A PHENOMENOLOGICAL THERMAL AND IRRADIATION CREEP MODEL FOR ZIRCALOY

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Summary

A phenomenological Zircaloy creep model has been developed at KWU. This model assumes that total creep strain is given by a linear superposition of thermally activated and irradiation induced creep. Both mechanisms consist of a primary creep strain ε_p and a steady state creep strain $\dot{\varepsilon}_s \cdot t$, so that the total creep strain is $\varepsilon_{p,\,th} + \dot{\varepsilon}_{s,\,th} \cdot t + \varepsilon_{p,\,irr} + \dot{\varepsilon}_{s,\,irr} \cdot t$.

From the evaluation of creep strain vs. time curves it has been found that the maximum creep strain due to primary creep, $\varepsilon_{p,o}$, increases with steady state creep rate: $\varepsilon_{p,o} = c \cdot \dot{\varepsilon}_s^{\,p}$, where c and p are material constants depending on the amount of cold work. They are identical for thermal and irradiation creep. For the time dependence of primary creep an exponential function $\varepsilon_p = \varepsilon_{p,o} \cdot [1 - \exp(-k \cdot \sqrt{t})]$ is assumed, (k = material constant).

The essential effects of temperature T, stress σ, fast neutron flux ϕ and metallurgical conditions on the creep behaviour are taken into account in the thermally activated and irradiation induced steady state creep rates, $\dot{\varepsilon}_{s,th}$ and $\dot{\varepsilon}_{s,\,irr}$.

For thermal creep the temperature influence is given by exp (-Q/RT), where Q = activation energy, R = gas constant. On the other hand, the temperature is also important in the combination with the effect of stress. It has been demonstrated that an introduction of a "plastic flow factor" $\alpha(\sigma/\bar{\sigma}) = \cos(\frac{\pi}{2}\frac{\sigma}{\bar{\sigma}})$ or $\alpha(\sigma/\bar{\sigma}) = 1 - (\sigma/\bar{\sigma})^2$ (both functions agree within 10 % for $\sigma/\bar{\sigma} \leq 0.7$) in analogy to the elasto-plastic fracture mechanics, improves the description of stress effects. The guiding parameter for $\alpha(\sigma/\bar{\sigma})$ is the limiting stress $\bar{\sigma}$, which is close to the ultimate stress and depends on temperature and metallurgical conditions. Using $1/\alpha(\sigma/\bar{\sigma})$ as a creep enhancement factor, the creep rate $\dot{\varepsilon}_s$ can be expressed as $\dot{\varepsilon}_s \sim \frac{\sigma^n}{\alpha(\sigma/\bar{\sigma})}$; n is independent of σ and may have different values for $\dot{\varepsilon}_{s,\,th}$ and $\dot{\varepsilon}_{s,\,irr}$.

Furthermore, it is assumed that $\alpha(\sigma/\overline{\sigma})$ can be applied to the maximum shear stresses: $\tau_{ta} = (\sigma_t - \sigma_a)/2$; τ_{tr}, τ_{ar}. Then the creep strain calculations under multiaxial stress conditions can be performed easily:

a modified stress function for each direction can be defined: e.g. in the hoop direction $f_t(\sigma_i, n) = \tau_{ta} \cdot \frac{|2\tau_{ta}|^{n-1}}{\alpha(\tau_{ta}/\overline{\tau})} + \tau_{tr} \cdot \frac{|2\tau_{tr}|^{n-1}}{\alpha(\tau_{tr}/\overline{\tau})}$; i = direction index, $\overline{\tau} = \overline{\sigma}/2$.

Many results of creep experiments have been evaluated for the calibration of material constants. The data analyzed have been taken from the literature and from KWU measurements including post-irradiation examination results from fuel rods of light water reactors.

