



## An assessment of rupture of calandria / coolant tube due to fuel bundle impact

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### ABSTRACT

A guillotine rupture of a coolant channel inside a PHWR could lead to fuel bundles being ejected and striking the adjacent channel. This could lead to a propagation of failure. A simplified thermal hydraulic analysis is used to determine the ejection velocity of the bundles. Plastic hinge theory is used to determine the global damage. Possibility of penetration is checked using available correlations. A simplified fracture mechanics calculation is also carried out. It is shown that propagation failure is unlikely.

### INTRODUCTION

Inside the calandria of the 500 MWe Indian PHWR, the coolant channel assemblies provide the pressure boundary between the low pressure moderator and high pressure coolant. An assembly consists of a zircalloy coolant channel (also called pressure tube), surrounded by a zircalloy calandria tube. The two tubes are kept separated by garter springs. The calandria tube is rolled onto the calandria side tube sheet, and the pressure tube onto the end fitting. There are 392 such assemblies in the reactor. A sketch of one assembly is shown in fig. 1.

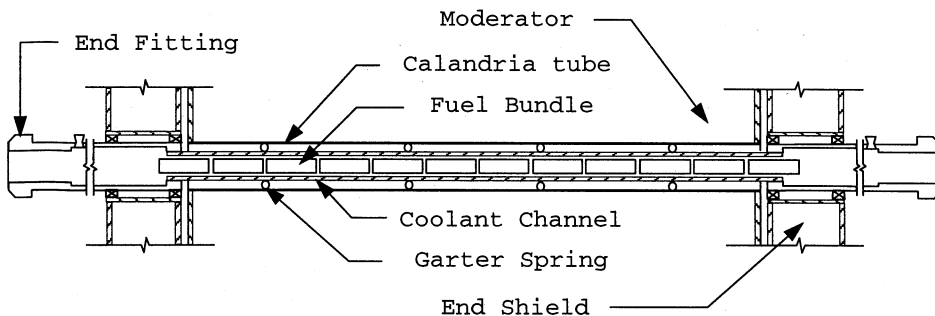


Fig. 1. Coolant Channel Assembly

In the 500 MWe PHWR, one of the postulated accidents is the rupture of a pressure tube. This will result in the ejection of high pressure, high temperature coolant. There is also the possibility of fuel bundles (missiles) ejecting and striking a neighbouring calandria tube. It has to be ensured that such a rupture should not lead to the rupture of a second pressure tube, ie. there should be no propagation of failure. There could be five physical mechanisms for possible propagation failure of adjacent channel assembly [1] :

- 1) Impulsive pressure loading
- 2) Missile damage
- 3) Collapse of vapour packets
- 4) Sustained jet impingement
- 5) Pipe whip

This paper deals with the Missile damage aspect of the problem.

#### DATA AND ASSUMPTIONS

The calandria tubes being very thin, cannot withstand the external pressure created by rupture of a pressure tube. Hence, the calandria tubes are assumed to be collapsed onto the coolant channels. The combined cross section is equivalent to an ID of 103.4 mm and an OD of 114.8 mm. The configuration is taken as a circular hollow beam with ends completely restrained. The yield stress of Zircalloy-2 at the operating temperature is equal to 705 kg/cm sq.

#### EJECTION VELOCITY CALCULATIONS

An important parameter in the analysis is the velocity of ejection of the striking fuel bundle. It has been assumed conservatively that the double ended guillotine rupture occurs in the mid length of the channel assembly. The bundle sees the full pressure differential between the coolant pressure and moderator pressure only when it approaches the break location. Before that, the bundle is carried along by the drag of the coolant. The bundle farthest from the break location (sixth bundle) will attain the maximum velocity. Therefore, the ejection velocity of the bundle is calculated in two stages. First, the velocity picked up by the farthest bundle as it is dragged to the break location is found. This velocity is then assumed to be the initial velocity of the bundle, when the full pressure differential of coolant and moderator propels the bundle out of the break opening.

##### *Drag induced velocity*

The total shear force on the wall and bundle surface is given by the following equation

$$F_s = \Delta p \times A_c = \tau_w + \tau_b \quad \dots (1)$$

where,  $\Delta p$  = pressure drop across bundle due to drag  
 $A_c$  = flow area =  $(\pi / 4) D_c^2 - (\pi / 4) D_f^2 \times 37$   
 $D_f$  = diameter of a fuel pin  
 $D_c$  = internal diameter of coolant channel  
 $\tau_w$  = shear force on the channel wall  
 $\tau_b$  = shear force on the bundle surface

The force on the bundle due to differential pressure across the bundle is given by

$$F_p = \Delta p \times A_b \quad \dots (2)$$

where,  $A_b$  = cross sectional area of fuel bundle  
 $= 37 \times (\pi / 4) \times D_f^2$

Therefore the total drag force on the bundle is

$$F_d = F_s + F_p - \tau_w = \Delta p \times (A_c + A_b) - \tau_w = (\Delta p \times A) - \tau_w$$

where,  $A$  = total area of channel =  $(\pi / 4) D_c^2$

Hence, conservatively, the drag force can be represented as

$$F_d = \Delta p \times A \quad \dots (3)$$

The pressure drop  $\Delta p$  is obtained from the standard equation relating pressure drop to friction factor.

