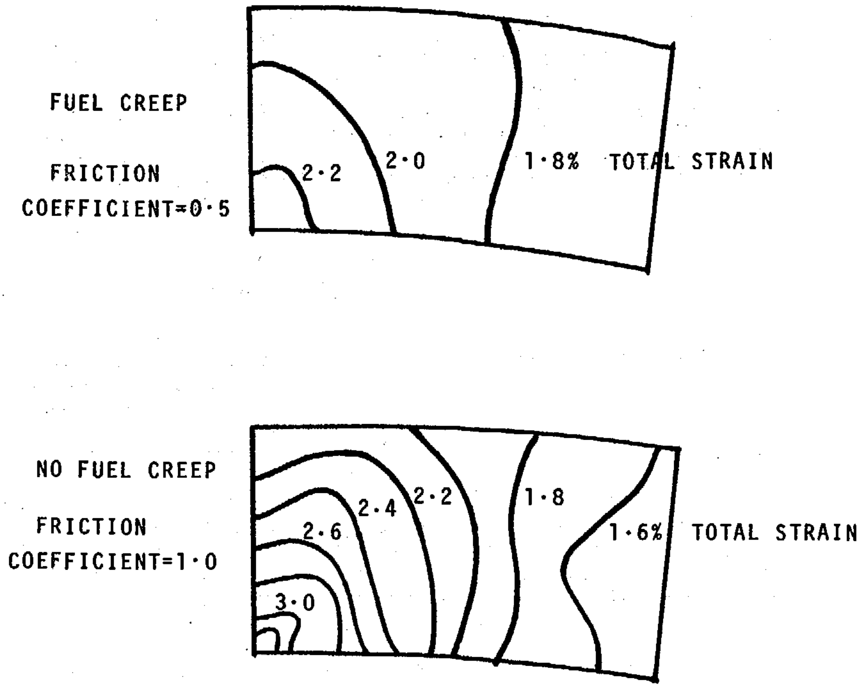
POTENTIAL STRAIN CONCENTRATIONS NEAR RADIAL FUEL CRACKS DURING A POWER INCREASE



THE FUEL TO CLAD HEAT TRANSFER COEFFICIENT IN ADVANCED MX-TYPE FUEL PINS

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1. Introduction

1.1. Present knowledge of h for He-bonded advanced fuels

Advanced fuels (mixed carbides, nitrides and carbonitrides) are characterised by a high thermal conductivity compared to that of oxide fuels (.5 times greater) and their behaviour under irradiation (amount of swelling, fracture behaviour, restructuring) is far more sensitive to the design parameters and to the operating temperature than that of oxide fuels.

The use of advanced fuels is therefore conditioned by the possibility of mastering the above phenomena, and the full exploitation of their favorable neutron characteristics depends upon a good understanding of the mutual relationships of the various parameters, which eventually affect the mechanical stability of the pin. By far the most important parameter is the radial temperature profile which controls the swelling of the fuel and the build-up of stress fields within the pin. Since the rate of fission gas swelling of these fuels is relatively large, a sufficient amount of free space has to be provided within the pin. This space originally appears as fabrication porosity and as fuel-to-clad clearance.

Due to the large initial gap width and to the high fuel thermal conductivity, the range of the fuel operating temperatures is mainly determined by the fuel-to-clad heat transfer coefficient h, whose correct determination becomes one of the central points in modelling.

During the many years of modelling activity in the field of oxide fuels, several theoretical models have been developed to calculate h, and a large amount of experimental data has been produced for the empirical adjustment of the parameters involved, so that the situation may be regarded as rather satisfactory.

The same is not true for advanced fuels. Here the different fuel properties and the variety of design concepts together with the relative scarcity of detailed experimental data make the calculation of h in the case of He-bonding very uncertain.

The strong feed back of the pin temperature field on h by way of the sensitivity of swelling and of crack behaviour of the fuel to the temperature itself, renders the correct prediction of h a difficult task.

However, modelling of h is not fundamentally different in oxides and advanced fuels. The phenomena are intrinsically similar, only the relative importance of the various parameters changes, and the feed-back is generally stronger in the case of advanced fuels. It is therefore reasonable to try at first to apply the same models which have proved valid for oxide pins, and if needed, to improve them either by modifying the empirical constants or by investigating the physics underlaying their algorithmic formulation in more detail.

According to Chow et al /1/ the Ross and Stoute /2/ model gives too low values for h for advanced fuels, while the model of Cooper et al /3/ which contains two calibration constants may be made to produce more reasonable values. A direct comparison of model predictions with experimental results has however not been published, at least to our knowledge.

Predictions of h values for design purposes are generally made on the basis of classical models for oxide fuels /4/, /5/, /6/.

In order to develop models which provide reliable h values under actual irradiation conditions, data from suitable experiments with advanced fuels are required, and such data are very scanty in the open literature. To our knowledge only Williams et al. /7/ have published data on the thermal conductivity of the interface between UN and various metals as functions of

- nature of the metal
- state of the surfaces
- temperature
- contact pressure
- time (modification of the contact microzones due to creep under pressure)

They found for various metals a relation:

$$(1) \quad h_s = KP^n \quad ; \quad 0.8 \leq n \leq 1.4, \qquad P = \text{pressure}$$

The experiments were performed under vacuum so that the pockets between the contact points did not contribute to the heat transfer. This limits the direct application of their results to pin modelling. Equivalent experiments in which UN is replaced with UC and UPuC would be very important. Recently, h has been measured in pile for carbide fuel pins, /8/, /9/, /10/. These experiments have provided experimental h values which in order to be correctly understood, have to be correlated with irradiation data, pin specifications, fuel thermal conductivity, thermomechanical properties and post-irradition analysis. They do not yet suffice to outline a model of general validity. However, we believe they will permit further progress.

1.2. Basic considerations for the description of h

Today it is generally accepted that, besides the radiation component h_T, which is easy to calculate and which under normal operating conditions only contributes a few percent to the total, two components of the heat transfer coefficient have to be considered, namely:

- h_g, the component due to the heat transfer through the gas filled gap between fuel and clad as functions of gas composition and gap width δ ;
- h_s, the component due to the direct heat transport from the fuel to the clad when the two are in contact, as functions of surface geometry and hardness and of contact pressure.

In order to describe h for a pin section at least one more parameter has to be introduced. This is usually defined as the fraction F of the fuel surface which is in "direct contact" with the clad and a linear relation between F, h_g and h_s is assumed /11/.

$$(2) \qquad h = h_s F + (1-F) h_g$$

In fact, under the conditions of an "open gap", the definition of F cannot be regarded independently of the relation by which h_s and h_g are combined with F to give the desired effective value of h, and of the relation between the contact pressure p and h_s , e.g. a pellet fractured into n pie-shaped pieces generally will have n-m (where $m < n$) pieces with different values of the fuel-cladding gap δ_i; and m pieces in contact with the cladding, but with different contact pressures P_j. This situation leads to a varying circumferential temperature distribution in the cladding and circumferential temperature gradients in the fuel. Thus one has to look carefully for an effective averaging procedure in order to describe such situations as functions of three parameters F, h_g and h_s only, and to relate these simply to linear heat rating, burn-up, initial gap width, and cladding temperature and their changes with reactor operating conditions.

F attains the value 1 only when fuel swelling and transfer of gap space towards the pellet centre through cracking and healing processes has taken up all available space between fuel and cladding. The time when this occurs depends upon the initial gap width, the fracture modes of the fuel and the operating conditions.

The problem of h modelling is fourfold:

- the determination of h_g (δ)
- the determination of h_s (δ)
- the definition and determination of F (δ)
- the relation by which h_g and h_s are combined to give h, for a given value of F.

