Proceedings of the Korean Nuclear Society Spring Meeting
Cheju, Korea, May 1996

Fretting Wear of Fuel Rods due to Flow-Induced Vibration

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Abstract

Recently several PWR Nuclear Plant experienced fuel rod fretting wear failures due to Flow Induced Vibration. When such multi-span supported fuel assembly has vibration excitation, it is important to know how fretting wears are progress and when the fuel rods are start to failure. In this study, we estimate the amount of wear depth using Archard theory when the fuel rod starts to relative motion against spacer grid dimples.

1. Introduction

Fuel rod fretting wear failure due to Flow Induced Vibration is a concern in the design of Light Water Cooled Reactors. Fretting damage of fuel rods may cause severe problem in the Nuclear Power Plant Operation and very high cost to repair of it. As utility and fuel vendor adopt higher utilization of uranium and improve thermal margin, fuels are needed flow mixing mechanism (mixing vane and mixing nozzle) and once or twice burned fuels are loaded at core pheripery. So recently several PWR Nuclear Power Plant experienced fuel rod fretting wear failures due to Flow Induced Vibration [1,2].

Similar multi-span supported fretting wear mechanism are studied in the heat exchanger tubes[3] and CANDU pressurization tubes but these studies are difficult to directly apply to this PWR fuel failure phenomena. It is very important to understand the fuel rod fretting mechanism and predict the amount of wear depth as a function of time. In this study, we estimate wear depth and failure time using Archard Theory[4].

2. Archard Theory of Adhesive Wear

The Archard wear equation[4] is based on the following assumptions;

- The wear volume V produced in sliding a distance L is proportional to the true area of contact.
- The true area of contact is formed by local plastic deformation.
- Particles removed by the sliding motion are hemispherical and all have the same diameter.

This Archard wear equations derived for unlubricated sliding surfaces due to fretting relates the worn volume to the normal force and the sliding distance as follows.

$$V = \frac{SF_s L}{4260H} \tag{1}$$

where,

V = wear volume (in^3)
S = wear coefficient
F_S = normal force on the contacting surfaces ($lb.$)
H = hardness (kg/mm^2)
L = total sliding distance (in)

The constant 4260 contains the shape factor and conversion constants.

If there exist sliding or relative motion of fuel rod against grid spring and dimples, we can calculate wear volume using equation *(1)*. To calculate wear volume, we need normal force F which is residual grid spring force at each different elevation.

3. Grid Spring force and Relaxation

Normal force on the contacting surfaces is equal to residual grid spring force during operation. But this spring force will be changed from initial spring force as a function of operating burn-up (fluence). The residual grid spring force depends on various parameters, initial spring force (initial elastic deflection, initial spring constant), irradiation-induced spring force relaxation, grid elevation, cladding creep down and thermal expansion difference between spacer grid and fuel rod, etc. [5].

In this study, for simplification residual grid spring force is simulated as follows ;

$$F_s = (BOL_F - K \cdot C) \times (1 - R) \tag{2}$$

where,

F_S : Residual spring force
BOL_F : Initial spring force
K : Initial spring stiffness
C : Cladding creep rate
R : Spring relaxation data

This equation is benchmarked from residual grid spring forces measurement of irradiated fuel.

4. Sliding Distance *L* at Grid Dimples, Slippage and Lift-off Threshold Amplitude

Relative motion between the fuel rod and side dimples initiates when the tangential force at a side dimple exceeds the friction force. The maximum single-peak vibration amplitude at which slippage starts, the slippage threshold amplitude[6], is given by (Fig. 2),

$$y_{sn}\phi_{dn}k_{dt} = \frac{F_s}{2} \cdot \mu$$

or

$$y_{sn} = \frac{F_s \cdot \mu}{2\phi_{dn} k_{dt}} \quad \text{for any mode } n \tag{3}$$

where y_{sn} is slippage threshold amplitude of the n^{th} mode, ϕ_{dn} is the maximum modal displacement of the rod at any dimple location, k_{dt} is the tangential stiffness of the side dimples, μ is the friction coefficient, and the F_s is the spring preload force.

