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Validation of Clad Collapse Analysis Code - CFLAT

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1. Introduction

Clad flattening is one of the fuel rod failure criteria specified in US NRC SRP 4.2 [1]. Clad flattening occur when the clad is collapsed into unsupported length of fuel rod like axial gap between pellets or plenum region due to inward creep deformation of clad caused by the differential pressure between reactor coolant system pressure and fuel rod internal pressure. As the clad may undergo excessive deformation due to inward creep, fuel failure may take place resulting in release of radioactive nuclides within the fuel rod to the coolant. So it is very important for fuel rod design to predict whether the clad flattening failure will occur or not during operation time from exact calculation of clad collapse time. To this end, KNF has developed an analysis code to evaluate clad collapse of fuel rod, XGCOL [2], and changed its name to CFLAT (Clad Flattening Analysis Code). Governing equations of CFLAT which were derived considering (1) thin wall tube approximation, (2) generalized plane strain condition, (3) Hook’s law in stress/strain, (4) elastic and creep strain, and (5) ovality, are given in reference document.

2. Validation of Code Calculations

2.1 Validation Method

Validation of design code means checking that a code meets specifications and fulfils its intended purpose. The most important requirement is exact modeling of real phenomenon. There are several validation methods like comparison of the code calculation results with experimental data, comparison with hand calculation or comparison with another code results.

Fuel rod failure due to clad flattening had occurred in some reactors because pellets were easily densified and shrank by neutron exposure, and fuel rods were not internally pressurized in advance, until 1970s. But most reactors changed the fuel design, such as ‘non-densifying’ pellets to prevent axial gap formation and ‘pre-pressurized’ fuel rods to decrease cladding creep rate. So fuel rod flattening failures have not occurred since the early 1970s [3]. Thus it is hardly possible to get real clad collapse data of modern fuel rods for evaluating clad collapse. Therefore, this paper is prepared based on the comparison between the CFLAT calculation results and reference code results instead of real clad flattening data. CEPANFL code is used as reference code [4].

2.2 Test Cases for Comparison of Calculations

Fuel rod related parameters that influence clad flattening behavior are pellet specification, pellet fabrication method, clad specification, clad mechanical properties, and fuel rod design parameters such as clad outer diameter and thickness. Among them, some important parameters are selected as code input parameters. Base case has been set for the reference case and later one of input parameters is changed from the base case to compare the tendency of calculation result by variation of the selected parameter within their possible ranges for the fabrication and the rod conditions under operation in PWR. Differential pressure between fuel rod internal pressure and reactor coolant system pressure, clad temperature, clad outer radius, clad thickness, fast neutron (E>1MeV) flux, clad initial ovality, and axial gap length within fuel stack region are selected as input parameters and the base case is shown in Table I. The range of the selected input parameters is established based on the typical PWR fuel design and operating conditions.

Table I: Code Input Parameters for Base Case

Input Parameters	Value
Clad Thickness	0.0245 inch (0.6223 mm)
Clad Outer Radius	0.21225 inch (5.39mm)
Initial Ovality	1.1 mils (27.94 ㎛)
Clad Temperature	590 ℉ (310 ℃)
Differential Pressure	1450 psi (100 bar)
Fast Neutron Flux (E > 1MeV)	0.7×10^{14} n/cm^2·sec
Axial Gap Length	5 inch (127 mm)

3. Validation Results

Expected clad flattening time for the base case is calculated using both CFLAT and reference code. From the input data of the base case, the expected clad flattening times are calculated by CFLAT and reference code for various clad thickness, and shown in Figure 1. Clad flattening time of each case are shown as relative time scale, compared with reference code calculation for base case which was set to 1. The comparison shows that the thicker the cladding, the longer the flattening time. And this result shows the same trend of CFLAT as that of the reference code.

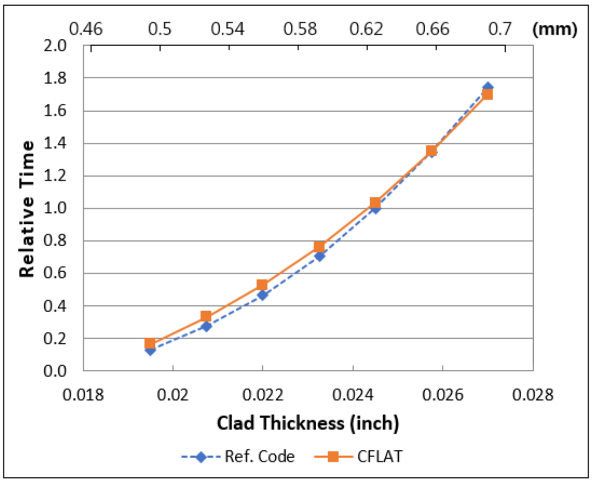

Fig. 1. Clad flattening time calculated by CFLAT and reference code for various clad thickness

Figure 2 shows the expected clad flattening time calculated by CFLAT and reference code for various cladding outer radius. The comparison shows that the bigger the clad outer radius, the shorter the flattening time. If the clad outer radius becomes larger and the clad thickness remains intact, clad outer diameter to clad thickness ratio (OD/t) becomes larger. This ratio also becomes larger when the clad thickness becomes smaller while keeping the clad outer diameter fixed, indicating that clad flattening time is more related with this ratio rather than clad outer radius or clad thickness separately. CFLAT results show this tendency very well, and comparable to reference code.

