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A COMPUTER ANALYSIS OF THE INFLUENCE OF DESIGN PARAMETERS, MATERIALS PROPERTIES AND OPERATION CONDITIONS ON THE IRRADIATION BEHAVIOR OF FAST BREEDER FUEL RODS WITH OXIDE FUEL

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SUMMARY

Due to fuel swelling sufficient and appropriate void volume must be provided within the fuel rods of fast breeder reactors. This can consist of four parts: the gap between fuel and clad, the pore volume, the dishing volume, and a fabricated central hole. One task in developing fast breeder fuel rods is to find out the optimal size and allocation of the void volume.

Irradiation experiments have shown that clad deformations due to contact pressure have occurred starting at a certain burnup value. This threshold is determined by two processes: time to gap closure and succeeding stabilization of the outer fuel region by crack healing. Irradiation experiments and modeling analyses have revealed that the gap volume is exhausted faster than expected due to fuel swelling only. Reasons for this effect are: formation of fission gas bubbles and their migration towards the central hole with simultaneous dislocation of the fuel pellet towards the clad and/or relocation of the cracked fuel pellet, e.g. due to power changes during reactor operation. It is known, moreover, from experiments and modeling analyses that high contact pressures and resulting clad deformations occur at non-steady-state operation. Necessary conditions are: residual gap width smaller than the difference between the thermal expansion of fuel and clad, sufficient degree of crack healing, and increase of the local rod power above the level maintained a certain time. Contact pressure and clad deformation are determined by following parameters: start and end level of the rod power, the power ramp, the mechanical stability of the fuel which is influenced by its density and crack structure and volume, and creep and/or plastic properties of fuel and clad which are governed by temperature and rod power.

SATURN-1 calculations have shown that the load onto the clad expected at power ramps depends heavily on three factors: thermal expansion of the fuel pellet (dependency on O/Me ratio, actual temperature level), healing of the peripheral radial cracks, and mechanical properties of the outer fuel region.

The results of the computer analysis lead to the following conclusions: Pellet density and gap width must be chosen in such a way that in case of gap closure under the foreseen operation conditions a sufficiently large central hole has been formed unless an appropriate hole has been provided in fabricating the pellets. The larger the fabricated gap, the larger is the crack volume in the outer region of the fuel pellet when the gap has been exhausted by swelling and relocation effects. This decreases the mechanical stability of that region. The decision for a higher smear density must be combined with a reduction of the target burnup. But this value can be higher for a lower frequency of power changes.

1. Introduction

Nuclear fuel irradiated by neutrons has not only the positive characteristic to produce heat but also the negative characteristic to expand its volume. This fuel is put in to Fast Breeder Reactors within claddings of stainless steel. In order that these claddings are not strained intolerably or, eventually, destroyed by the expanding fuel, in their inside one must provide void volume sufficient for the planned operation period. This void volume consists, in general, of a combination of three parts when fuel pellets are used: a gap between pellets and cladding, pore volume within the pellets, and dishing of the pellets. Additional void volume can be provided through a central hole. One task in developing an appropriate concept for Fast Breeder fuel rods is to find out the optimal size and allocation of the necessary void volume.

The performance of different rod concepts has been tested through various irradiation experiments. In these experiments an increase of the rod diameter has been observed starting at a certain burnup value. Figure 1 shows results from several irradiation experiments which were carried out in the thermal or epithermal neutron flux of the test reactors FR 2 (Karlsruhe) and BR 2 (Mol) and in the fast neutron flux of the DFR (Dounreay) (from /1/). They indicate beginning of clad deformation at about 4 % FIMA burnup and its increase with burnup. One can see, furtheron, that the degree of deformation seems to increase with the sinter density of the fuel pellets.

The observed deformations are, obviously, caused by mechanical interaction between fuel and clad. A necessary condition for this interaction is close contact between both materials and strong load onto the clad by volume changes of the fuel due to swelling or thermal expansion. The burnup threshold at which clad deformation starts is, therefore, determined by two processes: time to gap closure and succeeding stabilization of the outer fuel region by partial healing of the cracks resulted from the first startup of the reactor and following shutdowns and startups.

