LOCA STUDY FOR A HELIUM-COOLED SOLID BREEDER DESIGN FOR ITER

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ABSTRACT

The analysis of thermal processes after a loss-of-coolant accident (LOCA) in a solid breeder blanket is important because of the first wall and solid breeder maximum allowable temperature constraints. The objective is to design for a LOCA so that following a LOCA, the maximum solid breeder and structure temperatures are less than the limit beyond which irreversible damage is done, which would lead to loss of investment. The temporal temperature profiles for the solid breeder and first wall regions of a helium-cooled solid breeder design for ITER were calculated based on afterheat values for adiabatic and non-adiabatic conditions and the results are presented in this paper. It is found that, for this design, even when excluding radiation to the cooled inboard, a LOCA can be accommodated by energy removal through a flowing purge with a reasonable flow rate.

I. INTRODUCTION

The analysis of thermal processes after a loss of coolant accident (LOCA) in a solid breeder blanket is important because of the first wall and solid breeder maximum allowable temperature constraints. At the very least, a LOCA should not cause any catastrophic failure, for example due to the structure melting. The objective, however, is to design for a LOCA so that the blanket can still operate afterwards. The maximum solid breeder and structure temperature should then be less than the limit beyond which irreversible damage is done, such as loss of structural integrity for steel or sintering for the solid breeder, which would lead to loss of investment.

The helium-cooled solid breeder ITER blanket design of Ref. [1] is considered here. It consists of a number of canisters poloidally placed side by side on the outboard. Each canister contains a number of Li_4SiO_4 solid breeder and Be multiplier rods as shown in Fig. 1. A typical rod consists of an inner sphere-pac solid breeder cylinder surrounded by a cladded annulus of sphere-pac Be. A helium purge flows through both the solid breeder and Be regions. For this particular blanket, a LOCA analysis was done for various combination of passive and active methods of accommodation based on the afterheat evaluation.

II. AFTERHEAT EVALUATION

The evaluation of afterheat consisted of two steps: 1) neutron flux calculation using ANISN, the 1-D neutron transport code; and 2) activation analysis using the DKRICF code. For ANISN, P3S8 approximation and the 30-group neutron and 12-group gamma cross-section library based on ENDF/B-V data were employed. For the DKRICF computation, one-year steady-state operation with an average neutron wall loading of 1.148 MW/m^2 was assumed.

For the calculations, the canister was divided into four regions whose dimensions and compositions are shown in Table 1. The results are illustrated in Figs. 2a and b which show the average and maximum afterheat in unit of W/cm^3 of solid as a function of time after shutdown or LOCA. Note that the maximum and aveage afterheat values are about the same for the first wall but differ by about a factor of 2 for the breeder zones. For the LOCA calculations, the afterheat was modeled using approximate formulas with an accuracy of about 90%.

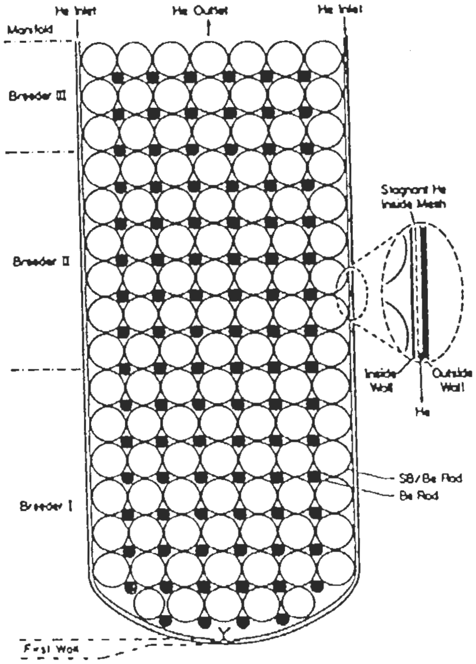

Fig. 1 Helium-cooled solid breeder blanket canister for ITER [1]

