# Fretting wear of the TVSA-T fuel assembly Zr cladding

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## Introduction

In NPP Temelín, units 1 and 2 are succesfully operated Russian fuel assemblies TVSA-T. As the part of the technical support to fuel cycle management some studies of the grid-to rod fretting wear are performed. It is well known that this phenomenon is one of the sources of failures of nuclear fuel rods. Key factors affecting the fretting wear is the spacer grid geometry, the coolant pressure pulsations generated by the main circulation pumps and work of friction forces between the the Zr cladding and spacer grid dimples. The work of the friction forces is function of the contact force between the Zr cladding,spacer dimple and of the value of the friction coefficient. In cooperation between Nuclear Research Institute Rez and University of West Bohemia in Pilsen, Dept. of Mechanics all performed works may be divided into the three categories such as development of the Zr wall thinning, study of the influence of the friction on the vibrations of the fuel rods and on the fretting wear, study of the impact between uranium pellets and the Zr cladding and study of the uncertainties in the work of the friction forces and friction coefficient on the wall thinning.

## Grid-to rod fretting wear model

Development of the engineering fretting wear model is based on the following assumptions

- a single contact is modeled and is located at all spacer grids
- the contact is supposed between Zr cladding and the spacer grid dimple
- the wear-critical component is the thin walled Zr cladding tube.

The following mathematical model has been developed /1/

$$\Delta m = \mu \frac{f(\omega)}{f_0} W \frac{t_{op}}{T_0} \tag{1}$$

where denote

$\Delta m$... loss of the mass of the Zr tube in contact with the dimple
$\mu$ … fretting wear coefficient
$f(\omega)$… friction coefficient as the function the rod sliding frequency
$f_0$… design value of the friction coefficient.
$W$ … work of the friction forces
$t_{op}$… time of the fuel rod operation
$T_0$… periode of the pressure pulsations generated by the main circulating pumps

Values of the $\mu$ and $f(\omega)$ must be obtained experimentally /2/. Work of the friction forces is calculated using our model of the VVER 1000/320 reactor. The lumped mass model with 137 degrees of freedom include all reactor internals, reactor pressure vessel, all fuel assemblies and the top head with all CRDMs. Excitation of the reactor model are pressure pulsations generated by the main circulation pumps which act on the core barrel and the reactor pressure vessel. The fuel assmblies are excited kinematically in the contact of the fuel assembly tail piece and the core barrel bottom and in the contact of the fuel assmbly with lower plate of the block of the protective tubes. Results of the calculations are illustrated in the next Tab. 1.

| Denotation | Dimensions | Symbols | Extremal values for grid № 1 | | | | |
|---|---|---|---|---|---|---|---|
| | | | $u = 9$ | $u = 11$ | $u = 28$ | $u = 31$ | $u = 46$ |
| Contact forces | $N$ | $N_{u,1}$ | 29.0 | 20.7 | 21.8 | 20.9 | 22.6 |
| | | $N_{u,2}$ | 20.7 | 21.3 | 21.5 | 20.5 | 21.1 |
| | | $N_{u,3}$ | 24.2 | 21.1 | 22.1 | 20.7 | 21.1 |
| Slip displacement | $\mu m$ | $z_{u,1}$ | 5.98 | 6.53 | 6.9 | 6.12 | 6.56 |
| | | $z_{u,2}$ | 7.54 | 8.34 | 8.64 | 7.71 | 7.92 |
| | | $z_{u,3}$ | 2.98 | 2.98 | 3.39 | 2.91 | 3.48 |
| Slip velocity | $mm/s$ | $c_{u,1}$ | 1.15 | 1.02 | 1.04 | 1.00 | 1.00 |
| | | $c_{u,2}$ | 1.53 | 1.46 | 1.38 | 1.26 | 1.18 |
| | | $c_{u,3}$ | 0.47 | 0.54 | 0.57 | 0.48 | 0.56 |
| Output of the friction forces | $mW$ | $P_{u,1}$ | 5.35 | 4.07 | 4.15 | 4.01 | 4.00 |
| | | $P_{u,2}$ | 6.08 | 5.92 | 5.66 | 4.98 | 4.73 |
| | | $P_{u,3}$ | 1.91 | 2.13 | 2.42 | 1.92 | 2.34 |
| Work of the friction forces | $\mu J$ | $W_{u,1}$ | 123.5 | 96.0 | 104 | 98.1 | 102 |
| | | $W_{u,2}$ | 164 | 131 | 134 | 122 | 121 |
| | | $W_{u,3}$ | 50.8 | 49.2 | 53.5 | 46.8 | 54.0 |

