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PERFORMANCE EVALUATION OF UO_2-ZR FUEL IN POWER RAMP TESTS

by

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1. INTRODUCTION

Rapid power increases may lead to failure of irradiated UO_2-Zr fuel pins. Consequently, it can be necessary to impose restrictions on the manoevering of power reactors. In order to avoid undue conservatism in such limitations, it is desirable to have access to an experimental data base on power ramp performance. Also, fuel performance code calculations are useful in the consequence analysis of given modes of operation.

This paper extends the existing power ramp experience by presenting details on ramp tests with three high-burnup pellet UO_2-Zr fuel pins. Performance code calculations show how the experimental results can be predicted by computer analysis. In addition, ramp test results with two vipac fuel pins are reported and evaluated similarly to document ramp performance and feasibility of analysis for this fuel type. Data from two of the tests have previously been summarized elsewhere (1).

2. DESIGN

The fuel pins were pre-ramp irradiated in the Halden reactor as part of the Danish test fuel assembly IFA-164, which consisted of an upper and a lower cluster. Important design details are given in table I. The UO_2 enrichment was 4%, and the cladding of all pins was cold-worked and stress-relieved Zr-2, autoclaved on both sides. The pellets were dished at both ends, and the vipac powder was sintered UO_2 granules with a particle density of 98% TD. The fuel column length was 824 mm and the filling gas was 1 at. He.

3. IRRADIATION

3.1. Pre-Ramp Irradiation

IFA 164 was irradiated in the Halden reactor at boiling D_2O conditions of 34 at. and 240°C. An average assembly burn-up of 20,600 MWD/t UO_2 was accumulated during a total time at significant power levels of about 2½ years. A summary of the entire power history is shown in fig. 1. The maximum assembly power was 440 KW for a period of about ½ day early in life, and the latest "power peak" was 280 KW.

Axial power shapes for individual fuel pins were obtained from Zr-Nb gamma scans and are illustrated in fig. 4.

3.2. Ramp Testing

The fuel pins were subjected, one at a time, to overpower ramps in a water-cooled facility (2) in the DR 3 reactor at Risø. The primary coolant was pressurized to 70 at. The flow time from the fuel pin to the monitor giving failure indication is estimated to be about 6 minutes.

The overpower application procedure has been described elsewhere (3). Details for the present test are given in table II and figs. 2 and 3, in each case with reference to the axial pin elevation that saw the maximum power in DR 3. The four X-es on ramp curves of figs. 2 and 3 are shown at times 6 minutes prior to the monitor signals, thus indicating the (latest) time of fuel pin failure.

Axial power shapes in DR 3 are illustrated in fig. 4. Such curves were obtained from the total pin thermal output, distributed axially by means of Ba-La gamma scans on pins PA 24-2 and P 18-1.

4. POST-IRRADIATION EXAMINATIONS

The post-ramp examination has so far comprised visual inspection, profilometry and eddy-current testing of all pins and neutron radiography of PA 21-3 and P 13-1. The integrity of P 18-1 was confirmed by the fission gas analysis.

The visual inspection revealed no change in surface appearance as a result of the ramp testing, except for M 34-1 where a faint X-mark could be seen near the bottom of the fuel column.

The Halden irradiation resulted in little diameter change (measuring uncertainty ∿ 10 µm). The overpower application caused maximum diameter increases along the lower 300-400 mm of the fuelled pin lengths as shown in table III. The eddy-current testing qualitatively confirmed the diameter changes seen in the profilometry, with distinct indication of clad penetration on M 34-1 only.

The neutron radiography of the pellet pin PA 21-3 revealed formation of additional transverse and longitudinal pellet cracks after the ramp test but did not show any hydriding of the clad. During the Halden irradiation, the vipac fuel column of P 13-1 sintered to a degree of coherence that permitted the formation of transverse fuel cracks during subsequent power changes. Many of these cracks were spaced rather regularly, with an appearance like "in-pile dished pellets" with an "H/D ratio" slightly larger than 1. After the ramp testing, more fuel cracks were seen as in the pellet pin. There was some indication of clad hydriding near the bottom of the pin where large diameter increases occurred.

5. MODEL ANALYSES

The irradiation experiments were simulated by means of the Danish one-dimensional fuel performance code HOTCAKE/T (4).

