BWR FUEL CLAD BEHAVIOUR FOLLOWING LOCA

S.M. CHAUDHRY, K.N. VYAS, R. DINESH BABU
Bhabha Atomic Research Centre,
Trombay, Bombay, India

Presented by P. Balakrishna

Abstract

Flow and pressure through the fuel coolant channel reduce rapidly following a loss of coolant accident. Due to stored energy and decay heat, fuel and cladding temperatures rise rapidly. Increase in clad temperature causes deterioration of mechanical properties of clad material. This coupled with increase of pressure inside the cladding due to accumulation of fission gases and de-pressurization of coolant causes the cladding to balloon. This phenomenon is important as it can reduce or completely block the flow passages in a fuel assembly causing reduction of emergency coolant flow.

Behaviour of a BWR clad is analyzed in a design basis LOCA. Fuel and clad temperatures following a LOCA are calculated. Fission gas release and pressure is estimated using well established models. An elasto-plastic analysis of clad tube is carried out to determine plastic strains and corresponding deformations using finite-element technique. Analysis of neighbouring pins gives an estimate of flow areas available for emergency coolant flow.

1. INTRODUCTION

India has two BWR units at TAPS (Tarapur Atomic Power Station). The units have a capacity of 210 MWe each. The plant design is by General Electric of USA and belongs to an earlier generation of GE BWRs. Unlike modern BWRs, TAPS continues to use 6X6 type of fuel assembly with comparatively higher heat ratings. As the stored energy is higher, the clad temperatures tend to be higher during LOCA. This may cause clad ballooning, inspite of lower internal gas pressures. This paper describes calculations of clad surface temperatures during design basis LOCA and subsequently clad deformations.

Table-I gives salient data of the TAPS fuel.

2. THERMAL HYDRAULICS ANALYSIS DURING LOCA

Fig-1 shows the schematic of the BWR plant. As shown in the figure, the basic system consists of primary feed water entering the reactor through the feed water sparger. The water flows down, enters the reactor core and gets heated. Steam is taken out from the top via steam separator. The separated water also flows down and passes through recirculation loop consisting of a recirculation pump and secondary steam-generator. It mixes with the primary feed water at the bottom of the reactor pressure vessel. The design basis LOCA is the recirculation line break. Subsequent to LOCA, the core cooling is achieved by two independent, full capacity, core spray systems, which pump water directly on to the fuel assemblies in form of fine droplets.

During LOCA the scenario is as follows:

i) Recirculation line breaks resulting into depressurization of reactor vessel.

ii) During initial stages of LOCA, convective heat transfer co-efficients are relatively large.

iii) However, the heat transfer co-efficients drop rapidly within a period of 12 seconds to a very low value, and the fuel decay heat is transferred only by radiation.
TABLE I. SALIENT DATA OF TAPS FUEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel assembly configuration</td>
<td>6X6</td>
</tr>
<tr>
<td>Cladding outer diameter, mm</td>
<td>14.3</td>
</tr>
<tr>
<td>Cladding inner diameter, mm</td>
<td>12.52</td>
</tr>
<tr>
<td>Pellet diameter, mm</td>
<td>12.27</td>
</tr>
<tr>
<td>Active fuel length, mm</td>
<td>3613</td>
</tr>
<tr>
<td>Fuel element pitch, mm</td>
<td>17.81</td>
</tr>
<tr>
<td>Fill gas pressure, MPa</td>
<td>0.35</td>
</tr>
<tr>
<td>Peak linear heat rating, W/cm</td>
<td>550</td>
</tr>
<tr>
<td>Peak heat flux, W/cm</td>
<td>123</td>
</tr>
</tbody>
</table>

FIG. 1. BWR plant schematic.

iv) After 40 seconds, the core spray starts delivering full flow. This delay takes into account the time of reactor depressurization, core spray pump start-up and system valve opening times. As a result heat transfer improves.

v) After about 200 seconds, the fuel rewetting takes place and hence clad surface temperatures tend to fall.