2. Changes of the pellet geometry

The gap provided between fuel pellet and clad at fabrication must be, at least, so large that the possible maximal thermal expansion of the fuel pellets at the beginning of their operation in the reactor can be compensated. Moreover, the gap is intended to be so large that it can accommodate a fraction of the volume increase of the fuel due to fission product swelling. The other fraction is thought to be accommodated by the pore volume.

2.1 Influence of fabrication tolerances

With the choice of the nominal gap width it must be taken into account that variations of the actual gap width occur due to unavoidable tolerances in fabricating pellets and clad. An impression about the order of such variations gives Fig. 2 (from /2/). It shows for a cross section of a fuel rod the rest gap width to be expected at hot state after the first startup as function of the tolerances of the fabricated gap width and the plutonium amount of the fuel. The nominal data and their tolerances for the considered cross section are: clad inner diameter 5.240 ± 0.025 mm, pellet diameter 5.09 ± 0.05 mm, Pu amount 25 ± 1 %, pellet density 86.5 % T.D., O/Me ratio 1.965, dishing volume 2 ± 0.5 %, total neutron flux $6.35 \cdot 10^{15}$ $cm^{-2}s^{-1}$, fast neutron flux (E > 0.1 MeV) $3.5 \cdot 10^{15}$ $cm^{-2}s^{-1}$, rod power 355 W/cm, and clad outer temperature 472 °C. The inner frame in that figure refers to a variation of 3 σ with the gap width and of 5 σ with the Pu amount. The oxygen content was kept constant at its nominal value with the calculations.

But a variation of the O/Me ratio also effects the size of the hot gap because the heat conductivity of the fuel depends on this ratio. The heat conductivity determines the temperature level and by that the thermal expansion of the fuel. The variation of the gap width demonstrated in Fig. 3 /3/ must, therefore, be added to that shown in Fig. 2. The input data for the analysis were:clad inner diameter 5.24 mm, pellet diameter 5.04 mm, pellet density 84 % T.D., Pu amount 20 %, rod power 435 W/cm, and clad outer temperature 348 °C. Fig. 3 further shows that the fuel surface temperature decreases due to the smaller gap, but the centre temperature increases due to the worse heat conductivity with decreasing O/Me ratio.

2.2 Relocation of fuel fragments

The analysis of irradiated fuel rods (essentially with relative large gaps and short irradiation times) has revealed that the gap volume was exhausted faster than expected as consequence of the assumed volume increase of the fuel due to thermal expansion and fission product swelling. For this phenomenon the power changes have been thought to be responsible to which the fuel rods were subjected during operation in the test reactors. From the analysis of 76 cross sections D.S. Dutt, R.B. Baker, and S.A. Chastain /4/ could deduce an equation which describes the variation of the gap width as function of fabricated gap clearance, local heat rate, local burnup, and the number of full power reactor cycles. Y.R. Rashid has presented a mathematical model capable for describing the behaviour of cracked fuel pellets /5/. In the frame of this model it is possible to calculate the relocation of the pellet fragment outwards to the clad under power cycles by assuming certain crack closing criterions.

A very simple model of this phenomenon is included in the computer code system SATURN-1 /6/ which is used at the GfK, Karlsruhe. It is based on the assumption of free thermal expansion of the pellet fragments around their centre of mass. The result of a modelling calculation is shown in Fig. 4. One can see that the largest variation of the pellet geometry occurs in the first cycle due to the very first cracking of the pellet.

The analysis of an experiment with central thermocouple has led to the result given in Fig. 5. The record of the centre temperature can only be approximated by calculation correctly when an additional decrease of the gap width is assumed from one cycle to the other. The respective result of a SATURN calculation is shown in the upper part of that figure. For comparision, some values are added which have been determined by means of the equation proposed by D.S. Dutt et al. /4/.