Determination of h_g: this is simply based on models to calculate the heat conductivity of a mixture of gases of known composition, and available models provide a reasonable precision in the calculations /12/. The composition of the plenum gas has to be known at any moment, and for this one has to relay on that part of a fuel or pin code which calculates the gas release.

Determination of h_s: experiments like those by Williams et al./7/ are of great importance to supplement data to adapt existing models or to develop new ones. Since h_s is a function of the contact pressure, its calculation depends on the thermomechanical part of the fuel pin code, which provides this quantity, and on the correct calculation of the fuel swelling. According to Ross and Stoute /2/ a linear relation between h_s and the contact pressure P is assumed.

$$h_s = A + BP \qquad \text{A,B constants} \tag{3}$$

Definition and determination of F: a deterministic model certainly is not able to solve the problem since fuel fracturing and fragment relocation are highly random phenomena. From the data of Kjärnheim et al./12/ for LWR oxide fuel, the following empirical relation may be derived

$$F = 0.1 + 0.9 \cdot 0.1^{\frac{100\delta}{r}} \tag{4}$$

where δ is a "mean" effective gap width and r the pellet radius. Advanced fuels show a much stronger fuel clad mechanical interaction and less in-pile plasticity than oxides, hence the validity of (4) becomes doubtful.

The relation by which h_s and h_g are combined to give h, for a given value of F: the simplest way to combine h_g and h_s, used for oxide fuels, is given in eq. (2), but recently Steiner /13) has proposed for He-bonded carbide fuels a nonlinear combination which may be approximated by

$$h = h_s F + h_g(1-F) + C(F^2-F) \tag{5}$$

In relation (5), account is taken of the fact that the irregular radial displacement of the various fuel fragments disturbs the radial symmetry of the heat flux field. We shall see later that (5) is in better agreement with our data than (2).

In order to improve our knowledge of h for He-bonded advanced fuels, two types of instrumented irradiations, GOCAR and POCY conducted by the Institute have been analysed to give information on the fuel clad heat transfer. This paper gives a first report on this analysis.

2. Experimental procedure

The purpose of the GOCAR series of experiments is the determination of the critical temperature of swelling in MX-type fuels with an instrumented capsule in the thermal reactor Siloe at Grenoble, France. This capsule permits a constant centreline temperature T_c by changing the He/Ne mixture in a gas gap and/or by varying the neutron flux by a limited displacement of the capsule in the flux profile of the reactor. Two experiments are analysed here.

The fuel centre temperature is measured by a chromel-alumel thermocouple placed in a rhenium protection tube. At the same axial position chromel-alumel thermocouples in a NaK bath measure the outer surface temperature of the clad. Neutron detectors of the "Collectron" type measure the thermal neutron flux at the same height as the thermocouples.

Since the fuel centre temperature, the outer clad temperature and the linear heat rating are recorded, the heat transfer coefficient, h, can be evaluated from the data.

The relevant pin data and the irradiation conditions for the experiments analysed below are summarised in Table 1.

In the experiment POCY 01 the effect of power cycling on the fuel-clad mechanical behaviour was studied during normal and transient irradiation conditions. The irradiation was carried out in the helium-loop of the FR2 reactor (KfK, Karlsruhe). Fuel characteristics and irradiation conditions are also given in Table 1.

The fuel centre temperature was measured with a tungsten-rhenium thermocouple and the outer clad temperature by means of 3 chromel-alumel thermocouples at different axial levels. The pins were cooled by circulating helium at an adjustable pressure. The helium flow and its temperature difference ΔT between entrance and exit of the capsule were continuously recorded and from the total power produced the linear heat rating can be calculated. The whole rig could be moved into and out of the neutron flux at defined rates during reactor operation. Using these data the thermal heat transfer coefficient, h, can be evaluated.

The interest in comparing these three irradiations resides in the different starting conditions. POCY 01 and GOCAR VII had cold radial gaps of 14 µm and 23 µm resulting in corresponding hot gaps at first full power (omitting the effect of fuel cracking) of 12 µm and 4 µm whereas the cold gap of GOCAR I was 22 µm and the initial hot gap 0 µm. If the effect of fuel cracking is taken into account, a higher contact pressure must have existed for GOCAR I at first full power than for the other two experiments.

Furthermore for POCY 01 the heat rating was increased at a defined rate during the first start up in order to follow the gap closure.

3. Experimental results

3.1. Check of experimental raw data for internal consistency

The experimental raw data consist of recorded values of : a) the pellet centre temperature T_c, b) the outer clad temperature T_{co}, c) the linear power χ

A set of data was recorded every hour for the GOCAR experiments but since a) and b) are recorded independently from c), a few minutes shift may exist occasionally between the two sets of data. During power changes this may result in sets of values which are not consistent.

Besides this, the thermocouples and recording systems may occasionally fail to give correct values. Among the four values of the outer clad temperature only the highest has been retained.

Careful screening of the original data is therefore necessary to eliminate or to correct erratic values whenever possible without introducing new ambiguities.

A simple check for internal consistency of the recorded temperatures and related linear ratings consists of plotting a lower bound, h_{min}, of h by taking the thermal conductivity of clad and fuel to be infinitely high, and using the recorded values T_c, T_{c_o} and χ

$$(6) \qquad h_{min} = \frac{\chi}{2 \; a_{c_o} \, (T_c - T_{c_o})} \qquad a_c = \text{clad outer radius}$$

If any of the three measured values χ, T_c or T_{c_o} is in serious error at a certain time t', a plot of h_{min} against time will show an irregularity at t = t'. The lower curves in Figs. 1 to 3 show the development of h_{min} with time or rating during the first heating and the following first reactor cycle for the three experiments. In Fig. 2 two examples of irregularities are present which can be explained by sudden changes in rating or cooling conditions.

3.2. Calculation of h-values

For the two GOCAR experiments, h was calculated from the corrected original data by means of TPROF. With T_c and the neutron flux known, the code calculates the surface temperature T_s of the pellet taking account of the exact temperature profile in the fuel due to the flux depression, any change of the pellet radius due to thermal expansion and swelling, and the porosity and temperature dependence of the thermal conductivity according to the relation.

$$(7) \qquad \lambda\,(p_o, T) = (a + bT + cT^2)\;(1 - P_o^{2/3})$$

Since the porosity p_o increases with increasing fission gas swelling $\lambda\,(p_o,T)$ depends upon the swelling model employed and on its burn-up variation. Calculation of the inner clad temperature T_{oi} is straight forward. The "experimental" fuel to clad heat transfer coefficient

$$(8) \qquad h = \frac{\chi}{2 \; a_{ci} \, (T_s - T_{ci})} \qquad a_{ci} = \text{clad inner radius}$$

thus is model dependent via the calculated changes in pellet radius a (t) and porosity $p_o(t)$ with time (or burn-up). The code calculates also a gap width δ (t). This is not used in eq. (8), but is necessary in section 4, in order to analyse eq. (2).

As to the precision of the numerical results, (χ and $(T_s - T_{ci})$ of eq. (8)) all errors of the thermocouple and linear power readings and the errors in $\lambda\,(p_o,T)$ are reflected. The total error may be evaluated as ± 50°C. This makes all values h ≥ 3 W/cm²°C and their strong variations unreliable, and such high h values have little meaning. In eq. (7), the coefficients a, b and c were measured for each batch of the GOCAR fuel pellets in the temperature range 700°C ≤ T ≤ 1500°C, see Table I. At T < 700°C the λ-values for 700°C were employed for lack of better data, but this gives wrong values of h, see Fig. 3. In the case of POCY a simpler calculation of h was performed by using a mean thermal conductivity $\bar{\lambda}$ deduced from a mean fuel temperature for estimating T_s.

3.3. Discussion of experimental results

3.3.1. Gap closure at start of irradiation

The results obtained so far indicate that the behaviour of h depends on the width of the initial cold gap, the initial hot gap and the mechanical fracture properties of the fuel during the first closure of the gap.