III. MATHEMATICAL MODEL

Based on initial approximations, the Biot conduction and radiation numbers, Bi_{cond} and Bi_{rad} for the canister rods and first wall are very small:

$$Bi_{cond} = \frac{hL}{k} << 1; \quad Bi_{rad} = \frac{\sigma_o F T^3 L}{k} << 1$$

Where h is the heat transfer coefficient, L the characteristic length for the rods or first wall, k the coefficient of thermal conductivity, σ_o Boltzmann's constant, F the absorptivity of the body, and T the

Table 1: Thickness and Composition of Each Blanket Region

Region	Thickness (cm)	Composition	
First Wall	1.86	35.27% PCA	64.73% He
Breeder-I	30	45.3% Be[a] 38.28% He	7.16% Li4SiO4[b] 9.26% PCA
Breeder-II	20	16.07% Be[c] 30.23% He	37.6% Li4SiO4[b] 9.26% PCA
Breeder-III	10	51.0% Li4SiO4[b] 28.44% He	20.56%

a) 90% Theoretical Density (TD)
b) 80% TD, ^{6}Li, enrichment 60%
c) 80% TD
Radius from plasma center to first wall = 1.53 cm

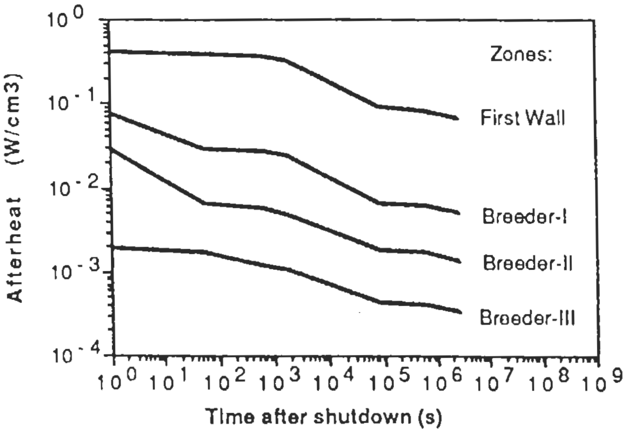

Fig. 2a Average afterheat in the different blanket regions as a function of time after shutdown

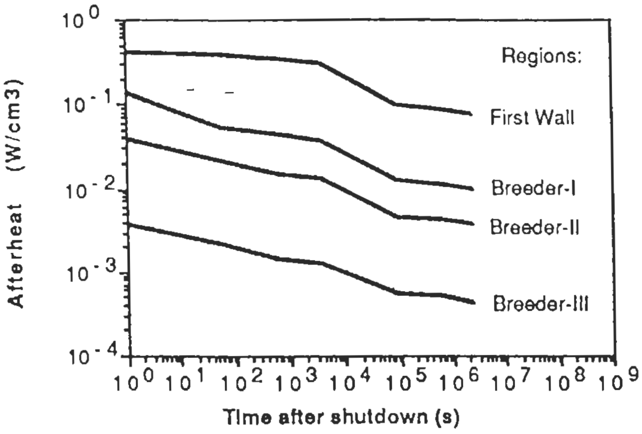

Fig. 2b Maximum afterheat in the different blanket regions as a function of time after shutdown

temperature. For these reasons, the temperature fields were considered uniform in all cases to simplify the main mathematical model. For the first wall zone, an energy balance over an incremental time, dt, gives:

$$(c\rho V dT)_{1w} = (q'''_{aft}\, V)_{1w}\, dt - (q''_{rad\text{-}1w} + q''_{rad\text{-}in})\, A_{1w}\, dt - q''_{c\text{-}Iz}\, A_{1w}\, dt \tag{1}$$

