BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
DOCTORAL BOARD OF FACULTY OF MECHANICAL ENGINEERING
PhD THESISBOOK

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Applies for the PhD grade with the topic of

Fretting wear of different rod supports of nuclear fuel rods

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1. Introduction

The fuel deployed in the reactor of a nuclear power plant takes the form of uranium pellets inserted inside fuel rod cladding tubes. The fuel rods are combined into a fuel assembly bundle by means of several spacer grids located at different elevations along the fuel assembly's longitudinal axis. The fuel assemblies consist of several fuel rods arranged in square grids at western design of pressurised water reactors (PWR).

In plants – equipped with pressurised water reactors – the heat produced by the fuel rods is transported by high-pressure water, called reactor coolant, out of the reactor to heat exchangers. To obtain a nuclear power plant with the highest possible power output capacity, the reactor coolant must be capable to absorb as much heat as possible. This can be achieved by means of high coolant flow velocity and a high degree of coolant's turbulence. The fuel rods are supported by the spacer grids. Several types of spacers exist. Spacers are fitted with flow channels or vanes that impart swirl to the flow. By means of these elements, which increase the turbulence flow of coolant, can provide a higher heat transfer.

At beginning of life of the fuel assembly there is an interference fit between fuel rod and spacer grid, the springs of spacers are supporting the fuel rod under a certain preload. The preload of the springs decreases during the reactor operation due to the neutron irradiation. This reduction is so enormous that the spring force can be decreasing till about 0 N, or sometimes leading to a gap between the fuel rod and the spacer spring [6].

In contrast to the fuel assemblies of the boiling water reactors, the fuel assemblies of the pressurised water reactors have no fuel channel. Therefore the cross-flow among the fuel assemblies decrease the local power peaks and thereby avoid the nuclear boiling inside a reactor [7].

The coolant flow induces vibration of the fuel assemblies and their fuel rods. The excitation arising from the flow of the coolant, and thereby the flow induced vibration can not be avoided fully. The motion of the fuel rods is greatly influenced by the fit.

The amplitude of the induced vibration (of fuel assembly and of fuel rod) is in the micrometer range. This low-amplitude vibration at the supporting points of the fuel rods causes sliding friction which lead to wear, fretting of cladding tube [8]. In extreme cases, fretting can result in perforation of the fuel rod cladding tubes, thus enabling radioactive substances to be released into the circulating coolant.

In the nuclear power plants fretting wear of the cladding tube reduces fuel assembly service life and increases reactor operating costs.

Considering the above mentioned facts the great important field of the development of the spacer grids is the design of such a fuel rod support which reduces the fretting wear of the fuel rod cladding.