If the initial cold and hot radial gaps are in the range 15 to 5 µm a linear increase of h with rating χ exists with slopes $\delta h/\delta\chi$ in the range

$$(9) \qquad 10^{-2}\,\text{cm}^{-1} \geq \frac{\partial h}{\partial \chi} \geq 10^{-3}\,\text{cm}^{-1}$$

for 50 W/cm ≤ χ ≤ 650 W/cm. This range also covers results obtained previously at the Institute /9/. The higher values of $\partial h/\partial\chi$ belong to "open" gaps and the lower values to hot initial gaps with nominal values $0 \leq \delta \leq 5$ µm.

In Fig. 3 the first rise to power for the POCY 01 experiment demonstrates clearly the mechanism of the gap closure. For $\chi > 50$ W/cm the minimum heat transfer coefficient, h_{min}, rises proportionally to χ and the intitial cold gap of 14 µm is closed already at χ = 250 W/cm with T_c = 515°C, when according to the thermal expansion a radial gap δ = 18 µm should still exist.

Consequently the $MC_{.8}N_{.2}$ fuel has fractured sufficiently in the range 50 W/cm ≤ χ ≤ 250 W/cm to close this gap and the following power increase from 250 W/cm to 670 W/cm brings little change in h_{min} at the azimuthal position where the clad temperature was measured. Very probably the increasing thermal expansion is compensated by a slight rearrangement of the fragments, thus keeping the contact pressure constant.

The high peak shown for h at χ = 250 W/cm in Fig. 3 is certainly incorrect, but is a consequence of the fact that for the unknown thermal conductivity in the temperature range 450°C ≤ T ≤ 515°C the measured λ-value at 700°C was used.

The start-up data for GOCAR I MC9 and GOCAR VII MCN7 with similar cold gaps of 22 um and 23 um, but with different hot gaps of 0 µm and 4 µm, unfortunately are not good enough to make the same analysis as for POCY 01. However, another experiment GOCAR VII MN7 with nitride fuel and cold and hot radial gaps of 30 µm and 10 µm again gave a clear linear increase of h from about 0.5 W/cm²°C at 100 W/cm to 1.04 W/cm²°C at 600 W/cm during the first start-up, lower end of the range of relation (9).

Material properties

Fuel thermal conductivity

MC $\lambda^{fuel} = 0.84.10^{-2} + 0.30 \cdot 10^{-3} \cdot T - 0.106 \cdot 10^{-6} \cdot T^2$ T/°C/

MCN $\lambda^{fuel} = 0.123 + 0.895 \cdot 10^{-4} \cdot T - 0.208 \cdot 10^{-7} \cdot T^2$ T/°C/

Fuel thermal expansion

MC and MCN $\alpha^{fuel} = 0.8230 \cdot 10^{-5} + 0.4380 \cdot 10^{-8} \cdot T - 0.1134 \cdot 10^{-11} \cdot T^2$ T/°C/

Clad thermal conductivity

Nb : $\lambda^{clad} = 0.66$ [W/cm.°C]

Steel : $\lambda^{clad} = 0.1508 + 0.1196 \cdot 10^{-3} \cdot T$ ["]

Clad thermal expansion

Nb : $\alpha^{clad} = 0.80 \cdot 10^{-5}$ [1/°C]

Steel : $\alpha^{clad} = 1.7 \cdot 10^{-5}$ ["]

3.3.2 Steady state behaviour of h (GOCAR irradiations)

Here the long term changes of h with increasing burn-up (up to 4 a/o) are of most interest. Apart from this, the following situations may influence h :

i) a short transient decrease of the reactor power leading to $- \Delta \chi \leq 150$ W/cm over minutes or a few hours.
ii) reactor scrams or shut downs affecting h during the next reactor start-up
iii) small variations in the coolant temperature and/or heat rating

Since the quantity h_{min} defined in equ. (6) exhibits less strong variations than h and is completely model independent, it can show best any long term trends. In fact, the h of equ. (8) will show all variations of h_{min} on an increased scale in addition to the model dependent phenomena.

Pin characteristics and irradiation conditions

TABLE 1

		GOCAR I MC9	GOCAR VII MCN7	POCY 01 MCN
Fuel composition		$(U_{0.85}Pu_{0.15})C$	$(U_{0.86}Pu_{0.14})C_{0.8}N_{0.2}$	$(U_{0.8}Pu_{0.2})C_{0.8}N_{0.2}$
Fuel porosity		7 %	6 %	7 %
Fuel outer radius⁺	/um/	3012 ± 2	3009 ± 2	3537 ± 2
Fuel inner radius⁺	"	918 ± 1	900 ± 1	885 ± 1
Clad composition		Nb + 1w/o Zr	Nb + 1w/o Zr	Steel : 1.4988
Clad outer radius	"	3982 ± 2	3541 ± 2	4005 ± 2
Clad inner radius⁺	"	3033 ± 2	3033 ± 2	3551 ± 2
Initial cold radial gap		22	23	14
Initial hot radial gap⁺⁺	"	0	4	12
Linear heat load	/W/cm/	580-655	620-660	800-1050
Centre temperature	/°C/	1090 ± 30	1000	1000-1100
Outer cladding temperature	/°C/	570-625	510-530	550
Averaged flux / surface flux		0.67	0.67	0.61

\+ measured at the position of the thermocouples.

++ Hot gap at maximum power without considering relocation by pellet fracturing.

Up to now, the general results of all GOCAR irradiations can be summarized as follows for fuels of type MN, $MC_{.8}N_{.2}$ and M(C,O):

1. During the first start-up and the following 2 and 3 reactor cycles h_{min} usually increases from a low value in the range $0.3 < h_{min} < 0.6$ W/cm^2 °C to a value in the range 0.95 to 1.00 W/cm^2 °C, and stays at about this value provided the irradiation conditions remain constant. The irradiation MN9 with nitride fuel produced an exceptionally high value $h_{min} \approx 1.17$ W/cm^2 °C which is not yet completely understood.

In the case of the carbide irradiation MC9 shown in part in Figs. 1a-d the behaviour of h_{min} was slightly different. h_{min} increased from 0.6 W/cm^2 °C at the beginning of the first cycle to 0.91 at the end of the second cycle, and then increased slowly further with occasional slight decreases to reach its maximum value $h_{min} \approx 1.005$ only during the 9th (last) cycle.

Thus the general trend indicates that under the conditions of the GOCAR irradiations a steady state with a certain stability is usually reached after 2 or 3 cycles corresponding to 1 to 1.5 a/o burn-up of the fuel near the clad interface and for fuel centre temperatures $T \leq 1100$ °C. (Note, however, that these pellets have a central hole, which may cause a somewhat different behaviour of h as compared to solid pellets).

Comparing the h-values calculated by TPROF for the first cycles of MC9 in Figs. 1a-c with those in Fig. 1d, one observes an increase in h for the high burn-up situation for equal h_{min}-values. This is clearly a consequence of the swelling calculated by TPROF and the assumed porosity dependence of the thermal conductivity in equ. (7). If λ is calculated to decrease with increasing burn-up then for the same measured ΔT and χ values T_s in eq. (8) becomes lower and hence h larger. In addition small measured fluctuations of T_c-T_{co} will now show up stronger in the calculated h-values than for larger values of λ. Thus in the assessment of calculated h-values any model dependence has to be remembered.

2. In principle the response of h_{min} (and h) to small variations of χ or T_{so} during steady state operation should imply more about the correlation between the fuel clad heat transfer coefficient and small variations of the contact pressure between fuel and clad.

Attempts to perform such an analysis for the GOCAR I MC9 irradiation did not lead to reliable results. As a consequence, only very well designed measuring and recording systems for temperatures and power, which are exactly synchronised, will give experimental data suitable for very detailed evaluations.

