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# Framatome creep fatigue-damage modelling on irradiated fuel cladding and its use for fuel design

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## ABSTRACT

A creep - fatigue model has been developed by FRAMATOME using a phenomenological approach. The coefficients of the fatigue model are identified by a non linear regression analysis for various confidence levels. Applied to various tests performed in different experimental conditions, the model predicts failure with sufficient safety margins. A method was developed and qualified to analyse the behavior of fuel rods with regard to the fatigue phenomena when they are subjected to grid follow at high burnup.

## INTRODUCTION

The fatigue phenomena produces damage in the cladding and could lead to rupture if the rods are subjected to power cycling during a long time. In addition, creep damage could be cumulated with fatigue if the cladding strains due to power transients are held during sufficient time. The characteristics of cladding materials and especially microstructure and inner surface roughness play a key role in the creep-fatigue resistance of the tubes. The improvement of fuel materials and manufacturing process connected with the generalization of grid follow in the EDF reactors led FRAMATOME to develop new models and methods on an updated data base to analyze clad fatigue behaviour.

## CUMULATIVE CREEP - FATIGUE MODEL

The model is based on the elementary creep and fatigue damage as defined by Lemaître et al. [1] and adapted to Zircaloy 4 by FRAMATOME [2]. The creep and the fatigue damages are related to the presence of defects inside the material . These defects modify the stresses which are applied to the sound material and the author introduces for this purpose the concept of efficient stress $\tilde{\sigma}$ defined by :

$$\tilde{\sigma}=\frac{\sigma}{1-D} \qquad [1]$$

where D is the cumulated damage and $\sigma$ the applied stress.

The elementary creep and fatigue damage, respectively $dD_c$ and $dD_F$ during elementary time dt and number of cyles dN are expressed as follows :

$$dD_c = g(D_c, t, t_c, \bar{\sigma}, T)dt \qquad [2]$$

$$dD_F = f(D_F, N, N_F, \bar{\sigma}, T)dN \qquad [3]$$

where : f and g are functions, N is the number of cycles, t the time, $t_c$ the creep life span, $N_F$ the number of cycles to rupture, $D_c$ and $D_F$ are respectiveley the creep and the fatigue damage, $\bar{\sigma}$ the mean stress during one cycle, T the temperature

The elementary cumulated damage dD is equal to :

$$dD = f(D, N, N_F, \bar{\sigma}, T)dN_F + g(D, t, t_c, \bar{\sigma}, T)dt_c \qquad [4]$$

The creep damage is expressed by the law of Kachanov and Rabotnov :

$$D_c = 1 - (1 - \frac{t}{t_c})^{\frac{1}{k(\bar{\sigma})+1}} \qquad [5]$$

where k is a function depending of the material.

To take into account the effect of the average stress, the variables $\sigma_M$ and $\sigma$ are introduced and after integration from 0 to 1 the equation of elementary damage $\delta D_F$ during the number of cycles $\delta N$ is expressed by :

$$\delta D_F = (1 - (1 - D_F)^{(\beta+1)})^{\alpha(\sigma_M, \bar{\sigma})} (\frac{\sigma_M - \bar{\sigma}}{M(\bar{\sigma})(1 - D)})^{\beta} \delta N \qquad [6]$$

where $\beta$ is a coefficient, M and $\alpha$ are functions, all depending of the material.

The ovality of the tube introduces an overstress. In order to be able to take into account this effect, the model uses a general formula given by Lemaître as an equivalent damage stress $\sigma^*$ which replaces $\sigma$ in the general law and is formulated as follows :

$$\sigma^* = \sigma_{eq} \sqrt{(\frac{2}{3}(1+\nu) + 3(1-2\nu)(\frac{\sigma_H}{\sigma_{eq}})^2)} \qquad [7]$$

Where $\sigma_{eq}$ and $\sigma_H$ are the von Mises equivalent stress and the hydrostatic stress respectively, $\nu$ the Poisson's ratio of elastic contraction.

## EXPERIMENTAL DATA BASE.

The internal pressurization test developed by FRAMATOME, EDF and CEA was used. This is the most representative with regard to the cladding stresses during PWR irradiations. The stress is given by the formula

$$\sigma_\theta = P_i \frac{\varnothing_i}{2e} \qquad [8]$$

where : $\sigma_\theta$ is the cladd stress, Pi the internal pressure and e the clad thickness.