2. Scientific background

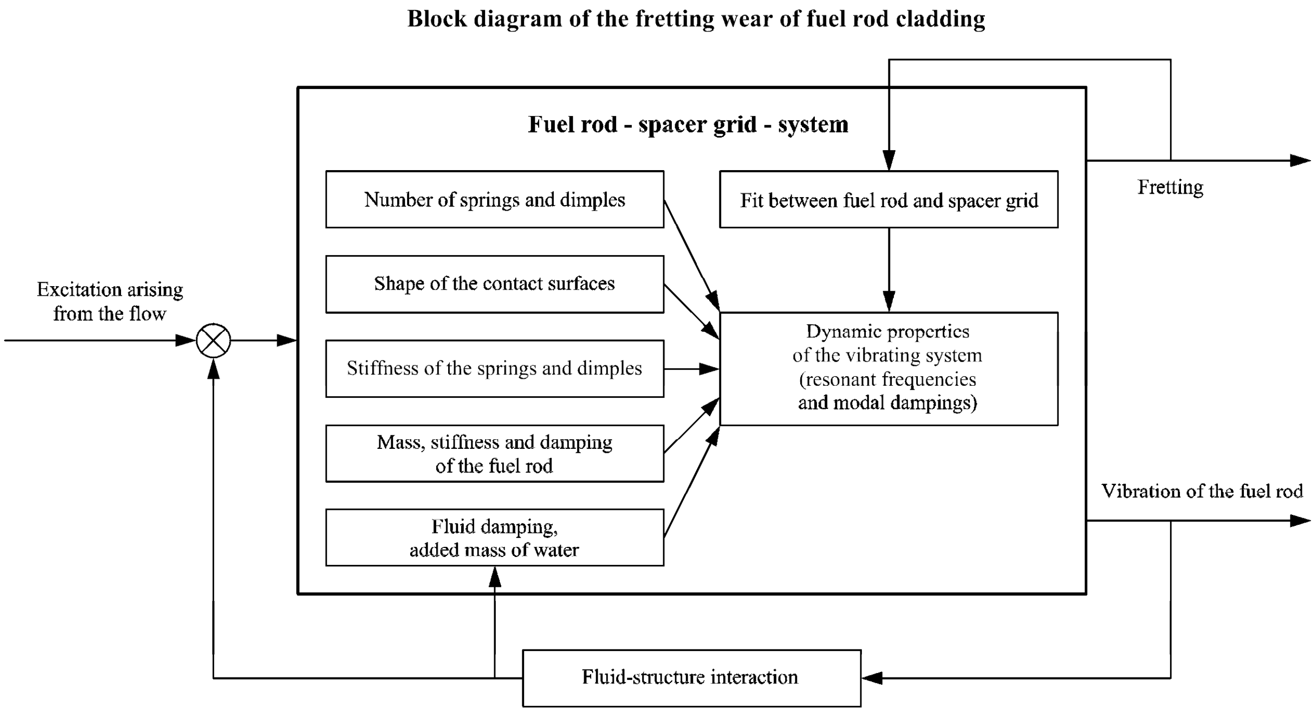

Figure 1: Block diagram of the fretting wear of the fuel rod cladding

The fretting of cladding tube is a really complex process. Its block diagram is shown on Figure 1. The scientific research of the fretting of fuel channel can be split into three major fields:

1. *Study of the intensity of the excitation arising from the flow of the coolant and spectrum of the excitation.* Both of them are influenced by volume flow rate of the reactor coolant, the shape of the spacer grids, the distance between the fuel rods and the motion of the fuel rods (fluid-structure interaction).
2. *Study of the dynamic behaviour of the fuel assembly and fuel rod with flow- and vibration measurements.* The dynamic properties (resonant frequencies, amplitude, damping) are influenced by several factors which are the following:
   - the fit between the fuel rod and the spacer grid;
   - the geometric shape of the spacer grid;
   - the stiffness of the fuel rod and spacer grid;
   - the mass of the cladding tube and the nuclear fuel – or the pellets as its substitutes during the experiments – and their internal damping;
   - the friction of the fuel pellets and the cladding tube;
   - the mass of reactor coolant moved by the vibration (added mass) during the motion of the fuel rod and the fluid damping.

3. *Wear tests*. These are such model tests where only a part of the fuel assembly (e.g. a part of fuel rod and one spacer grid cell) is taken and a wear test of the periodic sliding motion is made, or where a whole fuel assembly is laid into the flow channel. During

these experiments the most important parameters are studied, e.g. changing of the fit, the shape of the spacer grid and the different motion of the fuel rod (axial-, transversal sliding and impact).

In my PhD work I dealt with the third field of the fretting research. In this area there were and are going numerous researches [9], [10], [11], [12], [13], [14], [15]. In the experiments made in the flow channels whole or half fuel assemblies were taken for tests [9], [10], [11]. They determined that the amount of the fretting wear at clearance fit is larger than at interference fit (i.e. when the spacer grid spring had a preload). In addition they determined also that the shape of spacer grid springs had a great impact on the fretting wear. The tests in my PhD work give new results to this know-how. My work deals not only with the shape of contact elements of the supports (springs and dimples) but also with the motion of the fuel rod in respect of the fretting behaviour.

KIM, KANG, YOON and SONG [12] as well as KIM, KIM, YOON, KANG and SONG [13] carried out model tests with the focus on the shape of spacer grid springs. They investigated the impact of the rod motion on the fretting wear too. However in their tests performed in air the contact of only one cell of the spacer grid and a shortened cladding was investigated so that the excitation had a constant frequency of 30 Hz.

Later KIM and LEE [14], [15] in the continuation of their research studied the fretting behaviour of a short fuel rod which was supported on its both ends. The tests were carried out at first in air and after in water too. This model describes the connection between the test rod and the supports better. In this case the vibration amplitude of the test rod, as well as the fit between the test rod and the support, determines the amplitude of the sliding motion of the contact surfaces and the reaction forces at the supports. However in their tests the excitation had a constant frequency of 30 Hz and the amplitude of the lateral vibration of the test rod was the same – 0.7 mm –, and they changed only the fit between the rod and support during the tests.

Nevertheless KIM et al. [12], [13], [14], [15] did not consider that the excitation at a real fuel assembly has not a constant frequency and they neglected the effect of the dynamic properties of the fuel rod (resonant frequencies, damping). In the PhD work the spectrum of the applied excitation signal was determined on the basis of the research results of the excitation arising from the flow. The excitation with the wide range spectrum provides that the test rod which in each case stands in water can vibrate on its own resonant frequency. The aim of my research is to investigate the fretting wear of fuel rod cladding by means of a more realistic model tests.