For the Breeder-I, Breeder-II and Breeder-III zones, a similar energy balance yields:

$$\begin{aligned}(c\rho V dT)_{Iz} = {} & (q'''_{aft}\, V)_{Iz}\, dt + q''_{rad\text{-}1w}\, A_{Iz}\, dt \\ & - q''_{rad\text{-}IIz}\, A_{Iz}\, dt + q''_{c\text{-}1w}\, A_{Iz}\, dt \\ & - q''_{c\text{-}IIz}\, A_{Iz}\, dt - (\rho c u_o\, A_r\, dT)_{pur\text{-}Iz}\, \delta t\end{aligned} \tag{2}$$

$$\begin{aligned}(c\rho V dT)_{IIz} = {} & (q'''_{aft}\, V)_{IIz}\, dt + q''_{rad\text{-}Iz}\, A_{IIz}\, dt \\ & - q''_{rad\text{-}IIIz}\, A_{IIz}\, dt + q''_{c\text{-}Iz}\, A_{IIz}\, dt \\ & - q''_{c\text{-}IIIz}\, A_{IIz}\, dt - (\rho c u_o\, A_r\, dT)_{pur\text{-}IIz}\, dt\end{aligned} \tag{3}$$

$$\begin{aligned}(c\rho V dT)_{IIIz} = {} & (q'''_{aft}\, V)_{IIIz}\, dt + q''_{rad\text{-}IIz}\, A_{IIIz}\, dt \\ & + q''_{c\text{-}IIz}\, A_{IIIz}\, dt - (\rho c u_o\, A_r\, dT)_{pur\text{-}IIIz}\, dt\end{aligned} \tag{4}$$

where c is specific heat and ρ the density of the different zones. For the three breeder zones, the product (cρ) for the rod configuration, calculated as follows, is used:

$$(c\rho)_{rod} = \frac{(c\rho)_{gap}\,(d_r^2 - d_{SB}^2) + (c\rho)_{SB}\, d_{SB}^2}{d_r^2}$$

$$(c\rho)_{gap} = 0.7\,(c\rho)_{Be} + 0.3\,(c\rho)_{He} \cong 0.7\,(\delta\rho)_{Be}$$

$(c\rho)_{SB}$ assumes an 80% theoretical density of the solid breeder.

The other variables are defined as follows:

V,A = volume and heat transfer surface area; T = temperature; q'''_{aft} = afterheat per unit volume; t = time after shutdown; q''_{rad}, q''_c = rate of radiation and free convection heat flow; u_o = superficial velocity of the purge gas; A_r = cross-section of the rod.

Subscripts and indices have the following meaning: 1w = first wall; in = inboard shield; Iz, IIz, IIIz = first, second and third zones of solid breeder rods; pur = purge gas in rods.

The main assumptions are as follows: (1) the inboard first wall is assumed isothermal (with a separate active coolant) when thermal radiation between the first wall on the outboard and the inboard area is included in the calculations and adiabatic when thermal radiation to the inboard is excluded; 2) free convection in the canister can be approximated by an equivalent thermal conductivity, k_{eq}, corresponding to that of He, because the Rayleigh number is less than 1000; 3) for the case of the purge flow being used for afterheat removal, the outlet temperature of the purge gas is equal to the mean solid breeder temperature because of the relatively small purge flow rate and large heat transfer surface to the purge gas; 4) for thermal radiation in the canister, the surfaces of the first row of the different zones are considered parallel, separated by screens; and 5) the radiation factors of the bodies are equal.

The free convection and radiation heat fluxes are then estimated from the following equations:

$$q''_c(t) = \frac{k_{eq}}{L}\,[T_i(t) - T_{i+1}(t)] \tag{5}$$

$$q''_{rad}(t) = \sigma_o F_{sys}\,[T_i^4(t) - T_{i+1}^4(t)] \tag{6}$$

where L is the characteristic length between zones i and i+1, and F_{sys} is the absorptivity of the radiation system, calculated from:

$$F_{sys} \equiv \frac{1}{1+n} \frac{1}{\frac{1}{F_i} + \frac{1}{F_{i+1}} - 1} \tag{7}$$

where n is the number of rows between the first row of zones i and i+1, and F is their absorptivity, assumed to be 0.5