As the vibration amplitude increase further, lift-off occurs and severe damage may result. When the alternating radial reaction force acting at the dimples is greater than one-half of the spring preload force, lift-off occur. The vibration amplitude at which lift-off initiates, the lift-off threshold amplitude[6] is given by

$$y_{ln}\phi_{dn}k_{dr} = \frac{F_s}{2}$$

$$\text{or} \quad y_{ln} = \frac{F_s}{2\phi_{dn}k_{dr}} \quad \text{for any mode } n \tag{4}$$

where y_{ln} is the lift-off threshold amplitude of the n^{th} mode and k_{dr} is the radial stiffness of the dimple.

The ratio between the lift-off and slippage threshold amplitude is $\frac{y_{ln}}{y_{sn}} = \left(\frac{k_{dt}}{k_{dr}}\right) \cdot \frac{1}{\mu} \cong 6$ for any mode n where $\mu=0.3$.

It would be noted that lift-off occurs when a vibration amplitude is 6 times greater than the slippage threshold amplitude for the friction coefficient $\mu=0.3$.

In the following fuel rod analysis, we will assume that the dynamic characteristics of the system do not change due to slippage, and that the vibration amplitudes are such that no impacting occurs at the grid support. Then the total wear producing motion L.

Producing motion L at a side dimple during operating time t is

$$L = 4f_n t\left(\phi_{dn}y_n - \frac{F_s \cdot \mu}{2k_{dt}}\right) \tag{5}$$

where the subscription n denotes the mode number, f_n is the rod vibration frequency, ϕ_{dn} is the maximum normalized modal displacement of the rod at the dimple location, y_n is the maximum modal vibration amplitude of the rod, $F_s \cdot \mu / 2$ is the friction force acting on the dimple, and k_{dt} is the tangential stiffness of the dimple.

5. Wear Depth Calculation

Using above theory and equation *(1), (2), (3), (4), (5),* we calculated fuel rod slippage start and fretting wear depth, fretting wear failure time. Table 1 shows the flow diagram of the fuel rod wear depth calculation. The slippage and lift-off threshold forces are calculated for the frequency and amplitude of each mode. The effective sliding distance(L) will be calculated, as the relative motion between fuel rod and dimples starts, and then the fuel rod wear volume is calculated using Archard equation. Finally, the fuel rod wear depth will be calculated by using the wear volume calculation result and wear geometry.

6. Conclusion

To evaluate the sensitivity to fuel rod wear, the parametric studies for each important parameters, for example, frequency (each mode), amplitude, creep rate, initial spring force (spring deflection and stiffness), etc. was conducted(Fig. 3). The evaluation results are as follows ;

- Vibration amplitude (y_n) and frequency (f_n) is most influence to fretting wear. [Predominant at high mode. ex] 6th mode]
- High vibration mode (ex. 6th mode) and high amplitude [more than 3 mils] cannot avoidable fuel rod fretting wear failure during life time.
- Residual spring force (initial spring force and spring force relaxation) is important, it is recommended enough higher residual spring force must be maintained to provide no relative motion until EOL, if it is meet fuel rod bowing requirement.
- Cladding creep rate has minor influence within predicted creep range.
- The calculation results and FACTS loop test result are very consistency with plant operation experience of KORI #2 & Angra #1(Fig. 4,5,6).

[REFERENCES]

1. Y. H. Kim, S. Y. Jeon, "FACTS Loop Vibration Test for PWR Fuel Assembly", proceedings of Korean Nuclear Society Spring Meeting, 1995.
2. J. P. Kim, "Results and Evaluation of Poolside Examination of KORI #2 Failed Fuels", KNFC TR-026, 1994.
3. P. L. Ko, R. J. Rogers, "Analytical and Experimental Studies of Tube/Support Interaction in Multi-Span Heat Exchanger Tubes", Nuclear Engineering and Design, P399-409, 1981.
4. J. F. Archard, "Contact and Rubbing of Flat Surfaces", Journal of Applied Physics, Volume 24, 1953.
5. K. T. Kim, H. K. Kim and K. H. Yoon, "Development of a Methodology for In-Reactor Fuel Rod Supporting Condition Prediction", Journal of Korean Nuclear Society Volume 29, 1996.
6. Hae Lee, "Fretting Wear of Fuel Rods", Korean Society of Mechanical Engineering, Vol. 5, 1981.
7. P. L. Ko, "Wear of Zirconium Alloys Due to Fretting and Periodic Impacting", The International Conference on Wear of Materials, 1979.