3. Aim of work

The aim of this dissertation is to investigate experimentally the influence of different spacer grids as well as the influence of the fit between the fuel rod and the spacer grid on fretting wear in order to provide required information for the development of the spacer grid design. In addition to the fretting tests vibration measurements were carried out to study the dynamic behaviour of the test rod.

The relationship of the aggregate fretting volume and the fraction of the energy taking into the vibrating system that is dissipated by the fretting process and the damping of the vibrating system are analysed. The influence of a layer of corrosion, of the magnitude of excitation, of rod movement, of the stiffness of the space grid support elements (spring and dimple), and of the fit between the fuel rod and the spacer grid on fretting wear was investigated.

4. Investigation method

The investigation of fretting behaviour comprised two different stages. The study of the excitation arising from the flow and of the dynamic properties of fuel rod was separated from the fretting tests. The first stage – before the actual fretting tests – is the simulation of the flow prevailing inside a reactor by means of different axial- and cross-flow in a flow channel designed for the tests. The dynamic behaviour of a full-scale fuel assembly was investigated in the flow channel. The excitation signal for the fretting tests was generated on the basis of the test results (vibration amplitude and frequency). An excitation signal with the same spectrum was used in all of the tests in order to ensure comparability of the fretting test results.

In the second stage, at the fretting tests a single shortened-length fuel rod was investigated. Figure 2 shows the fretting test facility. The test rod is suspended from a thin wire and supported at three elevations along its axis. Both the cladding tube of the test rod and the spacer grids are made of a zirconium-alloy. The zirconium-alloy cladding tubes from actual fuel assembly fabrication lots were used as the test rods. For testing purposes the cladding tubes were filled with molybdenum pellets instead of uranium ones. Molybdenum pellets have simi1ar density as uranium ones have, and the great advantage of these pellets that they permit safe and easy handling of the rods. Among the molybdenum pellets a permanent magnet as a part of the excitation system was located. A thin wolfram wire with a diameter of 0.1 mm was inserted between the pellets and the inner wall of the cladding tube that the model will be realer regarding to the vibration properties. This wire simulates the reduction of the gap between the fuel and the cladding tube due to the neutron irradiation. The diameter of the test rod is 9.50 mm and his length is 1250 mm.