Integration of equations (1)-(4), using formulas for q'''_{aft} and assuming that the physical properties are unchanged over time, yields a system of four coupled non-linear equations. A numerical method was utilized to solve these equations which in vector form can be written as:

$$Ax + b = \mathbf{n}(x,x) \tag{8}$$

where A is a 4x4 matrix, $\mathbf{x} = [T_{Iw}, T_{Iz}\ T_{IIz}, T_{IIIz}]^T$, $\mathbf{b}$ is a 4-vector corresponding to the constant term, and $\mathbf{n}$ is a 4-vector corresponding to the non-linear term. Following Newton's method, $\mathbf{x}$ is decoupled into $\bar{x} + \hat{x}$, where $\bar{x}$ is the guessed value and $\hat{x}$ is the deviation from $\bar{x}$. Substituting $\mathbf{x} = \bar{x} + \hat{x}$ and linearizing the equation, we obtain:

$$A\hat{x} - \mathbf{n}(\hat{x},\bar{x}) - \mathbf{n}(\bar{x},\hat{x}) = b + \mathbf{n}(\bar{x},\bar{x}) - A\bar{x} \tag{9}$$

Eq.(9) is a linear equation with respect to $\hat{x}$. We can thus rewrite it in the form of:

$$A'\hat{x} = b' \tag{10}$$

which can be readily solved numerically by utilizing the Gaussian elimination method. The $\mathbf{x} = \bar{x} + \hat{x}$ is now considered to be the new $\bar{x}$. The above procedure was repeated iteratively until the convergence condition was satisfied (set as the absolute value of $\hat{x} < 10^{-10}$).

IV. ANALYSIS OF LOCA ASSUMING DIFFERENT CONDITIONS

The effects of the different heat transfer mechanisms on the temperature histories of the first wall and solid breeder regions are discussed below, based on calculations using the average afterheat values for each region [see Fig. 2(a)]. Since use of average region afterheats tends to be optimistic, conservative results using the maximum afterheat in each region [see Fig. 2(b)] are then shown for a couple of cases as a means of comparison.

(i) Adiabatic Conditions

Fig. 3 shows the temperature rise in the four regions after a LOCA for fully adiabatic conditions. Consequently, both the first wall and solid breeder regions eventually reach the allowable temperature limits. The first wall structural temperature limit of 850 K (half the melting point of austentic steel) is reached in about 70 minutes, while the temperature limit of 1000 K for the Li_4SiO_4 breeder (based on sintering) is reached in 2 days for the first breeder zone where the afterheat is highest.

(ii) Radiation and Free Convection

As is shown in Fig. 4, if thermal radiation to the cooled inboard and free convection (equivalent here to conduction through stagnant He) to the first breeder zone is assumed, the first wall temperature will stay well under the allowable limit of about 850 K. Including the effect of the helium purge in the solid breeder rod will reduce the first wall temperature by about 20 K. The purge is assumed to enter the canister at 325 K and to exit at the mean solid breeder temperature and its superficial velocity (based on the total flow area assuming 100% porosity) is assumed to be 0.005 m/s. As can be seenin Fig. 5, for the solid breeder rods of Zone I which are under the harshest conditions, free convection between the zones and the first wall (which is cooled by radiation to the inboard) protect the Li_4SiO_4 in the additionally. For the Breeder Zones II and III, the analysis shows that the Li_4SiO_4 maximum temperatures slowly rise to an asymptotic value below 1000 K even with the exclusion of the flowing purge effect, as shown in Fig. 6.

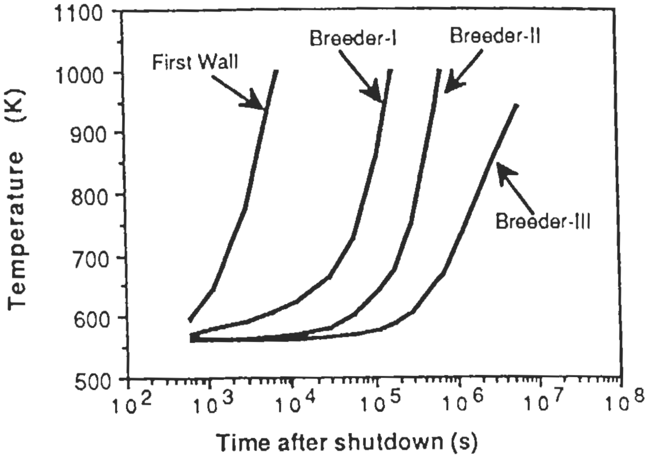

Fig. 3 Temperature history of the different blanket regions following a LOCA for adiabatic conditions (based on average afterheat values)