The relocation of pellet fragments due to cycling effects can be described through certain modelling assumptions which are more or less plausible. Nevertheless, the question is still open whether this process is controlled only by the behaviour of the fuel pellet. It might be possible that vibrations of the whole structure consisting of fuel pellets and cladding effect those relocations under variations of the thermal load.

3. Thermal behaviour of the fuel

As known, the structure of a fuel pellet changes under operation during the first hours and days. Due to the high temperature gradient the pores being included in the fuel migrate towards the centre line of the pellet. A central hole forms surrounded by a densificated fuel zone. This zone is essentially the so-called columnar grain growth region appearing in the cross sections of irradiated fuel rods.

The formation of the central hole effects a very large decrease of the temperature profile and, therefore, of the centre temperature of the fuel pellet. This effect can be seen in Fig. 6 which presents the result of a modelling calculation, again carried out by means of the computer code system SATURN. Input data for the considered cross section are: pellet diameter 5.09 mm, pellet density 86.5 % T.D., O/Me ratio 1.97, Pu amount 25 %, radial gap width 75 μm, total neutron flux $6.35 \cdot 10^{15}$ $cm^{-2}s^{-1}$, rod power 355 W/cm (axial shape factor 1.27), and clad outer temperature 472 °C (bottom 390 °C, top 590 °C). Fig. 6 shows, moreover, the thermal behaviour of the fuel in the course of operation under the influence of fission gas release. As far as a gap still exists two effects counteract: The heat transfer through the gap gets worse, thus increasing the fuel temperature

The closing of the gap due to fission product swelling,and possibly, relocation counteracts that process. After gap closing SATURN predicts as consequence of continuing fission gas release an increase of the thermal load of the fuel which contacts the clad under low pressure. The steps which appear in Fig. 6 have been caused by the fact that the computer analysis was based on three operation cycles with a linear rod power constant in each one but decreasing from one cycle to the other.

The increase of the thermal load with burnup even when the fuel pellets contact the clad is confirmed by irradiation experiments. Figs. 7 and 8 show results which have been obtained by the detailed analysis of the structural zones of 15 cross sections from a capsule test irradiation in the FR 2 (Karlsruhe) /7/. The cross sections were taken from several test rods with three different burnup values. In all rods the initial gap was closed immediately at reactor startup. The temperatures at the fuel surfaces have been deduced from the temperatures at the measured boundaries of the columnar grain growth and equiaxed grain growth region. And these temperatures have been calculated using appropriate models which describe the formation of the two regions /8,9/.

The heat transfer coefficients given in Figs. 7 and 8 follow from the fuel surface temperatures by a simple calculation. The model (based on /10/) which is applied in SATURN to calculate the heat transfer coefficient and the fuel surface temperature, respectively, yields results (drawn-out lines in Figs. 7 and 8) which agree with the experimental values very well. Summarizing one can state that the fuel surface temperature increases with burnup after gap closure. That means that the mechanical strength of the fuel decreases accordingly.

4. Mechanical interaction between fuel pellet and clad

4.1 Behaviour under steady-state operation

Computer analyses and irradiation experiments have revealed that under steady-state operation the fission product swelling of the fuel does not lead to clad deformations as far as sufficient void volume is available within the fuel rod /1,11/. The irradiation-enhanced creep capability of the fuel is sufficiently large to compensate already at low stresses the volume increase caused by the slow process of fission product swelling. The resulting contact pressures remain smaller in general than those pressures produced by fission gas release. Since even those pressures are not the reason for clad strains, the observed deformations (see Fig. 1) must be caused by the variation of the test rod operation conditions if clad swelling in the fast neutron flux was not responsible.

4.2 Behaviour under non-steady-state operation

Deformations under non-steady-state operation may occur when the following conditions are fulfilled:

1) The residual gap width is smaller than the difference between the thermal expansion of the fuel and that of the clad when the rod power is increased.
2) At reactor startup the rod power is brought to a level which is higher than that in the preceeding reactor cycle, or the rod power exceeds the level which was maintained a certain time.
3) The cracks in the outer zone of the fuel have partially healed or pellet fragments have been moved and stabilized in their new position.

