Experimental Investigation of Post-Pile Creep of Zircaloy Cladding Tubes

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Abstract

Post-pile creep tests of preirradiated Zircaloy cladding tubes have been performed at temperatures of 350 and 400 °C and at tensile hoop stresses of 50 and 70 MPa. A single test lasted 8000 h. The test samples came from two different in-pile creep programs carried out at KWO and FRG-2.

The most important result of the post-pile creep test is that the post-pile creep behaviour is obviously influenced by the preirradiation conditions. The experimental results can be interpreted by assuming the existence of residual internal stresses in the cladding. The relaxation of the internal stresses at test temperatures results in a restrain of the tubes and contributes to the strain caused by the actual applied stress.

1. Introduction

To confirm the reliability of dry long-term storage of Zircaloy clad spent LWR fuel, R & D work is being performed by Kraftwerk Union (KWU) in cooperation with Deutsche Gesellschaft für Wiederaufarbeitung von Kernbrennstoffen (DWK) with the special emphasis on possible fuel rod degradation mechanisms / 1, 2, 3 /. Our theoretical analysis has yielded the result that cladding creep is the mechanism which primarly limits the storage temperature of the fuel in an inert atmosphere.

The creep behaviour of unirradiated Zircaloy (out-of-pile creep) as well as the creep behaviour of Zircaloy cladding tubes during irradiation (in-pile creep) has been investigated in full details / 4 /. On the contrary, creep investigations of irradiated Zircaloy cladding after irradiation (post-pile creep) are completely missing. For this reason KWU carried out an experimental post-pile creep program to provide a reliable data base for performance predictions and licensing discussions.

2. Test Program

The post-pile creep program includes original PWR cladding samples from two different in-pile creep test programs. 14 cladding samples have been preirradiated in the research reactor Geesthacht FRG-2 / 5 /. The irradiation temperature was 400 °C, the fast neutron flux was around $3 \cdot 10^{13}$ $cm^{-2}s^{-1}$, the tensile and compressive hoop stresses were between 70 and 120 MPa, and the irradiation periods were 540 and 1170 h.

Further 10 cladding samples have been preirradiated in the Obrigheim power plant KWO / 6 /. The irradition lasted up to 5 reactor cycles corresponding to up to 1500 d. The irradiation temperature was around 300 °C. The samples contained an internal prepressure of 32 bar (at room temperature) that leads to a compressive stress of around 65 MPa against the primary coolant pressure. The integral fast neutron flux was in the range of $5 \cdot 10^{21}$ to $1 \cdot 10^{22}$ cm^{-2}.

For the post-pile creep tests with the FRG-2 samples a temperature of approximately 400 °C was choosen. The tensile hoop stress was adjusted to 70 MPa and controlled by a joint gas pressurization of 110 bar (at operational temperature) for all samples. The KWO samples were tested at a temperature of 350 °C. The internal prepressure of these sealed samples leads to a tensile hoop stress of 50 MPa at operational temperature.

A post-pile creep test lasted 8000 h. The experiments were interrupted 5 respectively 4 times for measuring the diameter of the samples. Spiral traces of the samples were recorded.

3. Verification of Equipment Reliability

The irradiated samples as well as unirradiated reference samples coming from the same cladding tube fabrication lots were subjected to the same test conditions. The creep results are shown in figure 1 for the 2 KWO reference samples and in figure 2 for the 4 FRG-2 reference samples.

From the results of out-of-pile creep tests performed in the KWU fuel laboratory, an empirical formula has been derived which is valid for KWU PWR cladding tubes at internal overpressure and at temperatures between 250 and 400 °C.

$$\varepsilon(\%) = 1.89 \cdot 10^{-3} \left(\frac{610}{T} - \frac{\ln(\sigma/450)}{\ln t} - 1\right)^{-2.58} \qquad (1)$$

where T(K) is the creep temperature, σ(MPa) the hoop stress, and t(h) the creep time. The creep curve according to this formula is also drawn in the figures 1 and 2.

The measured creep deformation of the reference samples follows the creep formula very well. This agreement implies an excellent verification of the reliability of the empirical creep formula as well as of the post-pile creep test equipment.

