A Methodology for Determining Grid-to-Rod Fretting Wear of CNPP Fuel Rods

Muhammad Rafique[1], Shakir Hussain[2], Anwar Ahmad[3], Muhammad Omair Khan[4] and Syed Waseem Akhtar[5]

Abstract

The grid-to-rod fretting wear methodology is developed based on Archard wear equation to calculate the cladding wear depth of CNPP fuel rod during its residence time within the reactor core. This methodology is coupled with FRV, FRPV, FRCB and ANSYS computer codes to determine the input parameters such as residual spacer grid spring force, effective sliding distance, cladding creep down, RMS displacement at dimple location, and initial hold-down force of the spacer grid spring etc. of wear equation. After determining all these parameters, the wear depth of CNPP fuel rod due to FIV (considering the effects of thermal expansion, cladding creep and irradiation induced spring relaxation) is calculated to be about 9.5 µm which is less than the design criterion (i.e., 10 % of the Zircaloy-4 cladding tube wall thickness, 70 µm at the end of life). In case of CNPP, for an initial spring force of 14.5 N the slippage of fuel rod occurs when the spacer grid spring relaxation caused by irradiation reaches to 76%.Based on these results, it is expected that the fretting wear depth of CNPP fuel rod will remain within the acceptable limits during its entire lifetime.

Keywords: Fuel Rod, Spacer Grid, Spring Relaxation, FIV, RMS, Fretting Wear Depth, EOL

Introduction

In Pressurized Water Reactors (PWRs), the nuclear fuel rods consist of slightly enriched UO_2 ceramic pellets contained in Zircaloy-4 tubing which are plugged and seal welded at the ends to encapsulate the fuel meat. The fuel rods are loaded into the skeleton so that there is a clearance between the fuel rod ends and the top and bottom nozzles to accommodate the effects of thermal expansion and irradiation induced growth. Within a fuel assembly, the fuel rods are supported by the spacer grids located at intervals along the axial direction which also maintain the lateral spacing between the rods (rod pitch) throughout the designed lifetime. In each grid cell, a fuel rod is supported by six contact support points (two springs and four dimples) provided in the orthogonal directions. The dimples and springs, being the key elements of the spacer grid cell, play a major role as the support system of the fuel rods. The springs provide elastic support, whereas, dimples provide rigid support to the fuel rod. The magnitude of the supporting force provided by the grid cell is set high enough to minimize the fretting wear of the fuel rods at the end of life (EOL), without overstressing the cladding surface at the contact points. The contact arrangements of the spacer grid with the fuel rod are shown in Figure 1.

At reactor operating conditions, these fuel rods are subjected to turbulent excitation exerted by the coolant flowing parallel to their axes. The flowing coolant produces energy to induce vibrations, known as flow induced vibration (FIV), in the fuel rods. The fuel rods FIV phenomena have been studied by several researchers. Wambsganss and Chen S.S. (1971) studied FIV by considering a cylinder simply or elastically supported at both ends. However, they were unable to model the specific effects of forces, produced at the spring/dimple supports similar to the actu al fuel rods. The FIV problem was also studied by Burgreen D. et al (1958), Quinn E.P. (1962), Sogreah H. (1962), Pavlicaand Marshall R.C (1965), Paidoussis M. P., (1968) and Morris A. E (1964) . Burgreenet al gave the earliest correlation for determining the vibration amplitudes of the fuel rod. Paidoussis extended the work of Burgreen et al and published a revised correlation for the fuel rod vibration amplitude. Kang et al (2001) proposed an analytical model of FIV for a rod supported by two translational springs at both ends. Since the high coolant flow is inevitable for reactor heat transfer, therefore, it is impossible to control or restrain the fretting wear phenomena induced by FIV within the reactor core.

1-3 Directorate General Nuclear Power Fuel, Pakistan Atomic Energy Commission,

At the beginning of life (BOL), the frictional forces within the spacer grid cell of fuel assembly are set sufficiently high enough to limit the relative motion between the fuel rods and the springs/dimples induced by FIV. However, due to the spacer grid spring relaxation with increase in burn up and cladding creep down, a clearance may emerge between the grid and the fuel rods, which changes the grid-to-rod contact conditions. Therefore, flow-induced vibrations (FIV) caused by turbulence coupled with the spring relaxation may lead to fretting wear of fuel rods. If the tube is perforated as a result of severe wear damage, radioactive fission gases are released into the primary heat transport system. As a result the radioactivity level exceeds the regulatory limits, the condition which is not preferred by the utilities.

