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# FUEL-CLAD HEAT TRANSFER COEFFICIENT OF A DEFECTED FUEL ROD

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Centre d'Etudes Nucléaires de Grenoble

# DIFFUSION

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| MM. TANGUY | DSN/S |
| FONTERAY (11 ex.) | " |
| PELCE | DSN/SETSSR/S |
| RINGOT | " " |
| VIDAL | " " |
| ANSELIN | " " |
| RAPIN | DMECN/S |
| LALLEMENT | DTech/S |
| DELAFOSSE | DTech/SECS/S |
| LESTIBOUDOIS | DTech/SECS/SEEC/S |
| de CONTENSON | " " |
| COSTE de BAGNEAUX | PILES/G |
| PERRIN | PILES/EDTI/G |
| FRIBOULET | " " |
| BLIN | DMG |
| MORGAND | DMG/SEM |
| DELMAS | DMG/SER |
| FRANCOIS | DMG/SER/LDC |
| BARBIER | DMG/SER/LR |
| BRUET | " " |
| CHENEBAULT | " " |
| JANVIER (4 ex.) | " " |
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| CHALLIER | " " |
| STORA (10 ex.) | EDF/SEPTEN |

# FUEL-CLAD HEAT TRANSFER COEFFICIENT OF A DEFECTED FUEL ROD

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## SUMMARY

The knowledge of the heat transfer coefficient with steam atmosphere inside a fuel rod is necessary to determine the fuel temperature profile in the case of water ingress.

In steady state conditions, depending on the power level, this temperature profile is needed to predict the chemical reactions in the fuel rod as well as the energy stored before a power cooling mismatch accident such as a LOCA.

For this purpose a special rod has been built with a stack of $UO_2$ pellets inside a thick zircaloy clad. The atmosphere inside the fuel rod can be changed and particularly the introduction of water is possible.

The capsule was inserted in the Siloe pool reactor in a special device equipped with a neutron flux monitor, the power level being adjusted by linear displacement.

The power determination is based both on dosimetric measurement and on a mock-up thermal calibration. The accuracy of such determination is better than 2 %. The fuel centerline temperature and the temperature at a certain radius of the clad are recorded by two thermocouples.

During each step of power the temperature profiles in the fuel and in the cladding have been calculated and then the heat transfer coefficient. As a result, a relation between the heat transfer coefficient and the gap (deduced from the differential thermal expansion) has been plotted.

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In the first part of the irradiation, two steps of power have been performed with an helium atmosphere inside the fuel rod, in order to check the proper functionning of the device. The heat transfer coefficients thus obtained were in excellent agreement with the results of previous determinations where the heat transfer coefficient had been related to the gap and heat conductivity of the filling atmosphere (He, Ne, Xe, Kr, Ar).

Then the helium atmosphere inside the fuel rod was removed and replaced by water at room temperature, and the power was increased in 8 steps. At the end of the 8th step, the center thermocouple failed so that is was not possible to follow the thermal behaviour of the device when the power was decreased.

The heat transfer coefficient derived from the first measurement at a low power level is in agreement with the value given by our model based on thermal conductivity. However, for higher power levels, the heat transfer coefficients become higher than those based on the calculated gap.

These results can be explained in different ways but the most probable explanation is thought to be related to the build-up of localized and temporary high water vapour pressure in fuel cracks (in the case of pulsated vaporisation phenomena above the fuel for example) ; the fuel fragments would be separated and this would reduce the gap between fuel and cladding in comparison to a normal rod. This interpretation is supported by the important fragmentation of the fuel as it can be observed on a final neutrography.

Further experiments with various initial gaps and a more reliable center thermocouple have been planned so that firm conclusions could be drawn.

However, it can be already stated that the difference in mean fuel temperature between a rod with cladding failure and a normal rod is not so high as one would expect by considering respectively the helium and water vapour thermal conductivity.

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## INTRODUCTION

As the probability of having some defected fuel rods in the core of a pressurized water reactor is not quite negligible, it is highly desirable to give a description of the irradiation conditions of these rods. As a matter of fact, the temperature distribution can be largely influenced by the presence of steam in the free volumes of the rod and the consequences on stored energy have to be known. On another side, this situation can result in an oxidation of the fuel and hydriding of the sheath.