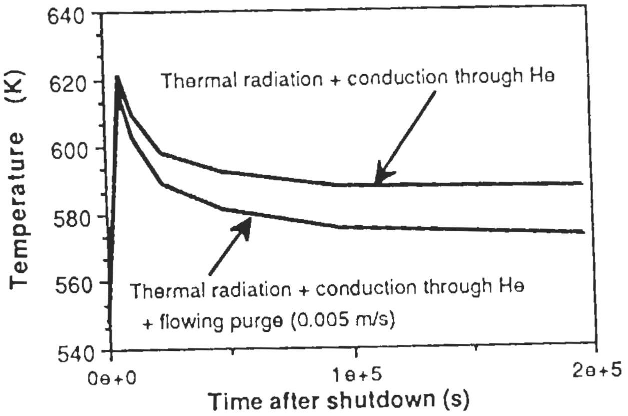

Fig. 4 Temperature history following a LOCA for different heat transfer conditions (based on average afterheat values)

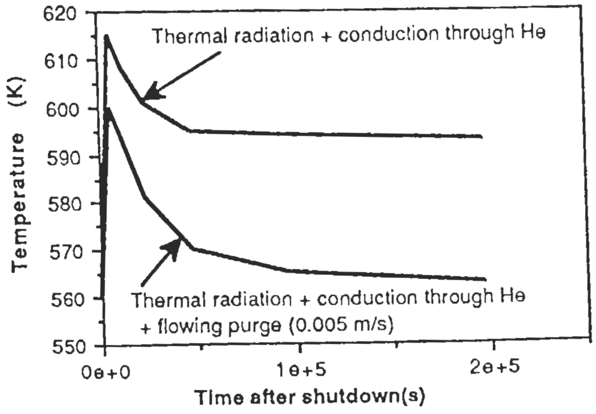

Fig. 5 Solid breeder temperature history in Zone I following a LOCA for different heat transfer conditions (based on average afterheat values)

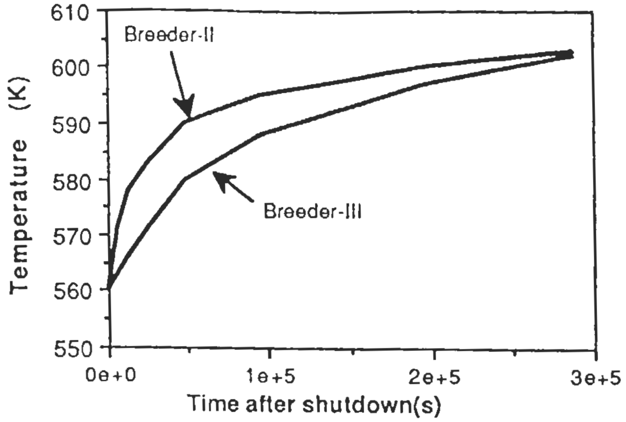

Fig. 6 Solid breeder temperature history in Zones II and III following a LOCA assuming radiation to the inboard and conduction through He (based on average afterheat values)

