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Development of Structural Analysis Modelling for KALIMER Fuel Rod

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Abstract

The U-Zr metallic alloy with low swelling HT9 cladding is the candidate for the KALIMER fuel rod. The fuel rod should be able to maintain the structural integrity during its lifetime in the reactor. In a typical metallic fuel rod, load is mainly applied by internal gas pressure, and the deformation is primarily caused by creep of the cladding. The three-dimensional FEM modelling of a fuel rod is important to predict the structural behavior in concept design stage. Using the ANSYS code, the 3-D structure analyses were performed for various configuration, element and loads. It has been shown that the present analysis model properly evaluate the structural integrity of fuel rod. The present analysis results show that the fuel rod is expected to maintain its structural integrity during normal operation.

1. Introduction

The KALIMER is supposed to be the first liquid metal reactor(LMR) in Korea where a commercial LMR is necessary to be operated in future. The core is fueled with metallic fuel which has a good negative reactivity characteristic to enhance inherent safety. Each fuel assembly has an individual hexagonal duct to channel the coolant flow.

During the period of development in the 1970's at EBR-II, the perceived performance disadvantages of metallic fuel were satisfactorily resolved and as well additional attributes of metallic fuel were discovered[1,2]. In 1980's, the metallic fuels were continually developed to enhance on physical properties which have enabled improvements in reactor safety and an economical fuel cycle. The technical feasibility of IFR had been demonstrated and the technology database had been established to support its practicalilty before IFR project was suspended in 1995[3].

In order to obtain concept design data and design improvment, the structural analysis modelling on fuel rod is desirable to develop. The structure analysis under specific loads is performed to confirm the structural integrity of fuel rod. Various loads in the present structural analysis are considered with respect to rod internal pressure buildup and thermal creep during the reactor operation. The structure analysis is carried out by using the FEM structural analysis code. A reliability of FEM modelling for fuel rod has been studied under several load and constraint conditions. The present study is to set up the structure analysis method by an appropriate FEM modelling to show the strain and stress behavior on fuel rod.

2. Structural load

The fuel pin is made of sealed HT9 cladding containing metal fuel slug in columns. The fuel is immersed in sodium for thermal bonding with cladding. A fission gas plenum is located above the fuel slug and sodium bond. The bottom of each fuel pin is a solid rod end plug for axial shielding. The internal pressure build-up in the plenum of fuel rod is due to fission gas release which is caused by burnup according to power history. The various pressure values under certain conditions are obtained by the MACSIS code[4] which is a performance code of metallic fuel rod, before structural analysis is performed.

The plenum pressure P_p at various operation conditions can be approximately estimated. A common method for calculating the plenum pressure is to calculate the volume, V_0 , of fission gas at a standard temperature T_0 = 273 K and pressure P_0 = 1 atm, and use the perfect gas relation equation. The gas plenum is contained within same cladding as a fuel slug done. Setting that V_p and V_f are the volumes of gas plenum and fuel slug, respectively, the plenum pressure P_p is calculated by the following relations, since the volume ratio V_p/V_f is equal to the length ratio, L_p/L_f.

$$P_p L_p = \alpha_0 L_f \frac{T_p P_0}{T_0}, \qquad \alpha_0 = \frac{nRFT_0}{P_0} \tag{1}$$

where, α_0 = volume of fission gas released per cubic meter of fuel at T_0.

n = kg-mol fission gas produced/m^3 fuel

R = universal gas constant (8317 J/kg-mol. K).

F = fission gas release fraction

Creep is a time-dependent strain occurring under constant stress over long periods of time. When the fuel cladding is initially exposed to a stress field, the elastic and plastic deformations can be occurred. The deformation is caused by dislocation motion of material. Since the probability per unit time of supplying the energy, E, needed to start a dislocation moving is proportional to the Boltzman factor, exp(-E/kT), the thermal creep rate ε, can be generally expressed in the form[5]:

$$\dot{\varepsilon} \approx \sigma^{m} \exp\left(\frac{-E}{kT}\right) \tag{2}$$

Thus, the creep rate rapidly increases with stress level and temperature.

3. Structural analysis

3.1 Modelling

The objective of fuel modelling in this work is to investigate its response and in-reactor behavior of fuel rod due to static pressure load and thermal creep. The pressure load is assumed to be applied uniformly on cladding wall and top and bottom end cap. The rod is assumed to be located vertically in z-axis line. The bottom end cap is in full contact. The fuel rod is allowed to move in axial direction.