As a result of this evaluation the following relationship has been established:

$$\dot{\varepsilon}_{s,i}(\sigma_j, T, \phi) = A_{th} \cdot \exp(-Q/RT) \cdot f_i(\sigma_j, n_{th}) + A_{irr} \cdot \phi^{\ell} \cdot f_i(\sigma_j, n_{irr})$$

$$\dot{\varepsilon}_s\ [1/h], \quad \sigma_j\ [N/mm^2], \quad T\ [K], \quad \phi\ [n/cm^2 \cdot s]$$

where the creep constants for Zircaloy are:

$A_{th} = 2.0 \cdot 10^7\ (N/mm^2)^{-n_{th}}/h$; $n_{th} = 1.87$; $Q = 2.17 \cdot 10^8\ J/mol$; $R = 8.314\ J/mol \cdot K$

$A_{irr} = 7.2 \cdot 10^{-21}\ (N/mm^2)^{-n_{irr}} (n/cm^2 \cdot s)^{-\ell}/h$; $n_{irr} = 1$, $\ell = 0.85$.

The calculated total creep strain, $\varepsilon_p + \dot{\varepsilon}_s \cdot t$, (with c = 2400 h, p = 1, k = 0.1 $h^{-1/2}$ for ε_p) shows a good agreement with the observed results. A reasonably good agreement with other experimental data which have not been used for the calibration has been achieved.

The results of the calculations indicate that the KWU creep model is able to predict Zircaloy creep behaviour realistically over a wide range of temperature and stress.

1. Introduction

The knowledge of the creep properties of Zircaloy is the basis for predicting the deformation of a Zircaloy fuel rod as a function of time in reactor. The creep deformation behaviour of the cladding, if plotted against time to obtain the "creep curve", can be segregated into primary, secondary, and tertiary phases. In the initial phase the creep rate is high and diminishing continuously. For a metallurgically stable material tested at constant stress, the creep rate would continue to decrease, until the minimum creep rate is reached. In this phase the creep rate may remain constant for long periods of time. Fortunately such behaviour is observed in the most creep curves of Zircaloy material.

Mathematically the creep curve can be described as

$$\varepsilon(t) = \varepsilon_o + \varepsilon_p(t) + \dot{\varepsilon}_s \cdot t \tag{1}$$

where

ε_o = initial elastic strain
$\varepsilon_p(t)$ = time dependent primary creep
$\dot{\varepsilon}_s$ = steady state creep rate
t = time .

The applicability of this formula has been confirmed in a variety of creep strain measurements. It is valid in regions of small creep strains (up to 1 percent of creep strain) as well as in regions of higher creep strains. A typical creep curve for Zircaloy is shown in Fig. 1. Without initial elastic extension the creep strains are the sum of primary creep strain and the creep strain due to the steady state creep.

2. Primary creep

A variety of creep curves known from the literature and from the KWU measurements has been evaluated in order to analyse the creep deformation in the primary creep phase. As the result of this evaluation a phenomenological relationship between the maximum creep deformation and the steady state creep rate has been estimated. The relation $\varepsilon_{po} = \varepsilon_{po}(\dot{\varepsilon}_s)$ is shown in Fig. 2. It has been found that the ratio $\varepsilon_{po} / \dot{\varepsilon}_s$ is constant for creep curves obtained for laboratory-tests as well as for in reactor measurements:

$$\varepsilon_{po} = C \cdot \dot{\varepsilon}_s \tag{2}$$

where the constant C depends on the coldworking conditions of Zircaloy-4. Unfortunately the amount of cold-work is uncertain in many cases. Where a direct comparison could be made the cold-worked specimens evidently show higher creep deformation due to primary creep than the annealed ones. The following values can be deduced from the evaluation of Fig. 2 ($\dot{\mathcal{E}}_s$ [h^{-1}]):

$C \approx 10000$ h for cold-worked Zircaloy-2, -4
($\gtrsim 60$ - 70 % of cold-work)
$C \approx 2400$ h for cold worked and annealed specimens.