For analysis a computer code HANU was developed and used for determining fuel clad temperature profile under LOCA. The code solves one dimensional heat conduction equation for a cylindrical geometry.

\[ V \rho_s C_p s \frac{dT_n}{ds} = Q_s + S_k s \frac{dT}{dR} - S_{(s-1)} K_{(s-1)} \frac{dT_{(s-1)}}{dR} \]
TABLE II. GREY BODY SHAPE FACTORS USED FOR ANALYSIS

<table>
<thead>
<tr>
<th>Source</th>
<th>Sink</th>
<th>Grey body shape factor (Source→Sink)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod Type 1</td>
<td>Channel</td>
<td>0.28</td>
</tr>
<tr>
<td>Rod Type 2</td>
<td>Channel</td>
<td>0.18</td>
</tr>
<tr>
<td>Rod Type 2</td>
<td>Rod Type 3</td>
<td>0.15</td>
</tr>
<tr>
<td>Rod Type 3</td>
<td>Rod Type 4</td>
<td>0.11</td>
</tr>
</tbody>
</table>

where,

\[ V_n \] - Volume of the \(n^{th}\) zone  
\[ \rho_n \] - Material density in the \(n^{th}\) zone  
\[ C_{p_n} \] - Material specific heat in the \(n^{th}\) zone  
\[ K_n \] - Material thermal conductivity in the \(n^{th}\) zone  
\[ S_n \] - Annular surface area in the \(n^{th}\) zone  
\[ R \] - Radius  
\[ T \] - Temperature  
\[ Q_n \] - Heat generated in the \(n^{th}\) zone

having the boundary conditions,

\[
\frac{dT}{dR(x=s_0)} = 0 \quad \text{and} \quad \frac{dT}{dR(x_s)} = \frac{h(T_s-T_r)}{K_s}
\]

where,

\[ h \] - heat transfer co-efficient  
\[ T_w \] - Sink temperature

For evaluation of heat transfer co-efficient by radiative mode grey body shape factors shown in Table-II are used.

Fig-2 shows the clad surface temperature variation up to a period of 1000 seconds.

3. FUEL PERFORMANCE ANALYSIS

3.1 FUEL PERFORMANCE ANALYSIS DURING STEADY STATE

Fuel performance analysis is done using computer code COMTA\(^2\). It is a code which takes into consideration the heat generation profile as a function of burn-up till end of life. It also takes into consideration the axial flux profile along the length of the fuel element. The code performs one
FIG. 2. Clad surface temperature variation during LOCA.

FIG. 3. Heat flux variation with burn-up.
FIG. 4. Axial flux profile.

FIG. 5. Internal fission gas pressure build-up.
TABLE III. CONSTANTS FOR CREEP LAW

<table>
<thead>
<tr>
<th>Phase</th>
<th>Temperature</th>
<th>A (MPa(^n)s(^{-1}))</th>
<th>n</th>
<th>Q/R (1/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>T ≤ 1073</td>
<td>2000</td>
<td>5.32</td>
<td>34220</td>
</tr>
<tr>
<td>β</td>
<td>T ≥ 1273</td>
<td>8.1</td>
<td>3.79</td>
<td>17110</td>
</tr>
</tbody>
</table>

Dimensional calculations at each axial node taking into consideration the following effects to evaluate pellet-cladding gap conductance:

i) Pellet-clad differential thermal expansion. At the maximum heat flux location pellet average temperature is about 850 °C higher than the cladding average temperature. In addition, the differences in the thermal expansion co-efficients are also taken into consideration.

ii) Pellet cracking and relocation. Temperature gradient across the pellet causes the pellets to crack. The cracked pellet relocates and causes a soft pellet-clad contact and increases gap conductance. The extent of relocation is dependent also on fuel burn-up.

iii) Pellet swelling. Pellet swelling both from solid and gaseous fission products is taken into consideration. Swelling also reduces the effective pellet-clad gap and increases the gap conductance.

iv) Clad inward creep due to external pressure. The computer code uses Nichol's\(^3\) model for calculation of irradiation creep.

v) Fill gas dilution. Fill gas (helium) is diluted by the fission gases viz. xenon and krypton, having a lower thermal conductivity. This is a function of burn-up and fuel operating temperatures.