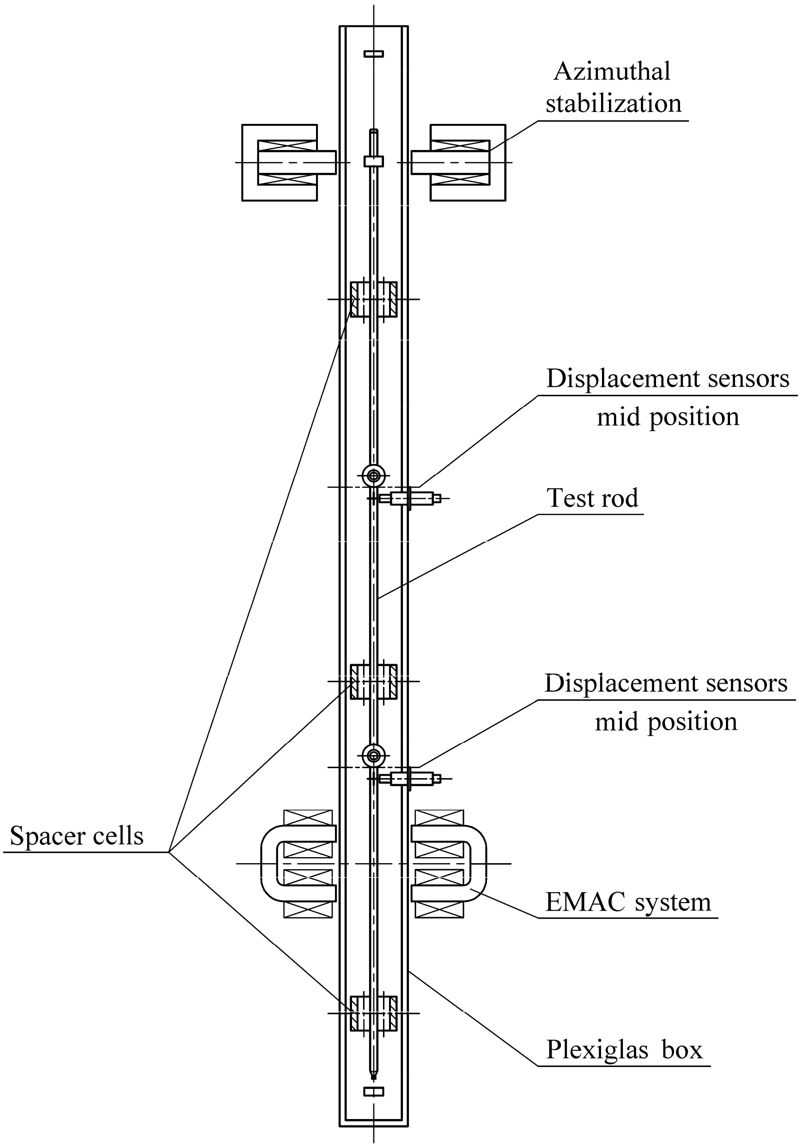

Figure 2: Fretting test facility

The quadratic supporting cells are made of a zirconium-alloy and they have depending from the type of the fuel assembly different number of springs and dimples with different shapes. Seven different spacer grid types (“A” — “G”) were investigated. The figures 3-9 show schematically one cell of these spacers. In addition the figures show also the direction of excitation. The extent of the springs and of the dimples in the supporting cells is in a range of millimetres, and the width of their strips is in a range of tenth millimetres. The height of the supporting cells is between 40 and 50 mm as the height of the real spacer grids.

The rod’s lateral oscillations in and perpendicular to the direction of excitation can be measured using the displacement sensors mounted in the wall of the Plexiglas box. The excitation force applied to the rod was a stochastic signal both at the fretting tests and at the vibration measurements. The tests were performed in water at room temperature. At the end of the fretting tests, the depths of the fretting marks on the test rod were measured using an interferometer, and their volumes subsequently calculated by a computer program.

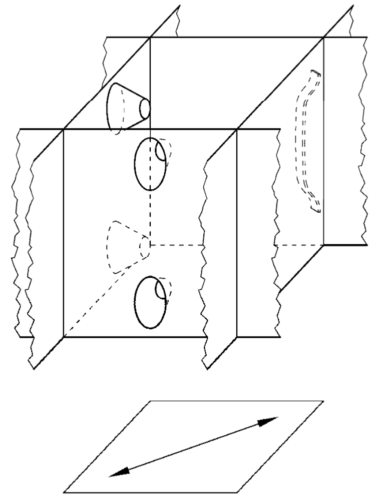

Figure 3: Supporting cell of type “A”

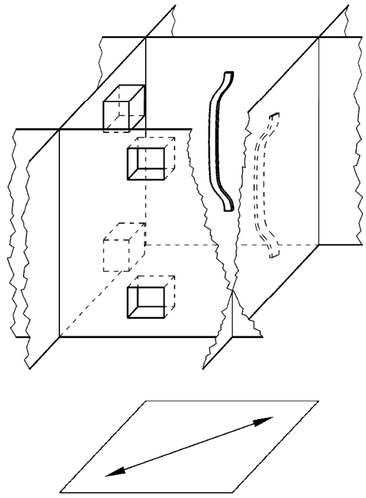

Figure 4: Supporting cell of type “B”

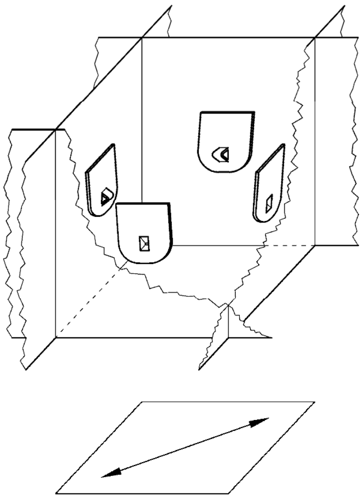

Figure 5: Supporting cell of type “C”

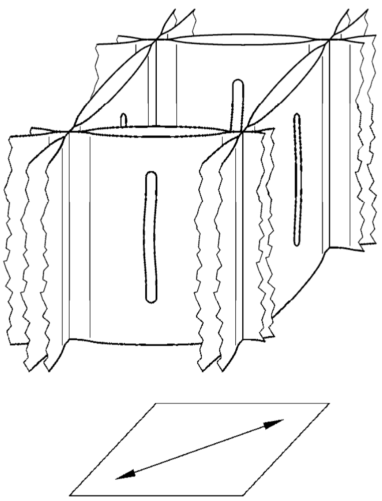

Figure 6: Supporting cell of type “D”

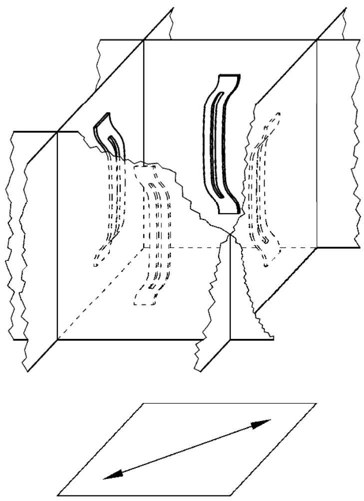

Figure 7: Supporting cell of type “E”