Another possibility to correlate $\mathcal{E}_{po}$ to $\dot{\mathcal{E}}_s$ may be done by assuming a 0.75-power dependence on creep rate

$$\mathcal{E}_{po} = C^* \cdot \dot{\mathcal{E}}_s^{3/4} \tag{3}$$

$C^* \approx 176$ for cold-worked Zircaloy
$C^* \approx 56$ for annealed Zircaloy

The relationships (2), (3) correlate nearly all measured values in a scatter band of ± 20 %.

The time dependence of primary creep can be correlated by assuming a exponential dependence on time:

$$\mathcal{E}_p(t) = \mathcal{E}_{po} \cdot [1 - \exp(-k \cdot \sqrt{t})] . \tag{4}$$

The parameter k determines the time to reach the maximum creep deformation due to primary creep, $\mathcal{E}_{po}$. The evaluation of k-values on the basis of KWU-creep tests has shown that k is practically independent of stress but slightly dependent on temperature (T = 300-400°C):

$$k = 1.12 \cdot \exp(-12140/RT) \tag{5}$$

R = 8.3143 J/K · mol, k [$h^{-1/2}$].

3. Steady-state creep rate

The dependence of the creep rate $\dot{\mathcal{E}}_s$ on stress σ, temperature T, and neutron flux Ø is the basis to an understanding of creep. It is not the objective of this paper to evaluate the present status of theoretical knowledge on the physical mechanisms that control creep of Zircaloy. The effects of stress, temperature and neutron flux on the creep rate are described in /1/. The parameters influencing the creep behaviour are schematically shown in Fig. 3. Only the important assumptions for the presented creep model will be given here.

The effect of stress σ on the steady-state creep rate $\dot{\varepsilon}_s$ is represented as a power function of the stress combined with an additional plastic flow factor, $\alpha(\sigma/\bar{\sigma})$.

The introduction of the plastic flow factor

$$\alpha(\sigma/\bar{\sigma}) = \cos\left(\frac{\pi}{2}\frac{\sigma}{\bar{\sigma}}\right) \tag{6a}$$

or alternatively

$$\alpha(\sigma/\bar{\sigma}) = 1 - (\sigma/\bar{\sigma})^2 \tag{6b}$$

(both functions agree within 10 % for $\sigma/\bar{\sigma} \leq 0.7$), known from the elasto-plastic fracture mechanics, /3/, improves the description of stress effects on the steady-state creep rate /1/, /2/.

Using $1/\alpha(\sigma/\bar{\sigma})$ as a creep enhancement factor, the creep rate $\dot{\varepsilon}_s$ can be expressed according to

$$\dot{\varepsilon}_s \sim \sigma^n/\alpha(\sigma/\bar{\sigma}). \tag{7}$$

The exponent n is then substantially constant over a wide range of stresses and temperatures, and may have different values for $\dot{\varepsilon}_{s,th}$ and $\dot{\varepsilon}_{s,irr}$.

The guiding parameter for $\alpha(\sigma/\bar{\sigma})$ is the limiting stress $\bar{\sigma}$, which is close to the ultimate stress and depends on temperature and metallurgical conditions. Under irradiation hardening effects may change $\bar{\sigma}$ too.

The effect of temperature T is described by an Arrhenious type of expression for thermal creep:

$$\dot{\varepsilon}_{s,th} \sim \exp(-Q/RT), \tag{8}$$

where Q = activation energy, R = gas constant. On the other hand, the temperature is also important in combination with the effect of stress: in general the limiting stress $\bar{\sigma}$ decreases with increasing temperature. Therefore both steady state creep rates $\dot{\varepsilon}_{s,th}$ and $\dot{\varepsilon}_{s,irr}$ are also influenced by the temperature dependence of $\bar{\sigma}$, particulary at high stresses.