This code analyses one cross-section of a fuel pin throughout its power history. The analysis takes account of fuel cracking in two directions: radially and transversally. Fuel secondary creep and clad primary and secondary creep, both thermal and irradiation-enhanced, are accounted for as well as clad yielding. Further, densification and swelling of the fuel and fission gas release are modelled.

The code, being one-dimensional, calculates average stresses and strains in the cladding as a function of the operational history. In reality there will be local concentrations of cladding stress and strain in the vicinity of fuel cracks and pellet interfaces. Therefore, the code will generally underpredict the severity of a given load condition.

The results of the simulations are presented in figs. 5 through 8. The pre-ramp power histories for the five pins as used in the simulation were derived from the assembly power history of fig. 1 by means of suitable scale factors. The levels of pre-ramp heat load for the five pins can be derived from table II. The ramp heat load histories are shown in figs. 2 and 3.

The HOTCAKE/T code is designed for pellet fuel pins. Simulations were run, however, for all five cases. In simulating the vipac pins it was tentatively assumed that the vipac fuel sinters to form a coherent solid with increased density, which in turn cracks transversally to form pellet-like fuel fragments. This assumption is supported by neutron radiography, as reported in chapter 4.

The analyses indicate that pins PA 21-3, P 13-1 and P 18-1 yielded during the ramp, while pin PA 24-2 achieved about half of the stress necessary for yielding. The last pin, M 34-1, did not yield but did achieve fuel-clad contact during the ramp.

These analytical results are mutually consistent, as shown in the following paragraphs.

The pellet pins: PA 21-3, PA 24-2, and M 34-1 are of similar design, except that M 34-1 has a stronger clad. The pre-ramp histories of PA 21-3 and PA 24-2 were much the same, but PA 21-3 was ramped to 720 W/cm, PA 24-2 to only 600 W/cm. This explains why the model predicts yielding for PA 21-3 but not for PA 24-2. M 34-1 was pre-irradiated at a 20% higher level than PA 21-3. However, because the model does not in either case predict fuel-clad contact before the ramp, this would not significantly influence the behaviour during the ramp. The ramp to 485 W/cm was not sufficient to impose yielding on the cladding, even though the gap did close and the stress did begin to rise.

The vipac pins, P 13-1 and P 18-1, were of similar design. In the analysis the as-fabricated smear density of 84.1% was assumed to change to 90% on in-pile sintering and densification. Initial fuel-clad contact was avoided in the analyses by artificially reducing the fuel as-fabricated diameter and correspondingly increasing the as-fabricated smear density by slight amounts. This simulates the "looseness" of the vipac fuel on first going to power. The pre-ramp power histories were much the same for these two pins but during the ramp P 18-1 went to 735 W/cm, and P 13-1 to only 640 W/cm. Therefore, P 18-1 yielded more than P 13-1.

The ramp power histories of pins PA 24-2 and P 18-1 display several days' hold times at intermediate power levels. For P 18-1 this gave rise to considerable relaxation, but still there was significant yielding during the continued power rise.

Fig. 5 indicates that for pins PA 21-3 and P 13-1 the outer diameter decreased by 0.09%, or 12 micron, during the pre-ramp irradiation. This change is due to irradiation-enhanced creep under the applied system pressure, as no fuel-clad contact was calculated before the ramp.

6. EVALUATION OF EXPERIMENT AND ANALYSIS

6.1. Ramp Tests

The ramp rates of the three pellet pins was high, and they all failed. Examination of table II and figs. 2-3 indicate that these failures occurred fairly consistently around 450-475 W/cm (although 720 W/cm is given as max. possible failure level for PA 21-3, the actual cladding penetration may well have occurred at a lower level, depending on the time required for fission products to migrate against the system pressure). The dimensional changes were small, and visual inspection and eddy-current testing did not clearly identify any failure locations, except for M 34-1. This shows that the failures were marginal and, further, points to stress corrosion as a likely failure mechanism.

The vipac pin P 13-1 with the fast ramp failed at 640 W/cm, i.e. somewhat higher than the pellet pins. This could be expected; although the powder particles did sinter to a significant extent, the outer rim of the fuel cross section could still have a structure less likely to cause stress concentrations than a pellet surface.

The other vipac pin, P 18-1, was ramped to 735 W/cm but at a slower ramp rate and with an intermediate hold of 48 hrs. The fact that it survived the ramp could be attributed to the slow approach to peak power. The model analysis, however, does not support this view. Other reasons for the difference in performance are discussed in the next section.

