7 Be (0.65) 0.1 0.4 (0.8)	7.1 Be (0.65) 0.1 0.4 (0.8)
τ (sec)	84.617	114.84	155.31	236.37
$\bar{T}_b$ (K)	614.95	584.0	574.1	558.61
$\bar{T}_c$ (K)	352.25	352.25	352.25	352.25

Doubly Lumped Parameter Model

The singly lumped parameter model yields the average thermal behavior of the blanket element under a LOFA condition. If the thermal behavior of the breeder itself is important to determine the likelihood of failure as a result of LOFA, when the plasma stays on for a significant time for example, a better estimate of the local breeder thermal behavior should be considered. A simplified analytical way to determine the thermal behavior of critical and non-critical regions separately is to use a doubly lumped parameter model. For the present analysis, different thermal energy balances are written for the breeder region and for the combined clad and multiplier regions. The results of the average breeder, lumped Be region and coolant temperature histories are shown in Figures 7 and 8 for the mid-plane of the outboard blanket region 1 for 3 cases: 1) time before plasma shutdown following LOFA = 10 s, t_p = 1.5 s; 2) immediate plasma shutdown, t_p = 1.5 s; and 3) immediate plasma shutdown, t_p = 0.5 s. Fig. 7 shows that the average breeder and lumped Be temperatures increase during the plasma on period and fall immediately after the plasma is turned off. Although the initial solid breeder temperature is substantially higher than that of the lumped Be region, they reach the same quasi-equilibrium value after about 80 s following the LOFA. This is due to the time constant of the breeding zone being relatively short compared to the time constant of the lumped Be region. If the plasma is turned off immediately after a LOFA (see Figure 8), the average coolant temperature stays under the boiling point for about

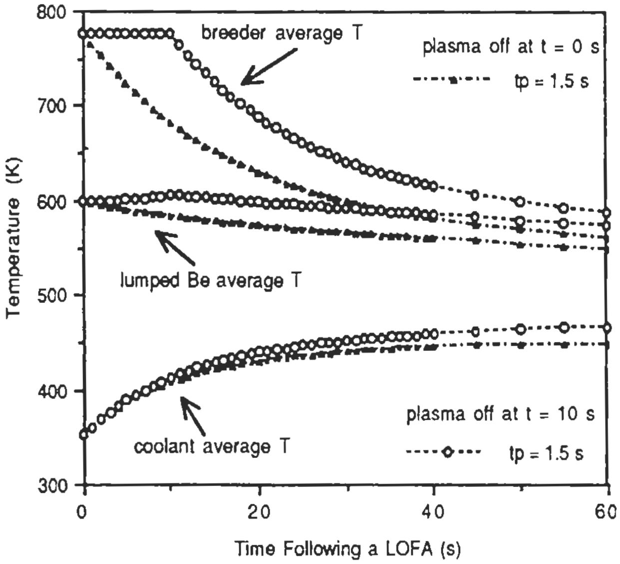

Figure 7 Temperature Histories of Solid Breeder, Lumped Be Region at Mid-Plane Outboard Blanket Layer 1, and of the Coolant Following a LOFA for Different Plasma On Times for t_p = 1.5 s.

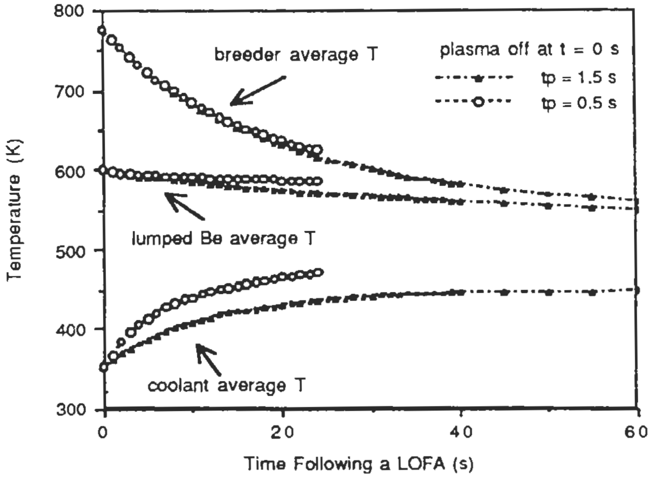

Figure 8 Temperature Histories of Solid Breeder, Lumped Be Region at Mid-Plane Outboard Blanket Layer 1, and of the Coolant Following a LOFA for Different Pump Half Times (Assuming the plasma is off.).