Primarily, there are three types of wear mechanisms caused by FIV namely: i) impact wear, ii) fretting wear and iii) sliding wear. The impact wear is associated with very large vibrations amplitude leading to rapid fuel failure. Whereas, the fretting and sliding wears are typically related to relatively smaller vibration amplitudes. It results from the combined action of rubbing and tapping between the fuel rod and its support structure within the spacer grid cell. Actually, the slippage of the fuel rod within the spacer grid cell is allowed by the designer to accommodate the irradiation and thermal expansion effects. However, such movement of the fuel rod is restricted from top and bottom ends (i.e. by top and bottom nozzles). Consequently, the fretting wear is largely caused by the rotation or motion of the fuel rod inside the grid cell in horizontal plane. Whereas, the sliding wear occurs only by rubbing or sliding motion between the grid support and fuel rod cladding tube. Nevertheless, it is very difficult to distinguish between these later two types of wear mechanisms Perumont A, Sep (1982), Kim Y. H., et al, Aug, (1997), Shuffler C.A, (2004), Tong L. S. and Weisman J., (1996).

The fretting wear is one of the most common causes of fuel failures in PWRs which may shorten the lifetime of the fuel rods which are designed for 3–5 years. The factors, which predominantly affect the fretting wear of fuel rod include the spacer grid spring force, area of contact surfaces, temperature at support points, coolant flow velocity, grid growth, reduction in rod diameter due to cladding creep down, water chemistry, etc. Among these, the spacer grid spring force is the key parameter which has a crucial impact on the grid-to-rod fretting tendency during the in-reactor lifetime of the fuel. Moreover, the fuel assembly bow and formation of oxide layer on the contact surfaces also contribute to alter the grid-rod support conditions Rubiolo P. R. and Young M., (2009). In short, due to involving multi-variables and uncertainties associated with the fuel assembly mechanical properties and reactor parameters, the analytical prediction of the fretting-wear damage of a PWR fuel rod is a complex problem. No general solution of fretting wear problem covering all aspects can be found in spite of its importance. Resultantly, the most effective method of investigating such complex problems is to combine the computational methods with the experimental studies.

In this study, a simple grid-to-rod fretting wear (GTRF) methodology based on the Archard Wear Theory Kim Y. H., et al, Aug, (1997) is developed to calculate the wear depth of the CNPP fuel rod for its designed life time mainly from mechanical viewpoint. In order to determine various input parameters, this methodology is coupled with FRV, FRPV, FRCB and ANSYS computer codes. Based on these analyses, the results for onset of fuel rod slippage, effective sliding distance and fretting wear volume / depth have been presented for the case of 300 MWeCNPP fuel rod.