Tab. 1

u....positions of the fuel rods in the 1/6 segment of the fuel assembly
g....number of the spacer grid
s....number of the 1/6 segment

**Influence of the gap between the uranium pellets and the Zr tube on the vibration of the fuel rod.**

Theory has been developed in the report /3/, simulation is performed for five operating states. Supposed is linear behaviour of the following parameters i.e. gap between uranium pellet and the Zr tube $\delta$, spacer grid dimple force $F_0$ and upper pring fixing device force $F_F$. Numerical values are illustrated in the next Tab. 2.

| State | $F_0[N]$ | δ $[\mu m]$ | $F_F[N]$ |
|---|---|---|---|
| I | 20 | 65 | 5 |
| II | 16.25 | 48.75 | 6.25 |
| III | 12.5 | 32.50 | 7.5 |
| IV | 8.75 | 16.25 | 8.75 |
| V | 5 | 0 | 10 |

Tab. 2: numerical values of the parameters for the simulation of the fuel rod vibrations

In the next Figs.1 and 2 are uillustrated changes of the sliding velocities in the spacer grids1, 4 and 8 as the functions of the limit state I and V. In both Figs are also shown critical velocities $c_{crit}$ when for all velocities $c < c_{crit}$ exist seisure and not sliding. In the Fig.1 are to seen typical changes given by the presence of impacts in the state I. For the state V impacts are very rare ond only in special cases.

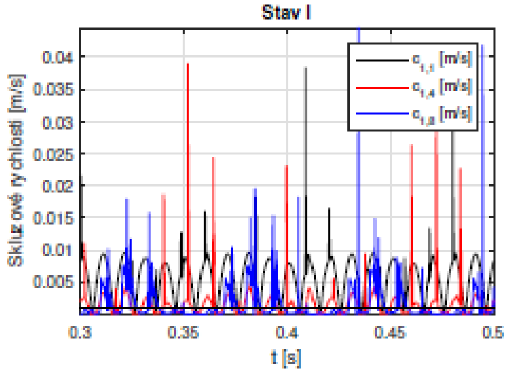


Fig. 1

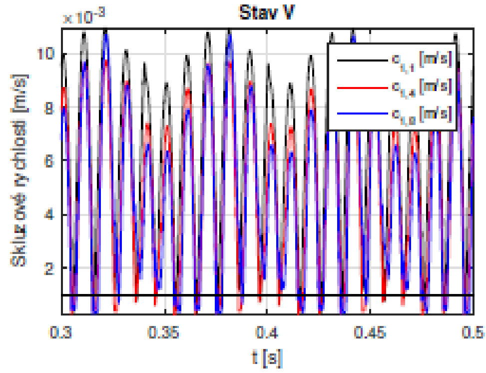


Fig. 2

Sliding velocities between the spacer grid and the Zr tube

In the Figs.3 and 4 are illustrated normal forces in the dimples of the spacer grids 1, 4 and 8 in both limit states. Typical are oscillations of the dynamic component of the pushing force against static value $F_0$. For the dtate V is typical decreasing of the force $N_{1,1}$ to the zero value. This represent loss of the contact between Zr tube and the related dimple of the spacer grid.

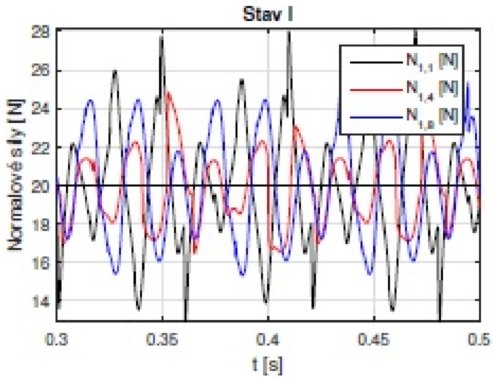


Fig. 3

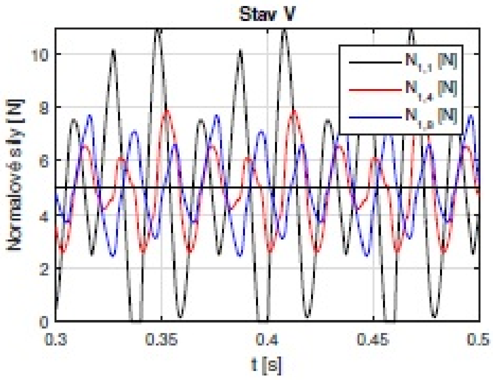


Fig. 4

Normal forces in the spacer grids 1,4 and8

In the Figs.5 and 6 are illustrated normal impact forces between uranium pellets and Zr tube in selected points of the fuel rod discretization. Significant are high amplitudes of the impact forces in the state I when the gap δ has maximal nonzero value.