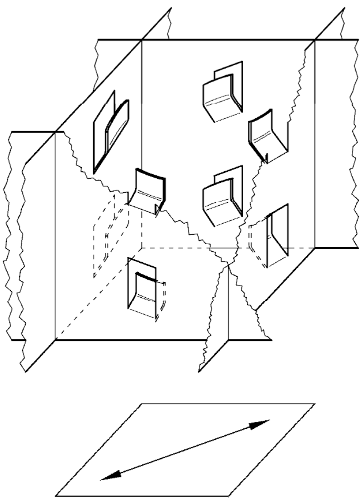

Figure 8: Supporting cell of type “F”

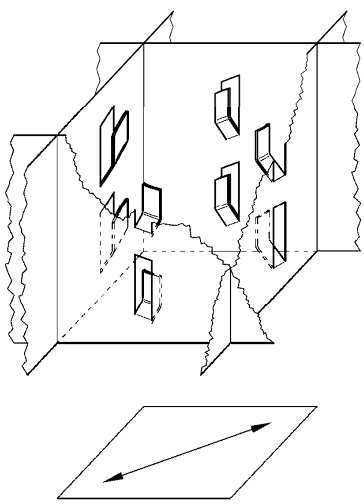

Figure 9: Supporting cell of type “G”

5. New scientific results

The results of my PhD word are summarised in the following theses:

1. The damping of the vibrating system was determined by means of vibration tests. The different damping mechanisms of the vibrating system largely influence the energy dissipated by the material removal. Damping mechanisms of the vibrating system are:
   - Material damping of the cladding tube of the model rod;
   - Friction originating from the fuel pellets' moving in the cladding tube;
   - Fluid damping of the ambient water;
   - Friction acting between the rod and the support arising from the slipping and impact of the contact surfaces (one part of the frictional work dissipates to heat, the other part used for removal of particles).

   At the examining of different dampings it was determined that the largest part of the vibrating system's damping $\left(D = 1 \cdot 10^{-2} - 15 \cdot 10^{-2}\right)$ **arises from the fluid damping, and the friction and impact of the rod. The friction and impact of the pellets of the model rod** $\left(D = 0.507 \cdot 10^{-2}\right)$ **and the material damping of the cladding tube** $\left(D = 0.016 \cdot 10^{-2}\right)$ **play smaller, but not negligible part in the damping of the vibrating system. The material damping of the cladding tube is roughly one thirtieth (1/30) of the damping originating from the friction and impact of the pellets of the model rod.**

2. The influence of the corrosion layer on the fretting was investigated by means of fretting tests [4]. A thin zirconium dioxide protective layer that is harder and more resistant to wear than the zirconium alloy arises by the corrosion of the cladding tube. **Unlike in the tests carried out with a non-pre-corroded rod/support system, no fretting marks of a size large enough to be measured were detected in the tests carried out with a layer of corrosion. On the basis of the results it was determined that a corrosion layer that is only around 2 μm thick is more than sufficient to protect a fuel rod effectively against fretting.** However the thermal resistance of a cladding tube (cylindrical tube) with 2 μm thick corrosion layer is about 2.3-4.9 % and with 10 μm thick corrosion layer about 9.0-18.6 % higher than the thermal resistance of a non-pre-corroded cladding tube. This increase of the thermal resistance is not advantageous with respect to the operation.

3. The influence of the excitation force's change on the fretting and on the dynamic behaviour of the vibrating system by means of tests were investigated [4]. The extent

of excitation force resulted from the flow of the cooling water has determinant consequence on the fretting of the fuel cladding. **It was determined on the basis of the results from the fretting tests that the reducing of the excitation current intensity (excitation force) by half (50 %) cut the fretting rate to approximately one fourth (22 %). It was concluded from the change of these fretting rate's ratios that: if I reduce the excitation current intensity the energy dissipated by fretting will decrease quadratic.**

4. **In the analysis of the results derived from the fretting tests it was determined that the shape and the stiffness of the support elements that is in contact with the model rod has a significant effect on the volume- and time history of the fretting [1], [3], [5].**
    a.) It was determined on the basis of the tests' results that the requirement for the reduction of wear is the larger contact surfaces as well as springs, dimples without sharp edge but with rounded edge.
    b.) The stiffness of springs and dimples of three different types ("A", "B" and "D") was measured and the effect of the stiffness on fretting was also investigated by means of fretting tests [5]. In case of the types "A" and "B" of the investigated three support types the fretting tests showed that the average wear volume was at the points of rod-to-dimple contact more than nine times greater than one at the points of rod-to-spring contact. On the other hand at the support type "D" the larger wear was perceptible in the points of rod-to-spring contact. The average volume of the wear marks at the points of rod-to-spring contact was about six times greater than one at the points of rod-to-dimple contact.