6.2. Results With Performance Code

It was pointed out in the previous section that stress corrosion is a likely failure mechanism for the present experiments. Stress corrosion seems to start acting at stresses close to the clad yield stress. According to the model analyses for the pellet pins, clad yielding occurs for only one of them, namely PA 21-3. This pin, therefore, would be expected to fail, while PA 24-2 and M 34-1 would be expected to survive.

It appears, however, that, according to the analysis, pin PA 24-2 was very close to yielding, since the stress had reached about half of the yield value and the curve rises rapidly. Also, pin M 34-1 had begun to develop a rapidly rising clad stress, according to the analysis. Thus, in these two cases the analysis may not be too far from reality. It should also be noted that the model does not consider local effects, which tend to increase stresses and strains in the clad near fuel cracks and pellet interfaces. The X-mark found on pin M 34-1 indicates that at least for this pin local effects could have been important in producing the failure.

The calculated creep-down of 12 μm for pin PA 21-3 agrees fairly well with the experimental observation.

The two vipac pin experiments resulted in one failure (P 13-1), while one pin survived (P 18-1).

According to the analysis, both pins yielded during the ramp. P 18-1, which actually survived, yielded some more than P 13-1. Hence, in this case the discrepancy between model calculation and experimental fact cannot be easily explained. Possibly, the assumption of densification to 90% underestimated the true in-pile sintering. By increasing the assumed final density the yielding could be avoided in both cases. Still, this would not explain the fact that the analysis predicts heavier fuel-clad mechanical interaction for P 13-1 than for P 18-1. To rationalize this we must assume the action of a physical mechanism, possibly of stochastic nature, which is not in the model. For example, it is conceivable that a difference in fuel temperature between the two vipac pins during the pre-ramp irradiation could lead to a different degree of in-pile sintering, or, that random fuel fragment relocation enhanced fuel-clad mechanical interaction in the case of P 13-1.

Destructive post-irradiation examination is expected to give clues to a better understanding of the relative performance of the vipac pins.

7. CONCLUSION

The experiments led to ramp failure of all three pellet type fuel pins.

Of the two vipac pins only one failed.

Computer simulations by HOTCAKE/T predicted reasonably well the relative performance of the pellet pins. The predictions of clad mechanical loads were somewhat low, because local stress-rising effects are not presently considered in the model.

The applicability of the model to vipac fuel depends critically on the assumption used regarding in-pile sintering.

REFERENCES

(1) KNUDSEN, P., BAGGER, C., KJAER-PEDERSEN, N., Trans. Am. Nucl. Soc. 24 (1976) 172.
(2) HANSEN, K., LETH, J.A., RISØ-M-1862 (1976).
(3) KNUDSEN, P., KJAER-PEDERSEN, N., ASME Publication 75-WA/HT-68 (1975).
(4) KJAER-PEDERSEN, N., to be published.

TABLE I. FUEL PIN DESIGN DATA

Pin No.			PA 21-3	PA 24-2	M 34-1	P 13-1	P 18-1
Fuel	Type	-	Pellet	Pellet	Pellet	Vipac	Vipac
	OD	mm	12.61	12.61	12.65	-	-
	L	mm	19.4	19.4	13.2	-	-
	Density (a)	% TD	95.1	95.1	95.1	84.2	84.1
Clad	ID	mm	12.84	12.84	12.84	12.85	12.86
	WT	mm	0.58	0.60	0.57	0.58	0.56
	YS,25°C (b)	MN/m^2	432	432	570	432	432
	YS,300°C (b)	MN/m^2	294	294	417	294	294
Pin	Gap (diam.)	mm	0.23	0.23	0.19	-	-
	Bundle pos.	-	Lower	Lower	Upper	Upper	Upper

Notes: (a) Vipac densities are smear densities.
(b) As-delivered.