4.2.1 Influence of operation conditions

In order to analyse this phenomenon experiments were carried out by W.Dienst et al. in the FR 2 (Karlsruhe) /11/. Fig. 9 shows the maximal clad deformation which was measured with one of those experiments. It can be clearly seen that deformations of the clad occurred when the rod power was increased after a period on low power without or with preceeding shutdown.

The result of a computer analysis is presented in Fig. 10 /12/. The calculation started with a cracked fuel pellet contacting the clad. The stresses built up in the fuel by the first power ramp to the level of 250 W/cm were reduced slowly by irradiation-enhanced creep of the fuel. The contact pressure decreased simultaniously. A considerable contact pressure was generated with the increase of the rod power up to 450 W/cm by the thermal expansion of the fuel which was restrained in radial and axial direction. The consequence was a permanent deformation of the clad. Power cycling resulted in new loads of the clad because the gap which opened during power decrease was smaller than the difference between the thermal expansion of fuel and clad. Since a relatively high temperature of the clad was chosen for the computer analysis ($T_{co}=650^{\circ}C$), its deformation occurred by creep at stresses below the yield strength. This deformation was very smaller under the chosen conditions. Creep deformations are not to be expected at lower clad temperatures even with high stresses. A strong pressure load by the expanding fuel must then exceed the yield strength of the clad material in order to produce permanent deformations.

The load of the clad is determined by the start level of the power ramp, the ramp rate, and the amount of the power increase. Fig. 11 demonstrates, for example, the dependence on the amount of the power increase from a start level of 200 W/cm. As the fuel temperature increases with rod power and thus the fuel becomes weaker, the effect of the power ramp diminishes with larger power increments. The contact pressure is reduced by creep deformation of the fuel to a growing extend. This tendency is the greater, the higher the start level of the power ramp.

The results given in Fig. 11 refer to a power increase within 10 hours which is very slow. The faster the power increase, the greater is the inertness of the fuel to reduce the contact pressure by creep. The mechanical load increases and, therefore, the clad deformation. Fig. 12 illustrates this effect with a power ramp of 200 W/cm from a start level of 200 W/cm. For short power ramps the stresses in the clad can exceed the yield strength of the clad material. The clad deformations observed in irradiation experiments were mainly caused by such loads /11,13,14/.

4.2.2 Influence of the fuel void volume

W. Dienst and D. Brucklacher have found out from experiments /15,16/ that the creep capability of the fuel depends on the amount of its porosity. The higher this amount, the higher is the overall creep velocity of the fuel. The contact pressure between fuel and clad and, therefore, clad deformations should be less with higher amounts of porosity in the fuel. This tendency can be found in Fig. 1.

The computer analysis demonstrates this effect more clearly which can be seen from the comparison of the behaviour of 86.5 and 90.0 % dense fuel shown in Figs. 13 and 14 . It refers, as an example, to a power ramp from 60 to 100 % (= 355 W/cm) within 10 hours at relatively cold fuel with an O/Me ratio of 1.97.

The extend of the mechanical interaction depends, moreover, on the size of the crack volume in the outer zone of the fuel pellet. Besides the hypothetical case of complete crack healing a second case is presented in Figs. 13 and 14 for a length of the radial cracks of about 10 % of the thickness of the total fuel zone. Due to the very slow power ramp only low contact pressures occur in all cases although the fuel has been chosen relatively cold. They remain below the yield strength of the clad material very clearly.

5. Final remarks

Nuclear power reactors will reach the highest possible burnup without significant mechanical interaction between fuel and clad under operation with ideal constant or decreasing power level if sufficient void volume is available in the fuel, e.g. as central hole. Frequent power changes or even periodical power cycles can significantly increase the load of the clad. During the first operation period relocation effects result in a faster closing of the fabricated gap. With this process gap volume is transformed into crack and central hole volume. Because a certain degree of crack healing is necessary for the occurring of mechanical interaction, a relatively larger gap volume should delay the begin of this interaction, also with cyclic operation.