5. **It was determined on the basis of the fretting tests' results that the larger motion than spacer spring preload's decrease or the gap between the rod and the spacer spring's increase leads to larger wear [2].**

    It was demonstrated that the test rod with a clearance fit is able to move more freely and more extensively at the same level of excitation. The effective vibration amplitude in the direction of excitation was at clearance fit about one and a half and two times greater than one at interference fit. In addition to the intensity of rod motion is not only in the direction of excitation but also perpendicularly to it significant larger than at interference fit. In the case of a clearance fit of 0.10 mm, the effective vibration amplitude perpendicular to the direction of excitation was about four times greater than one at interference fit.

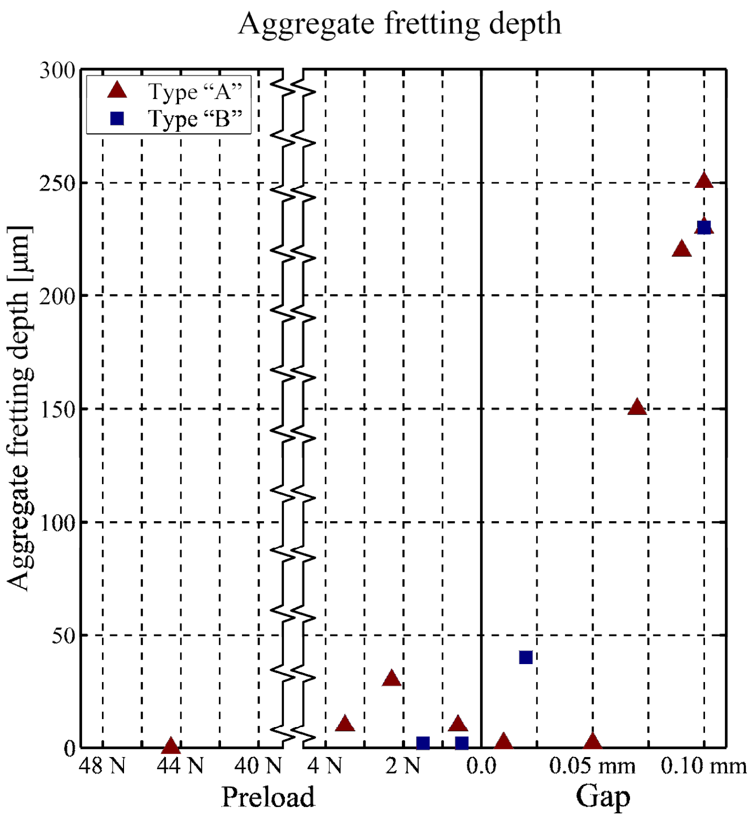

Figure 10: Aggregate fretting depth

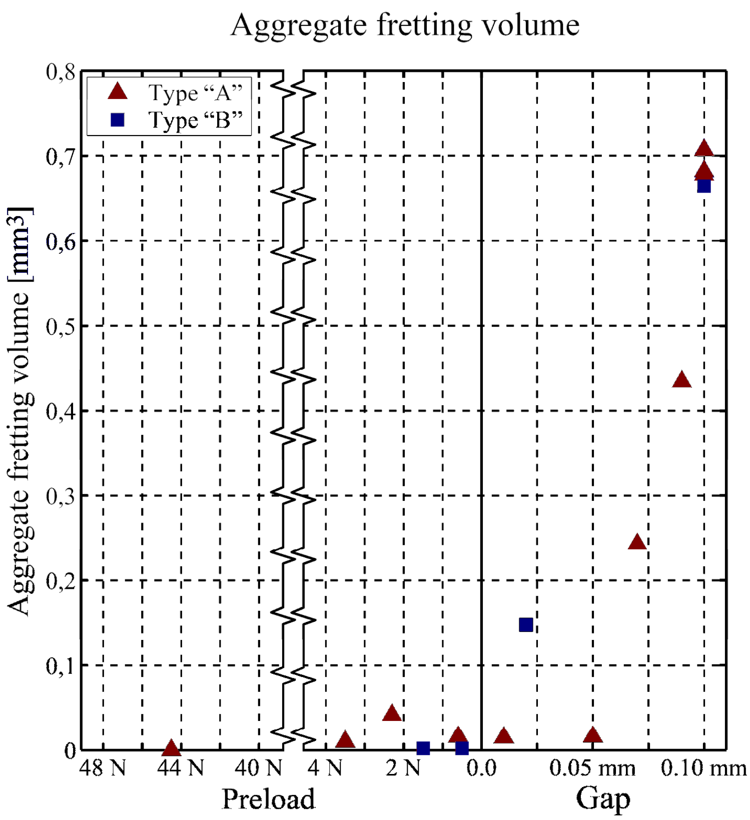

Figure 11: Aggregate fretting volume

At the fretting tests both the aggregate wear depth (sum of maximum depths of all marks, figure 10) and the aggregate wear volume (sum of volumes of all marks, figure 11) increase significantly as the gap between the rod and the spacer spring increases. In the case of a clearance fit of 0.10 mm, the aggregate wear volume at the type “A” was 0.678-0.707 mm^3. Before this case the aggregate wear volume of the tests at interference fit was never greater than 0.042 mm^3. This means that the aggregate wear volume in the case of a clearance fit of 0.10 mm is at least 16 times greater than one at interference fit. In the case of the type “B” the aggregate wear volume (0.664 mm^3) was 332 times greater than one at interference fit (0.002 mm^3).

6. **For the support type with concave contours (Type “G”) a “limit clearance fit” (gap: 0.16/0.16/0.125 mm) was defined. As soon as the gap is larger than this limit clearance fit, the fretting increases very rapidly in the former section of the test. In case of the limit clearance fit the rod comes into contact also with the edges of the support springs. This contact leads to growth of the wear rate.**