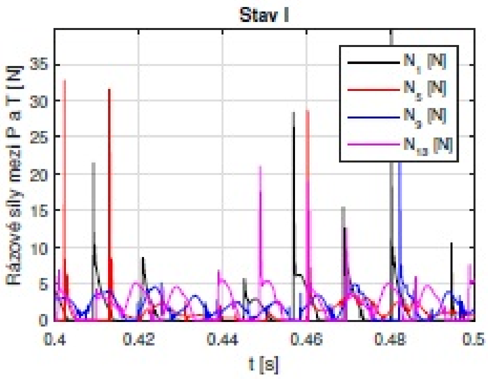


Fig. 5

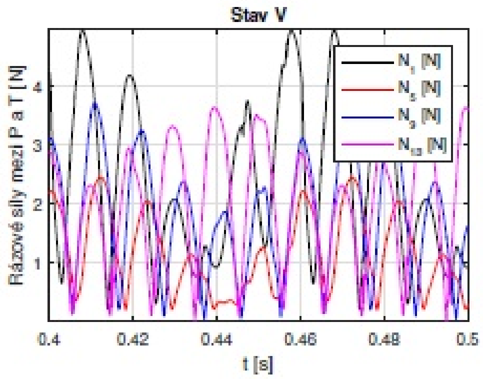


Fig. 6

**Impact forces between Zr tube and uranium pellets**

In the Fig.7 is illustrated fretting wear per one hour in states I, IV and V in all eights spacer grids and in all three dimples. It is evident that in the state I the maximal frettinfg wear exist on the spacer grid No 1 and for the spacer grids from 2 to 7 decrease. Increase in the spacer grid No 8. Expected is is the decreasing of the fretting wear in the states from II to IV. In the state V is interesting the nearly uniform values of the fretting wear in all spacer grids. It may be clarified as the decreasing of the pushing forces, see Figs. 2 and 4.

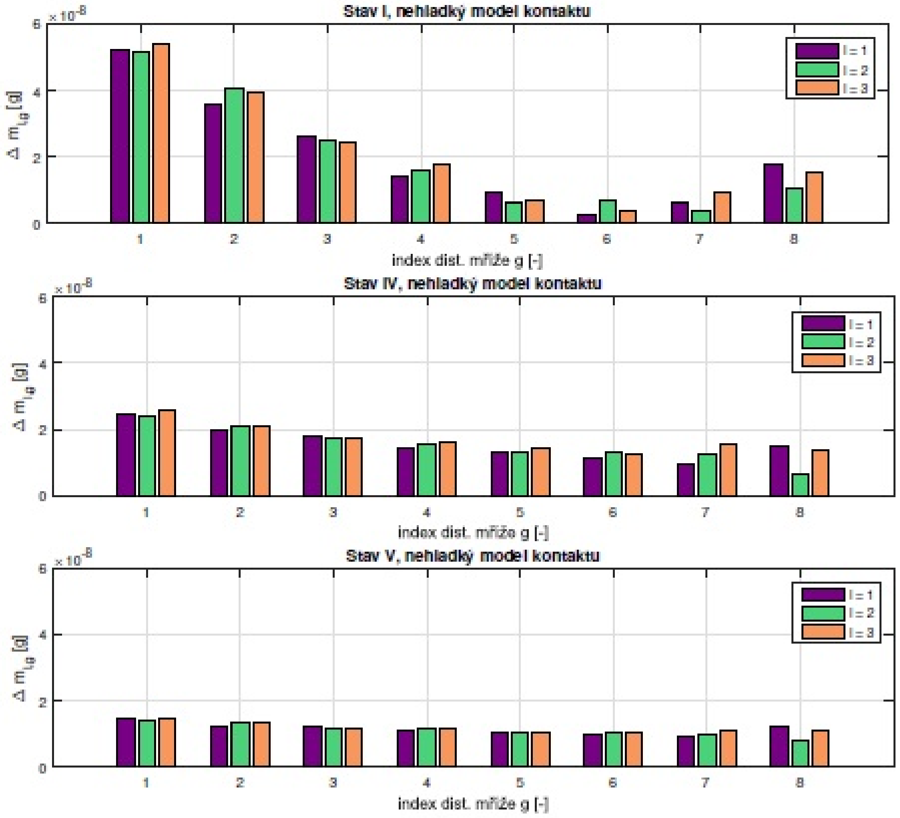


Fig. 7: Fretting wear per one hour as the function of the spacer grids in states I, IV and V.