Clad deformation due to mechanical interaction can be avoided or restricted to a low extend when power ramps are sufficiently slow. They should be the slower, the higher the pellet density is. The fuel must be given enough time to reduce the arising stresses by creep deformation of its own. One can expect that this process will be intensified with burnup because the surface temperature of the fuel pellet is very likely to increase as consequence of fission gas release.

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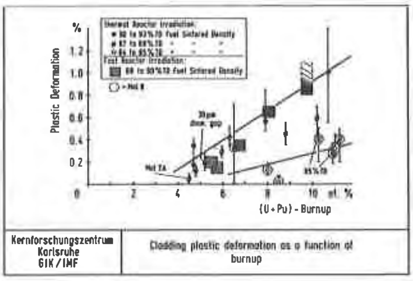

Fig. 1

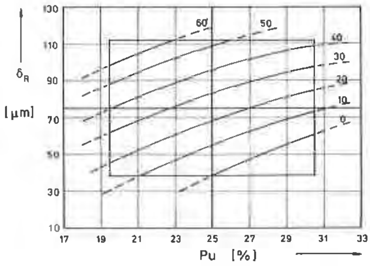

Fig. 2 Residual gap width (µm) at first hot state in dependence of initial radial gap width δ_R and plutonium content Pu of the fuel pellet

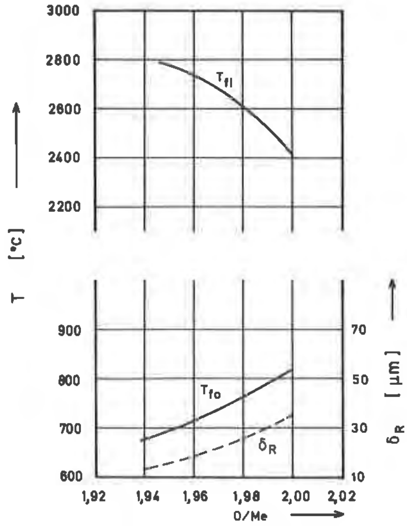

Fig. 3 Fuel centre and surface temperature, T_{fi} and T_{fo}, and radial gap width δ_R versus O/Me ratio of the fuel

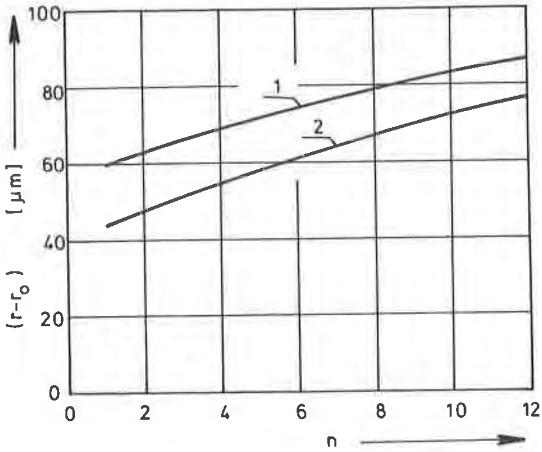

Fig. 4 Increment of the fuel outer radius versus the number of power cycles (r_o: initial fuel outer radius, 1 : hot state, 2 : cold state)

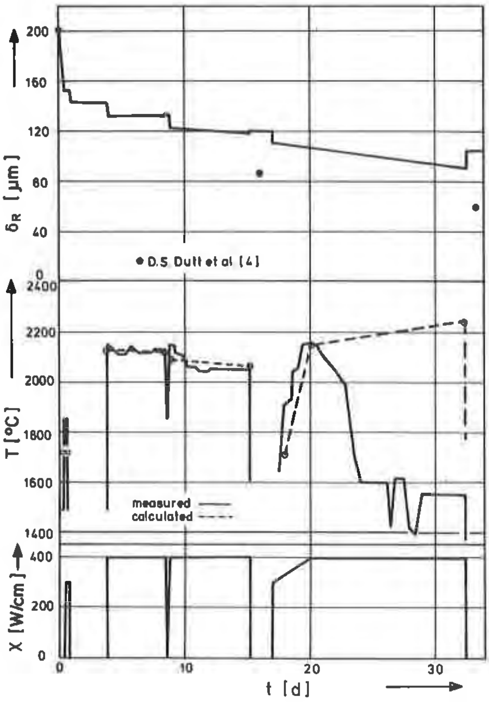

Fig. 5 Calculated radial gap width δ_R, fuel centre temperature T, and linear rod power χ versus time (irradiation experiment Mol-8D/A)

