PCMI EFFECT STUDY IN THE FUEL ROD OF A PWR REACTOR TYPE SUBJECTED TO POWER RAMPS

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ABSTRACT

PWR reactor type, when subjected to the power ramp regime, a mechanical interaction between the cladding and the UO_2 pellet (PCMI) may occur in the fuel rod. To investigate this phenomenon were used two softwares, the first was a modified fuel performance code to verify the behavior of fuel rod with steel cladding and another to analyze structural mechanical behavior. The fuel performance code results show that there is no contact between the pellet and the cladding in the fuel rod, considering the estimated burning under normal conditions of reactor operation. Thus, it was adopted the hypothesis of the interaction pellet-cladding occurrence, generated by pellet fragmentation and relocation, and power ramp simulation conditions independent of the ramp time. The simulations results show that the fuel rod maintains its integrity under the conditions of the adopted hypothesis.

1. INTRODUCTION

PWR type power nuclear reactors, when used for propulsion, the occurrence of power ramp regime is common during operation. This fact leads to great uncertainty about phenomena that occurs in the pellet, such as the release of fission gases, cracks and relocation. These effects [1] are experimentally verified as the fuel behavior codes are not yet ready to be reliably analyzed, especially when using stainless steel as a cladding material on the fuel rods (VC). This observation is due to the purely random nature of how the cracks will form on the fuel pellet. They certainly existed in a larger quantity when there is power cycling, a typical occurrence in reactors for propulsion, than only those that operate most of the time at constant load, as is the case of reactors for power supply. It is known that, the first time the reactor is operated, the fuel pellets rupture with cracks in the three main directions (radial, axial, circumferential), due to the thermal gradient generated by the drive power ramp. The occurrence of power cycling causes mechanical fatigue and the pellet ruptures at points other than those already ruptured.

In the case of a power increase, the thermal expansion of the pellet results in an increase in pellet diameter accompanied by pellet crack opening. Moreover, at high power, gaseous fission products are created and stored in the fuel, causing an additional pellet diameter increase. If the gap is already closed, this causes enhanced stresses in the cladding that might lead to cladding failure. [2][3][4][5]

Thus, the existence of contact points by pellet chips or pellet relocation is a fact, in this type of the PWR reactors application. This way, it becomes necessary for the structural mechanical fuel element designer to analyze how the stresses in the cladding behave due to the imposition of deformation by the pellet and its chips [2]. This is also the hypothesis adopted by Mukai [3] in his publication for analysis of a Japanese propulsion reactor.

Therefore, in this work, the evaluation of the effect of pellet cladding mechanical interaction PCMI at VC with stainless steel cladding cladding will be conducted with the hypothesis of pellet relocation and/or pellet chip, which are facts that actually occur in reactors used for propulsion. Pellet relocation will cause contact with cladding, that also occor by pellet chip into the pellet/ cladding gap.

2. PCMI ANALYSIS

In order to carry out PCMI analysis, first, fuel behavior analysis, using a fuel behavior code, is performed to determine the temperature distribution in the pellet and the cladding, and their size variations. These nodal temperatures are imported into the structural analysis to calculate thermal stress. In this way, the thermal effect is considered in association with pressure loadings. Figure 1 outlines the flow diagram of fuel behavior and structural analysis.
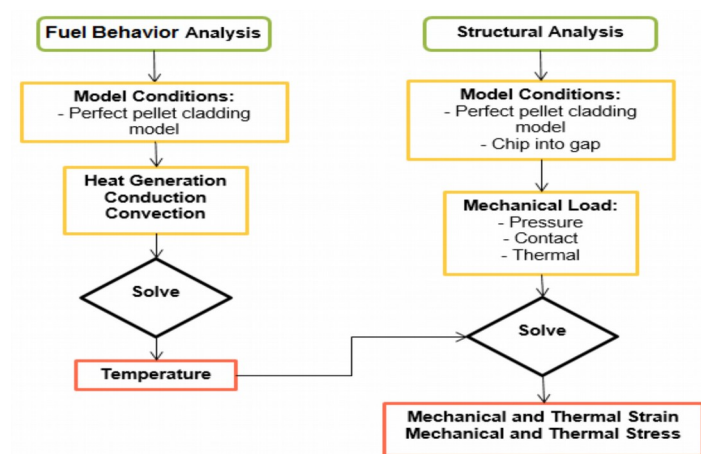

Figure 1: Flow chart of fuel behavior and structural analysis.