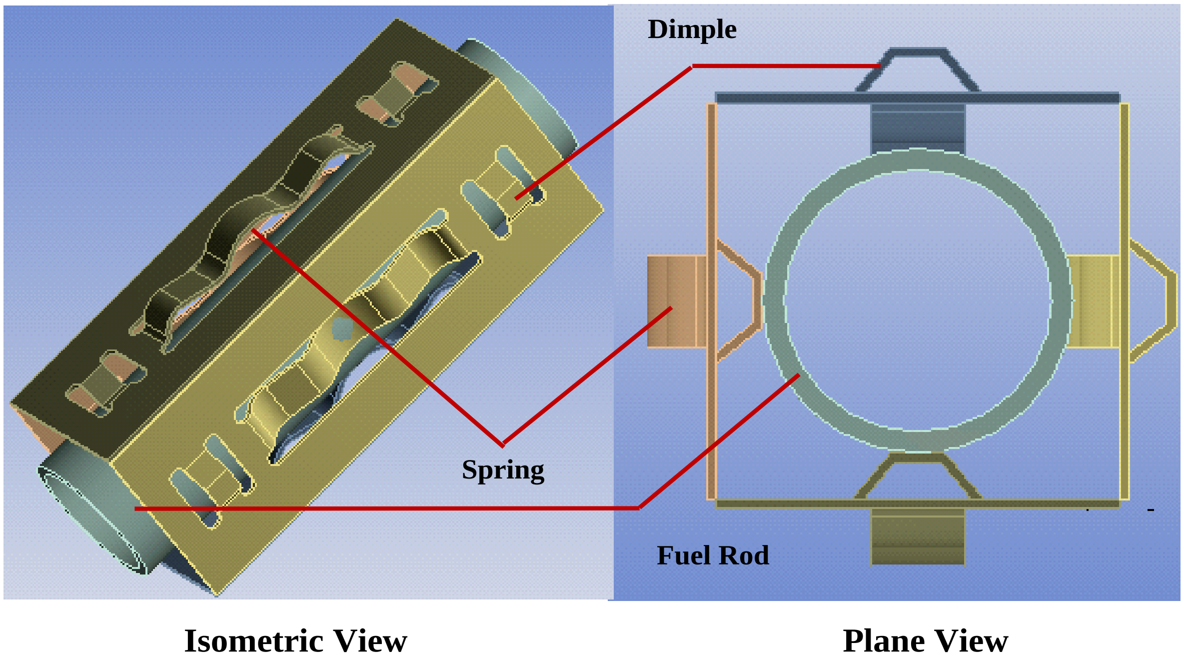

Figure 1: CNPP Spacer Grid Cell Showing the Grid-to-Rod Contact Arrangements

Design Criterion

The frictional force provided by the springs and dimples within the spacer grid cell shall provide sufficient support to limit the fuel rod vibration throughout the designed life-time and to maintain cladding fretting wear within acceptable limit. The cumulative fuel rod cladding wear depth due to fretting, fatigue, thermal expansion, oxidation, creep and irradiation induced growth should be less than 10% of the wall thickness of the cladding at EOL (i.e. <70 μm for CNPP fuel rod) Chashma Nuclear Power Plant Unit-2, Final Safety Analysis Report (FSAR), Mar (2009).

Calculation Methodology

The overall methodology used to calculate the fretting wear depth of the fuel rod is shown in Figure 2 Kim Y. H., et al, Aug, (1997).

The methodology developed , based on the concept of Archard wear theory, provides a good relationship to estimate the wear volume of fuel rod during its residence time within the reactor core at its operating conditions. For this purpose, the Equations 1, 2 and 3, explained in the proceeding sections, are used to estimate the wear volume of CNPP fuel rod. These calculations are coupled with FRV, FRPV, FRCB and ANSYS computer codes to determine various input parameters for solving these equations.

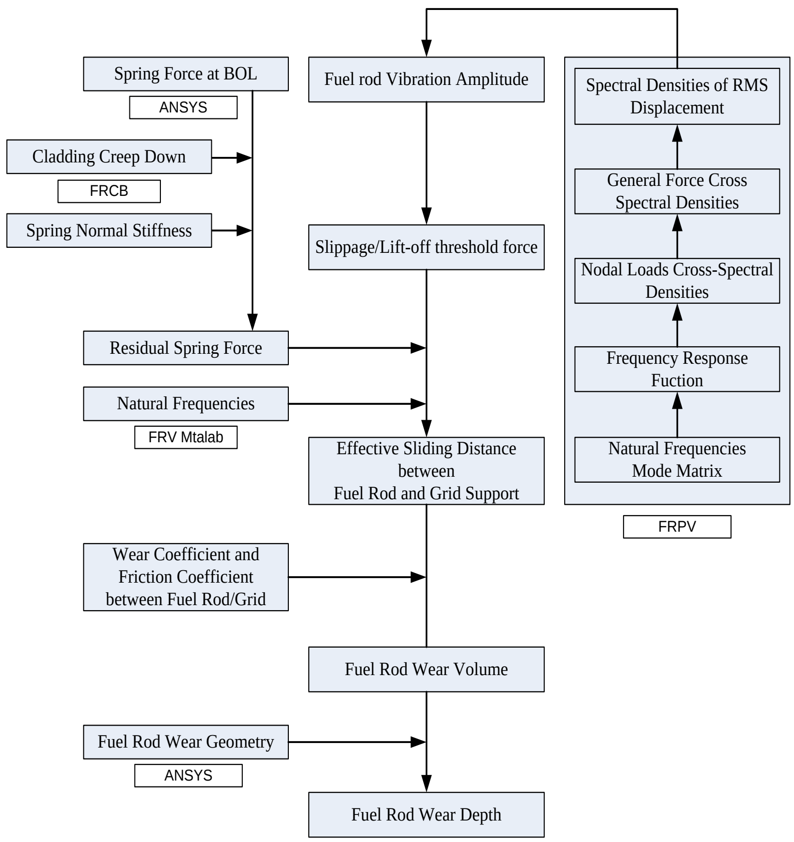

Figure 2: Flow Chart for Calculating the Fretting Wear Depth of Fuel Rod

Wear Volume

The wear volume of the CNPP fuel rod is calculated using the ArchardWear Equation which was based on the following assumptions [10]:

i) The wear volume (V) produced due to effective sliding distance (L) is proportional to the contact area.

ii) True area of contact is formed by the local plastic deformation of spacer grid spring.

iii) The material particles removed by sliding or rubbing motion are hemispherical and have same diameter.