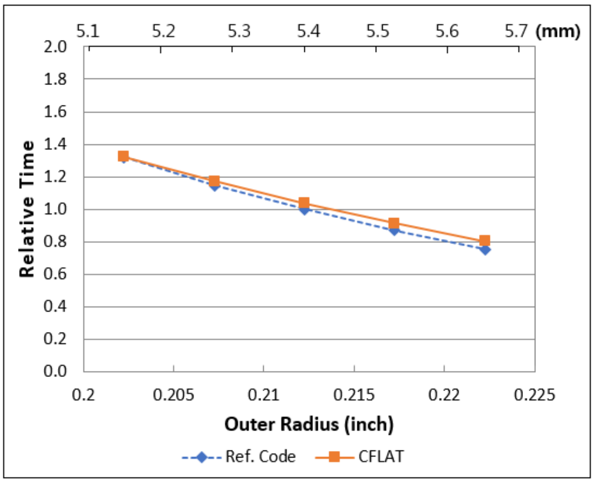

Fig. 2. Clad flattening time calculated by CFLAT and reference code for various clad outer radius

Figure 3 shows the expected clad flattening time calculated by CFLAT and reference code for various cladding initial ovality. All cladding has some initial ovality and this will continually increase during operation. When the ovality becomes larger and exceeds critical value, clad collapse may occur. So Figure 3 shows the larger the initial ovality, the shorter the clad flattening time. This tendency is revealed very well in both codes.

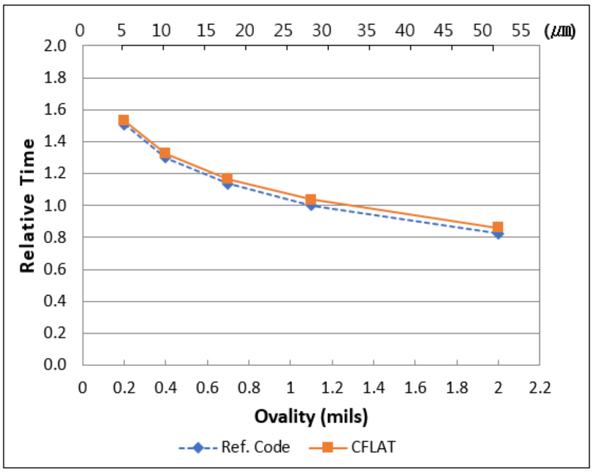

Fig. 3. Clad flattening time calculated by CFLAT and reference code for various initial ovality

Figure 4 shows the expected clad flattening time calculated by CFLAT and reference code for various cladding surface temperature. Higher clad surface temperature is related with lower clad yield strength and higher creep rate. So the clad flattening time becomes shorter. CFLAT shows similar trend with reference code.

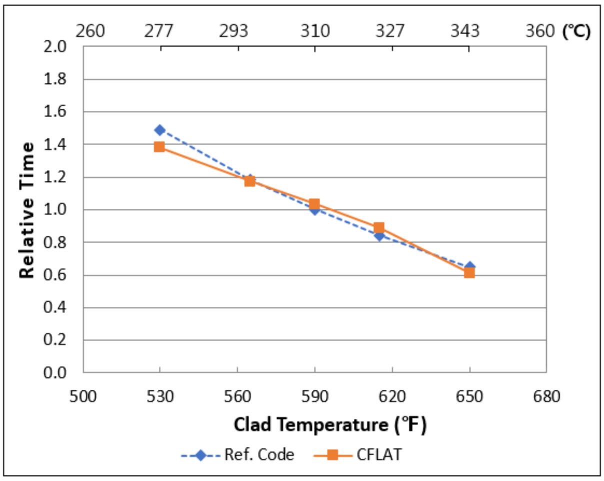

Fig. 4. Clad flattening time calculated by CFLAT and reference code for various clad surface temperature

Figure 5 shows the expected clad flattening time calculated by CFLAT and reference code for various differential pressures between the reactor coolant system pressure and the fuel rod internal pressure. As differential pressure becomes larger, clad hoop stress is larger resulting in shorter flattening time. In Figure 5, in the region of pressure difference less than 1,100 psi, CFLAT shows more conservative collapse time result than reference code. Different correction factors adjusting finite gap length used in two codes affect the different creep calculations in that region. And both codes show similar results when the pressure difference is greater than 1,100 psi.