The work described below is related to the measurement of the fuel-clad heat transfer coefficient when water vapour is intentionally introduced in a fuel rod at the beginning of its life.

## 1 - DESCRIPTION OF THE IRRADIATION DEVICE

The active part of the irradiation device used for the determinations is shown on Figure 1.

This active part was made by a stack of 13 mm $UO_2$ diameter pellets inside a thick zircaloy clad.

The fuel-clad diametral clearance was 330 µm at room temperature. Temperatures in the cladding and in the centerline of the fuel were recorded from thermocouples located in the middle plane of the rod (chromel-alumel and tungsten-rhenium 5-26 % respectively).

The fuel rod was communicating with a pneumatic circuit which allowed to change the gas gap atmosphere with different fill gases i.e. He, Ar, Kr, Xe or $H_2O$.

During irradiation in the Siloe reactor, the capsule was placed inside a cooling sheath rigidly locked with a waterbox, the position of which fixed the power level to the required value. The neutron flux corresponding to a given position of the waterbox was determined from the electric output of four flux monitors located outside the sheath in the middle plane of the fuel stack.

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## 2 - METHOD USED TO DETERMINE THE FUEL-CLAD HEAT TRANSFER COEFFICIENT WITH A GIVEN FILLING ATMOSPHERE

The device described in 1 has been irradiated at various power levels. Each step of power lasted for about 15 minutes, this time being sufficient to reach thermal equilibrium and to ensure stable recordings of the thermocouples and of the flux monitors.

The following measurements were performed at each step :

a) - linear power generated by the fuel $Q_L$
b) - temperature at a radius $r_m$ : $T_{(r_m)}$ (thermocouple in the cladding)
c) - temperature in the centerline of the fuel $T_c$

The linear power $Q_L$ (W $cm^{-1}$) was determined with an accuracy of 2 % from the mean electric output of the four flux monitors. A calibration was performed first, using a similar device equipped with two thermocouples in the cladding ; the precise location of these thermocouples was determined by optical microdensitometry on neutron radiography of the cladding.

The out of pile radial thermal conductivity had also been measured on a sample of the same zircaloy batch. The calibration device was irradiated in the same cooling sheath, just before the experiment ; the temperature difference between the two thermocouples $\Delta T$ was plotted against the mean current from the flux monitors.

Previous determinations had given the power generated in the cladding by the gamma flux $q_z$ (W $cm^{-3}$) as a function of the signal from the flux monitors. The linear power $Q_L$ is only dependent on $\Delta T$ and $q_z$. As $\Delta T$ and $q_z$ are both derived from the electric output of the flux monitors, $Q_L$ can be related to this electric output. From $Q_L$, $T_{(r_m)}$, $T_c$ and $q_z$, the following parameters were calculated :

- The temperature of the inner surface of the cladding $T_{ig}$

$$T_{ig} = T_{(r_m)} + \frac{1}{4\lambda}\left[\frac{Q_L}{\pi}\, \ell n\, \frac{r_m^2}{r_g^2} + q_z\left(r_m^2 - r_g^2\left(1 + \ell n \frac{r_m^2}{r_g^2}\right)\right)\right]$$

where : $\lambda$ is the cladding thermal conductivity,

$r_g$ is the internal radius of the cladding ;

The other parameters are as defined previously.

- The integrated thermal conductivity $I_{T_s}^{T_c}$

$$I_{T_s}^{T_c} = \int_{T_s}^{T_c} K_{(T)}\, dT = \frac{Q_L}{4\pi\,(r_u^2 - r_t^2)} \left\{ r_u^2 - r_t^2 \left(1 + \ell n \frac{r_u^2}{r_t^2}\right)\right\} \cdot f$$

where : $r_u$ and $r_t$ are the external and internal radius of the fuel ($r_t$ corresponding to the hole necessary for the thermocouple)

f is a correction factor taking into account the flux depression ; it is determined from the enrichment and from the $UO_2$ pellet diameter by using the nomograms of Runnals Morrison [ 1 ].