The effect of neutron flux Ø influences the irradiation induced steady-state creep rate $\dot{\varepsilon}_{s,irr}$ only. It is taken to be proportional to

$$\dot{\varepsilon}_{s,irr} \sim \emptyset^{\ell} \tag{9}$$

It is assumed that the thermally activated creep rate $\dot{\varepsilon}_{s,th}$ is not directly correlated to the neutron flux. However, through the change of $\bar{\sigma}$ due to the irradiation induced hardening effects an influence on the creep rates $\dot{\varepsilon}_{s,th}$ (and $\dot{\varepsilon}_{s,irr}$ also) is possible.

Calibration

Considering the effects of the variables σ, T and $\emptyset$ on the steady state creep rates $\dot{\mathcal{E}}_{s,th}$ and $\dot{\mathcal{E}}_{s,\ irr}$, the following expressions are assumed:

$$\dot{\varepsilon}_{s,th} = A_{th} \cdot exp(-Q/RT) \cdot \sigma^{n_{th}} / \alpha(\sigma/\bar{\sigma}) \tag{10}$$

$$\dot{\varepsilon}_{s,irr} = A_{irr} \cdot \phi^{\ell} \cdot \sigma^{n_{irr}} / \alpha(\sigma/\bar{\sigma}) \ . \tag{11}$$

Many results of creep experiments have been evaluated for the calibration of the material constants /1/. The data analyzed have been taken from the literature and from KWU measurements including post-irradiation examination results from fuel rods of light water reactors.

As a result of this evaluation the following material creep constants for Zircaloy-2 and Zircaloy-4 have been established:

$$\begin{aligned}
A_{th} &= 2.0 \cdot 10^{7}\ (N/mm^2)^{-n_{th}} \cdot h^{-1} \\
n_{th} &= 1{,}87 \\
Q &= 2.17 \cdot 10^{8}\ J/mol \\
R &= 8.314\ J/mol \cdot K \\
A_{irr} &= 7.2 \cdot 10^{-21}\ (N/mm^2)^{-1}\ (n/cm^2 \cdot s)^{-\ell} \cdot h^{-1} \\
l &= 0.85 \\
n_{irr} &= 1 \\
\dot{\mathcal{E}}_s\ &[h^{-1}],\ \ \sigma\ [N/mm^2],\ T\ [K],\ \emptyset\ [n/cm^2 \cdot s]\ .
\end{aligned} \tag{12}$$

The stress dependence of $\dot{\mathcal{E}}_{s,irr}$ and $\dot{\mathcal{E}}_{s,\ th}$ including the effect of $\bar{\sigma}$ are shown graphically in /1/. For typical LWR loading conditions the effect of $\bar{\sigma}$ is small. In this case $\bar{\sigma}$ = 265 N/mm^2 has been set up according to the evaluation of /1/.

4. Creep deformation under multiaxial stresses

The Zircaloy-cladding of fuel rods under the in reactor operating conditions is multiaxially stresses. For the description of multiaxial creep a flow law is needed, that indicates the direction of permanent deformation, i.e. the ratios between the creep strain components. In the classical theory of plasticity the following assumption has been made:

$$\frac{\dot{\varepsilon}_i - \dot{\varepsilon}_j}{\sigma_i - \sigma_j} = f \tag{13}$$

which leads to the Prandtl-Reuss flow equations:

$$\dot{\varepsilon}_i = [\ \sigma_i - (\sigma_j - \sigma_k)/2\ ] \cdot f \tag{14}$$

(The indices throughout this paper refer to i,j,k = 1,2,3; $i \neq j \neq k$ corresponding to 1 = hoop, 2 = axial, 3 = radial directions).
f is a constant for a point in the stressed body under consideration but may vary with point location and time. f is then correlated to the effective strain rate $\dot{\varepsilon}_{eq}$, ($\dot{\varepsilon}_{eq} = \frac{2}{3}\{[(\dot{\varepsilon}_1-\dot{\varepsilon}_2)^2+(\dot{\varepsilon}_2-\dot{\varepsilon}_3)^2+(\dot{\varepsilon}_3-\dot{\varepsilon}_1)^2]/2\}^{1/2}$), and the effective stress σ_{eq}, ($\sigma_{eq} = \{[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]/2\}^{1/2}$), according to the expression:

$$f = \dot{\varepsilon}_{eq} / \sigma_{eq} \; . \tag{15}$$

The next step in the classical treatment of the permanent deformations is to assume that $\dot{\varepsilon}_{eq}$ is a function of the equivalent stress σ_{eq} according to the experimentally estimated creep rate $\dot{\varepsilon}$:

$$\dot{\varepsilon}_{eq} = \dot{\varepsilon}\,(\sigma_{eq}) \, . \tag{16}$$

In this way the proportionality factor f can be derived.

