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Projekt Schneller Brüter

# Motivations and Performances of Carbide Fuel Development

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# Motivations and Performances of Carbide Fuel Development

von

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## ABSTRACT

Different strategies have been elaborated for the future development of nuclear energy. One of them has been described in the UNIPEDE study, which was edited by the European Community in March 1974. This study underlines the necessity of breeder reactors under the aspect of saving uranium resources. Especially the carbide reactor will be very effective by its small Plutonium inventory and high breeding gain. Therefore a research and development program, performed by GfK, CEN, RCN, TUI, EIR, Alkem and Nukem within the Coordinated Carbide Program, will develop a fuel element for a carbide fuelled power reactor until 1985. The fuel element concept foresees a linear rating of 800 W/cm, a pin diameter of approximately 8mm with helium bonded pins. Because of restrictions by clad material swelling the maximum neutron dose of about $1.5 \times 10^{23} n/cm^2$ > 0,1 MeV will limit the maximum nominal target burnup in the range of 60-90.000 MWd/tm. Up to now these burnups have been reached within this program without indication of principal difficulties, even under conditions of higher fuel swelling and mechanical interactions with the cladding. Therefore the present design seems to be capable to meet the target conditions.



## KURZFASSUNG

### Begründung und Durchführung der Entwicklung eines karbidischen Brennelementes

Für die zukünftige Einführung nuklearer Energieerzeugung sind verschiedene Strategien entwickelt worden. Eine davon wird durch die Unipedestudie beschrieben, welche von der Europäischen Gemeinschaft im März 1974 veröffentlicht wurde. Diese Studie unterstreicht die Notwendigkeit von Brutreaktoren unter dem Aspekt der Schonung der Uranreserven. Der Karbidreaktor mit seinem kleinen Plutoniuminventar und hohem Brutgewinn wird in dieser Hinsicht besonders wirksam sein. Daher wird durch ein koordiniertes Karbidprogramm die Forschungs- und Entwicklungsarbeit bis 1985 durchgeführt. Die Partner, welche das karbidische Brennelement entwickeln werden, sind GfK, CEN, RCN, TUI, EIR, Alkem und Nukem.

Das Brennelementkonzept sieht eine lineare Stableistung von 800 W/cm, einen Stabdurchmesser von annähernd 8mm und Heliumbindung vor. Wegen der Beschränkung durch das Hüllmaterialschwellen wird die maximale Neutronendosis von $1,5 \times 10^{23} n/cm^2$ > 0,1 MeV den maximalen nominellen Abbrand im Bereich zwischen 60 und 90.000 $MWd/t_m$ fixieren. Bisher sind solche Abbrände in diesem Programm ohne Hinweis auf grundsätzliche Schwierigkeiten erreicht worden. Dabei sind auch aus den Bedingungen des höheren Brennstoffschwellens und mechanische Wechselwirkung mit der Hülle keine neuen Probleme entstanden. Daher scheint das gegenwärtige Konzept geeignet zu sein, die gestellten Anforderungen zu erfüllen.

## Motivations and Performances of Carbide Fuel Development +)

(G.Karsten, G.Mühling, H.Plitz)

### A. Introduction

Different strategies have been elaborated for the future development of nuclear energy. One of these many examples can be given by fig 1, taken from the UNIPEDE study of the European Community. It can be seen that oxide breeder reactors reduce the consumption of $U_3O_8$ remarkably, even more effectively, if they are combined with HTGR's or HWR's. Because of its small inventory of fissile Pu and higher breeding gain the carbide reactor is even more effective. Therefore this reactor type has the potential to give economic relief in the decades to come. The savings would be about 2 million tons of $U_3O_8$ in the European Community. The incentive therefore to develop the carbide reactor as a profitable alternative even to an advanced oxide breeder is understandable. The decision which way finally will be chosen, can be made between 1980 and 1985. If carbide will be technically feasible, carbide will be introduced into the breeder system. Enough knowledge about oxide has been gained to build and operate an advanced oxide core of the SNR Mk I concept. The carbide development will be performed up to that point of decision as the only advanced materials alternative.