The irregularities in h_{min} and h which can be observed in Fig. 1b at t = 100h were caused by a sudden drop in reactor power and at $t \approx 150$h by a change in the cooling conditions of the capsule.

The reactor shut down at the end of each irradiation cycle, generally caused a slight decrease of h at the beginning of the subsequent cycle of $-\Delta h \leq 0.5$ W/cm^2°C. Only after the first, second and third cycles however was this effect sometimes absent or less pronounced.

3.3.3. Power cycling

Fig. 4 shows the h-values for the equilibrium conditions (i.e. after each change of the experimental condition) in the 21 cycles of the POCY 01 irradiation experiment. Up to the 8th cycle two clad thermocouples at the same axial position worked satisfactorily, and showed differences in the temperature of between 30 and 50°C at opposite sides of the cladding. Such differences have been recorded also in other irradiation experiments with advanced fuels /5/.

Assuming that under such conditions only a certain part of the pellet is in good contact with the clad, the centre temperature is determined by the lowest h-value, and only these values are shown in Fig. 3. The heat transfer coefficient h is then about 2.2 ± 0.2 W/cm^2°C for the whole irradiation with the following exceptions:

i) Temperature rise of the fuel

In the 7th cycle the clad and the fuel temperatures have been raised by about 100°C. Since the thermal dilatation of the steel is higher than that of the fuel, the contact should normally be reduced, but as a consequence of an additional reversible and irreversible diameter increase of the fuel the h-value is raised to 2.6. The complete evaluation of this experiment including its post-irradiation analysis will be published separately /14/.

ii) Crack formation

Additional cracks have been produced in cycles 9 and 10 by varying the thermal stresses. The lower value of 1.8 W/cm^2°C could be attributed to a reduction of the contact surface.

iii) Power cycling

In the 17th cycle the mechanical interaction between fuel and clad has been systematically reduced by lowering the linear power and rising the cladding temperature. As a consequence the heat transfer coefficient changed regularly from 2.2 to 1.6 W/cm^2 °C.

4. An attempt to analyse measured h-values

4.1. Scope of the problem

In this section an attempt is made to analyse the behaviour of h during the first cycle of the experiment MC9, see Fig. 1a and during the first 300 hours of the second cycle, Fig. 1b, when h rises slowly from about 1 W/cm^2 °C to 2 W/cm^2 °C, by applying equs. (2) and (5). Such an analysis necessarily is highly hypothetical, since the experimental h-values must be broken down into functions $h_s(\delta)$, $h_g(\delta)$ and $F(\delta)$ and the gap width δ must be known as a function of irradiation time. None of the four quantities could be measured, hence the analysis is totally model dependent. Nevertheless it gives some insight into the complexity of the problem. The fundamental quantity on which the analysis must be based is the gap width δ, which the code TPROF has calculated (independent of h) during the first 578 hours of this experiment. The correlation between the calculated δ-values and the measured h-values during this time can be expressed by an empirical relation

$$(10) \qquad h = a + b\delta + c\delta^2$$

At first full power ($t \approx 3$ hours) the code calculated $\delta = 4$ µm, and after 578 hours the nominal gap was closed, i.e. $\delta = 0$, and the code started to calculate an increasing mechanical interaction stress between fuel and clad.

For a better understanding and assessment of the results of this analysis, some remarks about the code and the meaning of the calculated nominal gap width δ are appropriate. The version of TPROF used here has various options, which allow either "normal" calculations, i.e. describing the behaviour of a pin section with known outer clad temperature and neutron flux calculations or adapted to various experimental conditions as, e.g. those of the GOCAR irradiations, see section 3.2. In this case the code calculated thermal behaviour, diameter increase of the pellets due to swelling, gas release and fuel-clad contact pressure; however, it cannot treat fuel fracturing and crack healing. Fuel restructuring and in-pile densification exist in the code, but were not used under GOCAR conditions. Thus the draw-back of omitting fracture phenomena is partly compensated by the neglect of in-pile densification in these calculations.

When the code was run in its normal mode, (only outer clad temperature and neutron flux given) in order to simulate several GOCAR irradiations,

The centre temperature was calculated in one case close to the experimental values and in another case 100 or 200 °C too high. In the case of the irradiation MC9 the diameter increase of the fuel was calculated correctly at the end of irradiation. This was taken as sufficient justification to attempt a more detailed analysis.

The initial hot gap of $\delta = 4$µm and its closure during 578 hours calculated by TPROF appears unrealistic, if one imagines the physical reality of the contact surface between fuel and clad. This direct physical picture, however, cannot be used to interpret the $\delta(t)$ values calculated by the code. It describes the actual complicated topology of the two surfaces in contact, which lack exact circular symmetry, by two perfect mathematical circles, with a radius difference δ. In this way, the complications which arise in modelling due to the unknown deviations from exact circular symmetry are suppressed. Relation (4), in fact, is an empirical solution to this problem in the case of oxide fuels.

4.2. Analysis of the Ross and Stoute model

The problem of establishing the unknown functions $h_s(\delta)$, $h_g(\delta)$ and $F(\delta)$ and investigating their compatibility with equ. (10) and (2) is treated as follows :

i) As long as $\delta > 0$, h_s can be taken to be independent of δ and of the contact pressure

$$(11) \qquad h_s = \text{const.}$$

and can be calculated by the Ross and Stoute model /2/.

ii) The function $h_g(\delta, x)$ can be calculated from standard models for various gas compositions x (filling gas plus released fission gas).

iii) In order to establish a relation between equ. (10) and (2), equ. (2) is differentiated with respect to δ giving with (11) :

$$(12) \qquad h + \Delta h = h_s \left(F + \frac{\partial F}{\partial \delta}\Delta\delta\right) + \left(h_g + \frac{\partial h_g}{\partial \delta}\Delta\delta\right)\left(1 - F - \frac{\partial F}{\partial \delta}\Delta\delta\right)$$

Taking a certain point h_i, δ_i of the curve for equ. (10) and choosing 5 pairs of values $\Delta\delta$ and Δh in the vicinity of δ_i gives a system of 5 equations for the 5 unknowns h_s, F, $\partial F/\partial\delta$, h_g and $\partial h_g/\partial\delta$ at $\delta = \delta_i$. This can be done for various values of δ_i. If both equs. (10) and (2) are compatible the results must be self-consistent.

The system (12) has been solved by varying F parametrically. The results are shown in Fig. 5 where h_s and h_g are plotted as a function of F. Fig. 5 shows also the value of h_g at $\delta = 3.8$ µm calculated for various gas compositions, with standard models based on gas mixture conductivities ($h_g t$) and h_s calculated with the Ross and Stoute model assuming a contact pressure $P = 0(h_s t)$.

The validity of the Ross and Stoute model implies that $h_g t$ crosses the actual curve h_g, and $h_s t$ the actual curve h_s at the same gas composition; the corresponding value of F is read from the F ordinate. The first condition is far from satisfied while eq. (4) would give for $\delta = 3.8$ um and $r = 0.301$ (our case), $F = 0.77$ corresponding on Fig. 5 to a negative value of h_g. It may be concluded that the Ross and Stoute model combined with eq. (12) is not compatible with the experimental h-values and the calculated δ-values in eq. (10) relating to an MC fuel with small initial gap.

The same analysis can be carried out for the combination of eq. (10) with Steiner's relation (eq. (5)). The corresponding system of equations has been solved by varying C and F parametrically. The variations of C have covered the field -1 to +2 while F has been varied between 0.99 and 0.4. The solution is subject to the condition that both $\partial F/\partial\delta$ and $\partial h_g/\partial\delta$ are negative. The solution proved that only values of $C \geq 0.005$ satisfy this condition. The results are reported in Fig. 6. One sees that h_s does not depend on C while h_g regularly increases with it.