In this model, the fretting wear volume of fuel rod produced as a result of FIV is related to the residual spring force and the effective sliding distance by the following expression:

$$V = \frac{SF_S L}{3H} \qquad (1)$$

Where

V = Wear volume (mm^3)

S = Wear coefficient (-)

F_s= Residual spring force on contact surfaces (N)

L = Effective or accumulative sliding distance (mm)

H = Material hardness (N/mm^2)

The numerical constant 3 in Equation 1 covers the shape factor. This equation is used not only to determine the fretting wear volume (*V*) but also to estimate the onset of fuel rod slippage within the spacer grid cell. Usually, wear coefficient (*S*) and hardness (*H*) of Zircaloy is determined experimentally. However, in the absence of such data, the values of these coefficients are taken from the literature. Whereas, the determinations of residual spring force (F_s), effective sliding distance (*L*) and other parameters are described below.

Residual Spring Force

During reactor operation, with the increase in fuel burn up (fluence) spacer grid spring force relaxation and cladding creep down takes place as a result of neutron irradiation. The values of residual spring force of the grid material(Inconel 718) after a fast fluence of 0.85×10^{21} n/cm^2 and 2.5×10^{21} n/cm^{2}arereported to be about 1/3rdand 1/7th, respectively, of their initial values Tong L. S. and Weisman J., (1996).Thus, for the case of CNPP, it is believed that the spring relaxation at EOL is about 80% or more for the central spacer grids that are exposed to the maximum fast neutron flux. Whereas, for the case of top and bottom spacer grids, the spring force relaxation at EOL is expected to be around60 % of the initial value. Therefore, the initial spring force needs to be set substantially higher to provide sufficient safety margin for the minimum hold-down force required at EOL.

The residual spring force is determined taking into consideration the parameters which influence the spring force relaxation during the reactor operation. These include: initial spring force, irradiation induced spring force relaxation, cladding creep down and thermal expansion. The residual spring force (F_s) is calculated by the formula:

$$F_s = (F_{BOL} - KC)(1 - R) \qquad (2)$$

Where

F_s=Residual spring force (N)

F_{BOL} = Spring force at BOL (N), calculated with the help of ANSYS from contact analysis

K = Initial spring stiffness (N/m)

C = Cladding creep down (mm), calculated from FRCB code

R= Spring force relaxation (%)

Effective Sliding Distance

The effective sliding distance is the overall distance caused by slippage of fuel rod both in axial and transverse directions. The slippage of fuel rod within the spacer grid cell is allowed not only to overcome the creep bowing effects but also to limit the stresses produced due to thermal expansion and irradiation growth of the fuel rod. The phenomenon of slippage between the cladding tube and the grid springs/dimples is initiated when the tangential force produced by FIV exceeds the frictional force of spacer grid springs. The spacer grid spring and dimples are designed in such a way that the resulting spring force is neither too high nor too low. If too high, it may lead to fuel rod creep bowing. If too low, it will cause fretting wear failure of fuel rod. Thus, the spacer grid spring force is the most important parameter to avoid such problems. The effective sliding distance L at a dimple location during fuel rod residence time t is related to the frictional force of spacer grid spring by the following relationship:

$$L = 4 f_n t\left(Y_{dn} - \frac{F_S.\mu}{2K_{dt}}\right) \qquad (3)$$

Where

L = Effective sliding distance (m)

f_n =Fuel rod vibration frequency of n^{th} mode (Hz), determined from FRV

t = Fuel rod residence time (sec) within the reactor

Y_{dn} = Maximum RMS displacement at dimple location (m)

F_s = Residual spring force (N)

K_{dt} =Dimple tangential stiffness (N/m), experimental value from literature

μ =Co-efficient of friction between fuel rod and spacer grid

In Equation 3,'Y_{dn}' is the RMS displacement of fuel rod produced by the FIV at dimple location and $F_s.\mu/2K_{dt}$'is the dimple displacement in tangential direction. Thus, the factor$(Y_{dn} - F_S.\mu/2K_{dt})$in Equation 3 is the relative motion between fuel rod and the spacer grid dimple. This relative motion occurs when Y_{dn} becomes greater than $F_s.\mu/2K_{dt}$ resulting in fretting wear of the fuel rod cladding at the grid-rod contact points.