+) Reported during ANS winter meeting 1974, Washington Oct 28 - 31.

B. Program Characteristics

One of the characterisitics is that this program is performed in a complementary way by contributions of seven partners, fig 2, since 1969.

After careful analyses, a reference design has been evaluated, which is characterized by modest design criteria in order to reduce pin failures to a minimum, fig 3. Therefore linear ratings are below 1000 W/cm; from reasons of high mass ratings the pin diameter will remain below 8 mm. It is important to notify, that He bonding is preferred, because it offers the smallest chance of failures due to mechanical interactions or bonding losses. In addition it is cheaper to make. By gas bonding the potential of carbide in terms of doubling time or burnup already will be exploited to a fairly large extent, fig 4. Burnup increases beyond 10 %, as could be reached by sodium bonding, probably would need a new cladding type because of the swelling problem. As is shown in fig 5 it is confirmed for solution annealed stainless steels that there will be a quick swelling increase from 4 to more than 10 % after about 6 x $10^{22}$ n/$cm^2$ dosis >0,1 MeV within only one month of operation of a great power reactor.[2) 3)]

From evaluations of representative simulation experiments, and also indicated by pin experiments, with cold worked stainless steels, it appears that the dislocation density after about 1 x $10^{23}$ n/$cm^2$ comes down to the same values of non cold worked specimens. This indicates a destruction of the cold worked effect by irradiation energy. Therefore it may be expected that the use of stainless steels of the non stabilized type will be limited to about 1 x $10^{23}$ n/$cm^2$ or a bit higher, if values of no more than 10 % or 15 % volume increase by swelling would be tolerated. Of course, the full potential to be reached by stabilization of stainless steels still is unknown. From fig 4 then it can be deduced that very advanced systems still could reach about 8 - 10 % peak burnup; this means average discharge of less than 7 % burnup.

The conclusion therefore can be drawn, that the moderate He bonded carbide or the advanced oxide concept could possibly still be operated with stabilized stainless steels in more advanced modifications. Carbide, however, which was demonstrated in fig 1 already, finally would have its maximum effect with highest ratings possible with the sodium bonded concept plus advanced cladding materials.

The time schedule foreseen for different irradiation experiments can also be seen from fig 2: As soon as the smaller screening tests will have been finished, bundle tests in PFR and KNK II will follow.

## C. Program performance

Up to now about 30 specimens have been tested, fig 6, both with gas and sodium bonding, to burnups of 80 000 and 90 000 MWd/t burnup. The first evaluation results indicate a modest diametral increase of the pins. From US results, fig 7 and 8, it appears that carbide fuel, swelling at about 2 % per % burnup could strain the pin diameter about 2 % per % also, if claddings with low creep resistance are applied.[4] With data, corresponding to 1.4970 stabilized stainless steel, cold worked, the following explanations of our low diametral changes are given:

Fig 9 represents fuel pressures, when fuel and clad creep as well as fuel and clad swelling are taken into account. The dotted lines especially include clad swelling, which is excluded in the rest of the lines. With such steady state pressures applied, only very small diametral changes can be expected, fig 10. Only the application of a model for short time fuel clad mechanical interactions, due to power cycling, results in greater strains as were found in the experiments, fig 11. Therefore it can be assumed, that claddings, such as 1.4970 with a high yield strength and slow creep properties, represent a strong restraint to carbide fuel.

Finally, some safety considerations have been made. Calculations, comparing temperature profile shifts due to 2-3 $ /sec power excursions, indicate that there will be no principle differences between oxide and carbide, fig 12, 13.

## C. Fabrication of U-PuC Carbide

For fabrication of mixed carbide fuel various procedures exist, but a real fabrication route on an industrial scale is not yet developed. Therefore a comparison of the fabrication costs between mixed oxide and mixed carbide is not possible to-day taking especially into account that the state of technology reached in mixed oxide fabrication is much more advanced in any case.

The basis of all used procedures for mixed carbide preparation is the carbothermic reduction of the pure oxides. This process has proven to be the most economic one and it is believed that the technological problems which still exist can be solved.