The finite element model of fuel rod clad is a shell model. Top and bottom end cap of fuel rod are all modelled with shell or solid elements, using same material properties. The cladding is modelled with 3-D solid elements for static pressure load analysis. To calculate the creep behavior of cladding, the cladding is modelled with 3-D plastic shell elements. The cross section of rod cladding is divided radially into 20 segments for solid element and 24 angle segments for shell element. The length of rod is divided into twelve segments. These fine elements are expected to obtain proper displacement, strain and stress. The centre nodes of bottom end cap have axial displacement restrained so that the all 6 translational degrees of freedom translation are fixed. The centre nodes of top end cap have their transverse displacements (Ux,Uy) restrained to fix these nodes in space. The top end cap is allowed to move in axial direction. Fig. 1 shows an modelling overview of the fuel rod.

3.2 Structural Analysis

In order to develop an appropriate modelling for analysing the structural integrity of the fuel rod, the analyses were performed by using the ANSYS code[6] which are calculated with several geometrical models, structural elements and constraint conditions. To verify a modelling simulation of fuel rod, the analysis results modelled with shell element were compared with those of another solid modelling. Both maximum stress values are found to agree with each results within 5% deviation. Therefore, it is enough to study the modelling for the structural integrity behavior. Both shell and solid element model for fuel rod consists of 360 nodes. The static analysis was performed first so as to seek the displacements, strain and stress behavior on fuel clad modelled as 3-D solid elements. The thermal creep analysis during the reactor operation is also considered to calculate the strain and stress modelled as 3-D shell element. The stress intensity in the cladding is evaluated to verify the mechanical strength, the stress intensity is the largest of the absolute values of in principle stresses $(\sigma_1, \sigma_2, \sigma_3)$, $\sigma_I=\max(|\sigma_1 - \sigma_2|,|\sigma_2 - \sigma_3|,|\sigma_3 - \sigma_1|)$.

4. Results and Discussions

An important source of static load in the fuel rod is plenum pressure load due to fission gas release from fuel slug. The pressure in gas plenum is normally in approximate equilibrium with pressures throught the fuel rod. Typical fission gas plenum pressures at discharge are in the range of 6 to 10 MPa. By the structural analysis results of fuel rod model, the maximum stress intensity distribution through various plenum pressure is shown in Fig. 2. It shows that the stress intensity values on cladding increase up to σ_{int} = 76.8 MPa when the plenum pressure was 10 MPa. The local higher stress intensities at several nodes were shown to be less than the stress intensity limit. From these results, it is apparent that the structure integrity of fuel rod is enough to maintain its integrity under maximum plenum gas pressure.

One of the radial cladding deformation is related to the thermal creep strain. In addition, the thermal creep is divided into stages representing primary, secondary, and tertiary creep. Primary creep occurs early in life and has comparatively high rates. Secondary creep follows primary creep and takes place at slower rates because of strain hardening. Tertiary creep is an accelerating rate which occurs near end of life. The predicted thermal creep behavior for HT9 material remains in the secondary stage at less than 920K. Fig. 3 shows the thermal creep strains for long reactor operation period. The strain values indicate an increase as a constant rate during operation time and also increase with temperature. The thermal creep strain value on the fuel cladding reached to be ε =0.0028 at 620 ℃.

5. Conclusions

The FEM model of a fuel rod was developed for the structural analysis. The local stress intensities of the fuel rod cladding were lower than the yielding strength. Therefore, the present fuel rod design is expected to maintain its integrity under maximum gas pressure. The new models of a fuel rod should continually be developed to solve fuel rod response under several static and dynamic loads.