(iii) Exclusion of Radiation to the Inboard

If the inboard coolant flow does not operate due, for instance, to a LOCA in the inboard coolant circuit also, there is effectively an adiabatic boundary between the outboard first wall and the inboard because precluding radiative heat transfer to the inboard. The use of the rod purge in combination with radiation between the regions can help to accommodate a LOCA in this situation. As shown in Fig. 7, if the purge flow average velocity is more than 0.003 m/s, the time for the solid breeder to reach its maximum allowable temperature (1000 K) in the first breeder zone is about 5 days whereas the time for the first wall structure to reach its maximum allowable temperature (850 K) is about one day. Increasing the purge average velocity to 0.004 m/s increases the time for both the solid breeder and first wall to reach their maximum allowable temperatures to weeks. This time would be slightly increased if the effect of conduction between the different outboard regions through stagnant helium is included (assuming, for example, a 1 atm He cover gas in the building). For example, Figs. 8 and 9 show the temperature histories of the first wall region and the solid breeder zone I following a LOCA assuming energy removal by a flowing purge of average velocity 0.003 m/s, for cases including and excluding conduction between the regions through helium. In both cases, radiation to the inboard is still excluded. The temperature profile in both cases tends to be only slightly lowered when including conduction through helium, indicating that heat transfer between the outboard zones occurs mostly through radiation and only slightly through gas conduction. Figs. 8 and 9 confirm that with a 0.003 m/s purge velocity, the maximum allowable temperatures for the first wall structure and breeder would be reached in about a day and 5 days respectively, as was indicated in Fig. 7.

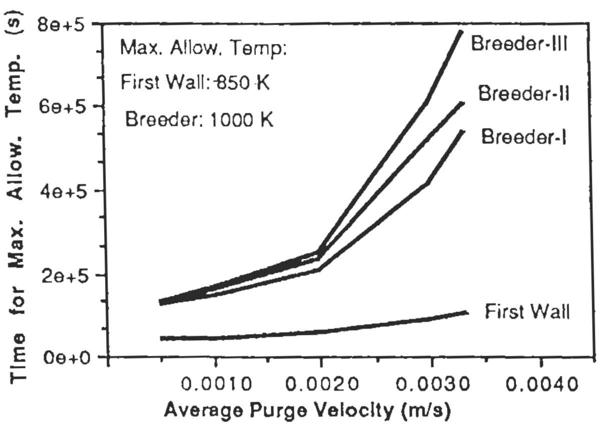

Fig. 7 Time to reach the maximum allowable temperature in the different blanket regions following a LOCA as a function of the average purge velocity (based on average afterheat values)

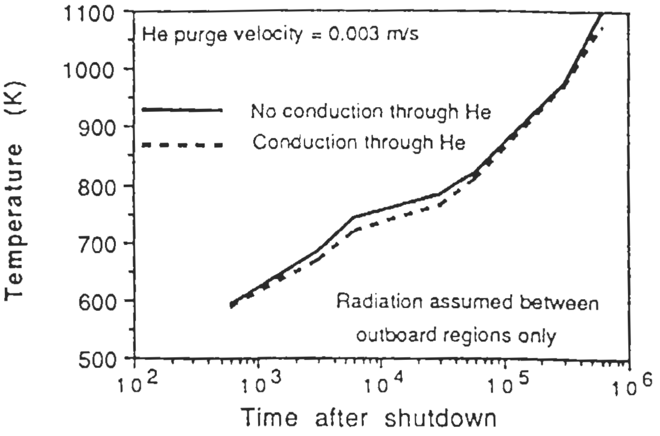

Fig. 8 First wall temperature history following a LOCA assuming no radiation to the inboard and assuming an average helium purge velocity of 0.003 m/s (based on average afterheat values)

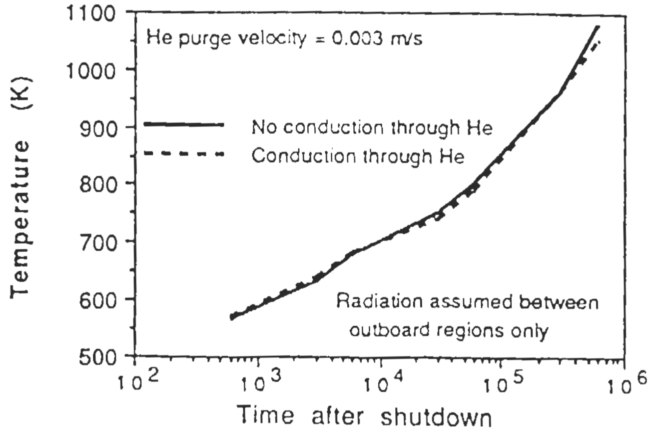

Fig. 9 Solid breeder temperature history in Zone I following a LOCA assuming no radiation to the inboard and assuming an average helium purge velocity of 0.003 m/s (based on average afterheat values)