2.1. Finite Element Models

The FEM used a model that was developed for this study, the fuel model with relocated pellet, cladding and a chip into the gap, as seen in Figure 2. Also, the mesh refinement used to ensure the results accuracy can be observed in the figure.
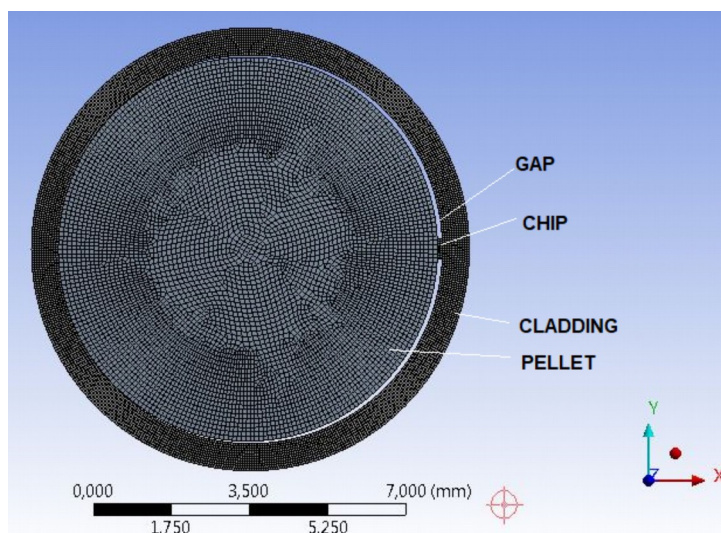
Figure 2: The fuel model for FEA analysis.

2.2. Material Properties

The material properties of UO_2 pellet and stainless steel cladding used in this analysis were taken from established properties for these materials [6]. Material properties such as elastic modulus, thermal expansion, and thermal conductivity as function of temperature were implemented in the FEA model. The cladding material is an austenitic stainless steel with stress yield (Sy) of 245 MPa at 275 ºC and 235 MPa at 330 ºC.

The gap of pellet and cladding was filled with helium gas with pressure of the 5,4 MPa. In the structural analysis, only the pressure was considered, the helium gas thermal propriety effect was neglected in the analysis.

2.3. Loading Conditions

The simulation of fuel behavior was carried out considering the fuel model with perfect pellet. This fuel model was submitted to a thermal stress transient by means of a power cycling as illustrated in Figure 3. A sequence of 5 power cycles applied at beginning of the fuel rod life was considered. Each cycle is composed of two power levels (30% and 100% of the nominal power) and the transition between them. The duration of the low power is 20 days and high power is 10 days were considered and the transition between them has seconds of duration, 60 seconds for increase and 30 seconds for power reduction. The fuel performance code results were evaluated to define the region of the rod that presented the greatest radial deformation tending to decrease or close the gap of pellet and cladding. The data from this region were used as input to structural mechanical analysis software. The cladding is also subjected to an external pressure of 13.78 MPa.
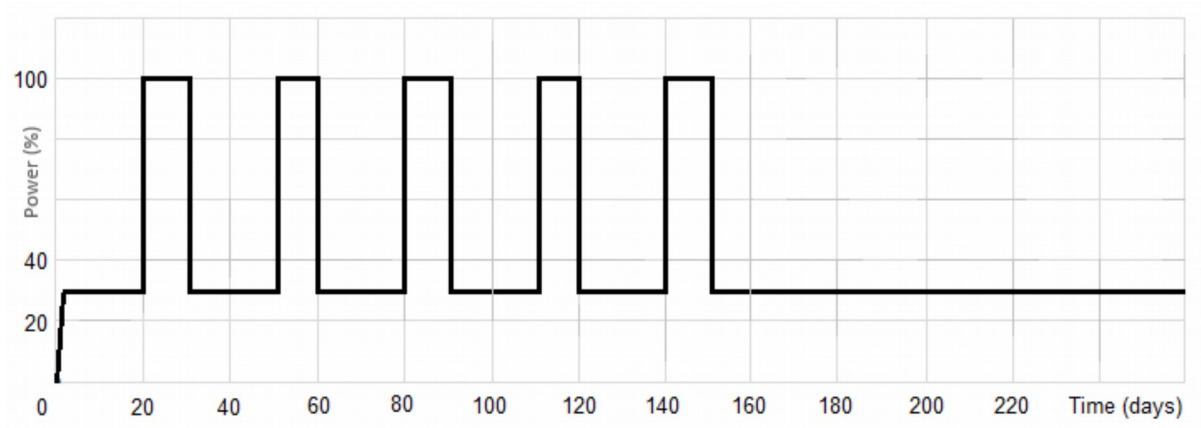
Figure 3: The power cycle for FEA analysis.

3. RESULTS AND DISCUSSION

In the fuel behavior analysis, using a fuel behavior code, it was carried out to determine the temperature distribution in the pellet and cladding and their size variations at the various stages of the 5-cycle sequence of applied power at the beginning of the useful life of the fuel rod, the results are shown in table 1.

Table 1: Fuel behavior by a fuel behavior code

Stage	Pellet T[°C]	Cladding T_{in}[°C]	Cladding T_{out}[°C]	Gap [mm]	Δ Gap [mm]
First	22	22	22	0,110	
Start 0% to 30%	351	284	274	0,090	0,020
(1) Ramp 30% to 100%	538	333	300	0,092	0,018
(1) Ramp 100% to 30%	274	271	271	0,098	0,012
(2) Ramp 30% to 100%	546	333	300	0,098	0,012
(2) Ramp 100% to 30%	274	271	271	0,102	0,008
(3) Ramp 30% to 100%	541	332	299	0,096	0,014
(3) Ramp 100% to 30%	274	271	271	0,104	0,006
(4) Ramp 30% to 100%	536	332	299	0,094	0,016
(4) Ramp 100% to 30%	274	271	271	0,106	0,004
(5) Ramp 30% to 100%	530	331	299	0,092	0,018
(5) Ramp 100% to 30%	274	271	271	0,108	0,002
End 30%	331	278	271	0,100	0,010

It's observed that stages that impose the greatest demands on the fuel rod are the initial stages ie, started 0% to 30% and (1) ramp 30% to 100%. The data of these stages were used as input data of structural mechanics analysis software.