References

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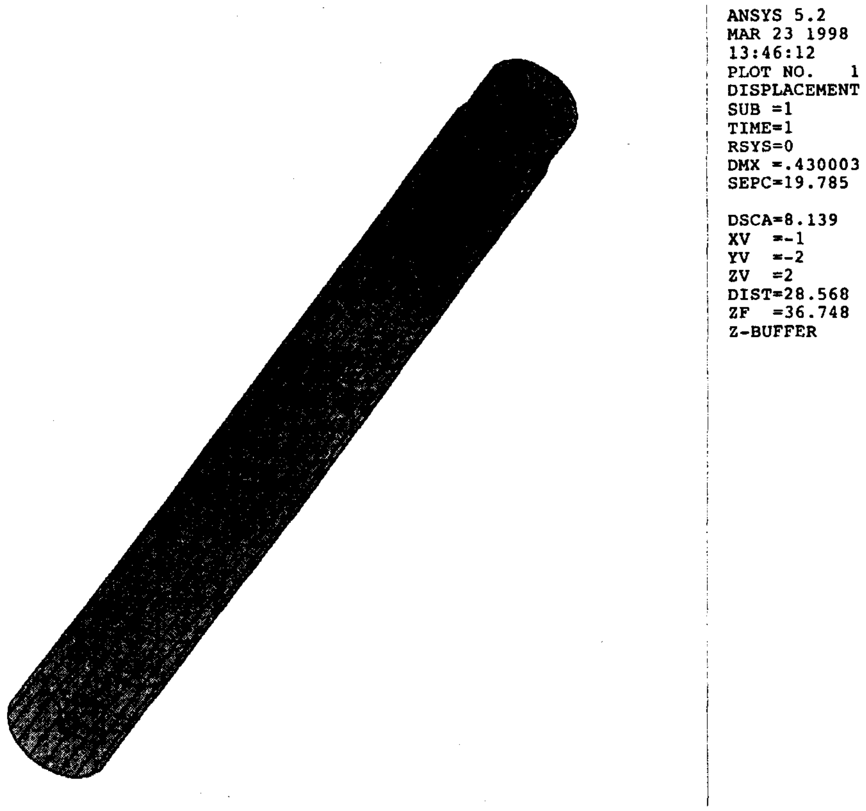

Fig. 1 Structural analysis model of fuel rod

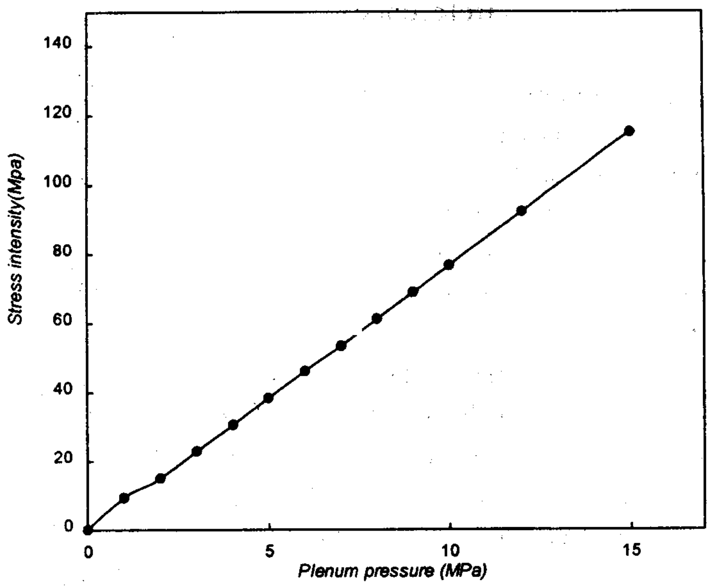

Fig. 2 Stress intensity distribution on fuel cladding versus plenum pressure

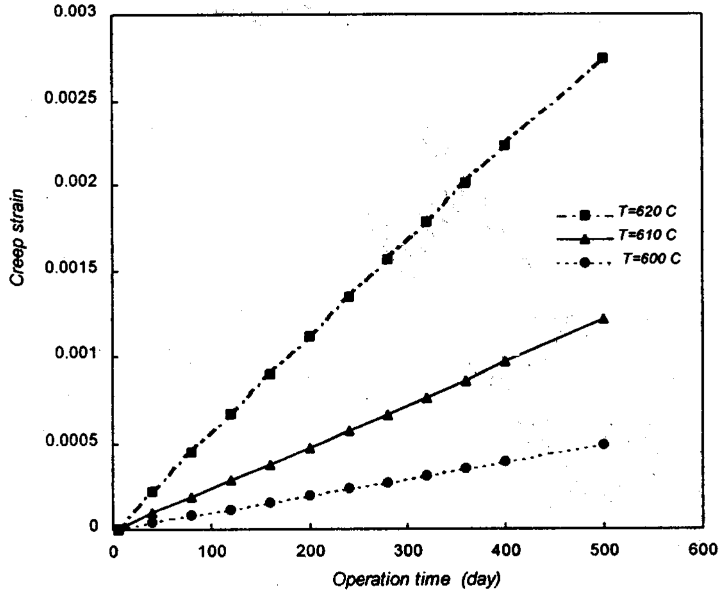

Fig. 3 Thermal creep strain versus operation time at temperature T=600, 610 and 620 C