The accuracy of the profilometry system is $\pm$ 3 µm. Hence the accuracy of the creep results (difference of two diameter measurements) is $\pm$ 0.05 % of the cladding diameter. For the KWO samples the accuracy could be improved to $\pm$ 0.02 % by recalibration of the traces at the end plugs of the samples.

4. Creep Results of FRG-2 Samples

The exact test temperature of the FRG-2 samples was 380 °C within the first 1000 h and 395 °C later on. The results of the creep deformation measurements are reproduced in figure 3. The mean value of the deformation of all samples is shown in figure 4.

It can be seen that an outwardly pointed deformation commences only after approximately 1000 h. The slope of the creep curve (= creep rate) is smaller than that of the curve derived from the creep formula. This means that the irradiated material is more creep resistant than the unirradiated material up to temperatures of 400 °C. The total creep deformation after 8000 h was around 0.25 % and thereby half as large as that of the unirradiated material.

5. Creep Results of the KWO Samples

The KWO samples are sealed at both ends with end plugs. The helium content leads to internal pressure of 69 bar at a test temperature of 350 °C. Figure 5 shows the results of the creep strain measurements. The total creep deformation after 8000 h was around 0.085 % on an average which is surprisingly the same value as for the unirradiated samples (figure 1).

Two of the KWO samples had lost their inner prepressure during reactor operation. Accordingly, the cladding tube is not mechanically loaded since then. The deformation measurement results of these two samples are shown in figure 6. Surprisingly again the samples had been strained without an applied stress.

6. Discussion of the Results

The two surprising post-pile creep results of the KWO samples are summarized in figure 7. A consistent interpretation can be given by supposing the existence of internal stresses in the material.

During reactor operation the samples had an outer overpressure of approximately 95 bar. At equilibrium between strain and irradiation hardening on the one hand and recovery on the other hand, an internal stress had been built up in the Zircaloy tube.

When the cladding tube is relieved of the external stress, the relaxation of the internal stress results in a restrain of the tube. The restrain rate depends on the temperature. Obviously the restrain rate at reactor operating conditions (300 °C sample temperature and irradiation hardening) is so low that the internal stress of the unpressurized samples has been frozen. Even during the thermal annealing at 350 °C (post-pile condition) the restrain rate is comparatively low so that the relaxation does not seem to be completely concluded after 8000 h.

According to this reasoning the "creep curve" of the leaking irradiated KWO samples represents exclusively the mentioned restrain. The direction of the restrain is the same as that of the post-pile creep strain. This means that the total post-pile creep strain ε_{tot} is the sum of the restrain ε_r and the strain ε_σ caused by the actual applied stress. This is presented in figure 8, where ε_σ has been derived by subtracting the strain values of the unirradiated samples from those of the irradiated ones.

The post-pile creep results of the FRG-2 samples can be explained in the same way. During the final irradiation phase the samples had an inner overpressure of 162 respectively 192 bar. Since at termination of irradiation the heat had been turned off first and then the pressure had been reduced, the internal stress of the samples has been frozen as well.

During the post-pile creep tests the FRG-2 samples had an inner overpressure of 109 bar at a temperature of 400 °C. According to that the pressure had been reduced by 53 respectively 83 bar against in-pile. Now the partial relaxation of the inner stress connected with a restrain was possible. The direction of the restrain is opposite to the post-pile creep strain in this case.

Obviously the restrain rate at 400 °C is relatively high so that the creep curve ε_{tot} runs into the regime of negative strain at first. Having passed a minimum it ascends again. In our case it enters the regime of positive strain after 1100 h again (figure 4). Unfortunately the quantitative course of ε_{tot} is unknown below 1000 h because of the lack of values measured.

If the given interpretation proves right, different amounts of pressure reduction should result in different restrains. 8 of the FRG-2 samples had an inner overpressure of 162 bar at the final irradiation phase and 4 of them 192 bar. In figure 9 the creep strains of these two groups of samples are reproduced separately. Actually the creep curve of the samples with more pressure reduction is lower than that of the samples with less pressure reduction, which implies that the opposite restrain is larger in the former case.

