FUEL BUNDLE (INDIAN PHWR) DEFORMATION UNDER ACCIDENT CONDITION

Ritu J Singh, K. Ravi, S. K Gupta
Atomic Energy Regulatory Board, Niyamak Bhavan, Mumbai, INDIA-400094
E-mail of corresponding author: ritusingh@aerb.gov.in

ABSTRACT

Degradation of fuel cooling is postulated for many accident scenarios in PHWR. For a postulated Loss of Coolant Accident, fuel bundle temperatures will be high due to mismatch between heat deposition and dissipation rate. This leads to onset of deformation and many other high temperature phenomenons. In a PHWR, fuel temperature may increase substantially leading to deformation of fuel bundle due to thermal loads. Additional thermal loads will result in different phenomenon like creep, swelling, bowing, end plate bending etc . This paper brings out the current understanding of the high temperature deformation mechanisms of a fuel bundle. This paper also presents structural analysis of fuel bundle under differential thermal loads which may lead to sagging of fuel pin, bending of endplate and fuel pin to pressure tube contact.

During LOCA scenario there is a possibility of flow stratification .During normal operating condition the fuel bundle temperature rise is limited because the heat generated is carried away by the coolant. However in an accident condition, when coolant flow to an individual channel is reduced, the remaining flow will be increasingly converted to steam as the mass flow decreases. In such a case the lower portion of fuel bundle is at low temperature as it is submerged in water, whereas upper portion of fuel bundle is at higher temperature as it is surrounded by steam. This differential temperature across the fuel bundle leads to thermal stresses and strains and bending of fuel bundle elements. In addition to the thermal strains, the bundle may experience substantial creep strains. So it becomes very important to model and analyze this accident scenario to ascertain the fuel bundle deformation. Lower fuel rods temperature is take as 300^o where as temperature on upper portion takes different temperature values Fuel rod weight and high temperature loads are modeled using a finite element code ANSYS. High temperature material properties are used for calculation. It is observed from the analysis that in the high temperature range, end plate yielded and accommodated the deformations of the fuel bundle. The fuel bundle deformation were found to be limited.

INTRODUCTION

In PHWRs fuel is in the form of small cylindrical pellets. These pellets are encapsulated inside Zircaloy-4 cladding and hermetically sealed at both the ends by welding with two end plugs. Each element is provided with spacer pads to maintain the inter element spacing. The fuel elements are assembled in the form of bundle by welding them to two end plates. In case of 37 element bundle the elements are arranged into 3 concentric rings around a central element. These bundles are half meter in length. The bundles are located horizontally in pressure tube in the reactor. The spacing between outer fuel elements and pressure tube is maintained by bearing pads. The fuel bundle schematic diagram is given in figure 1.

During normal operating condition the fuel bundle temperature rise is limited because the heat generated is carried away by the coolant. However in an accident conditions, the fuel element will be subjected to set of thermal and mechanical loads. These loads can lead to over all geometrical deformation of the fuel bundle. These deformations can lead to loss of bundle coolability or bundle distortions to the extent that it may hinder the removal of the fuel bundle from the channel. Also fuel channel integrity can be affected by fuel bundle deformations if the bundle contacts undeformed pressure tube. Some of the process that may cause bundle deformations are clad ballooning, creep sag at high temperature, fuel bundle subjected to differential temperature, end plate cracking due to fatigue, sagging and bowing due to differential expansion, fragmentation of the element on quenching etc. In an accident condition when coolant flow to an individual channel is reduced, the remaining flow gets increasingly converted into steam as mass flow decreases. In such a case the lower portion of the fuel bundle is at low temperature as it is submerged in water, whereas upper portion of the fuel bundle is at high temperature as it is surrounded by steam. This differential temperature across the fuel bundle leads to thermal stresses and strains. The differential expansion of various elements in the bundle will try to bend the endplate and also various elements. So it becomes important to model and analyze this accident scenario. To understand the mechanical deformation of the fuel bundle under differential temperatures a finite element model is developed in ANSYS.