Input Parameters Calculations

First of all, creep, contact, modal and FIV analyses of CNPP fuel rod have been performed to determine the input parameters of Equations 1-3. These studies involved the execution of computer codes such as FRV, FRPV, FRCB and ANSYS. The computer codes FRPV (fuel rod vibration analysis under parallel flow) and FRV (fuel rod vibration model analysis) are executed to determine the RMS displacement at dimple location, natural frequencies and mode shapes of the fuel rod F2.6, A Computer Code, FRV, (1994), A18.21, A Computer Code, FRV (1994). FIV analysis of CNPP fuel rod is carried out for a flow velocity of 3.4 m/s considering 0.3% damping to calculate the maximum RMS displacement at the dimple location. The computer code FRCB (fuel rod creep bowing) is used to calculate the cladding creep down A18.22, Oct (1993). The effects of temperature and neutron flux on the cladding creep down are also considered in these calculations. Contact analyses of fuel rod have been performed using ANSYS Workbench structural module ANSYS Release (2010) to calculate initial spring force, spacer grid spring normal stiffness, spacer grid dimple tangential stiffness and dimple contact area.

Table 1: Input Parameters for Fretting Wear Calculations

Parameters	**Values**
Initial spring force, F_{BOL}	14.5N
Initial Spring Stiffness, K	34 N/mm
Rod vibration frequency of 1st mode,f_1	56 Hz
Max. RMS displacement at dimple,Y_{dn}	8.54×10^{-6} mm
Dimple tangential stiffness, K_{dt}	1306 N/mm
Co-efficient of friction, μ	0.3
Hardness, H	92 kg/mm^2
Wear Co-efficient, S	1.0×10^{-7}
Residence time, t	3 cycles

Wear Depth

It has been reported Rubiolo P. R. and Young M. (2009) that the wear marks produced on surface of fuel rodby the dimple contact are much more severe than the spacer grid spring mainly due to: i) the spring being a flexible support partially absorb the impact, whereas the dimple has a rigid contact with the fuel rod; ii) the contact area is smaller for a dimple than a spring and for an equal force, the pressure exerted by a dimple is higher than the one applied by a spring resulting in deeper wear marks; and iii) the difference in specific geometry of dimples and springs. Therefore, in the present study, the fretting wear depth 'h' of the fuel rod has been calculated by dividing the wear volume 'V' with the dimple contact area, 'A_d'.Mathematically;

$$h = V/A_d \qquad (6)$$

Where

h = Wear depth (mm)

V = Wear volume at EOL (mm^3)

A_d= Dimple contact area (mm^2)

The wear volume due to FIV is calculated using Equation 1, whereas, the contact area between dimple and fuel rod surface is calculated by turning on contact status tool option of ANSYS software. The contact status tool precisely predicts the sticking area of fuel rod and spacer grid dimple sat the contact points.

Results and discussion

It is believed that the maximum spring relaxation due to irradiation would take place at middle spacer grids(# 4 & 5).Therefore, fretting wear calculations for the CNPP fuel rod have been performed forth 4^{th} spacer grid. Similar observations have also been made by Kim et al (1998) while developing the fretting wear methodology for predicting the capability of a newly designed spacer grid. The results of these calculations are presented and discussed below.

Wear Volume

The parameters (given inTable 1) are used to solve simultaneously the Equations 2 and 3 for residual spring force and effective sliding distance. The value of spring relaxation is chosen such that the necessary condition of Equation 3 for the onset of fuel rod slippage must hold true. Based on the spring relaxation and other parameters the residual spring force is calculated from Equation 2. The effective sliding distance due to the rod slippage is calculated for the fuel residence time within the reactor core. The calculations are iterated between the residual spring force and the effective sliding distance in order to determine the onset of fuel rod slippage by varying the spring relaxation and cladding creep down while keeping the other parameters constant. The results for the residual spring force and effective sliding distance of fuel rod as a function of spring relaxation is shown in Figure 3.