During this test the tube is subjected to stress cycling and the minimum , maximum and average stresses are respectively $\sigma_m = 0$, $\sigma_M$ and $0.5 \times \sigma_M$. Following the usual terms the stress variation is equal to $\Delta\sigma = \sigma_M - \sigma_m$ and the stress amplitude to $0.5 \times \Delta\sigma$. The pure fatigue tests are conducted following a triangular stress shape versus time at frequencies ranging between 0.5 Hz and 2 Hz, whereas a trapezoidal stress shape is imposed in order to simulate more realistic stress histories to take into account creep damage. The general aspect of the cycles is presented on Figure 1.

The tested tubes are made of stress relieved Zircaloy 4, the temperature of the tests is equal to 350 °C, the tubes have the standard 17×17 PWR design. The chemical composition was : Sn = 1,27 %, Fe = 0.20 %, Cr = 0.10 %, O = 0.103 %.

The tests were performed on non irradiated and irradiated tubes coming from rods irradiated in various operating modes (baseload irradiation, daily load follow and hourly grid follow, high burnups [3]) in GRAVELINES 3 and GRAVELINES 2, CRUAS 2 and CAP (Adanced Vessel Prototype at Cadarache) reactors. In addition, the influence of following irradiation conditions in PWR irradiation was tested : integrated fast flux, cladding temperature during the irradiation, external oxide thickness and conditions of cycling. The main results useful for modelling are presented on Figure 2.

## FATIGUE MODEL

The analyses show that the creep was not activated during the triangular cycles. The pure fatigue model was thus determined from the tests conducted following the triangular scheme, with a temperature equal to 350 °C and using tubes non irradiated or irradiated at constant LHGR. For each class of test (non irradiated or irradiated) the coefficients of the equation [7] were determined using a statistical method. The model considers the classical fatigue parameters and expresses the number of cycles to rupture which depends on the ultimate stress $\sigma_U$, $\sigma_M$, and the fatigue limit $\sigma_{l0}$. Dividing all the stresses by $\sigma_U$, we obtain :

$$N_F = \frac{ky}{1 - \frac{\sigma_{l0}}{\sigma_U} - y} \qquad [9]$$

where k is fitted versus $N_F$ as the main variable and y is a function of $\sigma_U$, $\sigma_M$ and $\bar{\sigma}$. The solution of this equation allows to minimize $N_F$ versus applied stress for a given confidence level. The 95 % confidence level curves are drawn on Figure 2 for unirradiated and irradiated material.

Taking into account the experimental uncertainties and the various irradiation conditions, the effects of different irradiation and experimental conditions were tested. The experimental results were compared to the prediction of the model. In particular the influence of experimental uncertainties related to the test conditions on the one hand and the irradiation conditions on the other hand was tested. Thus the effects of the following parameters were determined : temperature and frequency during the test, fast flux and power cycling during the irradiation in PWR [4]. The comparison of predicted and experimental results is shown on Figure 3.

## APPLICATION TO FUEL DESIGN

In order to use the model for design, the following general law for failure limit was established which takes into account the average stress effects.

$$\Delta\sigma = \sigma_{l0}\left(1 - \frac{\overline{\sigma}}{\sigma_U}\right) \qquad [10]$$

This formula determines a safe domain which is presented on Figure 4. This figure shows the maximum stress amplitude versus the average stress for the 100 % confidence level. From a safety point of view, to maximize the cladding stresses and to take into account the hourglassing effect, a constant factor (determined with a Finite Element Method [5]) was applied to the average cladding stresses computed with the fuel design code COPERNIC developed by FRAMATOME on the basis of the TRANSURANUS code [6].

The comparison of the maximum stress and $\Delta\sigma$ allows when possible to avoid a complete damage computation, in cases where the cladding stress is always lower than the limit. Otherwise a whole analysis is needed. In that case the linear cumulation of damage is possible and expressed by :

$$D = \Sigma_{j,k} \frac{n_j(\overline{\sigma_j}, \Delta\sigma_j)}{N_{F_j}} \qquad [11]$$

The cladding is subjected to k sequences of $n_j$ cycles, each sequence being characterized by $\overline{\sigma}_j$, $\Delta\sigma_j$ and a corresponding number of maximum cycles $N_{Fj}$.