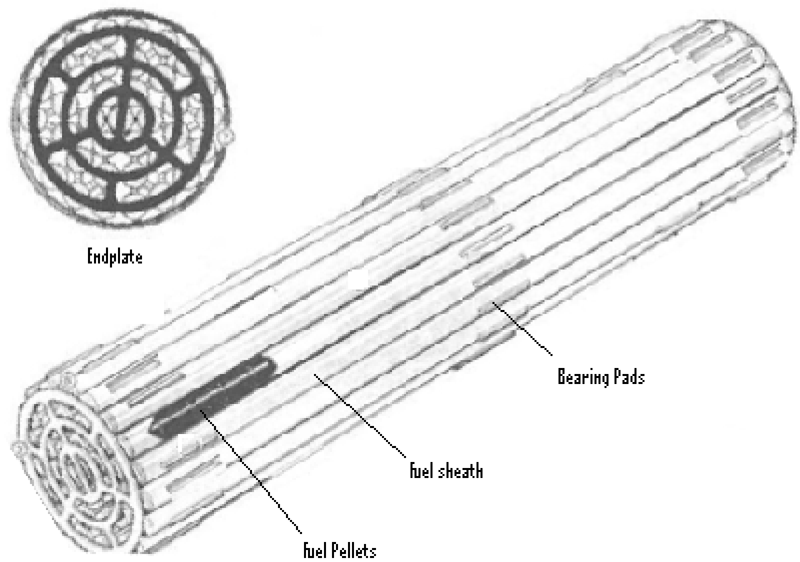

Fig. 1 schematic of 37 element fuel bundle

The following sections bring out the importance of the high temperature behavior of the fuel bundle. It also deals with the modeling of fuel bundle and analysis for the case of differential temperature across the fuel bundle.

SIGNIFICANCE OF HIGH TEMPERATURE UNDERSTANDING

During a postulated break in the primary coolant system coolant inventory in the primary circuit comes down. Primary pressure and coolant circulation also come down. As a result of decrease in coolant inventory there will be decrease in the heat removal from the fuel elements. This lead to rise in temperature fuel of clad. This temperature will increase further if the Emergency Core Coolant System (ECCS) is not available. During this scenario the remaining coolant in the channels slowly gets converted into steam. Due to this there will be a temperature gradient across the bundle. This will ultimately result in High temperatures in the bundle. High temperature deformation is important to understand as this has safety significance [1] [2]. Following paragraphs highlight the significance:

- Fuel bundle deformation will change the flow area of the coolant which will result in dry out scenario.
- Behavior of end plates under high temperature is important as it affects the bundle geometry. This in turn would disturb the fuel and sheath temperatures and these temperatures will be responsible for Zr/UO2 reaction, hydrogen production and for the fission product release throughout the bundle.
- Proper simulation of fuel bundle thermal behavior after postulated accidents is an important component of the safety analysis submissions by the power reactor licensees.
- For scenarios such as large LOCA, integrated modeling of fuel bundle and pressure tube thermal-mechanical behavior is critical in order to confirm that the pressure tube can indeed survive the effect of thermo mechanical interaction with a rapidly heating and deforming bundle.
- Thermo physical processes involved in unmitigated heat up of fuel within a fuel channel are numerous and complex.

FE MODELLING

Fuel bundle is modeled by a commercial finite element code ANSYS. Static analysis is performed with temperature as loads. Material properties and geometrical details are presented below.

Bundle details

Fuel bundle geometrical details and weight are summarized below.
Length, mm = 495
Bearing Pad thickness, mm = 1.35
Outside Diameter of Fuel element, mm = 13.08
Thickness of sheath, mm = 0.38
Thickness of endplate, mm =1.6

Material Properties

Bilinear material model which is available in ANSYS is used for material modeling. The material behavior is described by a bilinear total stress-total strain curve starting at the origin and with positive stress and strain values. The initial slope of the curve is taken as the elastic modulus of the material and yield stress values at different temperature are provided [3]. Zircaloy material properties like elastic modulus and Yield stress decreases with temperature is increased [4] as shown in figure 2. Table 1 shows the material properties as a function of temperature.