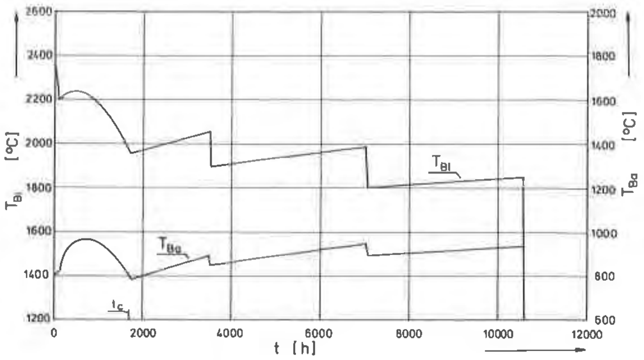

Fig. 6 Fuel inner and outer temperature, T_{Bi} and T_{Ba}, versus time (t_c = time of gap closure)

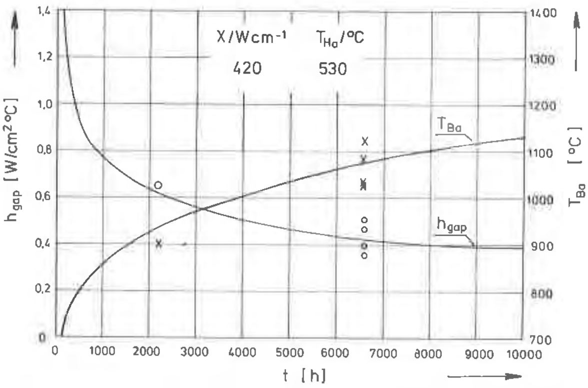

Fig. 7 Fuel surface temperature, T_{Ba}, and heat transfer coefficient, h_{gap}, versus time, experimental values T_{Ba}(x) and h_{gap} (o) from FR 2-KVE-test group 5a (calculated results as drawn-out lines)