To prepare the mixed carbide fuels for our irradiation program a modified procedure was developed (reactionsintering) where pure Uraniumcarbide is mixed with an intermediate reduction product coming out from the non-quantitative reduction of $PuO_2$ with carbon (Pu-O-C). The advantage of this method is based, as we believe, at first on the fact that the primary reduction leading to the intermediate product, which contains still a remarkable amount of Oxygen, can be performed at lower temperature and therefore the Pu-losses are less; and secondly the UC can be produced by a separate process without hazard penalties and is introduced to the Pu-line at a very late stage. A disadvantage of the described process is, that during the final sintering a reaction takes place leading to a CO-formation in form of larger pores. However fairly high fuel densities (above 93 % theor. dens.) can be gained by this method.

With this described process about 30 kg of mixed U-Pu-carbide fuel were produced during the last year for irradiation experiments with a good reproducebility. A capacity increase for KNK-II with approx. 400 kg/year is under preparation.

## D. Conclusions

1. Carbide fuel is an alternative to oxide.

2. The incentive to develop a carbide core is that a small Pu-inventory and high breeding gain will be very effective in saving uranium resources. This gain can be increased the more the earlier the carbide breeder will be introduced into the breeder system.

3. The gas bonded concept will exploit as well the carbide potential as the present materials' properties to a great extent.

4. The experience gained in the world up to now and the characteristics of the materials used will allow a sufficient burnup even with stainless steel, without danger for unacceptable amounts of clad deformation or failures.

5. The present target is to develop carbide fuel elements until, after successful development, the decision can be taken between 1980 and 1985 to construct carbide fuelled fast breeder reactors as power plants.

## L i t e r a t u r e

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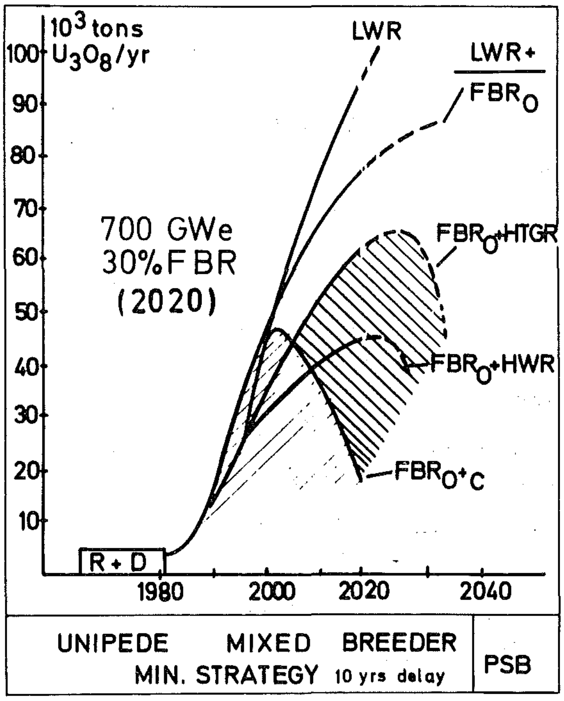