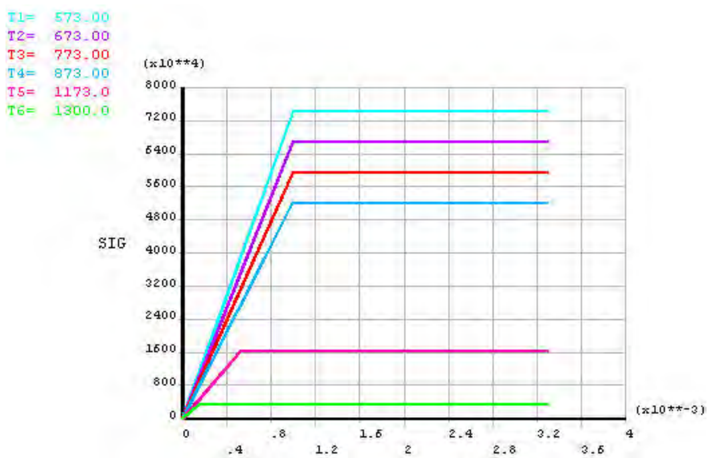

Figure 2: Material properties as used in the model

Table 1: Material Properties

Temperature (K)	Yield Stress (Mpa)	Young's Modulus (GPa)
573	94.5	74.2
673	79.5	66.9
773	68.7	59.5
873	55.103	52.16
973	42.203	44.81
1073	29.303	37.46
1173	16.403	30.11
1273	3.503	22.76

Modeling details
The 37 element fuel bundle consists of fuel pellets, fuel sheath, endplate, spacer pads, bearing pads and end caps. The FE model of the fuel bundle is presented using shell, pipe and link elements. The Endplates are modeled using

shell elements. The fuel sheath is modeled using pipe element where fuel pellet weight is accounted by increasing the density of the sheath material. The spacers and bearing pads are modeled using link element. The link element with compression only option is used. For the gap option, a positive strain indicates a gap. The gap must be input as a "per unit length" value in the real constants of the element. The gap strains for bearing pads were calculated by taking the gap between the outer fuel elements and pressure tube. The finite element model of the fuel bundle is shown in Figure 3.

Table 2: Finite element details

Fuel Bundle Component	Material	Finite element	Element Description	Remarks
Fuel sheath	**Zircaloy-4**	**Pipe 20**	**2node, six DOF**	**Total 1400 elements and 1517**
End plate	**Zircaloy-4**	**Shell 43**	**3-D, 4 node, six DOF**	**For each endplate No of elements:2064 No of nodes :2398**
Spacer pads	**Zircaloy-4**	**Link 10**	**Rigid link**	
Bearing pads	**Zircaloy-4**	**Link 10**	**3-D,Tension-only or Compression-only Spar, 3 DOF**	

