Model of Zircaloy Cladding Damage in Pressurized Water Reactors

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1 INTRODUCTION

The damage theory describes the macroscopic evolution of the material since the beginning of life up to the crack initiation. Damage is defined as a gradual deterioration of the material under loads resulting in a rupture of the volume element or even in a macroscopic crack. The damage mechanism corresponds to the localization and cumulation of stresses with an irreversible effect.
There can be two approaches to deal with the damage phenomenon:

- the parametric approach,
- the phenomenologic approach.

In our case, the model established is based upon a phenomenologic type approach. Such an approach consists in assuming that the material evolution towards crack can be predicted through two phenomenologic laws: one governing deformation (behaviour law), and the other governing damage (damage law).
This approach, based upon an original method /1/, is adressed in this paper, relying on experimental results /2/, /3/, and another damage method /4/.

2 THE DAMAGE MECHANISM

Damage relating to each one of the fatigue and creep phenomena is represented respectively by a variable set by the following differential equations:

$dDc/dt = h(\bar{\sigma}, T, Dc)$; (1) $\qquad$ $dDf/dt = g(\bar{\sigma}, T, \sigma M, Df)$; (2)

The cumulation of pure fatigue and pure creep effects is not linear. The resulting damage D is governed by the following differential equation:

$dD/dt = h(\bar{\sigma}, T, D) + g(\bar{\sigma}, T, \sigma M, D)$; (3)

The loads experimented by the clad do not result in a simple traction-compression cycle. Loading is not periodic. The cumulation of a type of damage in time (Life Fraction Rule) must be distinguished from the cumulation of different types of damages between themselves (effects of fatigue-creep interaction).

The model of damage cumulation should allow linking random loads with levels of average stress not equal to zero and with any holding time. Besides, this model should be highly representative of the physical phenomena involved.

3 PURE CREEP DAMAGE

3.1 FORMULATION

The type of damage studied is a viscoplastic damage. The pure creep damage of a material is a phenomenon that mainly depends on time.

The first interesting model is the one proposed by KACHANOV in 1958. This law was further improved by RABOTNOV. Various experimental correlations through identification demonstrated how this law is appropriate for simple loading sequences /1/. The following differential form is used:

$dD/dt = (\sigma/AO)^{Ro}\ (1 - D)^{-K(\sigma)}$; (4)

The integration of the equation between 0 and D* gives the evolution of failure time as a function of the stress.

$tr = (1/Ro + 1)\ (\sigma/Ao)^{-Ro}$; (5)

Therefore, the damage evolution as a function of time reduces t/tr:

$D = 1 - (1 - (t/tr))^{(1/(Ro+1))}$; (6)

Function K (σ) depends upon the stress level and the type of material. It allows translating the non linear cumulation phenomenon. The value of K (σ) is an increasing value since damage evolutions are faster for lower loadings.

Coefficients Ao and Ro are determined through identification with the damage evolution measured as creep under constant loading.

3.2 THE CREEP DAMAGE LAW FOR ZIRCALOY-4

Tests of pure creep damage cumulation were performed on stress-relieved Zircaloy-4 claddings /2/. Creep to failure tests were carried out on pressurized specimens, at a 350 °C temperature for circumferential stresses. This allowed ..taining NORTON laws associated to the material.

The various coefficients are determined by means of a scanning program with tests adjusting the model to experimental envelops. In a first time, Ao an Ro are determined taking account of KACHANOV's simplified form ($K(\sigma)$ = Ro).

$K(\sigma)$ form, which is of the ascending power function type, is then determined. The function obtained (Figure 1) is of the following form:

$K(\sigma) = (c/(\sigma_u - \sigma))^d + y\sigma + x$; (7)

The values of the coefficients so obtained are of the same magnitude as those of the coefficients used for other materials /1/. The pure creep damage law (Figure 2) is obtained through correlation of the experimental points /2/ of failure time according to the applied stress.
This allows deducing abacuses $D = f\ (t/tr,\sigma)$.

4 PURE FATIGUE DAMAGE

4.1 FORMULATION

The fatigue damage is caused by alternate loading cycles which result in the initiation and propagation of intercristalline surface microcracks. This damage can occur for stress levels far lower than the yield strength. The fatigue laws are generally drawn up according to the loading cycles and parameters defined for each cycle. Maximum and minimum stresses, cycling period, stress range are significant parameters.