FBRO = Na-cooled
oxide breeder

fig.1

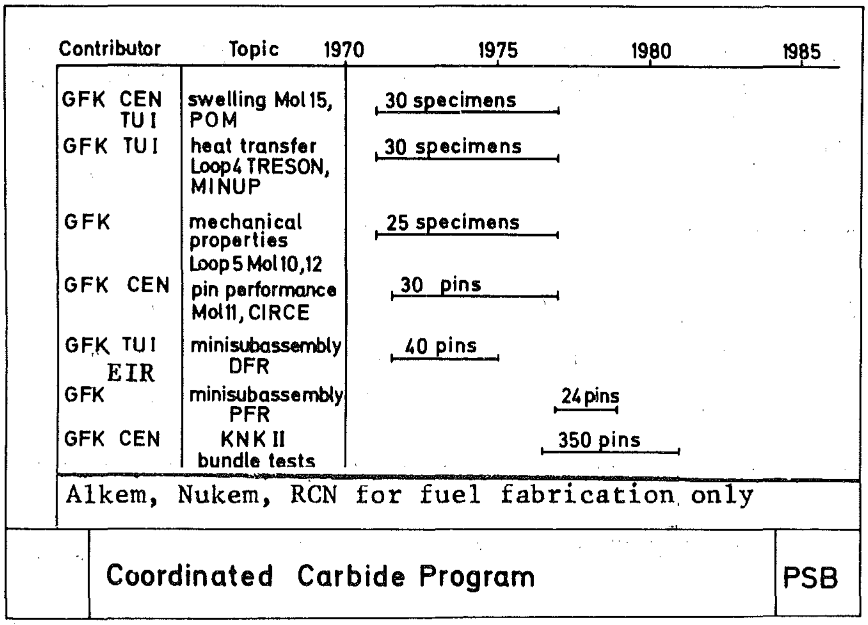



fig.2

| | |
|---|---|
| 1. Fuel | |
| Type | (U Pu) C |
| Smear density | 75-80% th.D |
| Bonding | Helium |
| 2. Cladding | |
| Type | Coldworked, stabilized austenitic stainless steel |
| Diameter | 7.5 - 8.5 mm |
| Wall thickness | 0.5 - 0.55 mm |
| 3. Operational condition | |
| Linear rating | 1100 - 800 W/cm |
| Specific power | 300 ± 50 W/g |
| Average discharge burnup | 50-70 000 MWd/t |

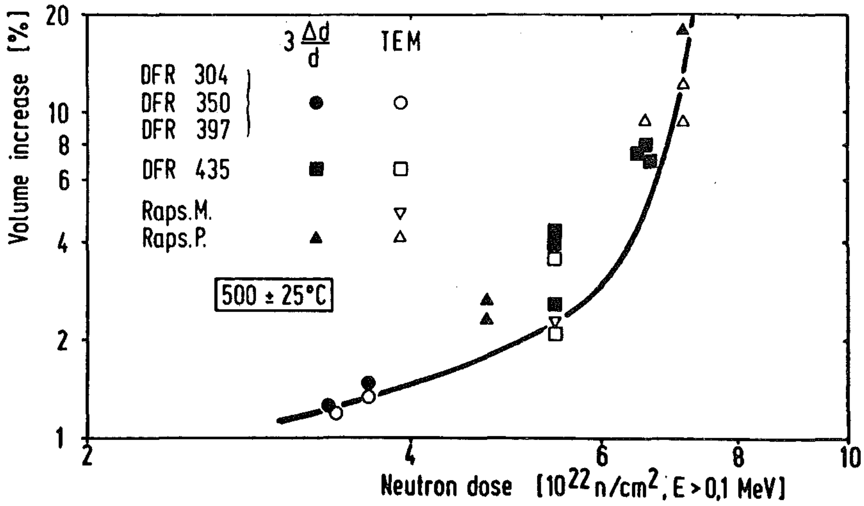
Reference Data for the SNR Carbide Fuel Element — PSB

fig.3

| | Rating $W/g_m$ <br> +) ± 50 | Pin Diam. mm | Breeding Ratio | Syst. Doubl.t years | Neutron Dosis >0.1 MeV Discharge burnup, average <br> 10% | <br> 7% <br> $x10^{23} n/cm^2$ | <br> 5% |
|---|---|---|---|---|---|---|---|
| Oxide | 170 | 7.5 | 1.15 | 40 | 3.0 | 2.0 | 1.5 |
| Adv. Oxide | 300+) | 6 | 1.25 | 20 | 2.0 | 1.5 | 1.1 |
| Carbide | 300+) | 7.5 | 1.35 | 15 | 2.0 | 1.5 | 1.1 |