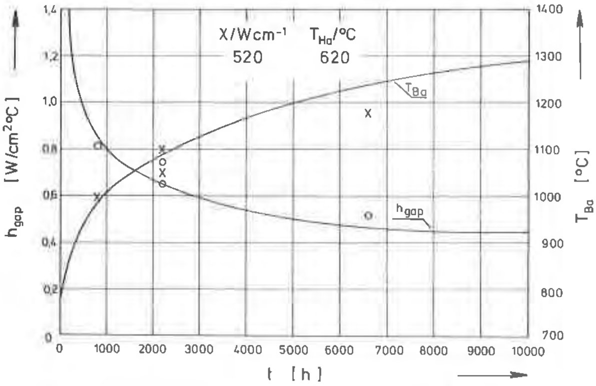

Fig. 8 - same as Fig. 7 -

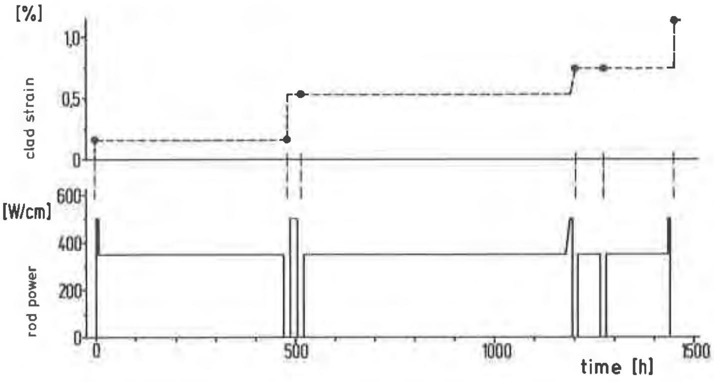

Fig. 9 Clad strain of a short UO_2-PuO_2 fuel pin after load cycles

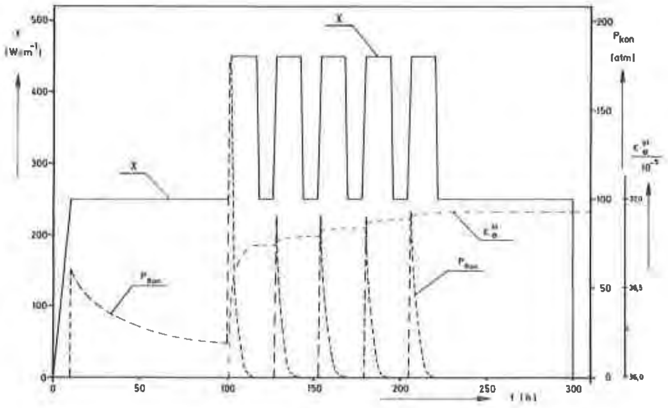

Fig. 10 Linear rod power, χ, contact pressure, p_{kon}, and relative permament clad strain, $\varepsilon_\theta^{b\ell}$, versus time

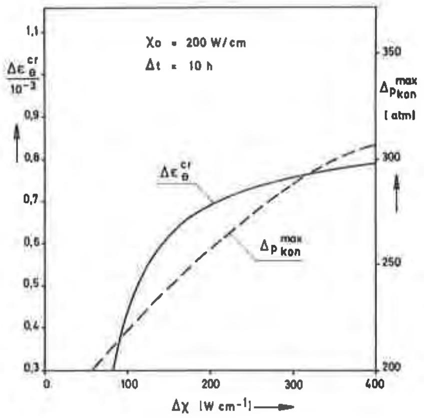

Fig. 11 Maximum of contact pressure, Δp_{kon}^{max}, and relative permanent clad strain, $\Delta\varepsilon_\theta^{cr}$, versus increment of the rod power, $\Delta\chi$

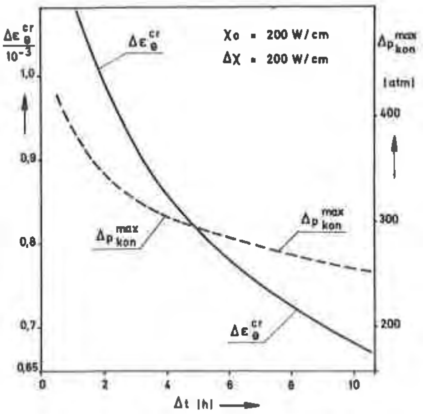

Fig. 12 Maximum of contact pressure, Δp_{kon}^{max}, and relative permanent clad strain, $\Delta\varepsilon_\theta^{cr}$, versus ramp period, Δt

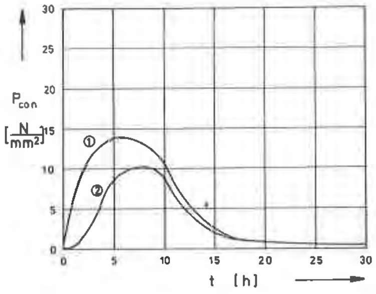

Fig. 13 Contact pressure versus time at a power ramp from 60 to 100 % (= 355 W/cm) in 10 h, ρ_p = 86.5 % T.D., crack length: 0 % (1); 10 % (2)

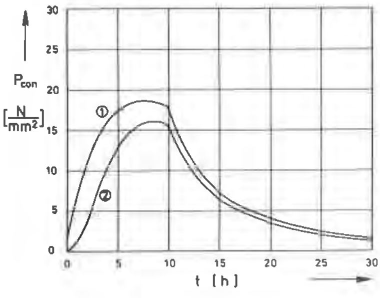

Fig. 14 Contact pressure versus time at a power ramp from 60 to 100 % (= 355 W/cm) in 10 h, ρ_p = 90 % T.D., crack length: 0 % (1); 10 % (2)