ANALYSIS OF BALLOONING OF A COOLANT CHANNEL UNDER POSTULATED SEVERE ACCIDENT IN A PHWR


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1. INTRODUCTION

Coolant tubes in a PHWR form a primary heat transport system boundary. Each coolant tube is connected to the rest of the circuit through a rolled joint at either end. These rolled joints are designed and made to achieve adequate pull out strength and leak tightness. The design of a coolant tube accounts for the effects of pressure, temperature, irradiation, corrosion and such other environmental factors. Thus apart from the limits in terms of stresses, one has to also satisfy limits in terms of the other parameters, such as, creep induced deformations, thresholds for delayed hydrogen cracking, loss of ductility through hydrogen embrittlement, possibility of the growth of a part thickness flaw to critical size without occurrence of leakage, etc. While these analyses are necessary as a part of design and in-service-review processes, the coolant tubes also play an important role in situations involving postulated beyond-design-basis accident. In one of the postulated accidents, involving loss of coolant accident (LOCA) and failure of emergency core cooling system (ECCS), the heat up of the coolant tube enables the deformed coolant tube to come in contact with the surrounding calandria tube. This establishes a heat transfer mode from fuel bundles to low temperature moderator in the calandria (reactor vessel). It is through the establishment of such heat transfer mode that the maximum temperature in a fuel is limited below melting point under such severe accident. This imposes a kind of limitation on the source term that containment has to isolate from reaching outside.

The deformation of a coolant tube is due to internal pressure and fuel bundle loads, along with the high temperature. There are two modes of deformations of a coolant tube. These are ballooning and sagging. The ballooning is expected to occur if the collapse is mainly due to internal pressure. Whereas the sagging is due to fuel bundle weights. A detail analysis is required to know the real mode of deformation in case there is enough internal pressure along with the fuel bundle weights. There is always a fear of channel rupture during ballooning. In case it happens, the accident scenario changes significantly as internal pressure from the coolant channel is transferred to calandria tube. In such a situation, there is a fair chance of
simultaneous failure of the calandria tube. The probability of channel rupture during ballooning is high in those locations where there are flaws. This probability further increases, if during an accident the circumferential temperature distribution in a channel is such that the flaw lies in hot zone and major part of the channel is relatively cold. Once the contact between the two tubes is established, one has to know the effective heat transfer area obtained through this contact. In this context, the ballooning mode of deformation is preferred over the sagging mode, as the former is expected to provide more heat transfer area. In case of sagging, the contact is generally established at the centre and then it progresses along the length and the circumference. This progress is generally slow due to effective cooling provided by the moderator once contact is established. However, the mode of deformation during ballooning is different. Ballooning can occur at the number of cross sections simultaneously, as it is a local phenomena. It is also expected that a major portion of the ballooned cross section may come in contact with the calandria tube. Due to these two reasons, the heat transfer area obtained through ballooning is expected to be much more than the sagging.

Hence analysis of the deformation of a coolant tube under such severe accident is necessary to provide the answer to the following questions.

i) Whether the contact between the calandria tube and the coolant tube is essentially due to ballooning or sagging of the coolant tube?

ii) During the deformation of the coolant tube, is there any chance of rupture of the coolant tube?

iii) Whether contact between the two tubes provides enough heat transfer area to limit the temperature of the fuel bundles below melting point?

In the present paper we are reporting the analysis done to understand the ballooning behaviour of a coolant tube. The analysis mainly concerns with the possibility of rupture during ballooning under the presence of longitudinal flaws and asymmetric circumferential temperature gradient.

2. ANALYSIS DETAILS

2.1 Geometrical modelling- A cross section of the tube is modelled as a two dimensional case. Finite element technique has been used for this purpose. There are 180 isoparametric elements with 560 nodes employed in the model. The model has been modified accordingly for considering various sizes of longitudinal flaws.

2.2 Temperature profile- The temperature distribution following severe accident in a coolant tube can be known only by a detail thermal hydraulic modelling of the process transient. However, the present analysis is done for different assumed asymmetric circumferential temperature profiles. The profile has been assumed to vary according to the equation [1]

\[ T(\theta) = T_{\text{min}} + \Delta T \left[ 1 - (\theta/\phi)^n \right] \]

\[ \text{....(1)} \]

Different temperature profiles have been obtained by varying \( \Delta T = T_{\text{max}} - T_{\text{min}} \) and the exponential parameter \( n \). Here \( \theta \) is the angle measured from the maximum temperature point \( T_{\text{max}} \). It may be noted here that the lower value of \( n \) localises the high
temperature zone near to $\theta=0$. The uniform temperature $(T(\theta)=T_{\text{max}})$ is thus obtained for $n=\infty$. The reason for such assumed variation is to study the effect of localised high temperature near the flaw. The temperature is assumed to increase at a rate $5^\circ$C/sec.