For the 500 MWe PHWR, experimentally obtained friction factor 'f' for fuel bundle is given by [2]:

$$f = 0.16685 \text{ Re}^{-0.1351} \quad \dots (4)$$

where,  $\text{Re}$  = Reynold's number =  $\rho v D_e / \mu$   
 $\mu$  = coefficient of viscosity

The blowdown velocity of coolant ' $v_f$ ' is found from the Homogeneous Equilibrium Model (HEM) which gives the critical mass flux for a given enthalpy and pressure [3].

Critical blowdown velocity =  $v_f = 122.9 \text{ m/s}$ .

The equation of motion of the bundle can be written as :

$$d^2x / dt^2 = (F_d - \mu Mg) / M \quad \dots (5)$$

where,  $F_d$  = drag force  
 $\mu$  = coefficient of friction = 0.245  
 $M$  = bundle mass = 25 kg

The equation of motion is solved using the RK4 method. The velocity picked up by the bundle due to fluid drag, as it approaches the rupture location is found to be 76.4 m/s.

*Velocity picked up due to differential pressure of coolant and moderator*

It is assumed that the full differential pressure acts over one bundle length (0.5 m), before the bundle gets ejected out. The accelerating force 'F' is given by

$$F = \Delta P \times A_b \quad \dots (6)$$

where,  $\Delta P$  = pressure difference between coolant and moderator  
= average pressure of coolant inside the channel = 108 bars.

Bundle area = 4941.4 mm<sup>2</sup>  
 $\therefore F = 108 \times 49.41 = 5336.7$  kgf.  
 $\therefore$  acceleration =  $a = F/M = 5336.7 / 25 = 2094.1$  m/s<sup>2</sup>.

From the equation :  $v^2 = u^2 + 2as$  with an initial velocity of 76.4 m/s, bundle acceleration of 2094.1 m/s<sup>2</sup> and a bundle length of 0.5m, the ejection velocity is found to be 89.1 m/s.

*Angle of incidence and normal impact velocity calculations*

The coolant channel assemblies are arranged in a square lattice pattern with a separation of 286 mm between channel centres. In case of a double ended rupture in the centre of the channel assembly, the maximum angle by which the channel can whip is approximately 11.6°. Hence the bundle, after ejection will make an oblique impact on the adjacent channel assembly. It is assumed that the energy effective in this impact is that corresponding to the velocity component of the bundle normal to the adjacent channel.

This normal velocity is :  $89.1 \times \sin 11.6^\circ = 17.9$  m/s. The corresponding kinetic energy is :

$$0.5 \times M \times v^2 = 0.5 \times 25 \times 17.9^2 = 4010.5 \text{ N-m.}$$

**IMPACT ANALYSIS**

Impact problems generally have two types of deformation which are described below :  
a) Local deformation – where only local damage at the point of impact is considered. Local effect considered is the possibility of penetration.

b) Global deformation – where the response of the entire body to the impact force is analysed.

**Global Behaviour**

*Elastic analysis*

The global response is calculated by multiplying the static response by a dynamic amplification factor. The factor also incorporates the effect of the ratio of mass of striking body to the mass of the struck body [4]. The dynamic amplification is found to be = 52.9. The dynamic amplification factor when multiplied with the static stress of 38.075 kg/cm sq. gives a dynamic stress of 2014.8 kg/cm sq. This is greater than the yield stress of zircalloy at 300 °C ( 704.55 kg/cm sq.). Hence channel will experience plastic deformation.

*Plastic analysis*

Plastic hinge theory [5] is used to analyse this problem. Here it is assumed that three plastic hinges will form as shown in the figure below, and absorb energy by rotation of these hinges.

