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Revisit to the Methodologies of the Thickness Determination of PWR Fuel Cladding Tubes

Hyung-Kyu Kim, Kyung-Ho Yoon, Young-Ho Lee, Jae-Yong Kim, Kang-Hee Lee, Kun-Woo Song
Korea Atomic Energy Research Institute, 1045 Daedeokdaero Yuseong Daejeon 305-353 Korea
hkkim1@kaeri.re.kr

1. Introduction

A PWR fuel rod is a mechanical structure composed of a thin tube and welded end plugs. A plenum coil spring and stacked UO_2 pellets are inside it. It suffers from a high inside temperature caused by the heat of the pellets and an external high pressure of the reactor system. The important functions of a fuel cladding tube are to maintain mechanical strength and to provide a primary barrier of the radioactive materials through their lives in a reactor. It should also satisfy the neutron economy so that a material is confined to be zirconium based alloys nowadays. The thickness reduction due to fretting wear is considerably concerned recently to achieve a failure-free fuel.

These requirements affect the determination of a cladding tube thickness. Nevertheless, it is thought that studies on a cladding thickness have rarely been done. It may be attributed to the fact that the dimensions of a fuel rod are conventionally predetermined in general from the previous experiences in the nuclear industry. The fuel designers have usually focused on the enhancement of fuel performance and duty with maintaining the dimensions. In short, it may be unnecessary to deeply consider the dimension change of a fuel cladding.

However, the necessity should arise if a completely new concept fuel rod is attempted. A recently studied dual-cooled fuel could be a good example. A bigger diameter should be used in that fuel since it should provide an internal flow passage in addition to a conventional outer passage. If the diameter increases, the thickness may well increase correspondingly from a simple mechanical viewpoint.

This paper deals with the reasoning of the tube thickness presently used for the PWR fuel claddings. Firstly, the data of commercially used PWR fuel claddings are investigated especially for the thickness to diameter ratio. Then some formulae and methodologies for the thickness determination of the internally and externally pressurized tubes or pipes are reviewed. Challenging tasks for a thickness change are discussed.

2. What about the Thickness of Commercial Tubes?

Table 1 gives the cladding tube thickness data of some commercial PWR fuels [1]. It is apparently seen that the thickness increases as the cladding outer diameter increases. The range of the thickness is 0.57-0.725 mm for the outer diameter range of 9.14-11.18 mm. It is interesting to see that the thickness to outer diameter (t/D_o) ratio is in the range of 0.058-0.067. If we exclude the fuels of AREVA NP (especially, the HTP fuels), the range of t/D_o is narrowed down even further (mostly, 0.058-0.062). When all the data in ref. [1] are investigated, t/D_o is in the range of 0.058-0.067 for PWR fuels and 0.060-0.065 for BWR fuels.

This result drives us to ask a question, “why does the t/D_o ratio have such a range regardless of the fuel vendors and fuel types?” It must be a big challenge if a considerably different diameter is required for a new fuel design.

Table 1. Thicknesses (t, mm) and outer diameters (D_o, mm) of some commercial PWR fuels

Vendor	Fuel	Array	t	D_o	t/D_o
KNF	KSFA	16	0.63	9.7	0.065
	PLUS7	16	0.57	9.5	0.060
	ACE7	16	0.57	9.14	0.062
		17	0.57	9.5	0.060
Mitsubishi		14	0.62	10.72	0.058
		15	0.62	10.72	0.058
		17	0.57	9.5	0.060
AREVA NP	AFA 3G	15	0.62	10.72	0.058
		16	0.725	10.75	0.067
		17	0.57	9.5	0.060
	HTP	15	0.725	10.75	0.067
		16	0.725	10.75	0.067
		17	0.61	9.55	0.064
Westinghouse	ROBUST	17	0.57	9.5	0.060
Westinghouse CE		14	0.66	11.18	0.059
	System 80	16	0.635	9.7	0.065
NFI		14	0.66	10.72	0.062
		15	0.66	10.72	0.062
		17	0.57/ 0.64	9.5/ 9.5	0.060/ 0.067

3. Reviews of the Formulae for the Tube Thickness and Discussions

2.1 KEPIC Methodology (equivalent to the ASME Code Section III)

The KEPIC MNB provides a method for a thickness determination for each externally and internally pressurized tube [2]. However, this method should use an allowable stress for specific materials used in the nuclear industry, and the table of the allowable stresses for each material are provided independently in the KEPIC MDP [3]. The problem in using the KEPIC method is that the fuel cladding materials such as Zircaloy-4 are not included. It also implies that the fuel cladding tube is not regarded as a structural component.