Fig. 6 shows that for a gas release of 23 % $h_s t$ crosses h_s and $h_g t$ crosses h_g for $C \approx 1$, the corresponding F being 0.47. The microprobe analysis of the retained fission gas showed ≈ 30 % gas release at the end of the experiment but it is impossible that 23 % release had already been attained during the first cycle; besides, $F = 0.47$ for $\delta = 3.8$ um seems to be too low a value to be accepted.

Thus the analysis gives unsatisfactory answers in both cases of eq. (2) and of eq. (5). The following conclusions must be drawn.

a. A quantitative comparison of experimental h-values with existing models for h requires rather sophisticated instrumented irrdadiation capsules, which permit the measurement of mechanical data (concerning fuel and clad) together with heat rating and temperatures.

b. Even if it is not possible at present to discriminate between eq. (2) and (5) on experimental grounds, it is most likely that eq. (5) is more appropriate to He-bonded advanced fuels than eq. (2).

c. More and better well-instrumented irradiation experiments are necessary in order to make progress on this problem.

5. Summary and conclusions

- Irradiation experiments with He-bonded advanced fuels in which centre temperature and clad temperature are recorded, give useful information on the heat transfer coefficient h.

- A check for internal consistency of the recorded experimental data (temperature and rating) can be obtained by treating the quantity h_{min} defined in eq. (6) as a function of the irradiation history.

- One source of uncertainty in h is the limited knowledge of the in-pile heat conductivity of the fuel and its change with burn-up at > 2a/o.

- During the first rise to full power pellets fracture and h rises proportionally to the heat rating with a slope $\partial h/\partial \chi$ in the range

  $$10^{-3}\ \mathrm{cm}^{-1} \le \partial h/\partial \chi \le 10^{-2}\mathrm{cm}^{-1}$$

  for ratings in the range 50 W/cm $< \chi <$ 650 W/cm and for initial hot radial gaps in the range 5 um to 14 um (effect of fuel cracking not considered). The lower values of $\partial h/\partial \chi$ belong to smaller gaps and vice versa.

- After 1 to 1.5 a/o burn-up the h-values tend to stabilise around a value $2 \le h \le 3$ W/cm^{2}C under the experimental conditions used in this investigation.

- The h-values are sensitive to changes in the linear heat rating and/or clad temperature.

- A quantitative comparison of experimental values of h with existing models requires capsule irradiations, in which temperatures, rating and also mechanical parameters are all recorded during irradiation.

Captions of Figures

1a. Values of the heat transfer coefficient, h, between fuel and clad and of the quantity h_{min} defined in eq. (6) for the first cycle of the irradiation experiment GOCAR I MC9, see sections 3.1. and 3.2. Note the change in the time scale at t = 100 h. In this and the following figures b, c and d the h values were calculated by the code TPROF.

1b. Values of h and h_{min} for the second irradiation cycle of MC9. The two irregularities in h_{min} and h between 100 and 300 h were caused by transients in the coolant temperature and in the reactor power respectively.

1c. Data for the third irradiation cycle of MC9.

1d. Data for the 8th irradiation cycle of MC9. Whereas the quantity h_{min}, based only on directly measured data, shows little change compared with Figs. b and c, the quantity h has noticeably increased. This is caused by the model dependent decrease of the thermal conductivity calculated by TPROF.

2. The values of h and h_{min} for the first irradiation cycle of the experiment GOCAR VII MCN7.

3. The behaviour of h (χ) and h_{min}(χ) during the first rise to power in the irradiation experiment POCY 01. The initial cold gap is already closed by radial cracking of the fuel pellet at $\chi \approx 250$ W/cm as shown by the quantity h_{min}. The high maximum of h at $\chi = 250$ W/cm very probably is caused by using a wrong thermal conductivity when calculating h.

4. Measured h-values in the POCY 01 irradiation experiment. For the majority of the cycles the thermal heat transfer coefficient is about 2.2 ± 0.2 W/cm^{2}C. An increase of the clad and fuel temperatures of about 100°C raises the values of h. In contrast, crack-formation and power decrease lower h.

5. Results of the check of compatibility between eqs. (10) and (2).

   The solid curves represent values of h_s and h_g which satisfy eq. (2) as a function of the parameter F. They have been obtained by solving the system of equations of type (12). The dotted curves represent h_s and h_g calculated by the Ross and Stoute model assuming $\delta = 3.82$ µm and are called h_{st} and h_{gt}. They are shown as functions of the gas release, which appears in the lower abscissa. 100 % is the total amount of fission gas produced at the end of the first cycle.

6. Results of the check of compatibility between eq. (10) and eq. (5).

   The solid curves represent values of h_s and h_g which satisfy eq. (5) for $\delta = 3.82$ um and for various values of the parameter C (h_s is independent of C).

The dotted curves represent h_s and h_g calculated by the Ross and Stoute model, and are called h_{st} and h_{gt} in the figure, assuming δ = 3.82 um.

h_{st} and h_{gt} are shown as function of the gas release which appears in the lower abscissa. 100 % is the total amount of fission gas produced at the end of the first cycle.