Fig. 10 shows that, even if radiation to the inboard is excluded, the maximum allowable solid breeder and structure temperature will not be reached if the purge velocity is 0.005 m/s. Because of the much higher tritium removal from the solid breeder part of the rod than from the Be gap, most of the purge flows through the solid breeder center. Thus, for a 0.005 m/s overall average velocity, a 4-cm rod diameter and a 1-cm solid breeder center diameter [1], the purge velocity in the solid breeder is 0.03 m/s assuming that if it is 10 times higher than the purge velocity in the Be section. Depending on the mean diameter of the solid breeder spheres, the corresponding pressure drop in the purge is about 0.1-0.5 atm/m [2] which is quite reasonable.

(iv.) Comparison of results using average and maximum afterheat values

The results shown previously were obtained using average afterheat values and, thus, tend to be optimistic. The maximum afterheat values are only slightly higher than the average ones for the first wall but are about twice the average values for the breeder regions. Thus, in general the temperatures of the breeder zones are expected to increase more than that of the first wall when using the maximum afterheat values. This would help radiation heat transfer from the breeder zones to the first wall in the case of the first wall radiating heat to a cooled inboard. However, in the case of an adiabatic inboard, with radiation heat transfer only from the first wall to the breeder zones and heat removal in the breeder zones by the purge flow, the situation would be exacerbated. Calculations were thus done for this latter case using maximum afterheat values. Fig. 11 shows the first wall temperature history following a LOCA based on the maximum afterheat values of Fig. 2(h) assuming no radiation to the inboard for different purge flow superficial velocities. Whereas a velocity of 0.005 m/s was sufficient to keep the maximum first wall temperature under its limit based on average afterheat values, the purge flow velocity must be increased by at least one order of magnitude to prevent the first wall from reaching its assumed temperature limit based on maximum afterheat values.

Fig.12 shows the temperature histories of the four different regions following a LOCA for conditions similar to those in Fig. 10 but based on maximum afterheat values. Both the breeder and first wall stay below their temperature limit but the average purge velocity is high, 0.075 m/s. (Note that this velocity is required to keep the first wall below its temperature limit. A lower velocity would be acceptable for the breeder to stay below its limit.) This corresponds to a velocity of about 0.6 m/s in the breeder section only and to a pressure drop of about 7 atm/m. Thus, depending on whether the average or maximum afterheat values are used, a pressure drop of 1 atm/m or 7 atm/m is required for the purge flow to convect enough heat in order to keep the breeder an first wall under their temperature limit.

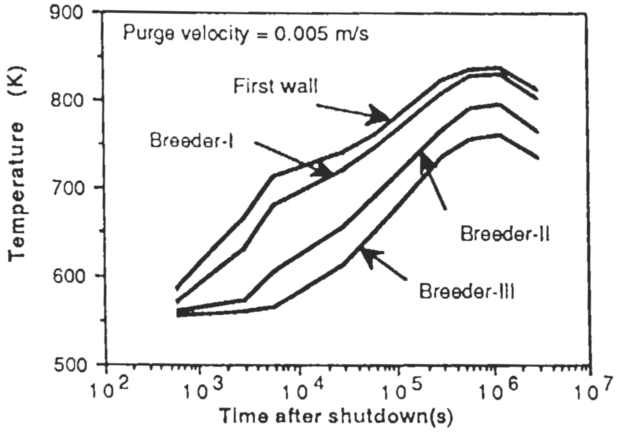

Fig. 10 Temperature history of the different blanket regions following a LOCA assuming no radiation to the inboard and an average helium purge velocity of 0.005 m/s(based on average afterheat values) (conditions: thermal radiation between outboard regions only; flowing purge; conduction through He)

CONCLUSIONS

Following a LOCA, the temperature of the first wall increases faster than that of the solid breeder rods for adiabatic conditions. If the maximum allowable temperature for reusable structure is assumed to be half of the melting point (which is about 1700 K for austentic steels), then it takes about 70 minutes for the first wall to reach this limit under adiabatic conditions for the solid breeder blanket design considered here based on average afterheat values. Under the same conditions, it takes about 2 days for the Li_4SiO_4 solid breeder to reach the maximum allowable temperature of 1000 K (based on thermal sintering).