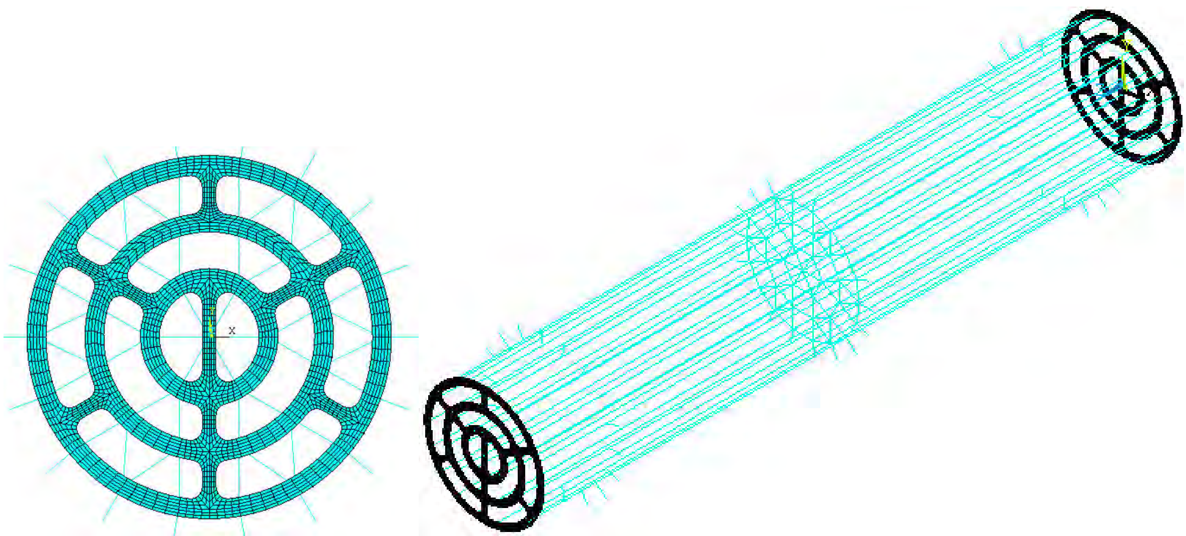

Fig. 3 Finite element model of the fuel bundle

Key assumptions and boundary conditions

- End plate and fuel elements are joined by a common node. So that weld at the end of each pin is treated as a continuous material with same property as zircloy-4.
- Un-irradiated material properties are used
- Fuel pellet weight and fuel sheath weight is accounted by increasing the density of sheath material.
- To model pressure tube as non deforming boundary, constraints were placed on all the nodes of the bearing pads so that deformation in the radial direction is limited to the gap between pressure tube and bearing pad.
- The spacer pads are modeled using rigid link elements.

- In the coolant channel there will be some space at the end of end bundle. Hence in present analysis one end of the fuel bundle is fixed in axial direction and other end is allowed to expand freely.
- In present model temperatures along each fuel pin is assumed to be uniform which is conservative assumption for safety analysis.
- The center node of the two endplates have transverse displacements (Ux, Uy) restrained to fix the nodes in space. The rotation about z axis (axial direction) is also restrained to avoid spinning.

Postulated Accident Scenario and Loads

During normal operating condition the fuel bundle temperature rise is limited because the heat generated is carried away by the coolant. However in an accident condition, when coolant flow to an individual channel is reduced, the remaining flow will be increasingly converted to steam as the mass flow decreases. In such a case the lower portion of fuel bundle is at low temperature as it is submerged in water, whereas upper portion of fuel bundle is at higher temperature as it is surrounded by steam. This differential temperature across the fuel bundle leads to thermal stresses and strains and bending of fuel bundle elements. A temperature profile was imposed on the bundle to simulate the response t the accident scenario. A temperature of 300C was applied to the bottom fuel elements to represent reactor coolant condition. A temperature of 1000C was applied to the fuel elements at the top to simulate steam environment. Figure 4 shows the temperature variation across the fuel bundle which was linearly increased from bottom to the top element.

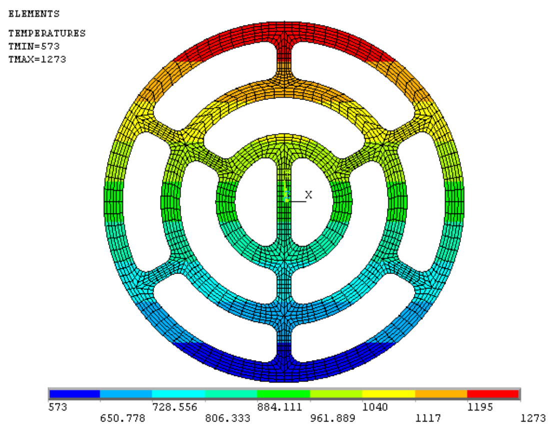

Fig.4 Case 1: Linear temperature variation across the fuel bundle

RESULTS AND DISCUSSIONS

The stress analysis of fuel bundle has been done for accident condition. Figure 5 gives the deformed shape of the fuel bundle. As expected the top fuel elements elongate more as there temperatures are high compared to bottom fuel elements. The endplate is flexible enough to accommodate the elongations of the fuel elements. The axial stress in the fuel sheath is tensile for the rods at lower temperature and compressive for rods at higher temperature. As the endplate is very flexible the stresses in the fuel sheath is not very high as shown in figure 6. The von mises stress distribution in endplate is shown in figure 7. As seen from the figure yielding occurs in the endplate. It can be inferred that endplate is performing well under such an accident scenario. The maximum deflections seen by the fuel sheath is limited to 0.186 mm in transverse directions. Maximum endplate deformation in axial direction was 2.2mm.