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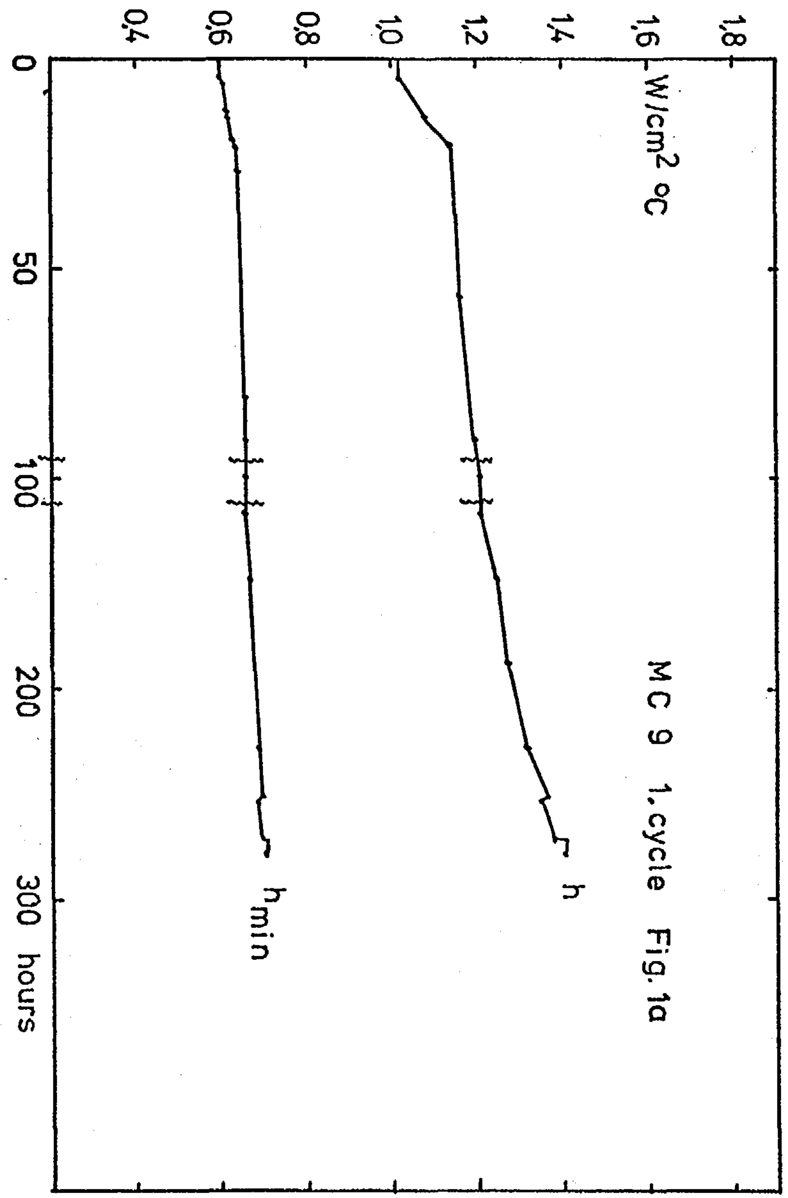
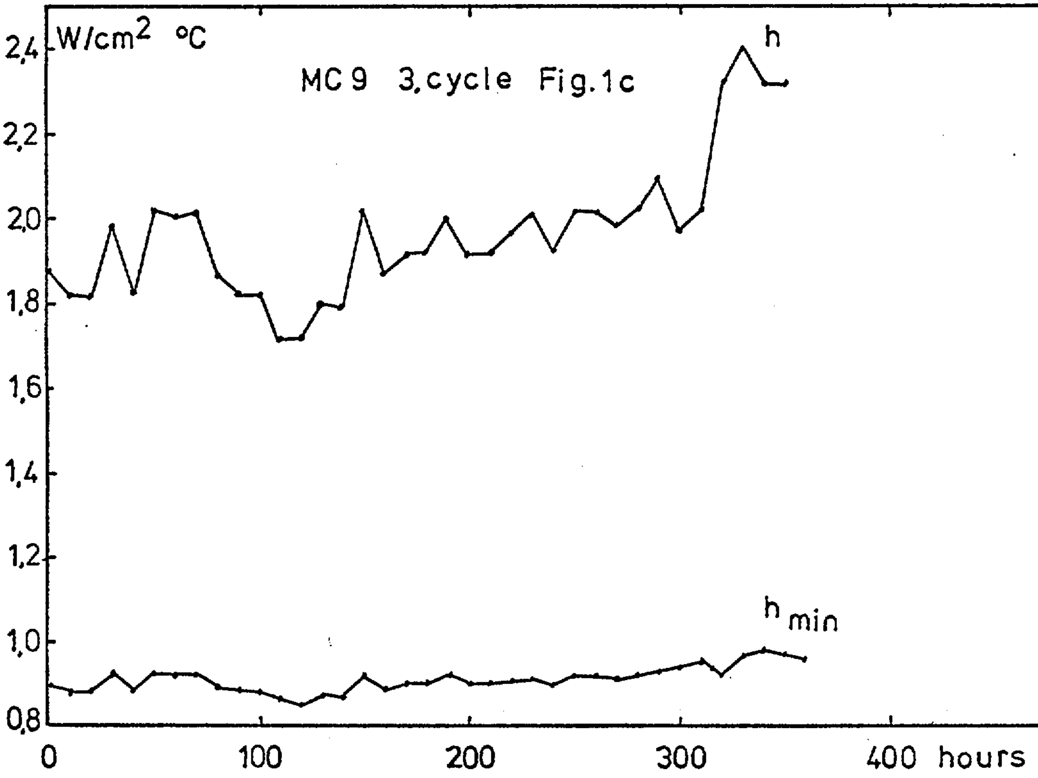