On the basis of the results of the fretting tests was determined that the wear process has a starting phase, the first 100 h of the test [3]. At this phase the gap and the dynamic behaviour of the vibrating system at all investigated support types changed largely in comparison to the other part of the test. After this starting phase of the fretting process the change of the gap and the dynamic behaviour of the vibrating system was dependent on the type of support configuration.

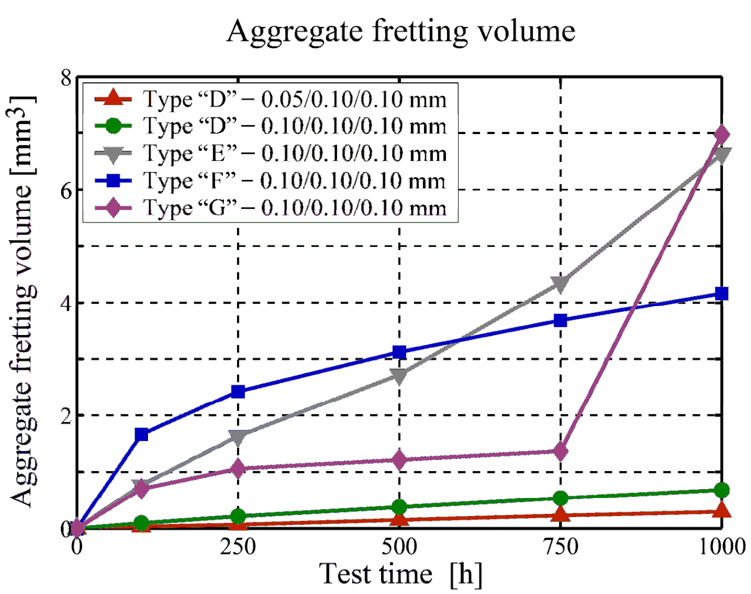

Figure 12: Aggregate fretting volume

The initial rod-to-grid gap increases during the fretting test as the wear marks become deeper. The test rod is able to move more freely and more extensively at the same level of excitation as the gap increases. This can result in an increase in fretting rate. Figure 12 shows the aggregate as a function of test time. The wear marks at the type “D” was not significant (the greatest mark was 36 μm deep after the test) and the aggregate fretting volume increased approximately linearly. At the two tests with the support type “D” (initial gap: 0.05/0.10/0.10 mm and 0.10/0.10/0.10 mm) the wear-rates were $0.3 \cdot 10^{-3}$ and $0.6 \cdot 10^{-3}$ mm^3/h, respectively. In case of the fretting test with the support of type “E” the wear marks were deeper (the largest mark was 80 μm after the test) and the wear-rate decreased up to a test time of 500 h and after 500 h increased. In the tests with the types “F” and “G” the wear rate’s increase was degressive through the convex (rod) – concave (spring) contact which is advantageous in respect to the large contact surface. However after 750 h the aggregate fretting volume at the test with the support type “G” increased rapidly. The wear-rate in the last 250 h of the fretting test was 30 times greater than before.