In the mechanical structural analysis, using a FEM soflware, it was carried out to determine the stress distribution in the cladding and it strain at criticals stages of the cycle sequence. The figure 4 showed the stress intensity (SI) at stage started 0% to 30% in which the maximum SI of 117,97 MPa and figure 5 the (1) ramp 30% to 100% of applied power in which the maximum SI of 153,80 MPa.
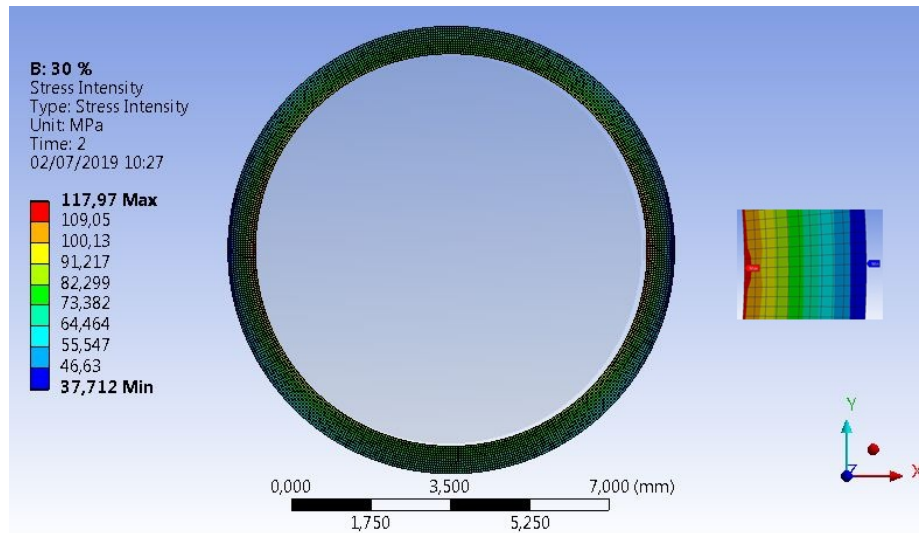

Figure 4: Stress intensity (SI) at stage started 0% to 30% of applied power.
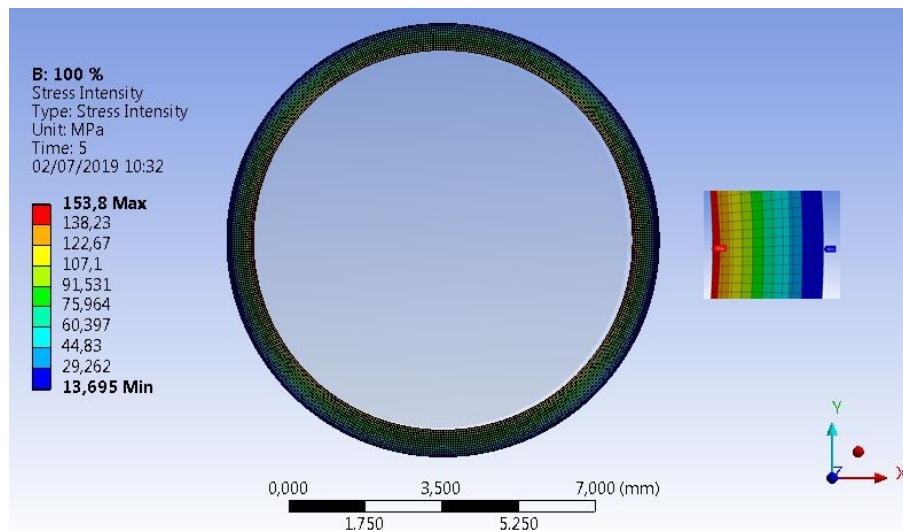

Figure 5: Stress intensity (SI) at stage (1) ramp 30% to 100% of applied power.

According to ASME III, division 1, subsection NB [7], the threshold stresses for materials are compared with the maximum SI values resulting from the analyzes performed. In this way, the threshold stresses (Sm) was considered as 2/3 Sy of the material, meeting this limit ensures that the component will not undergo plastic collapse. Therefore, the threshold stresses of Sm = 163.33 MPa are 275 ºC and Sm = 156.66 MPa at 330 ºC, were adopted.

4. CONCLUSIONS

The hypothesis of the pellet-cladding interaction in the fuel rod, generated by the pellet fragmentation and relocation, and submitted to the 5-cycle sequence of the power ramp applied at the beginning of the useful life of the fuel was investigated by simulation and the results show that the fuel rod maintains its integrity under the conditions of the hypothesis adopted.

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