The function $I_{(T)}$ is already known for $UO_2$ 3.4 % porosity [ 2 ]. It can be expressed between 0 and 2800°C by :

$$I_o^T = 5.8915 \times 10^{-2}\, T - 2.1777 \times 10^{-5}\, T^2 + 4.4413 \times 10^{-9}\, T^3$$

This integral has to be corrected when the porosity is different, with the Loeb-Ross formula :

$$(I_o^T)_{P'} = (I_o^T)_P\, \frac{1 - \alpha P'}{1 - \alpha P}$$

where P and P' are the respective porosities of the reference $UO_2$ and of the $UO_2$ to be determined ; $\alpha$ is the Loeb coefficient and its value, in the present case, is $\alpha \simeq 2,3$ [ 3 ].

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- The fuel surface temperature $T_s$

$T_c$ and $I_{T_s}^{T_c}$ being known, then it comes :

$$I_{T_s} = I_{T_c} - I_{T_s}^{T_c} \qquad \text{and} \qquad T_s = [\, I_{T_s} \,]^{-1}$$

- The temperature drop between fuel and cladding

$$\Delta T = T_s - T_{ig}$$

- The fuel-cladding heat transfer coefficient h (W cm$^{-2}$ °C$^{-1}$)

$$h = \frac{Q_s}{\Delta T} \; \# \; \frac{Q_L}{\pi \, \tilde{\varnothing} \, \Delta T}$$

where $\tilde{\varnothing}$ is the mean diameter of the gap between fuel and cladding.

But for a given filling atmosphere, the heat transfer coefficient is dependent on the existing gap during operation ; so this gap has to be calculated from the measurements performed at room temperature (25°C).

- The thermal expansion of the cladding inner radius : $\Delta r_g$

$$\Delta r_g \; \# \; r_g \, \tilde{\alpha}_{25}^{T} \left\{ T_{ig} + \frac{Q_L}{2 \pi \lambda} \left[ r_{ext}^2 \left( \frac{1}{2} - \ln \frac{r_{ext}}{r_g} \right) - \frac{r_g^2}{2} \right] \right\}$$

where $\tilde{\alpha}_{25}^{T}$ and $\lambda$ represent respectively the mean expansion coefficient and the conductivity of the cladding ; $r_{ext}$ is the cladding outer radius.

- The $UO_2$ thermal expansion

The stresses caused by differential expansion of the uranium oxide in the temperature gradient are supposed to be released by radial cracking of the fuel without relative displacement of the resulting fragments.

Then :

$$\Delta r_u \; \# \int_0^{r_u} \tilde{\alpha}_{(T)} \cdot T_{(r)} \, dr$$

with $\tilde{\alpha}_T = \tilde{\alpha}_{25°C}^{T}$ $UO_2$ thermal expansion coefficient (mean value between 25 and T°C).

$$\tilde{\alpha}_T = 6.797 \times 10^{-6} + 2.896 \times 10^{-9} (T + 25).$$

As a first approximation, the temperature profile in the fuel is supposed to be parabolic :

$$T_{(r)} = T_c - \frac{\Delta T_s^c}{r_u^2} r^2$$

The diametral clearance $J_\emptyset(T)$ during operation is given by :

$$J_\emptyset(T) = J_\emptyset(25°) + 2 (\Delta r_g - \Delta r_u)$$

For each step of power a couple of values h ⟷ $J_\emptyset(T)$ corresponding to a given filling atmosphere is thus obtained.

## 3 - DESCRIPTION OF THE EXPERIMENT

In order to check the proper fonctionning of the device two runs have been successively achieved with an helium atmosphere inside the fuel rod, the power level being increased by steps.

The results obtained are shown on Figure 2 (graph a). Considering the uncertainty on the various data used for the calculation, these results are in good agreement with previous determinations where the heat transfer coefficient had been related to the gap and to the heat conductivity of the filling atmosphere (He, Ne, Xe, Kr, Ar or a mixture of these gases).

Following these determinations, the helium atmosphere was removed and two moles of water were introduced, thus impregnating and covering the fuel at power zero. Then helium was introduced at a pressure of about 70 Torr (i.e. $\sim 7 \times 10^{-3}$ mole He) in order to avoid too high a vapour concentration around the connections with the upper part.