7. Conclusion

The most important result of the post-pile creep experiments is, that the post-pile creep behaviour is obviously influenced by the preirradiation conditions, especially by cladding stress and temperature during the final irradiation phase. The experimental results can be interpreted without discrepancies by assuming the existence of residual internal stresses in the cladding tubes as explained before.

Nevertheless the experimental data base is still too small to specify restrains for cladding tubes of original spent fuel rods quantitatively. To improve the insight in the discussed phenomena, it would be worthwile to supplement the performed experimental program by further investigations of the restrain of cladding samples coming from original spent fuel rods.

Up to now the post-pile creep of spent fuel rods at dry storage conditions has been theoretically predicted by out-of-pile creep laws supposing that this procedure would be conservative. The existence of a restrain having the same direction as the post-pile creep strain may consume some of the supposed conservatism. However, a comparison of calculated diameter changes of fuel rods after dry storage tests up to 450 °C proves that our out-of-pile creep formula overestimates a little the measured strain.

References

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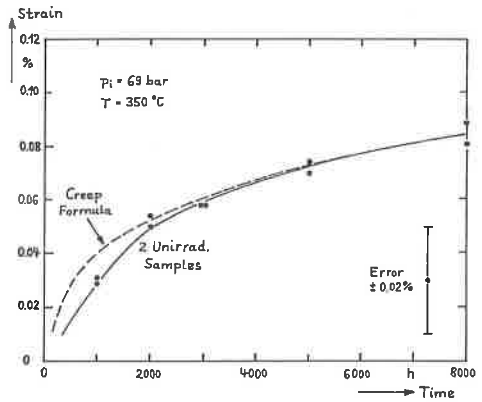