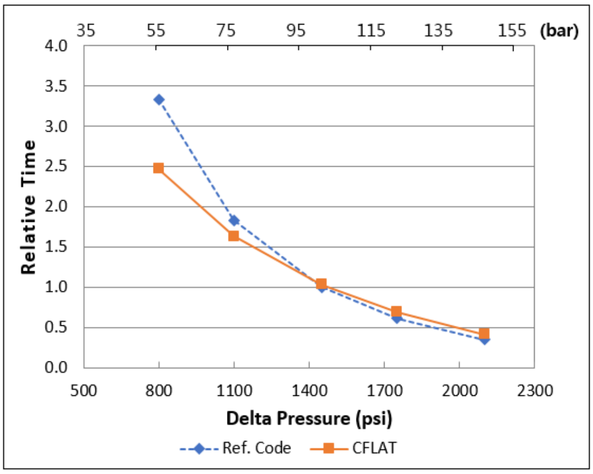

Fig. 5. Clad flattening time calculated by CFLAT and reference code for various differential pressure

Figure 6 shows the expected clad flattening time calculated by CFLAT and reference code for various fast neutron flux (E>1MeV). At in-flux region, neutron irradiation may accelerate clad creep deformation. In Figure 6, in the region of fast flux less than 0.7×10^{14} n/cm^2-sec, CFLAT shows shorter flattening time than reference code, but in other region, both codes show similar results. And both codes predict shorter flattening times as the fast flux becomes bigger.

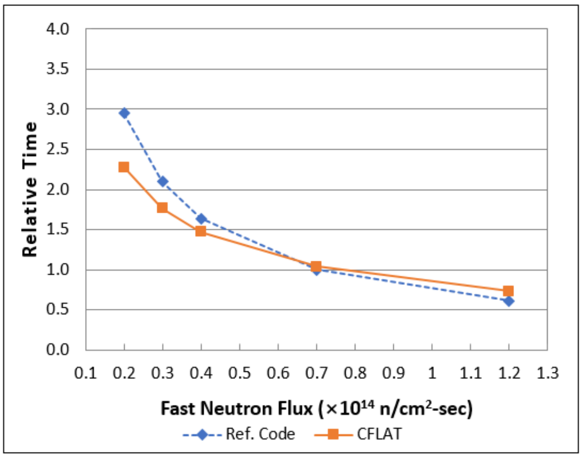

Fig. 6. Clad flattening time calculated by CFLAT and reference code for various fast neutron flux

Figure 7 shows the expected clad flattening time calculated by CFLAT and reference code for various axial gap length within fuel stack region. If there is no axial gap between fuel pellets, clad creep deformation would stop because the clad contacts with pellet, and collapse couldn't occur regardless of other parameters. So the axial gap length is the most important parameters. For 0.25 and 0.5 inch axial gap length, clad collapse doesn't occur within 100,000 hours by both codes. For 1.0 and 2.0 inch axial gap length, CFLAT shows more conservative result than reference code. And for more than 5.0 inch, both codes show the same flattening time with infinite axial gap condition.

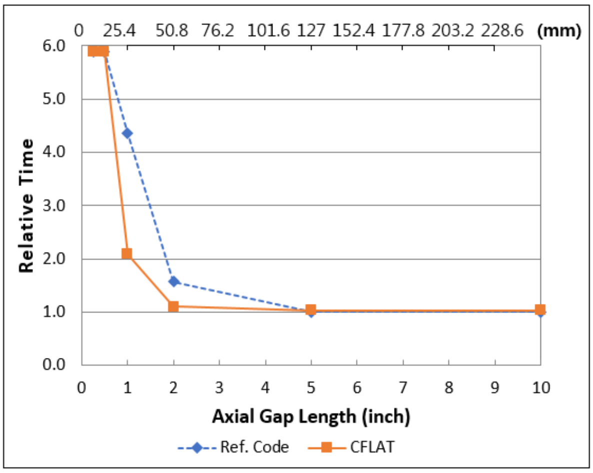

Fig. 7. Clad flattening time calculated by CFLAT and reference code for various axial gap length

In conclusion, CFLAT shows similar result with reference code for the base case. And clad flattening time is influenced by the change of base case and shows the similar behaviors with the reference code.

4. Conclusions

Validation of CFLAT is performed through the comparison of clad flattening time calculation results with reference code. Clad flattening time calculated by CFLAT and reference code become shorter as clad thickness becomes thinner, clad outer radius larger, initial ovality greater, clad surface temperature higher, differential pressure larger, fast neutron flux bigger, and axial gap length longer. Also, for the possible range of the selected input parameters studied the clad flattening time calculated by CFLAT shows very similar results by reference code and the tendency of clad flattening time with variation of input parameters is the same for both codes. Therefore, it can be concluded that the CFLAT is validated for clad flattening evaluation of the fuel rod in PWR.

REFERENCES

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