For the qualification of the method with regard with real reactor situations, the model with a 100 % confidence level was applied to rods which were subjected to daily and hourly grid follow in CRUAS 2 during four cycles. The use of this model provides a safety margin with a factor two on the fatigue limit. A typical power history during the irradiation in CRUAS 2 is shown on Figure 5. The results indicate that after 4 cycles in reactor the fatigue damage is less than 0.16, thus providing sufficient margins.

## CONCLUSION

The fatigue failure has to be taken into account for rod design in many countries. Until now the model generally used was the one published by Langer and O'Donnel. This model was built from a base of various type of cladding tubes irradiated or not and shows no difference between irradiated and non irradiated tubes. The FRAMATOME fatigue model shows the same tendencies as the Langer O'Donnel one for non irradiated tubes but it shows a decrease of the fatigue limit for irradiated materials. The model built from irradiated tubes with a confidence level equal to 100 % includes the experimental uncertainties, particularly temperature and hold time as well as power cycling in PWR. Applied to a real irradiation scheme, it indicates low damage. This model is now in current use by FRAMATOME to demonstrate the harmlessness of cladding fatigue during irradiation.

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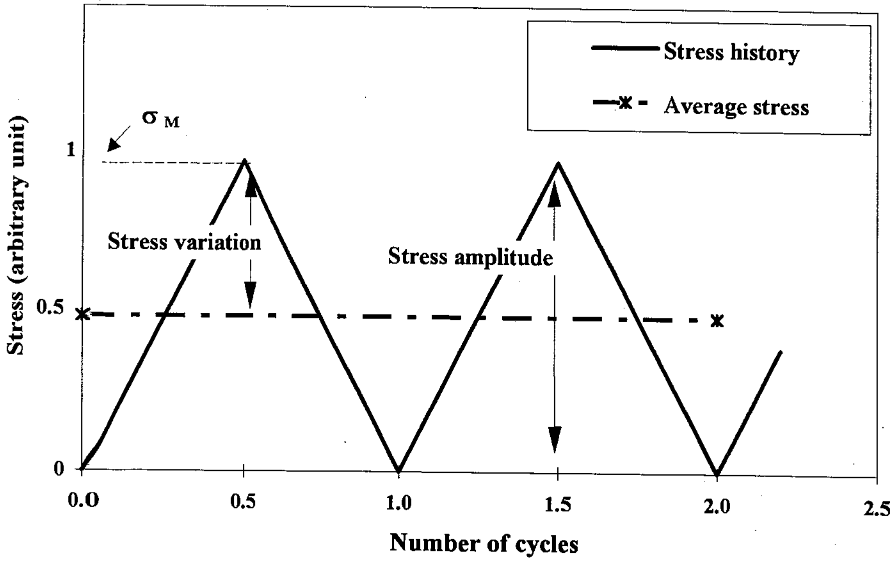

CEA test on irradiated tubes. Oil pressurized machine. Rupture detected by pressure shut down