Several aspects must be taken into account:

- initiation and micropropagation processes,
- effects of non linear cumulation under loading of various levels,
- the existence of a decreasing yield strength as a function of damage,
- effects of an average stress upon the fatigue limit and upon WOEHLER's curves.

The studied model /1/ uses WOEHLER's curves which express the results of the single-dimension fatigue tests. They represent the relation between the number of cycles to failure and the maximum stress, using the ration $R = \sigma$ mini/σ maxi as a parameter.

Each one of these curves has two limits. The first one, with a low number of cycles to failure, when the maximum stress tends towards the fatigue limit σP. This fatigue limit is governed by the following equation:

$$\sigma P = \bar{\sigma} + \sigma Po\ (1 - b\sigma);\quad (8)$$

where b is a coefficient specific to each material.

The differential equation governing damage evolution is based upon the remaining lifetime concept. This formulation can be expressed by the following relation:

$$\frac{dD}{dN} = \left[1 - (1 - D)^{(\beta+1)}\right]^{(\sigma N,\, \bar{\sigma})} \left[\frac{\Delta\sigma}{M(\bar{\sigma})\ (1 - D)}\right]^{\beta};\quad (9)$$

This is an universal formulation which can be applied to other materials /1/. The integration of this differential equation allows obtaining the number of cycles to failure Nr.

$$Nr = \frac{1}{(\beta + 1)\ (1 - \alpha)} \left[\frac{\sigma M - \bar{\sigma}}{M\ (\bar{\sigma})}\right]^{-\beta};\quad (10)$$

The damage evolution according to the N/Nr ratio can be expressed by the following relation:

$$D = 1 - \left[1 \left(\frac{N}{Nr}\right)^{(1/1-\sigma)}\right]^{1/(\beta+1)};\quad (11)$$

Function $M(\sigma)$ is defined by:

$M(\sigma) = Mo\ (1 - b\ \bar{\sigma})$; (12).

Function α allows taking account of the non linear cumulation effects and is defined by:

$$\alpha = 1 - a \left(\frac{\sigma M - \sigma l}{\sigma u - \sigma M}\right);\quad (13)$$

In this fatigue damage law, coefficients β, Mo, b, a, σu, σPo are a function of the material and temperature. Their determination is carried out through correlation by means of WOEHLER's curves.

4.2 THE FATIGUE DAMAGE LAW FOR THE ZIRCALOY 4

Tests of continuous fatigue damage cumulation were performed on stress-relieved Zy-4 claddings. These fatigue to failure tests were carried out at 350 °C on pressurized specimens, for various circumferential stresses /3/.

The test control was achieved according to a triangular signal with a high frequency so that creep interaction was reduced and the pure fatigue phenomenon could be approximated.

An experimental WOEHLER's curve was established. It allows obtaining the ultimate tensile strength as well as the endurance limit. Coefficients were determined through identification with experimental results /3/.

The obtained WOEHLER's curves are shown in Figure 3 for three characteristics value of R.

5 FATIGUE - CREEP INTERACTION

The non linear analytical combination of the two laws of creep and fatigue through the damage variable (3) allows quantifying the creep-fatigue damage experimented by the clad during a power transient.

Results of this analytical combination (3) were compared to fatigue-holding time test results /2/, that are representative of the fatigue-creep interaction and independent of the construction of the model.

There is a highly suitable correlation between the theoritical approach using the combination of two pure, analytically coupled phenomena, and the experience directly combining these two phenomena. Indeed, the difference between the predicted lifetime and the experimental lifetime is very small (Figure 4). This provides a major validation of the model and the method used.

A comparaison with the model developped by O'Donnel /4/, is shown in Figure 5. The differences between this two models are caused by a less important contribution of the creep in the model of ref 4.

6 CONCLUSION

The comparison of the experimental results obtained on Zircaloy-4 with the phenomenologic approach used, demonstrates a highly appropriate correlation between them. This shows the adequacy of an approach using combined pure phenomena analytically coupled through a common damage variable.

As far as predicted lifetime is concerned, the processing of various transients through this method gives results complying with the experience acquired. Indeed, the principle of non linear cumulation allows obtaining a realistic evolution of damage in time with a deterioration increasing rapidly near the end of life.

Besides, a comparison of this phenomenologic model with LANGER's model adapted to Zircaloy-4 on experimental fatigue-creep points allows showing a better prediction of damage with a more realistic consideration of creep.