Including the effect of radiation heat transfer to the inboard enables the maximum temperature of the structure to stay below its limit. The solid breeder temperature also stays beneath its limit in this case. This will be the case for a LOFA and also for a LOCA assuming a 1 atm He cover gas is present. Use of the purge flow in the canister rods greatly helps to accommodate a LOCA. Even if radiation to the inboard is excluded, the solid breeder and structure would not reach their maximum allowable temperatures for a purge flow average velocity of about 0.005 m/s or more, assuming radiative heat transfer between the different outboard zones based on average afterheat values. The purge pressure drop for that case is reasonable, about 0.5 atm/m.

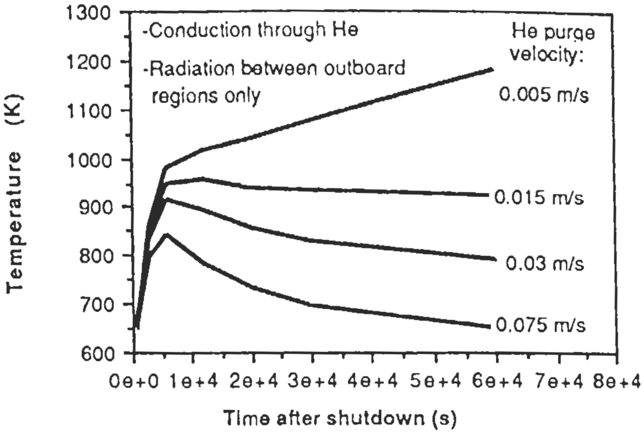

Fig. 11 Temperature history of the first wall following a LOCA for different purge velocities (based on maximum afterheat values) (conditions: thermal radiation between outboard regions only; flowing purge; conduction through He)

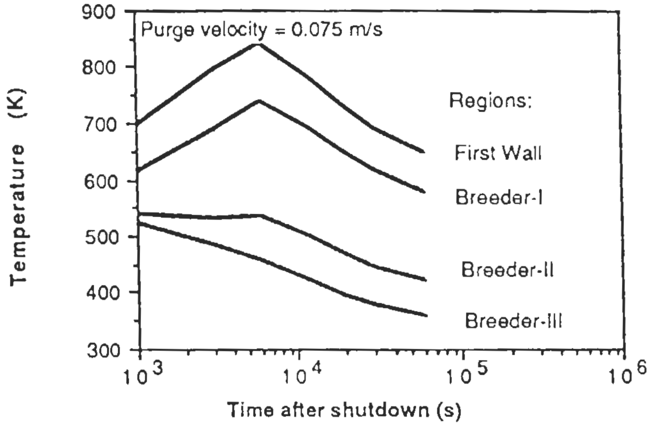

Fig. 12 Temperature history of the different blanket regions following a LOCA assuming no radiation to the inboard and an average purge velocity of 0.075 m/s(based on maximum afterheat values)

If maximum zone afterheat values are used the purge flow average velocity increases to 0.075 m/s and the pressure drop to 7 atm/m in order to keep first wall under its temperature limit. These results are conservative and the actual pressure drop values for the purge flow would be between the two values of 0.5 atm/m and 7 atm/m. This would be acceptable for the helium-cooled solid breeder blanket design considered here since the purge gas is operating at about a 15-atm pressure, but for other designs a trade-off would have to be made between the amount of afterheat removed by the purge flow and the required velocity and pressure drop. Note that the purge velocity requirement is set by the maximum first wall temperature limit. If this limit could be relaxed a lower velocity would be acceptable to keep the solid breeder under its temperature limit. In any case, the results indicate that forced convection through the purge flow is an effective means for at least partial afterheat removal.