LMFBR CHARACTERISTICS, approx. values — PSB

fig.4



Volume increase [%]
20
10
8
6
4
2
1
$3\frac{\Delta d}{d}$
TEM
DFR 304
DFR 350
DFR 397
DFR 435
Raps.M.
Raps.P.
500 ± 25°C
2
4
6
8
10
Neutron dose [$10^{22}$ n/cm$^2$, E > 0,1 MeV]


fig.5

## GfK-Carbide Fuel Irradiation Results

| Experiment | Number of pins | Bonding | Pellet density (% th.d.) | Gap size (mm) | Heat rating (kW/ft) | Max.burn-up (MWd/kgM) | $\frac{\Delta D}{D}$ (%) | Fission gas release (%) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| Mol-11.K.1.1 | 1 | He | 94 | 0.10 | 39.5 | 35 | 1.3 | 21.4 | UC-defect at 17 MWd/kg M (capsule failure) |
| Mol-11.K.2.1 | 1 | He | 83 | 0.14 | 36.5 | 41 | 0.19 | - | |
| Mol-11.K.2.2 | 1 | He | 83 | 0.18 | 38 | 77 | 0.77 | - | |
| Mol-15 | 3 | Na | 90 | 0.50 | 32 | 89 | - | - | Neutrographs o.k. |
| | 1 | Na | 90 | 0.50 | 32 | 67 | - | - | |
| FR-2 Vg.6A | 3 | He | 86 | 0.05 | 30.5 | 45 | - | - | 1 Defect (capsule failure) all other intact |
| FR-2 Vg.6A | 2 | He | 86 | 0.05 | 30.5 | 22.5 | - | - | |
| FR-2 Vg.6C | 3 | Ar | 86 | 0.08 | 30.5 | 45 | - | - | |
| FR-2 Vg.6C | 2 | Ar | 86 | 0.08 | 30.5 | 22.5 | - | - | |
| FR-2 Vg.6D | 3 | He | 86 | 0.50 | 30.5 | 45 | - | - | |
| FR-2 Vg.6E | 3 | Na | 93 | 0.50 | 30.5 | 45 | - | - | |
| DFR-330/1 | 7 | Na | 95 | 0.84 | 36 | 46 | 0.3-0.4 | 15.3/17.6 | 1 Defect ($\Delta D/D$ = 1.4%) |