TABLE II. RAMP TEST DETAILS (a)

Pin No.	PA 21-3	PA 24-2	M 34-1	P 13-1	P 18-1
Halden heat "440 KW" loads (W/cm) "280 KW"	330 210	355 225	400 255	390 250	410 260
DR 3 intermediate hold (W/cm) (days)	470 (b)	425 3	410 (b)	430 (b)	530 2
Ramp rate (W/cm min)	60	25	25	50	7
Max. possible heat load at failure (W/cm)	(c) 720	470	485	640	(d)
Max. overpower (W/cm)	720	600	485	640	735

Notes: (a) All heat loads refer to the axial location with max. power in DR 3
(b) 8-10 minutes
(c) Release of fission product activity occurred just at the end of a 4 minute power inrease from 470 to 720 W/cm, thus the clad penetration could possibly have occurred at a lower heat load level
(d) No failure indication

TABLE III. DIAMETER INCREASES IN RAMP TEST

Pin No.	Max. increase µm (a)	Max. ridge height µm (diam.)
PA 21-3	30	15
PA 24-2	50	25
M 34-1	30	20
P 13-1	70	(vipac)
P 18-1	45	(vipac)

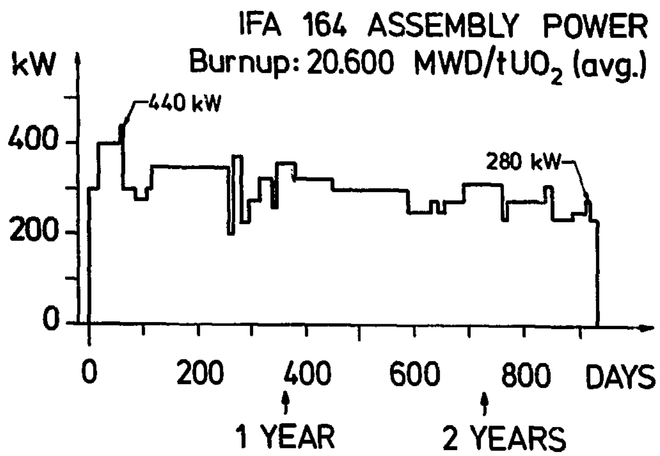

Fig. 1. IFA 164 assembly power

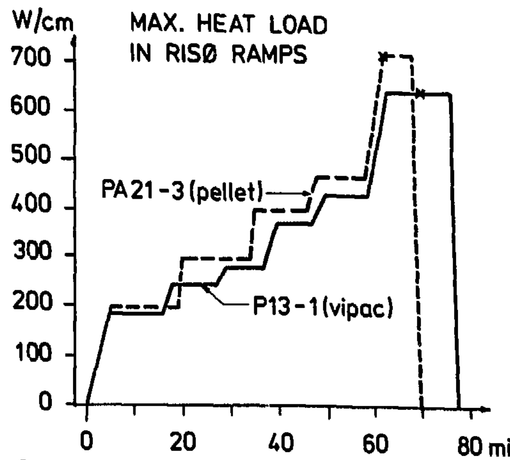

Fig. 2. Power ramps of PA 21-3 and P 13-1

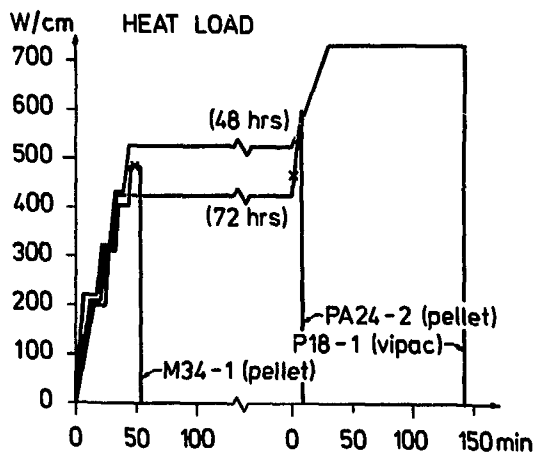

Fig. 3. Power ramps of PA 24-2, M 34-1 and P 18-1

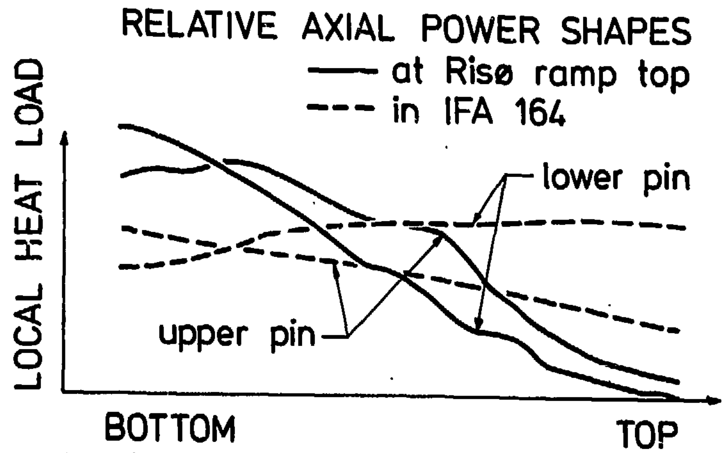

Fig. 4. Relative axial power shapes

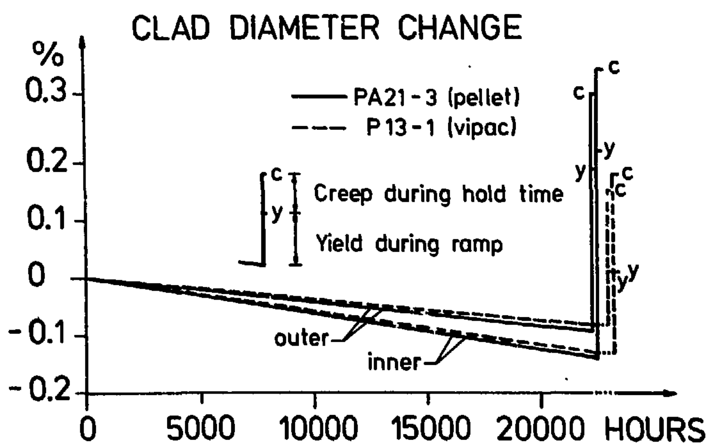

Fig. 5. Clad diameter change of PA 21-3 and P 13-1

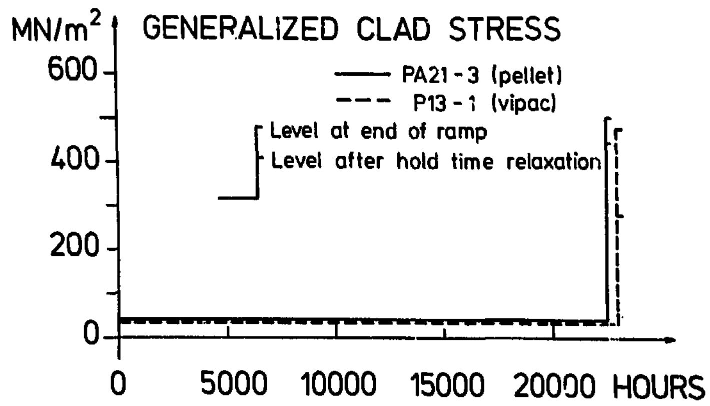

Fig. 6. Generalized clad stress of PA 21-3 and P 13-1

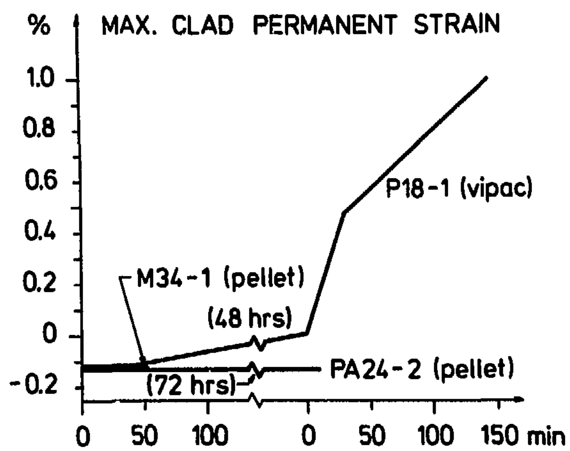

Fig. 7. Clad permanent strain of PA 24-2, M 34-1 and P 18-1

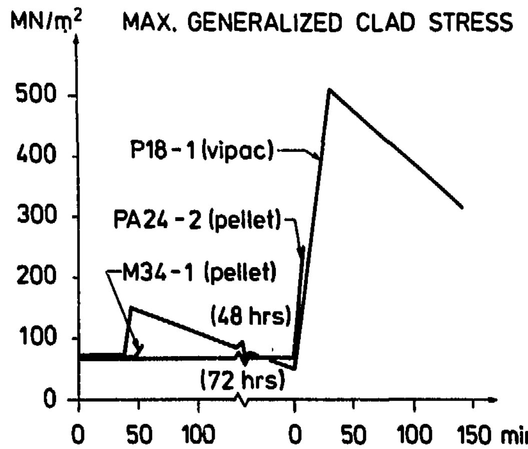

Fig. 8. Generalized clad stress of PA 24-2, M 34-1 and P 18-1