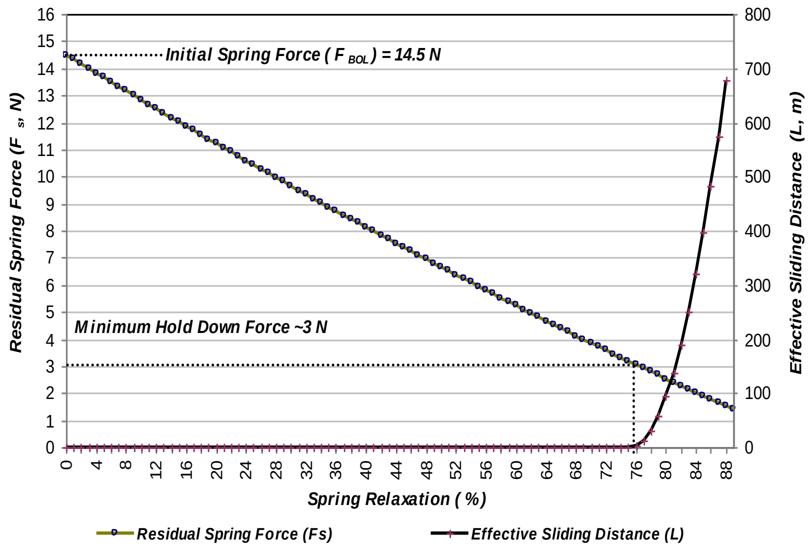

Figure 3: Residual Spring Force and Effective Sliding Distance VsSpring Relaxation

It is observed that the initial spring force decreases with the increase in spring relaxation. Whereas, the effective sliding distance remains negative until the relaxation reaches ~76% value, at which the slippage of fuel rod just starts. After the start of slippage, the residual spring force continues to decrease with the same rate, while the commutative/effective sliding distance sharply increases, with the spring relaxation. This is due to the fact that as the gap between the fuel rod and the dimple/spring progresses, the slip amplitude also increases which ultimately may lead to the perforation of fuel rod cladding due excessive fretting wear. If tube is perforated, radioactive fission products comes out of the fuel resulting in an increase in radioactivity level of the reactor coolant.

In order to prevent the cladding wear failure, the minimum hold-down force of spacer grid spring can also be calculated which is required to prevent the fuel rod fretting wear induced by FIV. Assuming that the effective sliding distance in Equation 3 as zero and doing some manipulations, the minimum hold-down force of spacer grid spring can be derived as follows:

$$Fs = (2K_{dt} \times Y_{dn})/\mu \qquad (6)$$

Where

F_s= Minimum hold-down force (N)

K_{dt}= Dimple tangential stiffness (N/m)

Y_{dn}= Maximum RMS displacement at dimple location (m)

μ= Co-efficient of friction between fuel rod and spacer grid

This Equation is similar to the formula proposed by Schrugar in 1970 F2.6, A Computer Code, FRPV, (1994) to calculate the minimum hold-down spring force. From Equation 6, the minimum hold-down spring force for CNPP fuel rod at EOL is determined to be ~3.0 N.

The calculations for the fretting wear volume of CNPP fuel rod are carried out for the third cycle year in five steps with a step of 0.2 year. From Equation 1, it appears that the wear volume of fuel rod is independent of fuel residence time but it is directly influenced by residual spring force and effective sliding distance. This does not hold true because the effective sliding distance is governed by the residual spring force and residence time. The wear volume is directly proportional to residual spring force and the effective sliding distance has an inverse relation with residual spring force. Thus the residual spring force will govern the effective sliding distance which means that larger the residual spring force the lesser will be the slippage at dimple location (Equation 3).

The results for the fretting wear volume of the fuel rod for various creep down (0.053 −0.059 mm) and spring relaxation (76−88 %) for third cycle year have been obtained and are given in Table 2.The slippage of fuel rod will not happen unless the spacer grid spring is relaxed up to ~76%, as already shown in Figure 3. The calculated wear volume at 76% spring relaxation is 1.043×10^{-6} mm^3. When the spring relaxation is increased to 79%, the wear volume is increased almost by a factor of 8. This is due to fact that the main contribution in wear volume comes from the effective sliding distance. The cumulative wear volume of CNPP fuel rod during its residence time is determined to be 4.7332×10^{-5} mm^3.