**Influence of the uncertainties of the work of friction forces and the friction coefficient on the Zr tube wall thinning.**

To calculate Zr tube wall thinning $\Delta t$ in the contact spacre grid dimple the master equation takes form

$$\Delta t = \mu \frac{1}{\sqrt{R_0^2 - (R_0 - \Delta t)^2}} - \frac{1}{2\rho} \frac{f(\omega)}{f_0} W \frac{t_{op}}{T_0} \qquad (2)$$

where denote
$R_0$… outer radus of the Zr tube
$\rho$… density of the Zr tube
l… length of the contact of the Zr tube with dimple

The iteration proces must be used.The friction coefficient $f(\omega)$ depend on the slip velocity. Using the Table 1 is evident that typical values range approximately from 1 to 1.5 mm/s. Values of $f(\omega)$ are illustrated in the Fig.8 /4/.

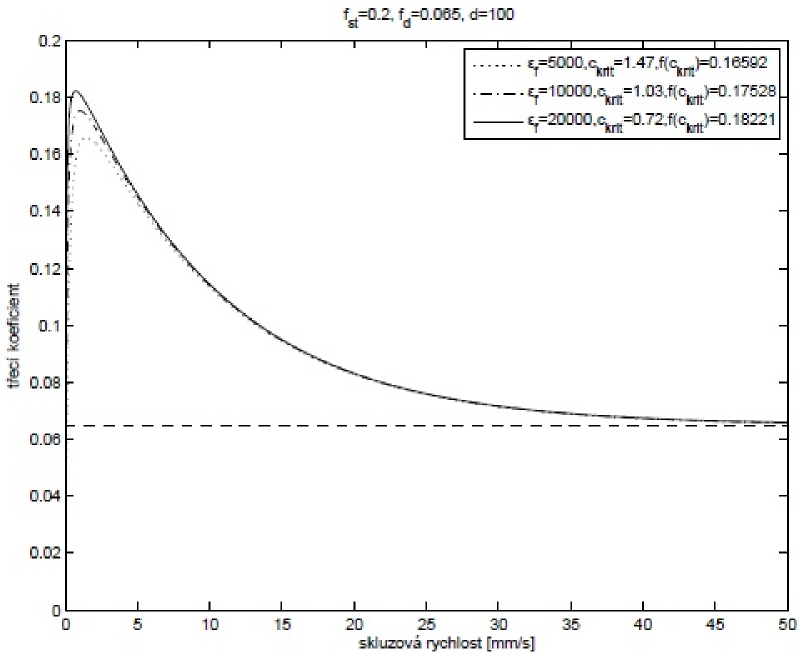


Fig. 8

$$f(\omega) = \frac{2}{\pi} arctg\ (\varepsilon_t; c_{j,g})\left[t_d - (f_{sk} - f_d)e^{-dc_{jg}}\right] \qquad (3)$$

It is obvious that for slip velocities 1-1.5mm/s the $f(\omega)$ range from 0.15 to 0.18. Next parameter which influence Zr tube wall thinning is work of friction forces. Some numerical values are presented in the table T1. It is obvious that W range from 163$\mu J$ to 96$\mu J$ related to specific dimple.To generalize this values to all fuel rods in the 1/6 segment the Student distribution function has been applied. As the result we have obtained range of W 158.8 : 110.2$\mu J$ with probability of 90%. In general both $W$ and $f(\omega)$ have a random character and this must be respected in calculation of the Zr wall thinning. The Simulation Based Reliability Analysis (SBRA) based on the Monte Carlo method has been applied /5/. The computer code Anthill has been used. In this case the master equation takes the form

$$\Delta t = \mu \frac{1}{\sqrt{R_0^2 - (R_0 - \Delta t)^2}} - \frac{1}{2\rho} \frac{f(\omega)}{f_0} W \frac{t_{op}}{T_0} < 68.5\mu m \qquad (4)$$

where $68.5\mu m$ is the acceptable wall thinning at the end of fourth campaing/6/. For the numerical calculations is supposed that both W and $f(\omega)$ have Gausssian distribution with standards deviation 10% of mean value. Resuls of calculation is illustrated in Fig. 9.