In conclusion, it is impossible to use the KEPIC method to determine the thickness of a fuel cladding tube.

2.2 Westinghouse and ABB-CE's Methodology

These fuel vendors do not provide deterministic formulae for the thickness. Rather than that, they evaluate a time to collapse by using in-house computer codes with a predetermined fuel rod dimension. The predetermination is based on the criteria that a volume averaged effective stress should be less than the yield strength after an irradiation (Westinghouse) [4] or the guidelines of the primary membrane and bending stresses specified depending on the operating condition in the ASME codes (ABB-CE) [5]. In short, these methods cannot be used directly for cladding tubes of considerably different diameters.

2.3 Siemens/KWU Methodology

This method is based on the elastic buckling and plastic deformation. They provide design formulae for each case as follows [6].

- Formula of elastic buckling

$$p_{cr,el} = \frac{E}{4(1-\nu^2)} \cdot \left(\frac{t_{\min}}{r_{m,\max}} \right) \tag{1}$$

where, $p_{cr,el}$ is the maximum external pressure of no elastic buckling, E and ν are the elastic modulus and the Poisson ratio, respectively. t_{min} and $r_{m,max}$ are the minimum required tube thickness and the maximum radius of the neutral surface of the tube.

- Formula of plastic deformation

$$p_{cr,pl} = \frac{2t_{\min} R_{p0.2}}{D_o - t_{\min}} \tag{2}$$

where, $p_{cr,pl}$ is the maximum external pressure of no plastic deformation and $R_{p0.2}$ is the yield strength. D_o is the tube outer diameter.

The minimum tube thickness is obtained from the following conditions.

$$S_{el} = \frac{p_{cr,el}}{p_D} > 1, \quad S_{pl} = \frac{p_{cr,pl}}{p_D} > 1 \tag{3}$$

where, S_{el} and S_{pl} are the safety margins corresponding to the elastic buckling and plastic deformation, respectively. p_D is the design pressure, i.e. the difference between the external and internal pressure of the fuel cladding tubes.

Fig. 1 shows the S_{el} and S_{pl} in terms of the minimum required thickness of the cladding in the case of the design pressure (p_D) of 10.5 MPa with an assumption of 15.5 and 5.0 MPa for the reactor system (i.e., fuel rod external) pressure and fuel rod internal one, respectively.

This method is based on an elastic buckling and plastic deformation.

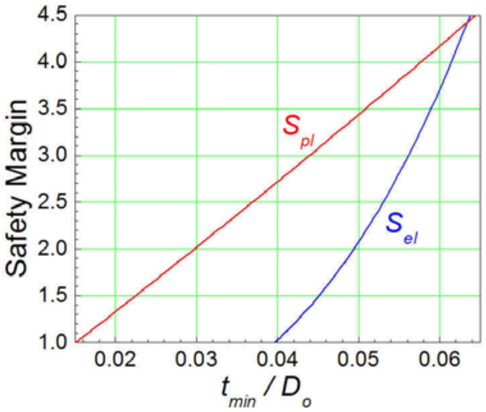

Fig. 1. Safety margins of the elastic buckling (S_{el}) and plastic deformation (S_{pl}) with respect to the minimum thickness to outer diameter ratio of a fuel rod cladding by using the KWU methodology.

It is shown that the tube thickness can be more conservatively obtained when the formula of the elastic buckling is used. According to Fig. 1, the safety margin is sufficiently larger than 3.0 if $t/D_o \geq 0.058$, which was found for the commercial cladding tubes (Table 1).

4. Concluding Remarks

It is found that the commercial cladding tubes of PWR fuels have a thickness to outer diameter ratio of 0.058-0.067. By using the presently available methods of the thickness determination for a fuel cladding tube (KWU method), a safety margin of the commercial tubes is more than 3.0. Present study can be used for a new fuel design that requires a considerable diameter change of the fuel rod.

ACKNOWLEDGEMENT

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