The power was increased in 8 steps ; unfortunately, at the end of the 8th step, the center thermocouple failed, due to corrosion of its sheath by steam. Consequently it was not possible to study the decrease at power zero and to perform another experiment with an helium atmosphere ;

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such an experiment might have shown how the heat transfer coefficient could be affected by an eventual oxidation of the inner surface of the cladding and/or by a slight hyperstoechiometry in the cortical zone of the fuel.

The results obtained for each power step are represented on Figure 2, graph b. The centerline temperature corresponding to the first power step (90 W $cm^{-1}$) is in good agreement with the value calculated by using the model derived from previous experiments, taking into account the gap during operation and the steam heat conductivity $[\lambda(P, T)]$. However, for higher power levels, the centerline temperature does not evolve at all as expected.

Figure 3 allows a comparison between the heat transfer coefficient obtained from the measurements and those derived by considering the water vapour heat conductivity and the calculated gap during operation. For the 8th step (322 W $cm^{-1}$), there is a factor of 2 between the expected value and the result of the measurement !

We examined various hypothesis related to a better thermal conductivity of the gas gap but the most probable explanation is thought to be related to a geometric origin : the build-up of localized and temporary steam pressure in fuel cracks, particularly in the case of pulsated vaporisation phenomena above the fuel stack, causes a relative displacement of the fuel fragments, such a displacement being more important when the initial gap is large. Then the method used to calculate the gap during operation, although it is correct with a filling atmosphere such as He, Ne, Ar, Xe, Kr, would not apply in the present experiment.

It is not possible get to drawn firm conclusions on this matter and further experiments with various gaps and possibly more reliable thermocouples have been planned. However it can be already stated that the difference of thermal profile between a normal rod and a rod with cladding failure is much less as one would expect by considering respectively the helium and steam thermal conductivity.

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For illustration purposes the thermal profiles and energy stored inside the fuel at a power level of 400 W $cm^{-1}$, with helium and steam are given on Figure 4.

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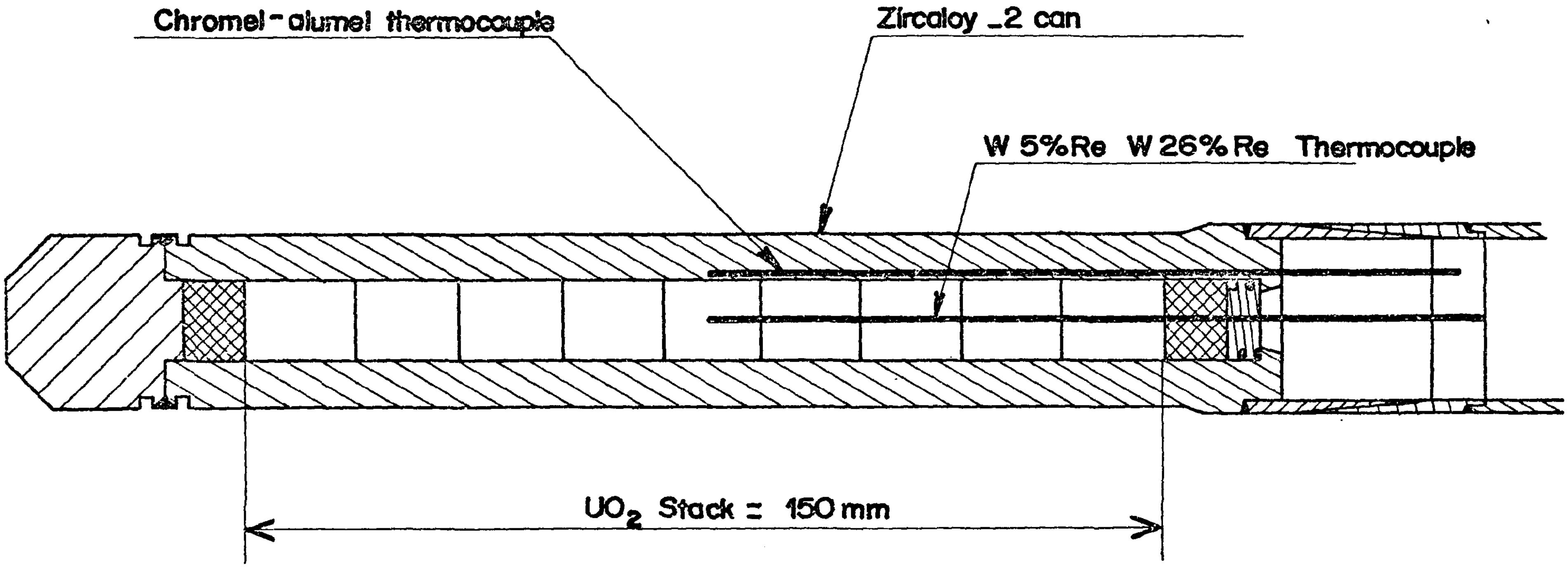