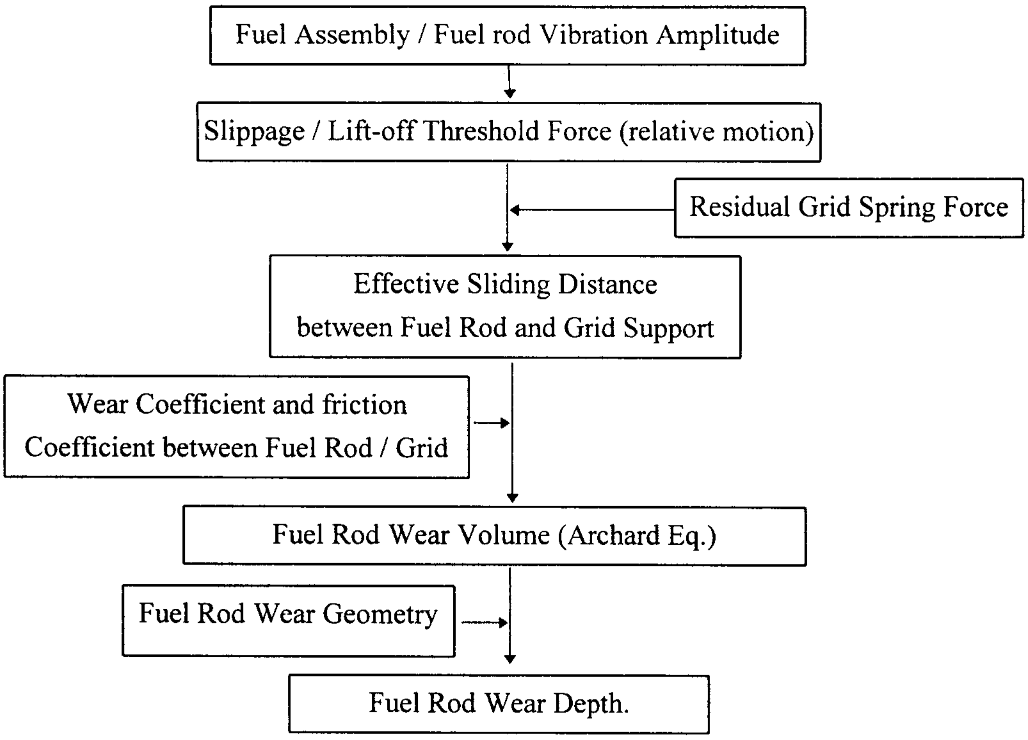


Table 1. Fretting Wear Calculation Flow Chart.

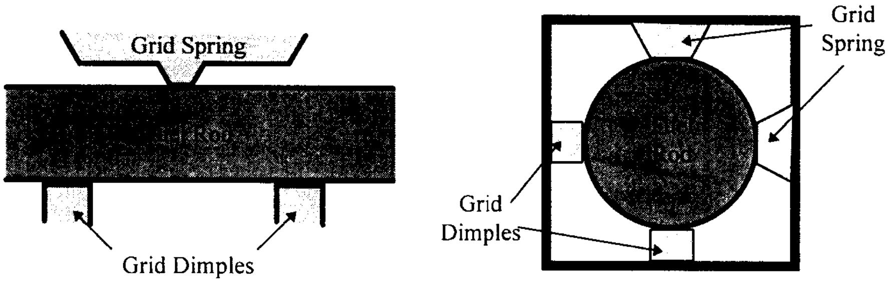
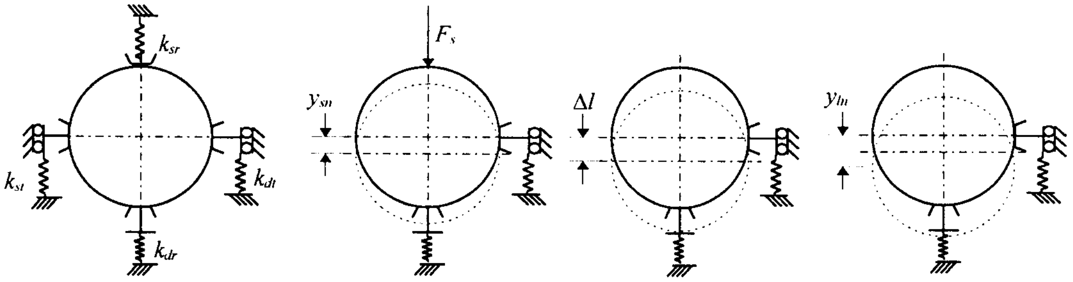