However, the assumption of eq. (13) that the factor f is equal for all principal shear strains, must not always be valid.
The Prandtl-Reuss equations (14) can be written as

$$\dot{\varepsilon}_i = \frac{\sigma_i-\sigma_j}{2} f + \frac{\sigma_i-\sigma_k}{2} f = \tau_{ij}\cdot f + \tau_{ik}\cdot f \tag{14a}$$

In order to generalize these equations it is assumed that the factor f is no more isotropic. Then three new plastic flow functions that are directly dependent on the shear stresses τ_{ij} can be defined according to

$$f_{ij} = f(\tau_{ij}) = \dot{\varepsilon}(2\tau_{ij})/(2\tau_{ij}) = |2\tau_{ij}|^{n-1}/\alpha(\tau_{ij}/\bar{\tau})\cdot A' , \tag{17}$$

where the limiting shear stress $\bar{\tau} = \bar{\sigma}/2$, and the constant A' includes all other variables that are independent of stress.

The creep rates for each deformation direction can then be established:

$$\dot{\varepsilon}_{s,th,i} = A_{th}\cdot \exp(-Q/RT)\cdot f_i\,(\sigma_j\,,\, n_{th}) , \tag{18}$$

$$\dot{\varepsilon}_{s,irr,i} = A_{irr}\cdot \phi^{l}\cdot f_i\,(\sigma_j, n_{irr}) , \tag{19}$$

where the stress functions $f_i(\sigma_j, n)$ are defined as

$$f_i\,(\sigma_j, n) = \tau_{ij}\cdot\frac{|2\,\tau_{ij}|^{n-1}}{\alpha(\tau_{ij}/\bar{\tau})} + \tau_{ik}\cdot\frac{|2\,\tau_{ik}|^{n-1}}{\alpha(\tau_{ik}/\bar{\tau})} \, . \tag{20}$$

5. <u>Creep model</u>

The description of the creep behaviour of Zircaloy cladding under the in-reactor loading conditions is based on the assumption that the irradiation induced and thermally activated creep can be added to get the total creep strain (Fig. 3):

$$\varepsilon_{tot,i} = \varepsilon_{p,irr,i}(t) + \dot{\varepsilon}_{s,irr,i}\, t + \varepsilon_{p,th,i}(t) + \dot{\varepsilon}_{s,th,i} \cdot t \;, \qquad (21)$$

where the primary creep terms depend on the steady state creep rates, too. The time dependence of primary creep is given by eq. (4) and the maximum primary creep strain ε_{po} by eq. (2).
For multiaxial stresses the creep rates $\dot{\varepsilon}_{s,th,i}$ and $\dot{\varepsilon}_{s,irr,i}$ are given by the eq. (18) and eq. (19), respectively.

The material constants of the thermal as well as the irradiation creep model have been calibrated by the evaluation of many results of Zircaloy creep experiments known from the open literature and from KWU experiments.

For the fine calibration of the creep constants for Zircaloy cladding the post-irradiation examination results from fuel rods of light water reactors have been evaluated. This calibration has been done using the KWU fuel rod code CARO /4/ which includes the creep model described above and takes into account the reactor power history. To account for the time dependent loading and temperature histories the time-hardening hypothesis has been used.