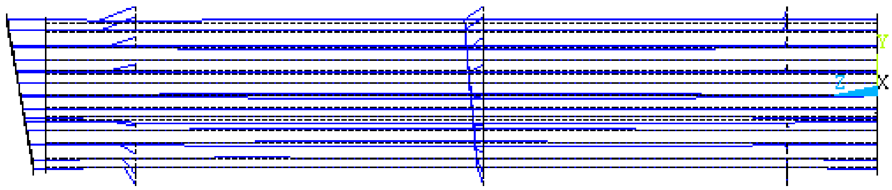

Fig. 5 Deformed and undeformed (dotted lines) shape of the fuel bundle

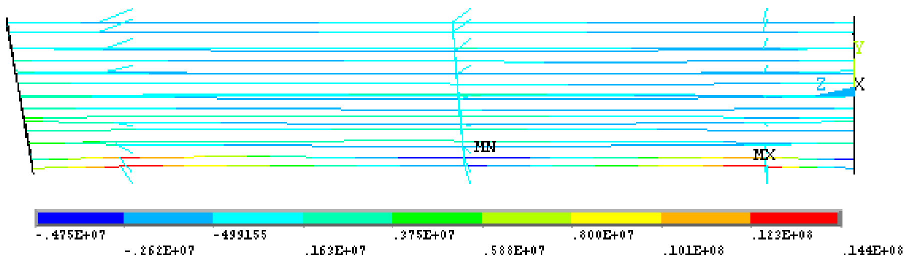

Fig. 6 Stress in axial direction of the fuel sheath

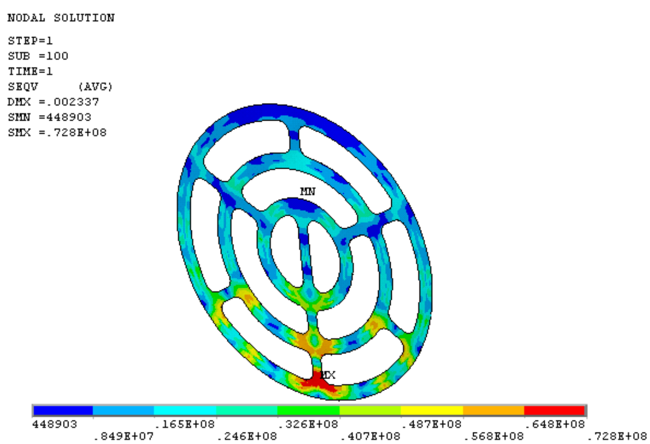

Fig.7 Von mises stress distribution of the end plate

CONCLUSION

- A finite element model of a 37 element fuel bundle was generated using ANSYS. The model was developed to understand the response of the fuel bundle subjected to accident condition where the bundle is subjected to differential temperature across the fuel bundle.
- The deformations and stresses in the endplate were obtained and it was observed that the end plate would yield in the scenario. The radial deflection of pressure was limited.
- There was no contact between the fuel sheath and pressure tube during the accident scenario.
- The fuel bundle performed well in the postulated scenario.

REFERENCES

[1] Structural behaviour of fuel assemblies for water cooled reactors Proceedings of a technical meeting, Canadarache, France, 22-26 November 2004

[2] Moon-sung cho, Ki-Seob Sim,Ho chun suk , Scok-kyu chang, “Static strength analysis of CANDU-6 reactor fuel bundle”, Journal of Nuclear Materials and Design, 2000

[3] Talia. J. E., Polovo.F, “Tensile properties of Zircaloy-4”, Journal of Nuclear Materials 67(1997) 198-206

[4] Gargi Choudhari, K.R. Gurumurthy, J.S.Dubey, S.Chattarjee , B.K.Shah., “Nuclear structural components & materials information and design data”