Fig.1: Schematic view of capsule

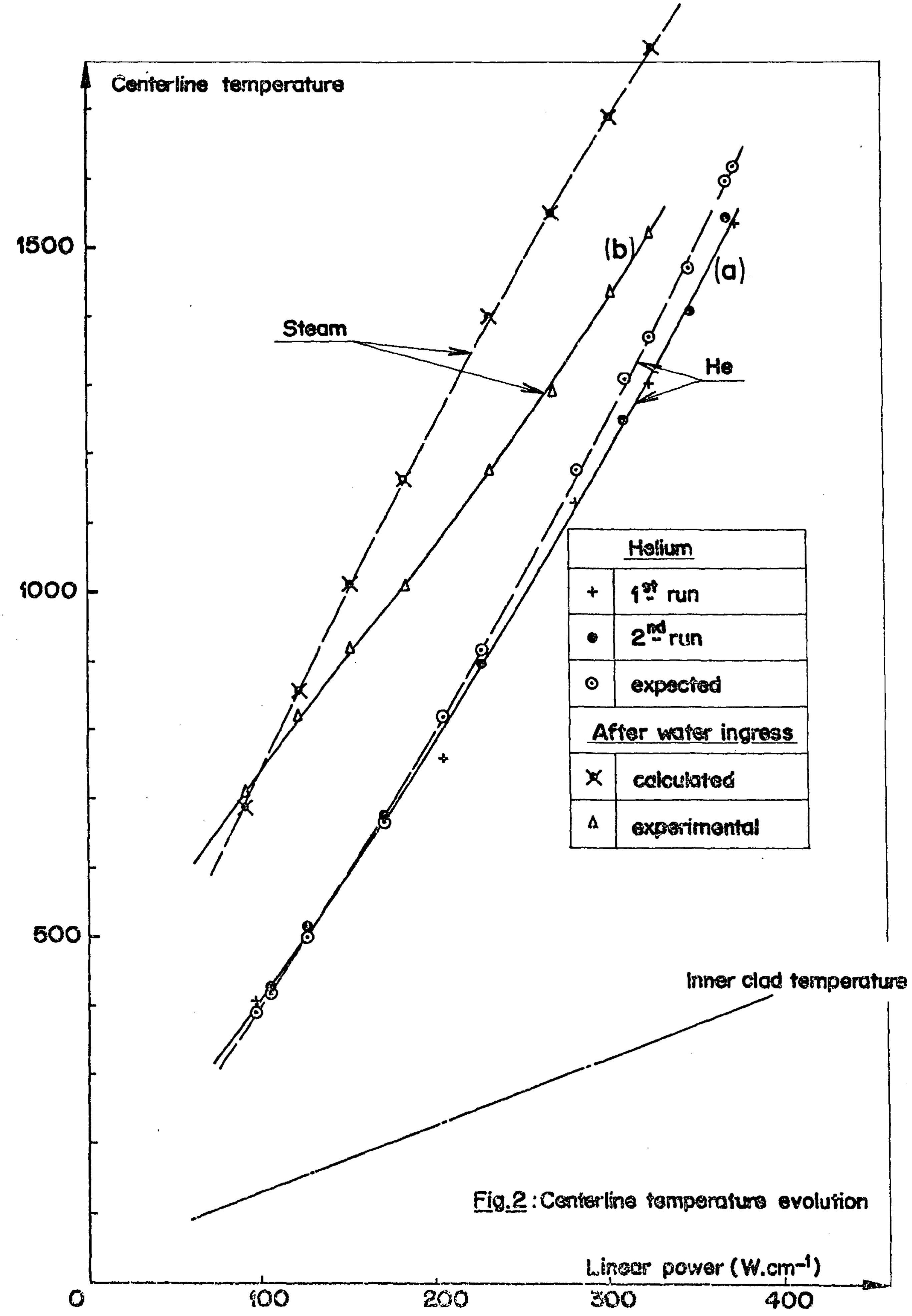

Fig.2 : Centerline