The creep constants presented here can be used for the determination of creep strains of Zircaloy cladding under typical LWR loading conditions.
In general, however, the validity range of the creep model is wider; but a fine calibration may be necessary for specific material conditions and to account for the tension/compression anisotropy /5/. Moreover the temperature dependence of $\bar{\sigma}$ must be taken into account, particulary at high stresses when the plastic flow correction factor $\alpha(\sigma/\bar{\sigma})$ becomes important.

6. Discussion of the creep model

Since the simple linear relationship of eq. (2) is assumed, the level of irradiation creep is independent of the elapsed time and depends on the ratio of the creep rates only:

$$\varepsilon_{irr,i} / \varepsilon_{tot,i} = \dot{\varepsilon}_{s,irr,i} / \dot{\varepsilon}_{s,tot,i} \;, \qquad (22)$$

where $\dot{\varepsilon}_{s,tot,i} = \dot{\varepsilon}_{s,irr,i} + \dot{\varepsilon}_{s,th,i}$. This relationship as a function of temperature and neutron flux is shown in Fig. 4.

Fig. 5 shows an example of the predictions of the model in comparison to experimental results of Ibrahim /6/. According to the low temperature of 258°C the contribution of the thermally activated creep is negligible. The calculated creep strains show a good agreement with the observed results for $\bar{\sigma}$ = 324 N/mm^2.

The diametral strains as calculated by the CARO code /4/ are shown in Fig. 6 as a function of the measured strains from light water reactor fuel cladding. Fuel rods with different design, e.g. with and without prepressure, with different diameter, and from various power reactors have been included in the calibration. Typical as well as high-power rods have been taken into account, the burnup of which reaches up to 30 MWd/kgU.
Fig. 6 also shows that a reasonably good agreement with other experimental data which had not been used for the calibration has been achieved.

Literature

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/2/ Brzoska, B., Cheliotis, G., Kunick, A., Senski, G., "A new high temperature deformation model for Zircaloy clad ballooning under hypothetical LOCA conditions", 4. SMiRT-Conf., San Francisco Aug. 1977;

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/4/ Eberle, R., Wunderlich, F., Distler, I., "The KWU Fuel Rod Code CARO", IAEA Specialists Meeting on Fuel Element Performance Computer Modelling, Blackpool, U.K., March 13-17, 1978.

/5/ Stehle, H., Steinberg, E., Tenckhoff, E., "Mechanical Properties, Anisotropy and Microstructure of Zircaloy Canning Tubes", in ASTM STP 633, 1977, 486-507;

/6/ Ibrahim, E., F., "In-Reactor Creep of Zirconium-Alloy Tubes and Its Correlation with Uniaxial Data", in ASTM STP 458, 1969, 18-36;

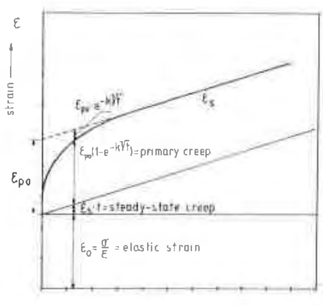

Fig. 1: Creep curve according to the exponential time function:
$\mathcal{E} = \mathcal{E}_o + \mathcal{E}_{po} \cdot [1-exp(-k \cdot \sqrt{t})] + \dot{\mathcal{E}}_s \cdot t.$