Fig. 1. Fuel Rod Contact Geometry



$y_{sn} = F_s\mu/(2\phi_{dn}k_{dt})$
Friction Force = $F_s\mu/2$

$$\Delta l = \phi_{dn}y_n - \frac{F_s\mu}{2k_{dt}}$$

$$y_{\mathrm{ln}} = F_s / (2\phi_{dn}K_{dr})$$

Fig. 2. Schematics of Grid Cell Dynamics

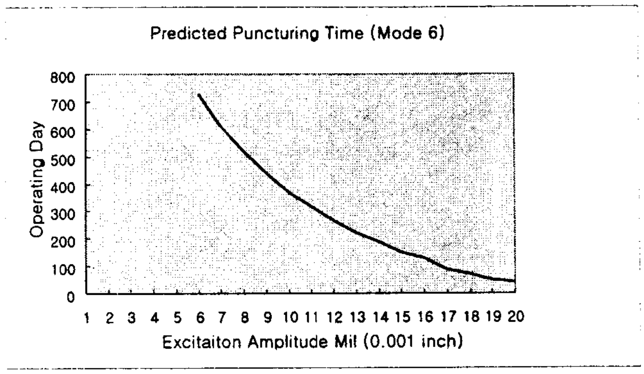


Fig. 3. Predicted Puncturing Time

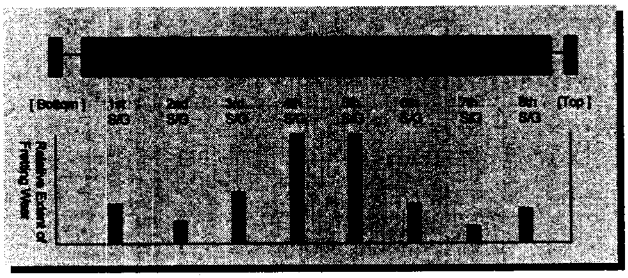


Fig. 4. Relative Fretting Wear Volume

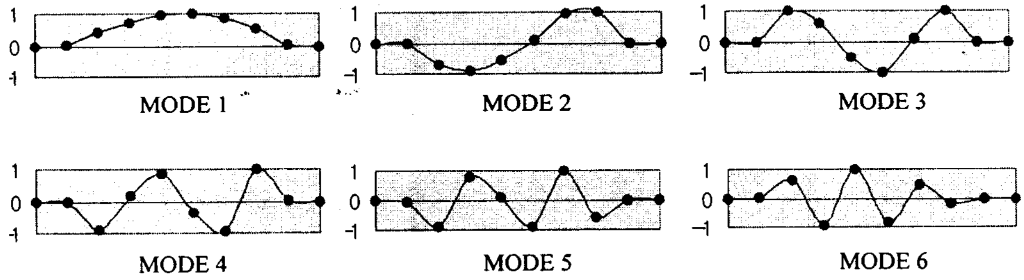


Fig. 5. Vibration Mode & Amplitude.

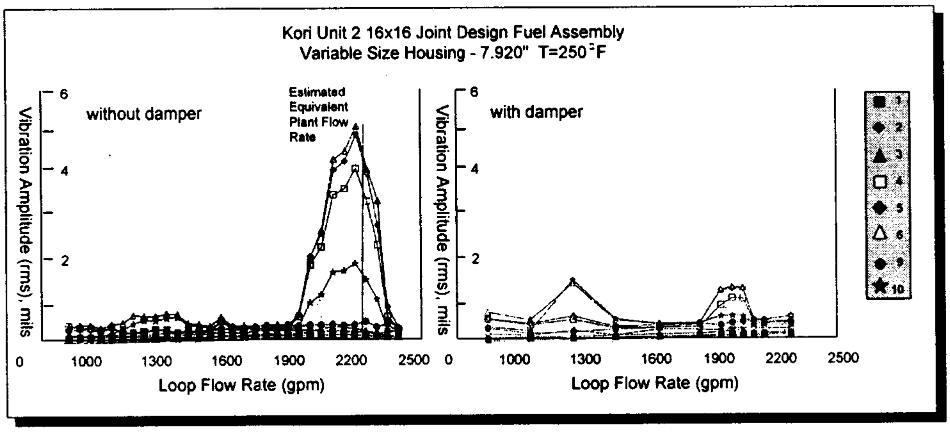


Fig. 6. Variable Pitch FACTS Loop Test Result.