Table 2: Fretting Wear Results

Creep-down (mm)	**Spring Relaxation (%)**	**Residence Time (Years)**	**Wear Volume (mm^3)**	**Wear Depth (μm)**
0.0526	76	0.2	1.0428×10^{-6}	0.21
0.0542	79	0.2	7.0849×10^{-6}	1.42
0.0558	82	0.2	1.1274×10^{-5}	2.25
0.0574	85	0.2	1.3656×10^{-5}	2.73
0.059	88	0.2	1.4274×10^{-5}	2.85
Total		**1.0**	**4.7332×10^{-5}**	**9.46**

Note: Calculations are performed for the third cycle year of fuel residence time in reactor core.

It may be noted that the fretting wear is basically a cyclic process. As grid to rod gap due the spring relaxation increases, the relative motion or slip amplitude between contacting surface also increases. In the present study, the effect of spring relaxation on fretting wear volume has been studied by fixing all other parameters. The wear volume is calculated by considering spring relaxation between 76–90%. The wear volume as a function of spring relaxation is shown Figure 4. This result shows that the wear volume increases with the increase in spring relaxation and is linear in nature. For 76% spring relaxation the wear volume is only about 1.043×10^{-6} mm^3. The wear volume increases with the increase in spring relaxation and reaches to a value of about 3.122×10^{-5} mm^3 when the relaxation is 90%. However, these predicted results needs experimental verification.

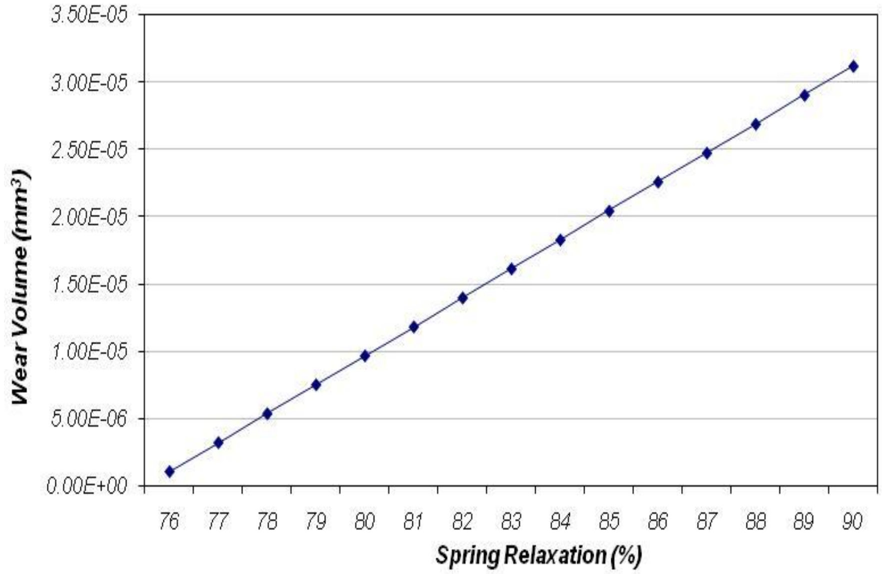

Figure4: Fuel Rod Wear Volume as a Function of Spring Relaxation

Wear Depth

The fretting wear depth of the fuel rod is determined by dividing the wear volume with the dimple contact area. The contact area between the dimple and the fuel rod surfaces is calculated to be 0.0052 mm^2usingANSYS software. It is noted that, being a rigid body, only a small contact area of dimple is formed. The calculation results (Table 2) indicate that the wear volume and wear depth increases with the residence time. The calculated fretting wear depth of the CNPP fuel rod during its residence time is 0.0095mm (9.5 µm) which is less than 10% of the wall thickness (i.e. 70 μm) of the cladding at EOL.

Conclusion

A calculation methodology has been developed to determine the fretting wear tendency of CNPP fuel rod during its residence time within the reactor core. This methodology is coupled with the FRV, FRPV, FRCB and ANSY computer codes to calculate the fretting wear volume and wear depth of fuel rod. Following conclusions are drawn from this study.

i) The residual spring force decreases with the increase in spring relaxation due to irradiation. The onset of rod slippage occurs when 76% spring relaxation is reached.
ii) The cumulative or effective sliding distance sharply increases with a slight increase in spring relaxation after the start of slippage.
iii) The fretting wear volume / depth of the fuel rod is strongly influenced by the effective sliding distance and residence time.
iv) The minimum hold-down force at EOL which is required to avoid rod slippage (the prerequisite for fretting wear), is determined to be 3.0 N.