Gap conductance is calculated by using modified Ross and Stoute\(^4\) correlation. Fuel temperatures are then obtained to calculate fission gas release and internal gas pressure. Other correlations used in the code are as given in MATPRO\(^5\). Fig-3 shows the heat flux variation against burn-up at the peak location. Fig-4 shows the axial flux profile along the length of the pin. Fig-5 shows the internal pressure build-up in the fuel element up-to the pin average burn-up of 20 GWD/Te.

3.2 FUEL ANALYSIS SUBSEQUENT TO LOCA

The temperature profile (shown in Fig-2) and the internal pressure at the end of life (shown in Fig-5) are the forcing functions for clad ballooning. It can be seen that the cladding temperatures are high and the cladding is in α + β or β phase. Secondary creep laws following the Arrheneous expression are used to calculate the plastic deformation viz.:

\[ \varepsilon = A\sigma^n\exp\left(-\frac{Q}{RT}\right) \]

where
\[ \varepsilon - \text{Strain rate (s}^{-1}) \]
\[ A - \text{Structure constant (MPa}^{-n}\text{s}^{-1}) \]
\[ \sigma - \text{Stress (MPa)} \]
\[ n - \text{Stress exponent} \]
\[ Q - \text{Activation energy (kJ-mol}^{-1}) \]
\[ T - \text{Temperature (K)} \]
\[ R - \text{Universal gas constant (kJ-mol}^{-1}\text{K}^{-1}) \]
For calculations, constants proposed by Rosinger & Bera\textsuperscript{6} are used. The constants for $\alpha$ and $\beta$ phases are shown in Table-3. For temperatures in the transition zone, values are obtained by interpolation.

Structural analysis is performed using a computer code NISA.\textsuperscript{7} This a general purpose finite element code which supports different types of elements and can perform elasto-plastic analysis. A mesh consisting of 4 elements across the thickness and 16 elements along the circumference of semi-circular cladding segment was generated. Analysis was done using plane-strain elements. The package has a provision for describing the creep law constants. Pressure and temperature profiles were supplied as the forcing function. Fig-6 shows the percentage tensile strains produced in the cladding. It can be seen that cladding is in $\beta$ phase for a very short period. During that period, strain rates are very high and a significant amount of strain is accumulated in that short period. It can also be seen that eventhough the internal pressure is low, accumulated creep strains are not very low.

4. CONCLUSIONS

During the LOCA, TAPS 6X6 cladding can experience the tensile strains of about 20%. This results into a maximum sub-channel blockage of about 45%. The value is within acceptable limits and does not cause a flow blockage during emergency core spray cooling. It is noticed that secondary creep rates are very sensitive to type of interpolation method used in $\alpha+\beta$ transition region. Choice of interpolation methods does not have a rigourous basis. Further investigations are being carried out to determine more accurate strain rates during transition region. The cladding temperatures are high and may result into cladding oxidation. The effect of oxide layer (i.e. reduction in effective thickness) as well the effect of diffused oxygen in strengthening of remaining layer is also being studied.
REFERENCES

1. GUPTA S. K. et. al., Effect of gap conductance on loss of coolant accident analysis of Tarapur Reactor. Internal report prepared at Reactor Analysis and Studies Section, Bhabha Atomic Research Centre.


7. COMPUTER CODE NISA (Numerically Integrated System for Analysis), by M/S EMRC (Engineering Mechanics Research Center), (Release-93)