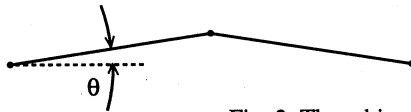


Fig. 2. Three hinges on a fixed beam

Hence if plastic moment at a section is  $M_p$ , then according to reference [5], equating the energy,

$$W \times H = 4 \times M_p \times \theta = 0.5 \times M \times v^2 \times K = 0.5 \times (W/g) \times v^2 \times K \quad \dots (7)$$

where  $W$  = bundle weight,  $H$  = drop height,  $V$  = impact velocity. Factor 'K' accounts for the effect of the ratio of mass of striking body to the mass of the struck body on the energy imparted. 'K' was found to be 0.09.

For three hinges, the energy absorbed is 4 times  $M_p \times \theta$  because the central hinge rotates through twice the angle of the other two hinges. Plastic moment for the annular section was found to be 47875 kg-cm. Using the formula given above, the value of ' $\theta$ ' is calculated to be :

$$4 \times [ 47875 \times 9.81 / 100 ] \times \theta = 4010.5 \times 0.09 \text{ (N-m)}$$

$$\therefore \theta = 1.1^\circ$$

### Failure Criteria

Acceptability of this rotation was evaluated by Finite Element Method. The ABAQUS FEM Code was used to model the channel assembly using hollow pipe elements with 5 integration points through a section. An elasto-plastic analysis was carried out and it was found that a  $1.1^\circ$  rotation of the hinge produced a strain of 0.44 %. It is seen that FEM predicts strains below 1 %. Ductility values of irradiated zircalloy are much above this [6–8]. Hence there is sufficient margin against global failure.

### Local Behaviour

#### Resistance against penetration

Possibility of a local failure was evaluated by using the penetration formula [9] :

$$E_f = 2.9 \times (T \times D_e)^{1.5} \quad \dots (8)$$

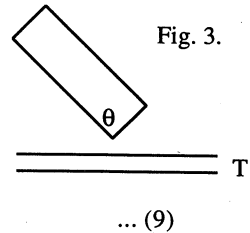
$E_f$  is the critical failure energy in Joules

$T$  is the plate thickness in mm

$D_e$  is in mm

$D_e$  is the equivalent diameter of the missile, which for a conical nosed missile is given by the formula :

$$D_e = T (1 + 2.9 \times \tan(\theta/2)^{2.1})$$



Although equations (8) and (9) are for Stainless Steel, it can be conservatively used for zircalloy as its toughness is slightly higher than that of S.S. at comparable temperatures [10].

For  $\theta = 90^\circ$ ,  $D_e = 22.23$  mm.

$\therefore E_f = 4136$  J which is more than the incident energy of 4010.5 J. Hence coolant channel assembly is safe against local failure by penetration.

### EFFECT OF FLAWS ON CHANNEL INTEGRITY

The above analysis assumes that the channel assembly is free of crack like defects. However if flaw size, J-resistance curve and Tearing Modulus of irradiated material are available, a fracture mechanics analysis can be performed to assess the integrity of the channel assembly. LEFM can be used for fracture mechanics evaluation of an irradiated pressure tube.

To calculate the  $K_{I \text{ applied}}$ , it is assumed that there is a part through circumferential flaw on the outer surface of the coolant channel. The flaw dimensions are taken as prescribed in the ASME Boiler and Pressure Vessel Code Section III Appendix G.

Length of the crack is taken as three times the pipe thickness, and the crack depth as one fourth of the pipe thickness. The nominal stress has been taken equal to the yield stress (705 kg/mm sq.). The equation for evaluation of  $K_1$  was taken from the Ductile Fracture Handbook [11]. The value of  $K_1$  was found to be 150.23 N/mm<sup>1.5</sup>.

The applied  $K_1$  has to be compared with the material toughness  $K_{1c}$  for irradiated zircalloy. For zircalloy specimens irradiated at 280 °C with neutron fluence of  $2 \times 10^{22}$  n/cm<sup>2</sup> and neutron energy greater than 1 Mev, the  $K_{1c}$  value is around 1775 N/mm<sup>1.5</sup> [12]. It can be seen that there is a lot of margin against unstable crack propagation.

## CONCLUSION

The velocity of impact of the fuel bundle on adjacent channel assembly was calculated to be 89.1 m/s. This is a conservative estimate of impact velocity of a fuel bundle against the CT/PT assembly because the simplified approach has made some conservative assumptions.

An elasto-plastic Finite Element analysis of global impact shows that the maximum strain in the channel assembly is 0.5%. This is less than the minimum fracture ductility of irradiated zircalloy. A penetration check shows that penetration of the CT/PT assembly by the impact of a fuel bundle can be ruled out. A simplified fracture mechanics calculation has been done to show that a minimum detectable crack on the coolant channel is safe against unstable crack propagation.

Calculations presented in this report primarily indicate that there is no propagation of failure from fuel bundle impact on an adjacent channel assembly.

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