120 seconds after the LOFA for a pump half time of 1.5 seconds, but reaches the boiling point about after only about 25 seconds following the LOFA for a pump half time of 0.5 second.

In designing the blanket cooling system, it is possible to have design redundancy by installing on line back-up pumps with the necessary valving arrangement and back-up generator. This design redundancy provides a heat removal capability under a LOFA for continued system operation at full load. The initiation of such a system following a LOFA can be controlled either by time or by coolant temperature. An example of this operation is illustrated in Fig. 9 for a control mechanism based on the coolant temperature. The back-up pump is put into operation at time around 22 s when the average coolant temperature reaches 450 K. During this transient, the average breeder and lumped beryllium temperatures increase by about 20 K and 27 K respectively at their peak (t =39 s and 23s, respectively) and then drop to their steady state values.

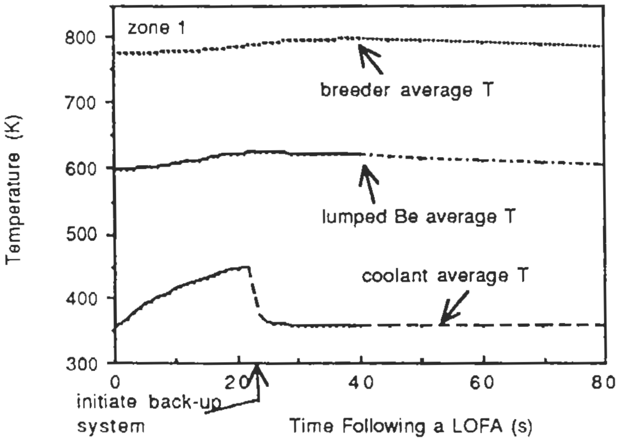

Figure 9 Temperature Histories of Solid Breeder and Lumped Be Region and Coolant in the Mid-Plane of the Outboard Blanket Following a LOFA With the Back-up System Operation Controlled By the Coolant Temperature.

4. CONSEQUENCE OF BOILING

As a result of rapid decrease in the coolant flow rate after a LOFA, the increase in the blanket coolant temperature or the production of vapor cause the coolant to expand if no corrective measures are taken. This volumetric change leads to increasing pressure unless sufficient space is available to accommodate the increased coolant volume. The pressure transient may be tempered by the condensation of the vapor phase that accompanies the increase of saturation temperature with pressure and by the design where the hot coolant is connected with the low temperature shielding regions. However, a large increase in the system pressure might result in excessive stress on the blanket module and in a loss-of-coolant accident emanating from the rupture of the blanket module. Thus, as an added safety measure, the design should include a system of expansion volumes and/or relief and safety valves that allow for control of pressure transients and prevention of excessive stress on the blanket modules.

5. SUMMARY

- For the US ITER blanket with coolant flowing in the radial/toroidal plane, global natural convection does not help much following a LOFA.

- In the extreme case of catastrophic pump failure where the flow stops completely, the water coolant will reach its boiling point about 25 seconds even if the plasma is shut off quasi-instantaneously following the LOFA. To prevent this, a corrective action such as putting back-up pumps on line or starting an emergency heat removal system would need to be implemented within these 25 seconds.

- In the case of a loss of power accident, the pump inertia can be helpful. For example, it will take several minutes for the coolant in the cooling channel closest to the first wall to reach its boiling point if the pump can be designed with a sufficiently large flywheel with $t_p > 2$ s, assuming the plasma stays on for 10 seconds or less following the LOFA. Even if the pump inertia is lower, it can extend quite appreciably the allowable time prior to the implementation of a corrective action such as putting back-up pumps on line or starting an emergency heat removal system.

- The breeder temperature rises following a LOFA only on the plasma on time following the LOFA. It falls immediately after the plasma is turned off and thus the coolant temperature limit is the binding constraint.

- As an added safety measure, the design shall include a system of expansion volumes and/or safety valves for accommodating coolant pressure transients.

ACKNOWLEDGEMENT

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