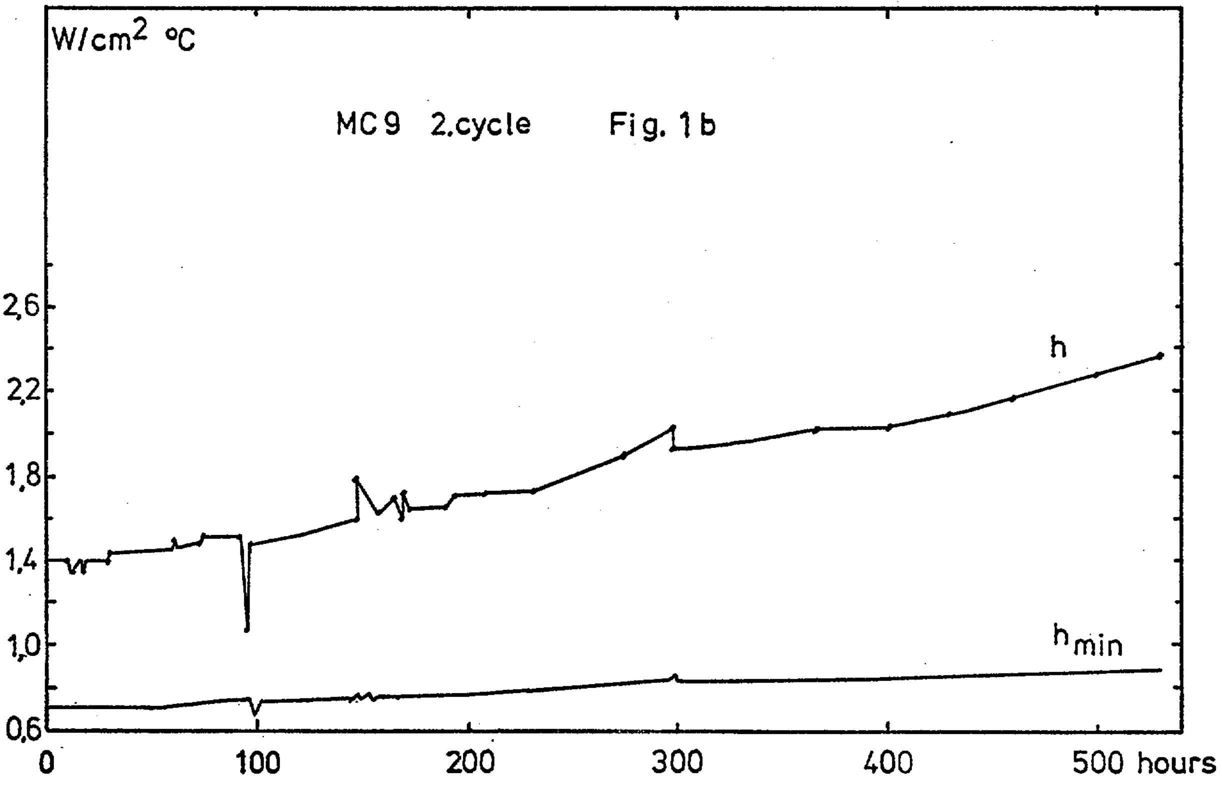
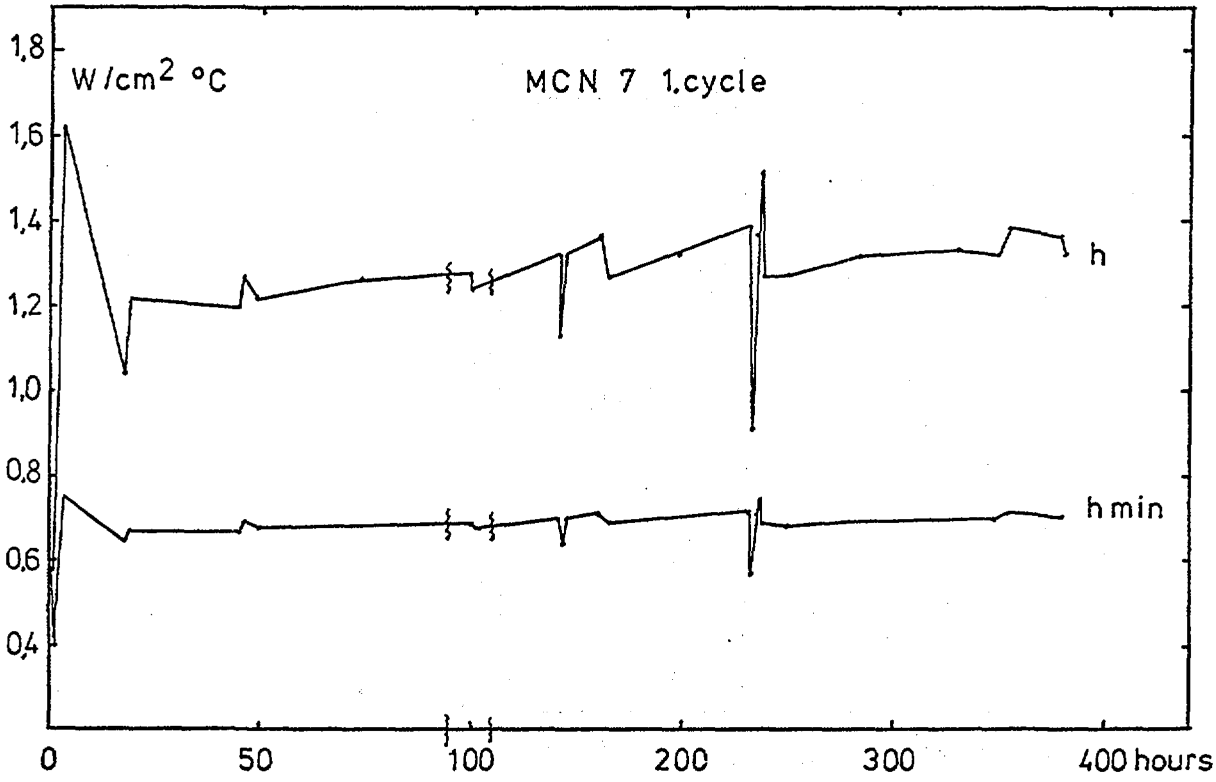
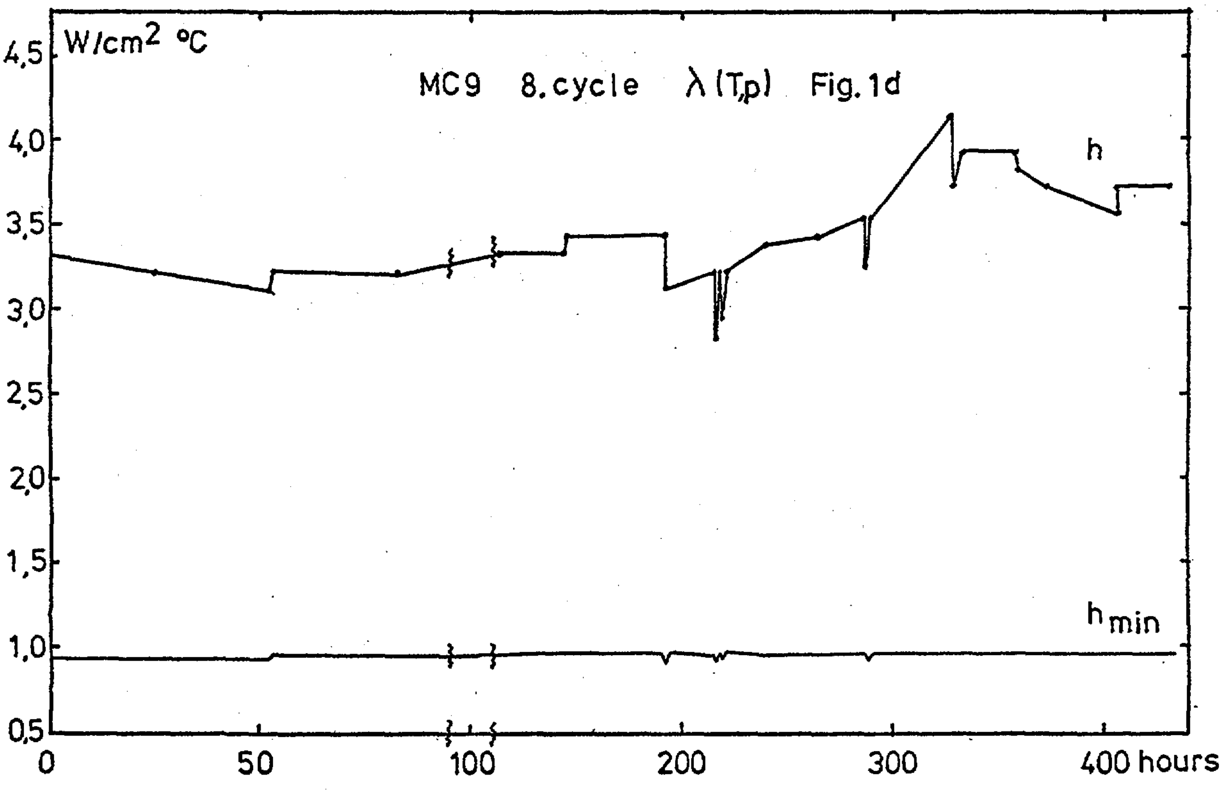
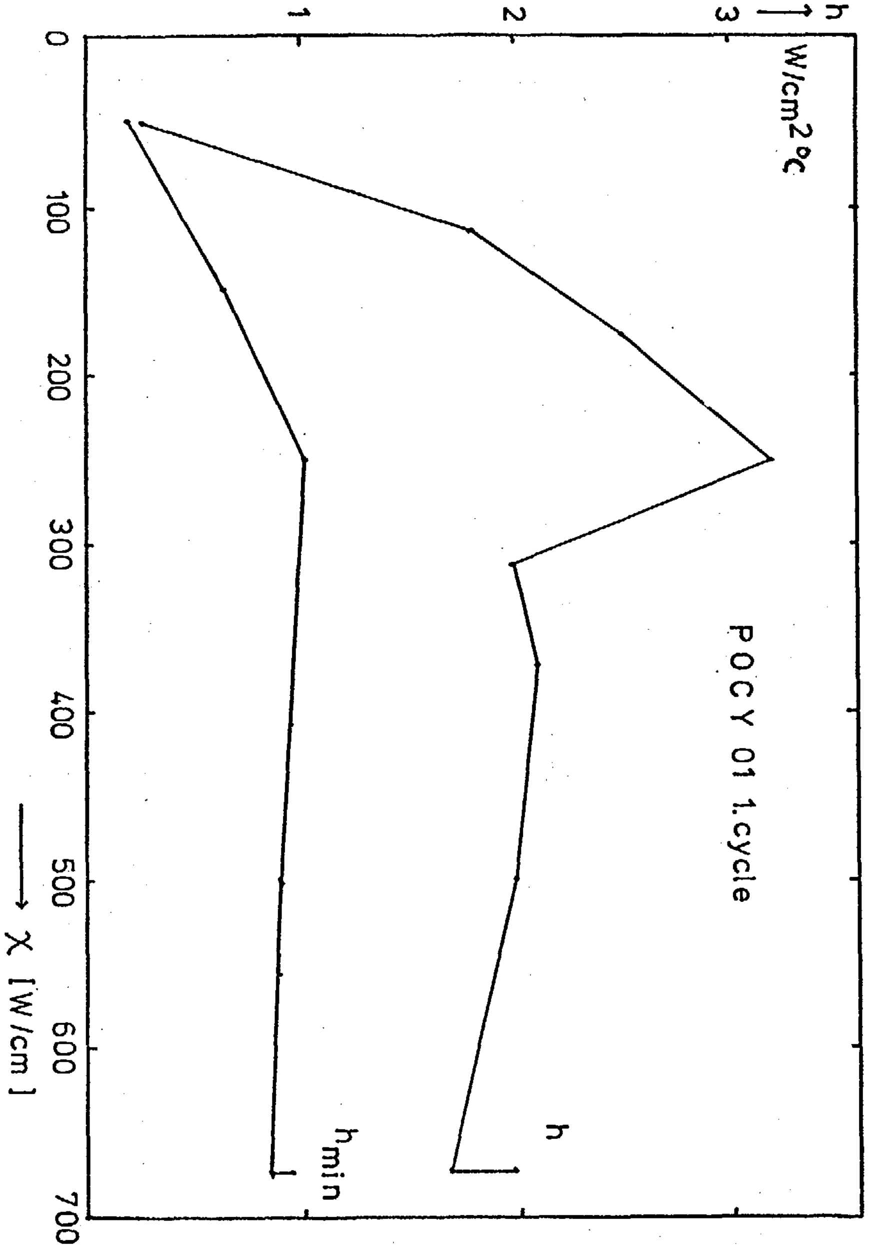