**Figure 1. Typical stress history during fatigue test.**

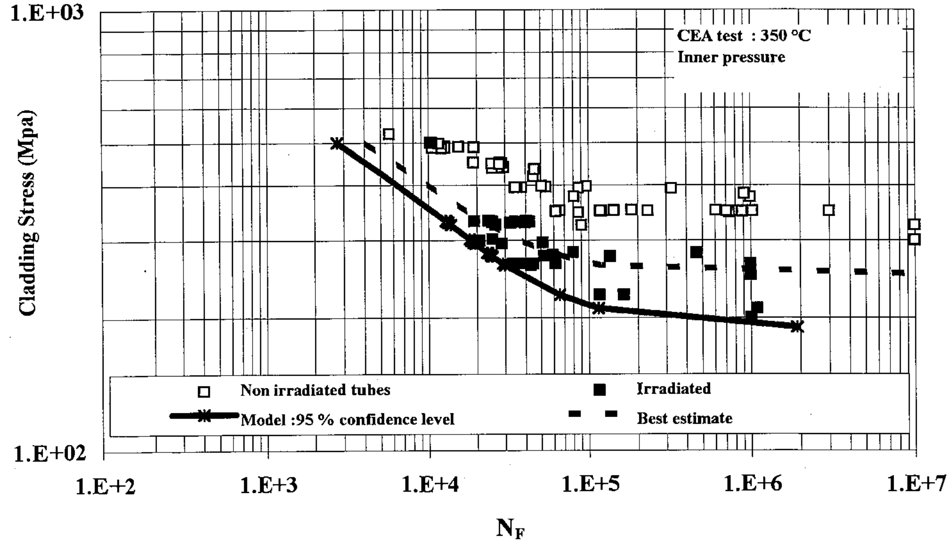

**Figure 2. Fatigue on FRAMATOME tubes. Experimental data base and model**

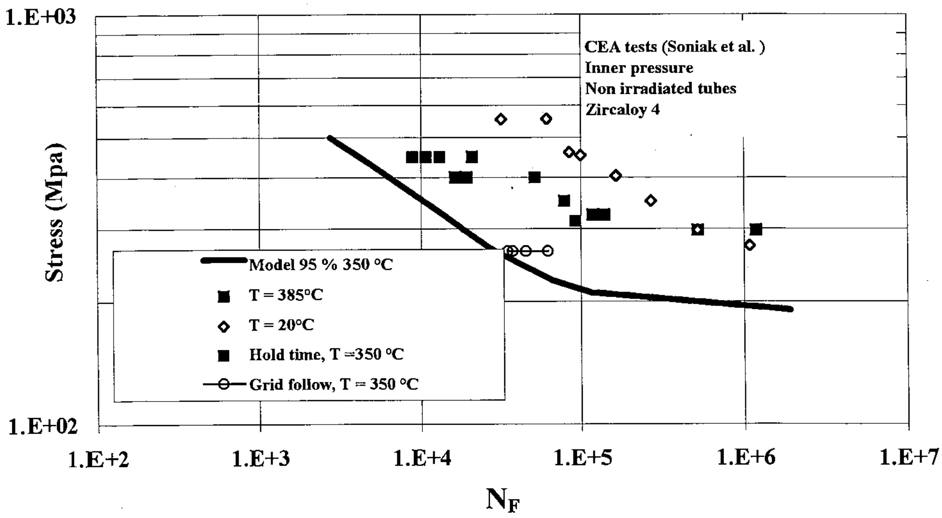

**Figure 3. Influence of experimental conditions and power cycling during irradiation**

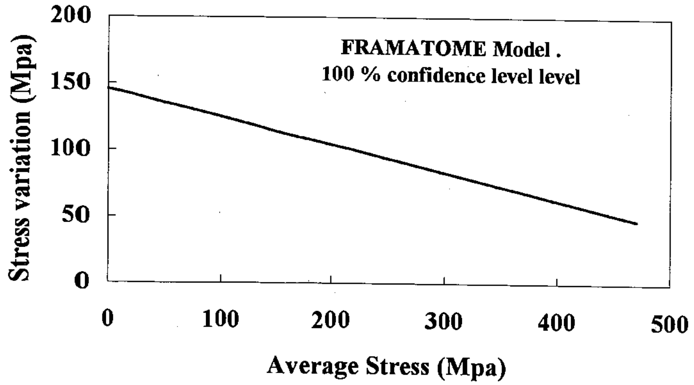

Fig 4. Fatigue model.
Influence of average stress on maximum stress variation

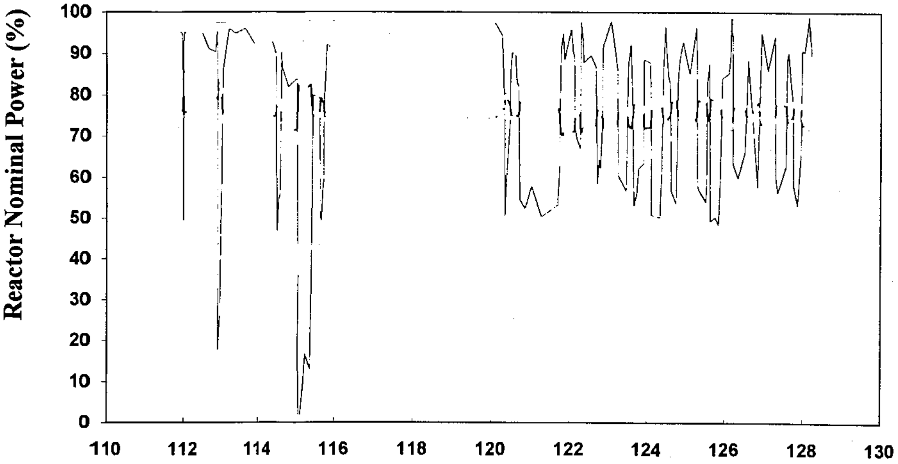

Fig 5. Power cycling. Typical power history during irradiation in CRUAS reactor

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