The maximum wear depth of CNPP fuel rod due to flow induced vibration (FIV) based on the various important design parameters is calculated to be 9.5 µm which is less than 10 % of the cladding wall thickness (i.e. 70 µm) at EOL.

Although, the wear model can be applied with a good confidence not only to predict the onset of fuel rod slippage but also to calculate the fretting wear depth .However, in reactor of wear coefficient, cladding creep and spring relaxation data is necessary to validate the analytical results.

Nevertheless, the development of fretting wear model, is very useful in improving the current understanding of the fretting wear phenomena which is important not only for determining the fuel rod support condition but also to limit fretting wear damage of fuel rod within the acceptable limits for its designed lifetime.

References

[1] Chen S. S. and Wambsganss W. M., Apr (1971) Tentative Design Guide for Calculating the Vibration Response of Flexible Cylindrical Element in Axial Flow, Report No. ANL-ETD-71-07, Argonne National Lab., USA.

[2] Burgreen. D, Byrnes J. J., and Benforado D. M., (1958) Vibration of Rods Induced by Water in Parallel Flow, Trans. of ASME (American Society of Mechanical Engineers), Vol.80,.

[3] Quinn E. P. (1962) Vibration of Fuel Rods in Parallel Flow, Report No. GEAP-4059, General Electric Company, USA.

[4] Sogreah H., (1962) Study of Vibrations and Load Losses in Tubular Clusters, Initial Special Report No. 3, EURATOM - EURAEC-288, SocieteGrenobloised'Etude et d' Applications Hydrauliques, Grenoble, France,.

[5] Pavlica R. T. and Marshall R. C., (1965) Vibration of Fuel Assemblies in Parallel Flow, Trans. of ANS(American Nuclear Society), Vol.8, 599p.

[6] Paidoussis M. P., (1968) An Experimental Study of the Vibration of Flexible Cylinders Induced by Axial Flow, Trans. of ANS, 11, 352p.

[7] Morris A. E., (1964) A Review on Vortex Shedding, Periodic Wakes, and Induced Vibration Phenomena, Trans. of ASME, J. Basic Engg., 85, 185p,.

[8] Kang H. S. et al, Dec (2001) FIV Analysis for a Rod Supported by Springs at Both Ends, Journal of Korean Nuclear Society (KNS), Vol. 33, Number 6, pp 6190~6,.

[9] Perumont A, Sep (1982) On the Vibration Behavior of Pressurized Water Reactor Fuel Rods, Nuclear Technology, Vol. 58.

[10] Kim Y. H., et al, Aug, (1997) Fretting Wear of Fuel Rods due to Flow Induced Vibration, Transactions of the 14th International Conference on Structural Mechanics in Reactor Technology (SMIRT 13, paper C04/4), Lyon, France, pp 17-22.

[11] Shuffler C.A, Sep. (2004). Optimization of Hydride Fueled Pressurized Water Reactor Cores, MS Thesis, MIT, USA.

[12] Tong L. S. and Weisman J., (1996) Thermal Analysis of Pressurized Water Reactors, Third Edition by American Nuclear Society, La Grange Park, Illinois USA.

[13] Rubiolo P. R. and Young M., (2009) On the Factors Affecting the Fretting-Wear Risk of PWR Fuel Assemblies, NED, Vol. 239, pp 68-79,.

[14] Chashma Nuclear Power Plant Unit-2, Final Safety Analysis Report (FSAR), Mar (2009) Chapter 4 Section 4.2, SNERDI, China,.

[15] F2.6, A Computer Code, FRPV, Jan (1994) for the Spectral Analysis of the Fuel Rod Vibration under Parallel Flow PWR, SNERDI, China,.

[16] A18.21, A Computer Code, FRV, Jan (1994) for the Calculation of Natural Frequencies and Mode Shapes of Fuel Rod Vibration, SNERDI, China.

[17] A18.22, Oct (1993) A Manual for computer Code, FRCB, for the Calculation of the Fuel Rod Creep Bowing in PWR, SNERDI, China.

[18] ANSYS Release 13.0, (2010) CFD Software ANSYS Inc. USA,
[19] Kim K. T., Kim H. K., and Yoon K. H., (1998) Development of a methodology for In-Reactor Fuel Rod Supporting Condition Prediction", (JOKNS), Volume 28, No. 1,.