7. **The spring type (“D”) with a convex contour – but without edge contact – is the most advantageous from all support types as regards fretting investigated in the dissertation [1], [3], [5].**

6. Utilization of the results, further research challenges

In my PhD work I studied the fretting wear of fuel rod cladding tube by means of model tests. In the fretting tests the characterization and the comparison of the cladding fretting were done at the different vibrating rod-support system on the basis of the depth and volume of the wear marks. The dynamic behaviour of the vibrating system was investigated by means of the RMS vibration amplitude and of the transfer functions.

The results of the tests help to develop better spacer grid design regarding the fretting wear, and help in their comparative estimation. The requirement for the reduction of wear is the larger contact surfaces as well as springs, dimples without sharp edge but with rounded edge. Fuel assemblies which have more resistant to fretting wear can be fabricated as a result of the spacer grid development. Thus the reduction of fretting increases fuel assembly service life and reduces operating costs over a ong time.

It must be taken into account when assessing the test results that they were obtained from model tests. A comparative study with the results of tests which were conducted under labor conditions was performed so that one parameter was changed and other parameters were constant. The results of these model tests can help provide a better understanding of real fretting processes inside the reactor, but do not give their identical description. Therefore a more real model has to be developed in the further research. For instance the two directional excitation which will be introduced at AREVA NP GmbH in the next years.

7. Publications coupled to the theses

Papers in the field of the dissertation:

[1] **Kovács, Sz.**, Stabel, J., Ren, M., Ladouceur, B.: Comparative study on rod fretting behavior of different spacer spring geometries, Wear 266 (2009), pp. 194-199

[2] **Kovács, Sz.**, Stabel, J., Ren, M., Ladouceur, B.: Influence of grid-to-rod fit on fuel rod fretting, Periodica Polytechnica, megjelenés alatt

[3] **Kovács, Sz.:** Fretting behavior in three different model support configurations, Periodica Polytechnica, megjelenés alatt

[4] **Kovács, Sz.:** A korróziós réteg és a gerjesztőerő hatása a fűtőelemburkolat frettingkopására, Magyar Energetika, 2008/5, pp. 42-45

Poster presentation and conference proceeding:

[5] **Kovács, Sz.:** Investigation of fretting on a mock-up fuel rod with rod-to-spring and rod-to-dimple contact, Gépészet 2008, Budapest, 2008. May 29-30.

8. Literature

[6] Billerey, A.: Evolution of Fuel Rod Support under Irradiation – Impact on the Mechanical Behaviour of Fuel Assemblies, in: Structural behaviour of fuel assemblies for water cooled reactors, (in Cadarache, France, 22–26 November 2004), IAEA-TECDOC-1454, pp. 101-111, Vienna, 2005

[7] Csom Gy.: Atomerőművek üzemtana, II. kötet, Az energetikai atomreaktorok üzemtana, 1. rész, Műegyetemi Kiadó, Budapest, 2005

[8] OECD: Glossary of Terms and Definition in the Field of Friction, Wear and Lubricant, OECD Publications, Paris, 1969

[9] Baillon, N.: Grid to Rod Fretting Wear in EDF PWR from Operating Problems to New Designs Qualification Method, in: Structural behaviour of fuel assemblies for water cooled reactors, (in Cadarache, France, 22–26 November 2004), IAEA-TECDOC-1454, pp. 209-219, Vienna, 2005

[10] Vallory, J.: Methodology of PWR Fuel Rod Vibration and Fretting Evaluation in HERMES Facilities, in: Structural behaviour of fuel assemblies for water cooled reactors, (in Cadarache, France, 22–26 November 2004), IAEA-TECDOC-1454, pp. 221-230, Vienna, 2005

[11] Kim, Y.H., Jeon, S.Y., Kim, J.W.: Fretting wear of fuel rods due to flow-induced vibration, in: Transactions of the 14th International Conference on Structural Mechanics In Reactor Technology (SMIRT14), Paper C04/4, Lyon, 1997

[12] Kim, H.K., Kang, H.S., Yoon, K.H., Song, K.N.: Experimental Investigation on the Parameters Affecting Fuel Fretting Wear, in: Transactions of the 16th International Conference on Structural Mechanics In Reactor Technology (SMIRT16), Paper #1548, Washington DC, 2001

[13] Kim, H.K., Kim, S.J., Yoon, K.H., Kang, H.S., Song, K.N.: Fretting wear of laterally supported tube, Wear 250 (2001), pp. 535-543

[14] Kim, H.K., Lee, Y.H.: Influence of contact shape and supporting condition on tube fretting wear, Wear 255 (2003), pp. 1183-1197

[15] Kim, H.K., Lee, Y.H.: Charateristic of slipping behaviour in vibratory wear of a supported tube, Wear 259 (2005), pp. 337-348