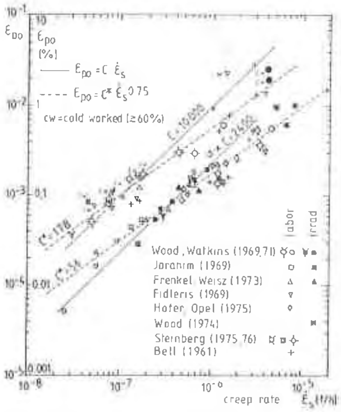

Fig. 2: Maximum creep strains due to primary creep vs. steady state creep rate

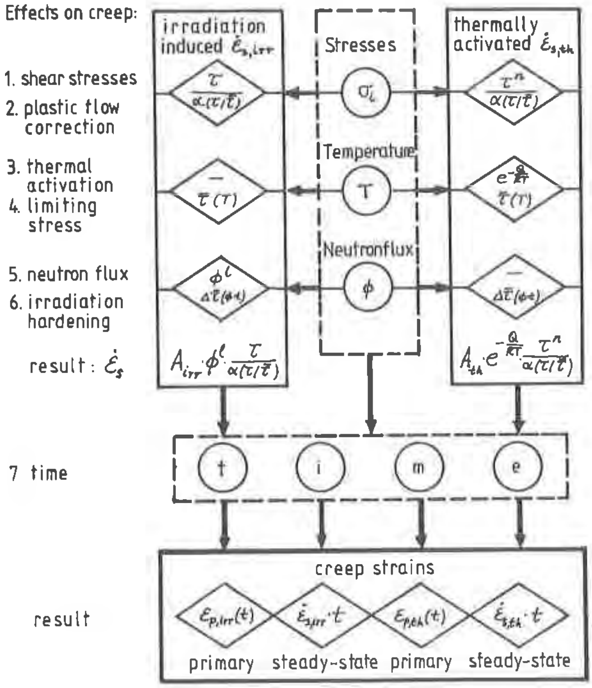

Fig. 3: Schematical description of the creep model

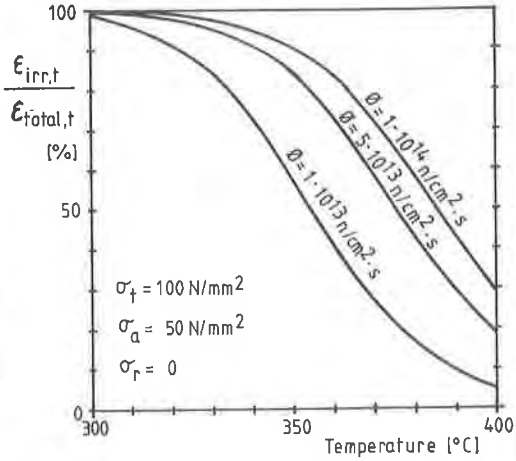

Fig. 4: Contribution of irradiation induced creep to the total creep for typical in-reactor loading conditions of Zircaloy cladding

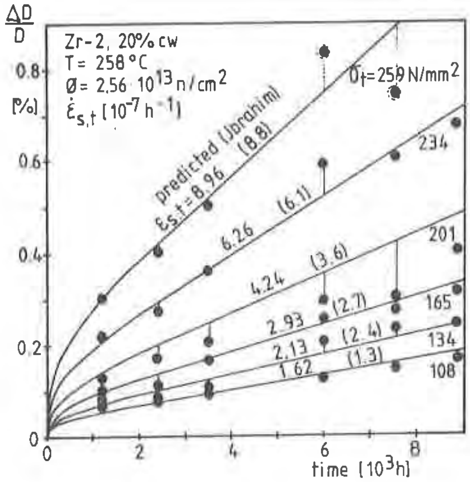

Fig. 5: Predicted creep curves for Zircaloy-2 specimens as a function of time and stress in comparison to the experimental results from Ibrahim /6/

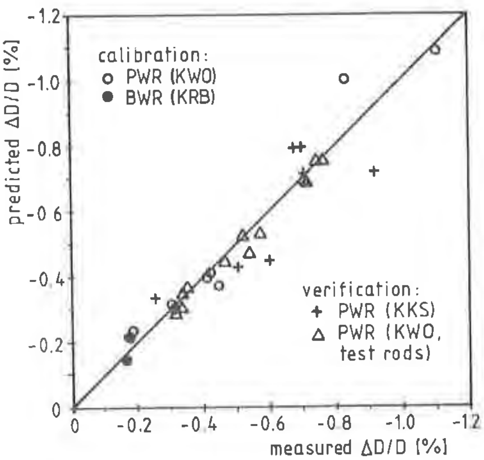

Fig. 6: Comparison between calculat and measured creep strains of Zirca- loy cladding of fuel rods from light water reactors