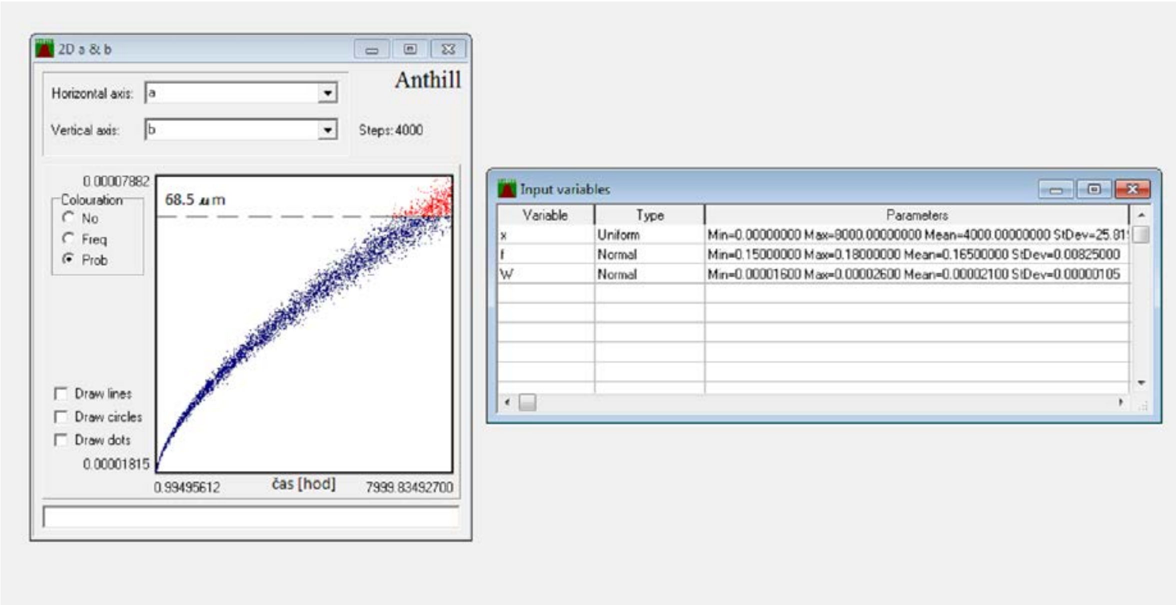


Fig. 9

**Conclusions**

The numerical simulation of the specific problems of the TVSA-T fuel assemblies has been presented.Obtained results may be summarized as follows

- friction and the impact forces influence the fretting wear in all spacer grids. Maximal values are expected at the lower spacer grids, minimal values on the central grids and on the top grid are slightly higher
- at the end of the fourth campaing the forces between Zr tube and spacer grid decrease from starting value 20N to approximately 5N. It result in loss of contact and to increasing of dynamic normal forces on the lowest grid No1 as the result of impact
- impact forces between the column of fuel pellets and Zr tube are maximal in the first campaing. At the lower part of fuel rod reach the value approximataly 30N. In the next campaings the gap between uranium pellets and Zr tube decrease to the zero value and the impact forces vanish
- values of fretting wear in the second and the next campaings decrease as the result of decreasing the force between the Zr tube and the spacer grid dimple. Distribution of the fretting wear the height over the fuel rod is nearly uniform
- since that slip velocities are approximately 1mm/s it result in random character of the friction coefficient. Some phenomenon may be expected in the case of the work of friction forces. To calculate the Zr tube wall thinning the application of the Simulation Based Reliability Analysis seems to be useful.

## References


/1/ Hlavac.Z : Zeman.V — Vibration of Nuclear Fuel Assemblies: Modeling, Methods, Application
LAP Lambert Academic Publishing, Saarbrucken, (2013)
Monograph

/2/ Pecinka L.: et al — Fretting wear of the fuel rod cladding ICONE 22, Prague,2014

/3/ Zeman V.: et al — Influence of the friction in the contact Zr cladding-spacer grid on the vibrations and the fretting wear of the fuel rod
Report University of West Bohemia in Pilsen, Dept. of Mechanic, 2016, in Czech language only

/4/ Brepta R.: et al — Mechanical vibrations Technical Guide 71, Publishing Sobotáles 1994, in Czech language only

/5/ Marek P.: — Probabilistic Assessment of the Structures using Monte Carlo Simulation TeReCo (Technical Reliability Concept using Simulation)
Leonardo da Vinci Programme 2001, ITAM, Czech Academy of Science, Prague

/6/ Mattia Del Giacco: et al — Fretting of fuel cladding materials for Pb cooled fast reactor-long term prediction using fretting maps
ICONE 21, Chengdu, China, 2013