temperature evolution

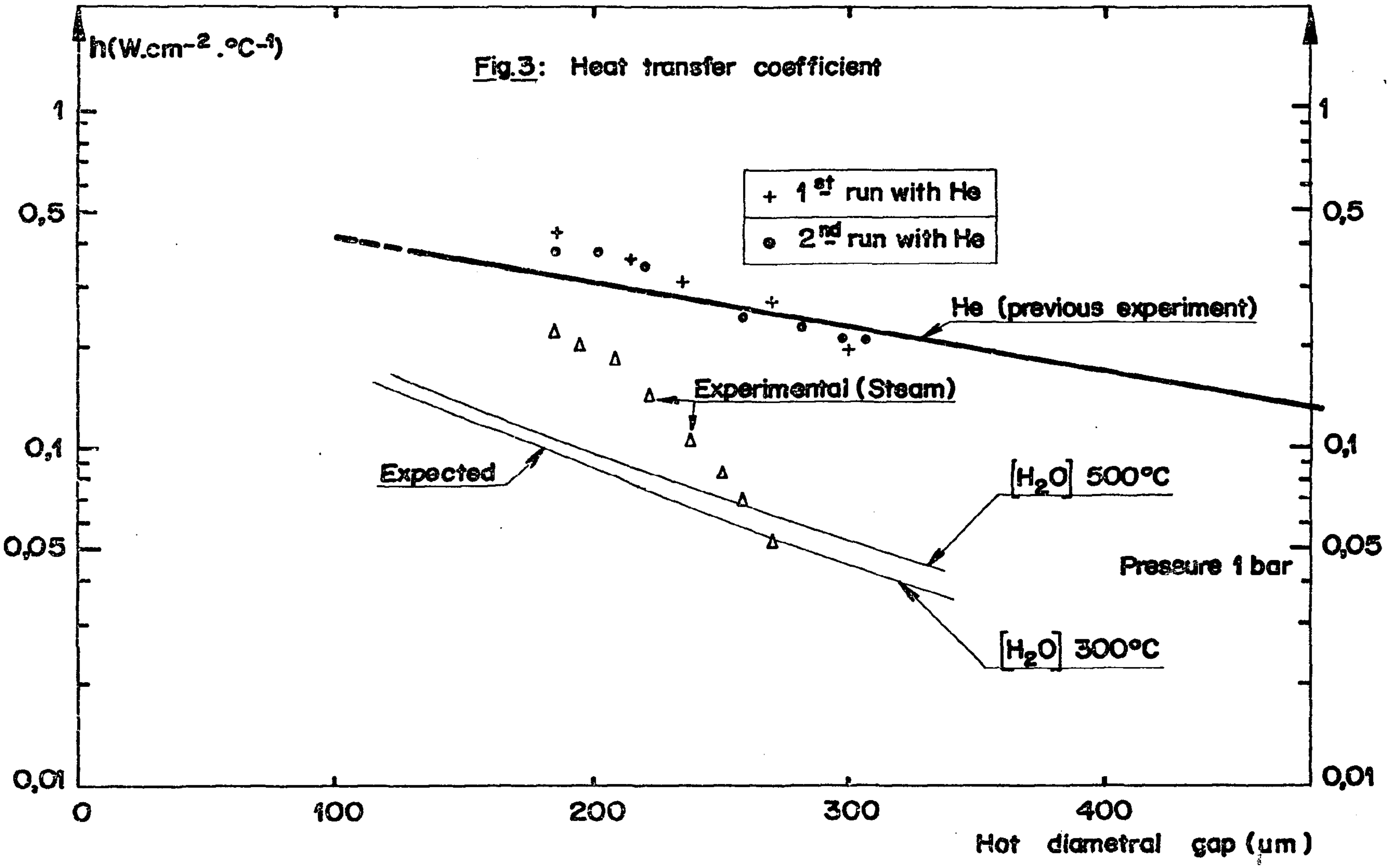

Fig.3: Heat transfer coefficient