Works carried out up to now mainly addressed non irradiated Zircaloy-4, and tests under progress at the CEA will allow applying the model to irradiated Zircaloy-4 also.

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NOTES

Zy-4	: Zyrcaloy-4.
N	: Number of cycles to fatigue failure.
Nr	: Number of cycles.
σ	: True stress.
σPo	: Fatigue limit with an average zero stress.
$\sigma P(\bar{\sigma})$	: Fatigue limit as a function of the average stress.
σm	: Minimum stress during the cycle.
σM	: Maximum stress during the cycle.
σu	: Ultimate yield strength.
$\bar{\sigma}$	: Mean stress during the cycle.
$\Delta\sigma$	: Stress amplitude over a cycle.
Mo, a, β, α	: Fatigue CHABOCHE coefficient.
D	: Material damage (D* value to rupture).
b	: GOODMAN's law coefficient.
N/Np	: Reduced number of cycles or usage factor.
R	: Ratio of the minimum stress to the maximum stress for the cycle.
Ro	: Model creep exponent of KACHANOV/ROBOTNOV.
Ao	: Model creep coefficient of KACHANOV/ROBOTNOV.
tr	: Creep failure time (CHABOCHE).
K(σ)	: Model creep exponent (CHABOCHE).
Dc	: Creep damage.
Df	: Fatigue damage.
c, d, x, y	: K(σ) coefficient.

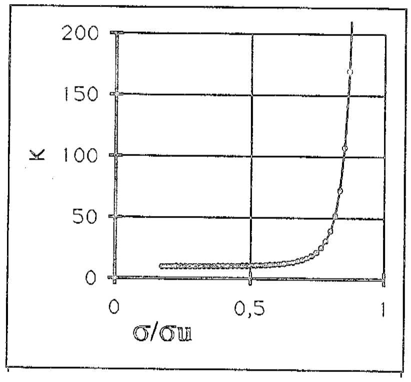

Fig.1 Curve of Function K.

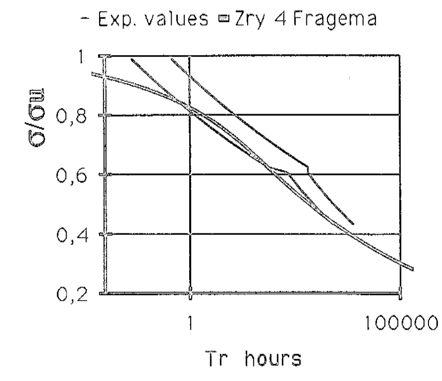

Fig.2 Creep Lifespan of Zircaloy 4 at 350°C.

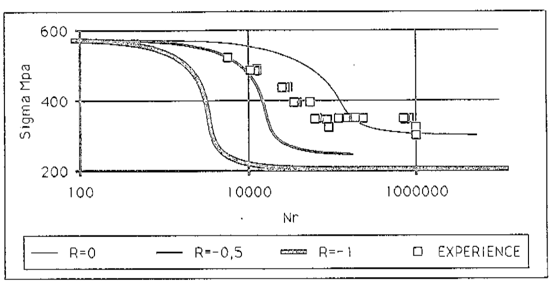

Fig.3 Woehler's Curve for Zircaloy 4 at 350°C.

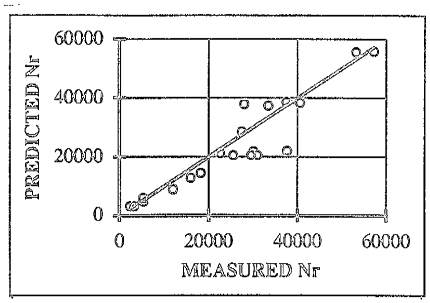

Fig.4 Creep-Fatique Interaction. Comparison predicted Values with Measured Values.

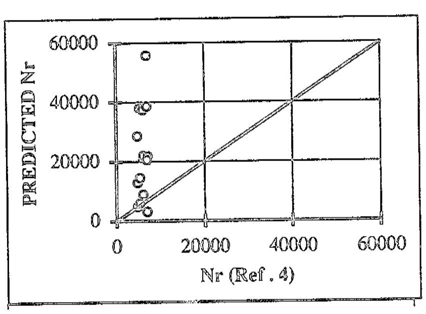

Fig. 5 Creep fatigue Interaction Comparison with ref. 4.