Fig. 1: Creep Strain of Unirrad. KWO Samples

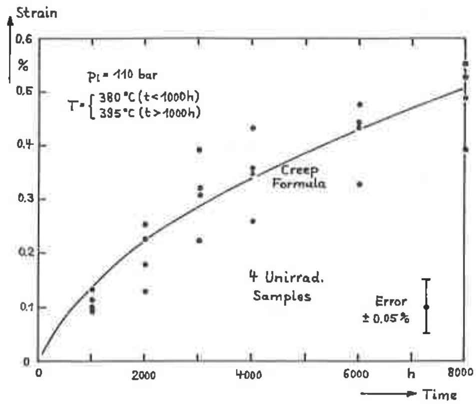

Fig. 2: Creep Strain of Unirrad. FRG-2 Samples

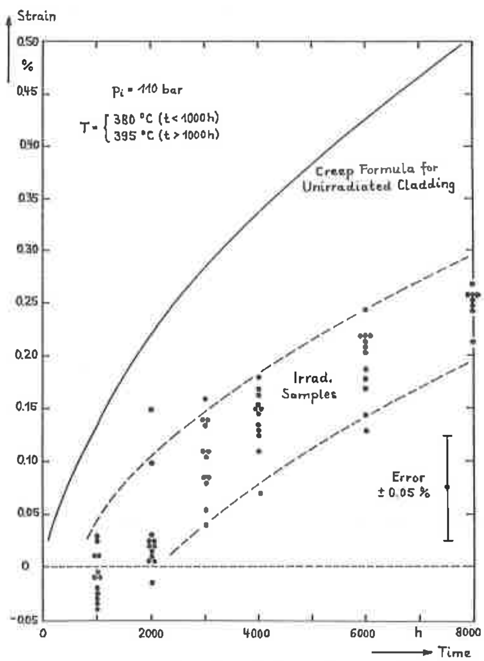

Fig. 3: Creep Strain of Irradiated FRG-2 Samples

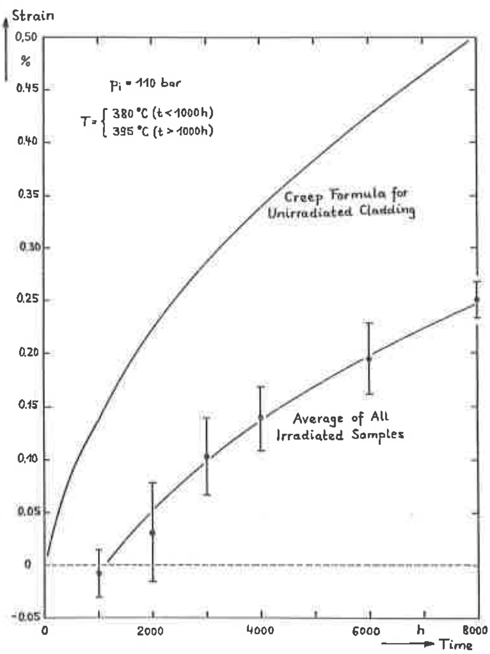

Fig. 4: Ave. Creep Values of Irrad. FRG-2 Samples

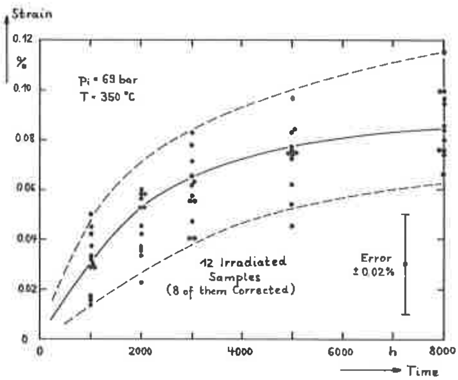

Fig. 5: Creep Strain of Irradiated KWO Samples

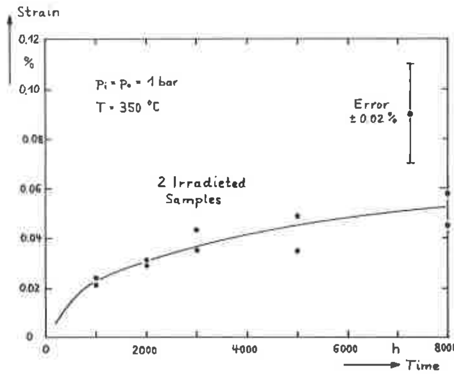

Fig. 6: Creep Strain of 2 Irradiated KWO Samples without Applied Stress

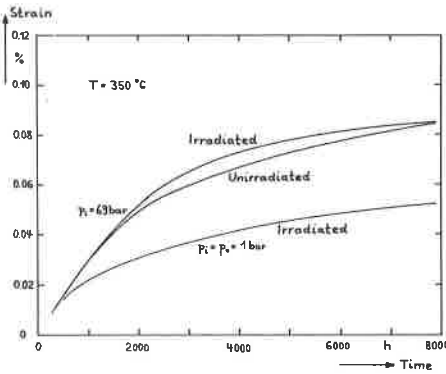

Fig. 7: Comparison of Creep Curves for KWO Samples

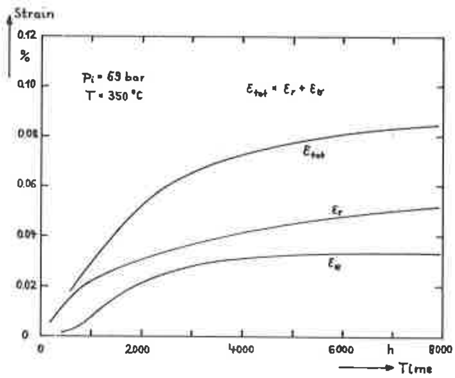

Fig. 8: Total Creep Strain of KWO Samples Composed by Actual Strain and Restrai

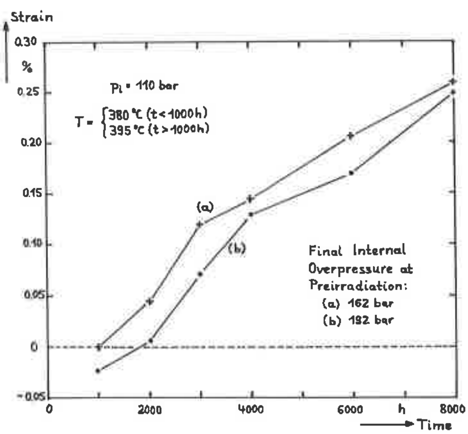

Fig. 9: Influence of the Final Stress at Pre-irradiation on the Post-pile Creep