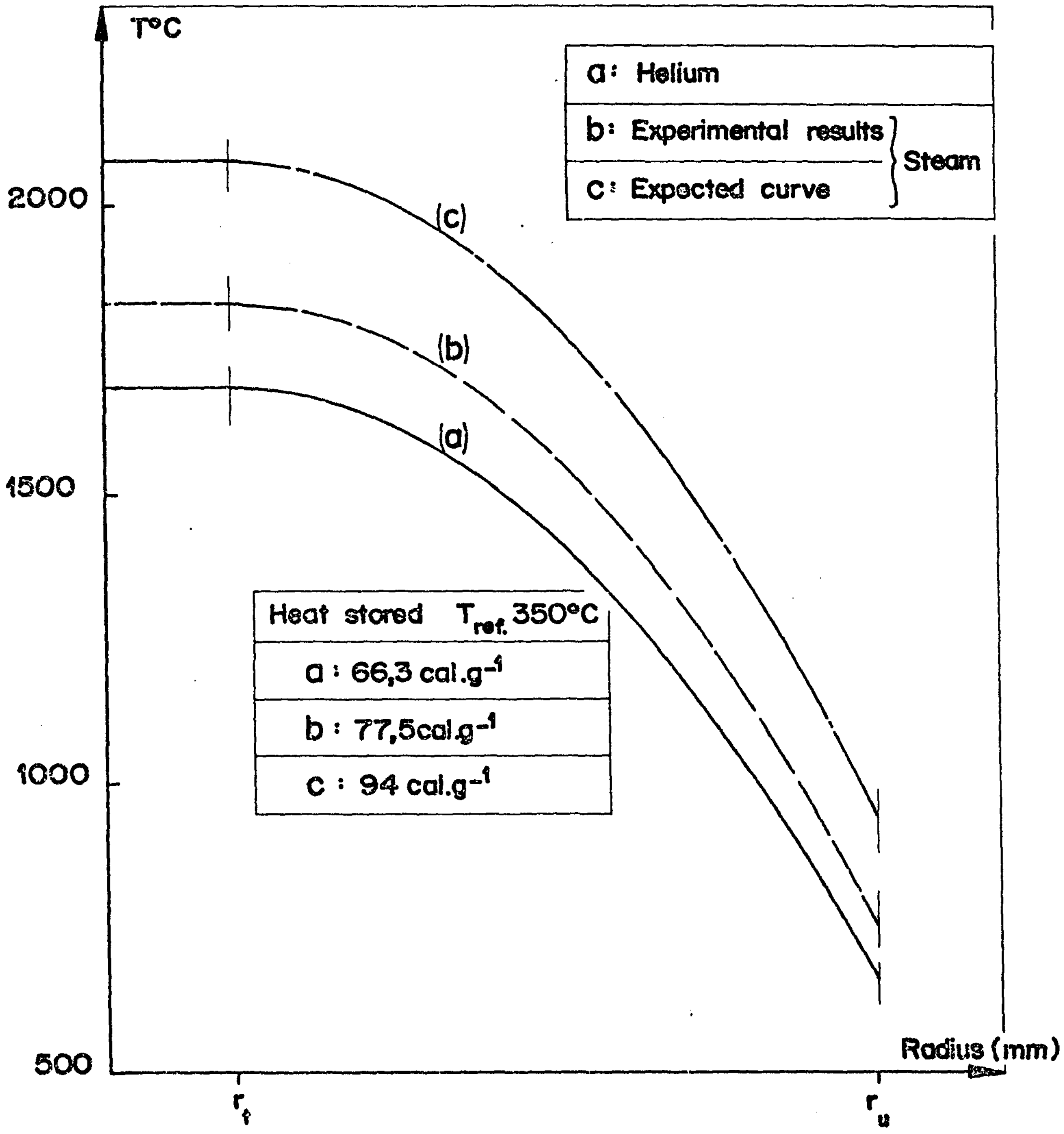

Fig.4 : Thermal profile in oxide ($400 W.cm^{-1}$)