2.3 Pressure loading- The temperature at which ballooning occurs in a coolant tube, depends on the internal pressure during ballooning. In a typical PHWR, the normal primary operating pressure is 10MPa. With the occurrence of loss of coolant accident, the pressure decreases with a rate depending on the size and the location of the break. The present ballooning analysis is done for different constant channel pressure, varying from 10MPa to 1MPa with a step of 1MPa.

2.4 Locations of flaws- Coolant tubes in a PHWR may have part through flaws. These flaws may be generated during manufacturing stage or during the movement of the fuel bundles while refuelling. These flaws act as stress risers during ballooning of the tube and may initiate rupture. The chances of having a flaw at the lower portion of the tube is more due to fuel bundle weights. On the other hand the maximum temperature along the circumference of the pressure tube during severe accident is likely to obtain at the top surface of the tube. However, in the present analysis, the location of the flaw is conservatively assumed at the maximum temperature point.

2.5 High temperature creep model- The progress of ballooning in a coolant tube is essentially due to flow of material at high temperature under internal pressure. Hence this phenomena can be modelled only by a visco-plastic analysis of the material. One of the important inputs for this type of analysis is the high temperature creep model. In the present analysis, we have used the creep model given in [2].

2.6 Computer code THESIS- The present analysis has been done by using the computer code THESIS (THERmoplastic analySIS), developed by the present authors[3]. This is a 2-D finite element code with the capability of considering geometric and material nonlinerities. The material nonlinearities include elastoplasticity and thermoplasticity. The capability of the code has been further enhanced to consider viscoelasticity and viscoplasticity effect of the material. It can consider four different types of creep laws, such as, power creep law, exponential creep law, strain hardening creep law and time hardening creep law.

2.7 Rupture criteria- As the ballooning progresses, the local strain at the tip of the flaw increases. It is conservatively assumed that the rupture occurs when the local effective strain at the tip of the flaw reaches 100%[4].

3. RESULTS

The analysis is done for various assumed temperature profiles obtained by changing the parameters $\Delta T$ and $n$ in equation (1). Three values of $\Delta T$ have been assumed. These are $100^\circ$C, $200^\circ$C and $300^\circ$C. By changing the exponent $n$, five different types of profiles have been considered. These are uniform, linear, quadratic, cubic and quartic. The various sizes of flaws have been considered ranging from 5% to 30% of the thickness of the coolant tube. The contact between coolant tube and the calandria
tube is established, once the average circumferential strain in the coolant tube during balloononing reaches 18%. The computations are done to calculate the local effective strain at the tip of the flaw at 18% average hoop strain for various combinations of the flaw size, the temperature profile and the internal pressure. The results for each combinations of these parameters are then used to calculate the critical flaw size, below which coolant tube can come in contact with the calandria tube without rupture. These results are plotted in Figs. 1, 2 and 3 for $\Delta T$ equal to 100$^\circ$C, 200$^\circ$C and 300$^\circ$C respectively.

4. CONCLUSIONS

The following conclusions may be drawn from the results shown in these figures.

a. The critical flaw size decreases with the increase in channel pressure.

b. The critical flaw size decreases by lowering the value of $n$, which in turn concentrates the high temperature zone near to flaw.

c. By increasing the diametrical temperature difference ($\Delta T$), the critical flaw size decreases for similar temperature profile and same internal pressure.

d. For an uniform temperature along the circumference, the critical flaw size is more than 30% for internal pressure less than 6MPa.

e. If the flaw size is less than 15%, the coolant tube can balloon to have a contact with calandria tube without a fear of rupture for any internal pressure below 10MPa and uniform temperature along the circumference.

REFERENCES


2. Shewfelt, R.S.W., Lyall, L.W. and Godin, D.P., 1984, 'A high temperature creep model for Zr-2.5 wt% Nb pressure tubes', Jl. of Nuclear Materials, 125, 218-235.


Fig. 1 Analysis of coolant tube ballooning
Circumferential temperature difference = 100 deg C

Fig. 2 Analysis of coolant tube ballooning
Circumferential temperature difference = 200 deg C
FIG. 3 ANALYSIS OF COOLANT TUBE BALLOONING
CIRCUMFERENTIAL TEMPERATURE DIFFERENCE = 300 deg C