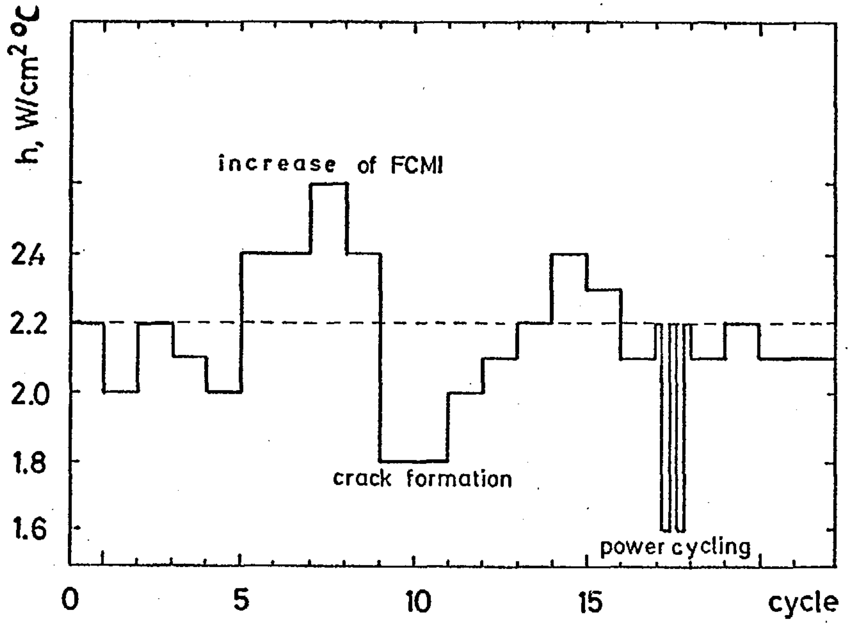

W/cm2 °C
MC 9 3.cycle Fig.1c
h
h min
2,4
2,2
2,0
1,8
1,6
1,4
1,2
1,0
0,8
0
100
200
300
400 hours

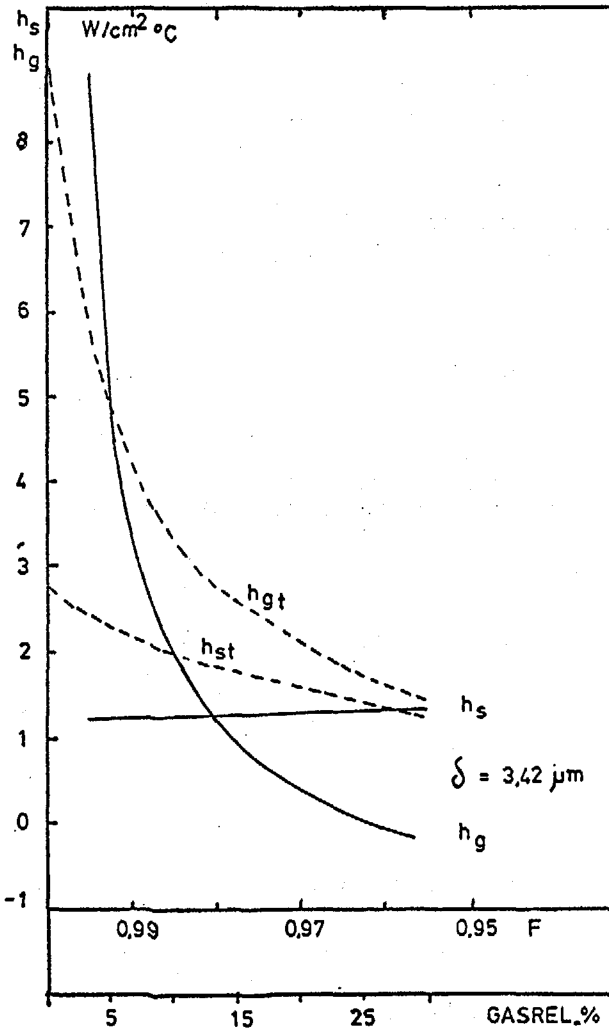

W/cm2 °C
MC 9 2.cycle Fig. 1b
h
h min
2,6
2,2
1,8
1,4
1,0
0,6
0
100
200
300
400
500 hours

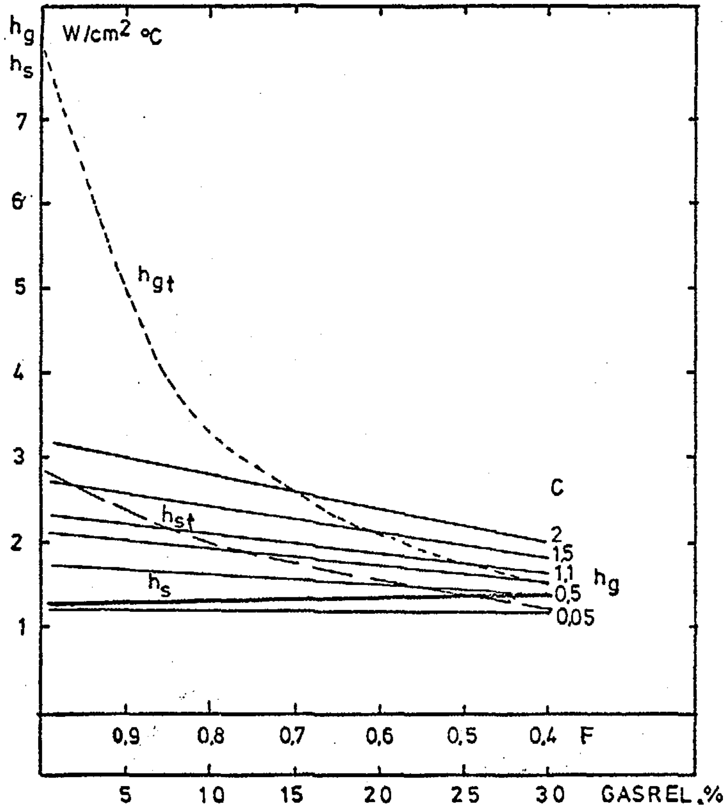

W/cm2 °C
MCN 7 1.cycle
h
h min
1,8
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0
50
100
200
300
400 hours


W/cm2 °C
MC9 8.cycle λ(T,p) Fig. 1d
h
h min
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0
50
100
200
300
400 hours


h
W/cm²°C
3
2
1
0
100
200
300
400
500
600
700
POCY 01 1.cycle
h
h_min
X [W/cm]


h, W/cm²°C
increase of FCMI
2.4
2.2
2.0
1.8
1.6
crack formation
power cycling
0
5
10
15
cycle


h_s
h_g
W/cm² °C
8
7
6
5
4
3
2
1
0
-1
h_{gt}
h_{st}
h_s
δ = 3,42 µm
h_g
0,99
0,97
0,95
F
5
15
25
GASREL.%


h_g
h_s
W/cm² °C
7
6
5
4
3
2
1
h_{gt}
C
h_{st}
h_s
2
1,5
1,1
0,5
0,05
h_g
0,9
0,8
0,7
0,6
0,5
0,4
F
5
10
15
20
25
30
GASREL.%