fig 6

SWELLING OF CARBIDE FUELS
WITH BURNUP & TEMPERATURE

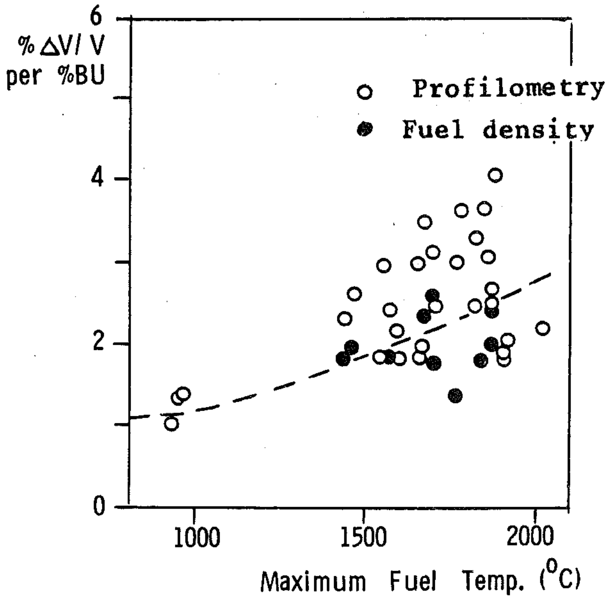



fig.7

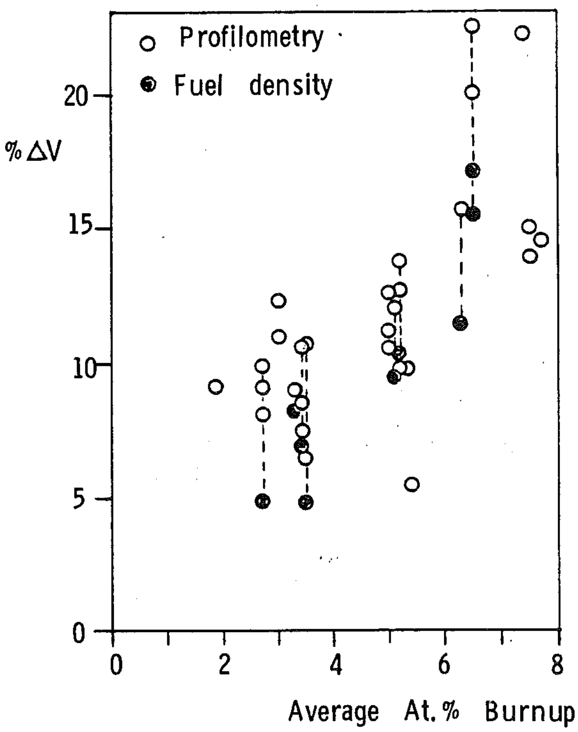
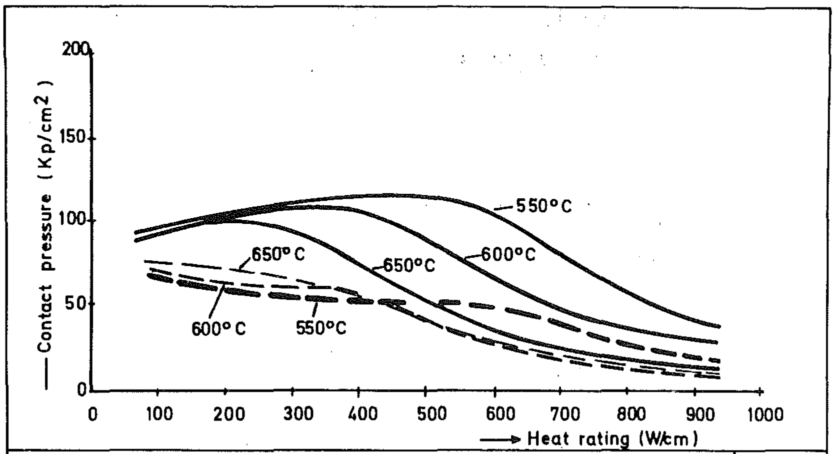
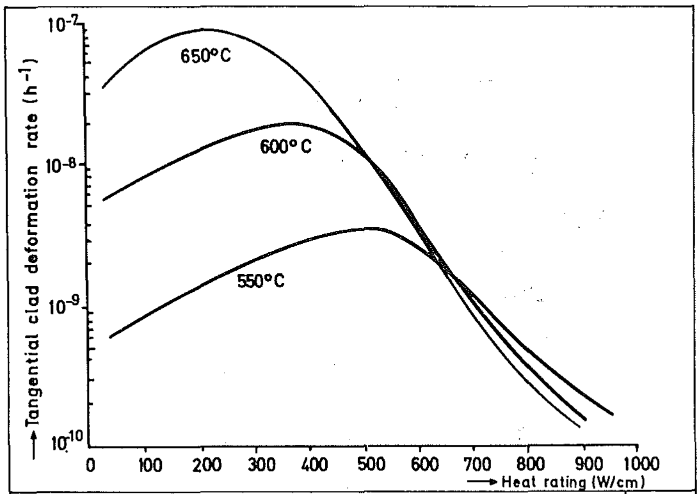



fig.8



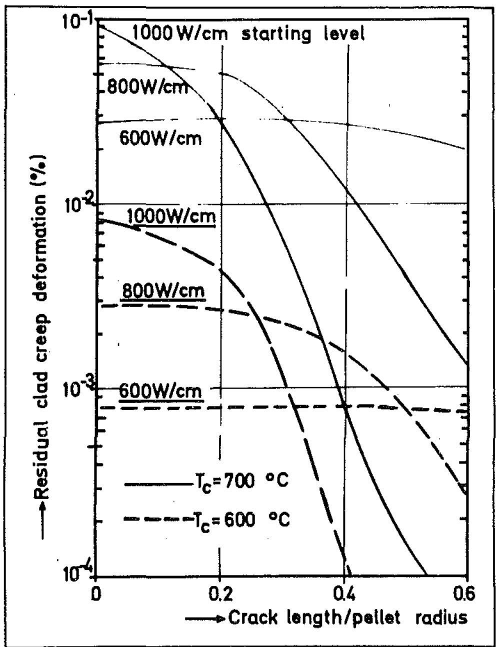

Swelling pressure/heat rating, parameter clad temperature | PSB

fig.9



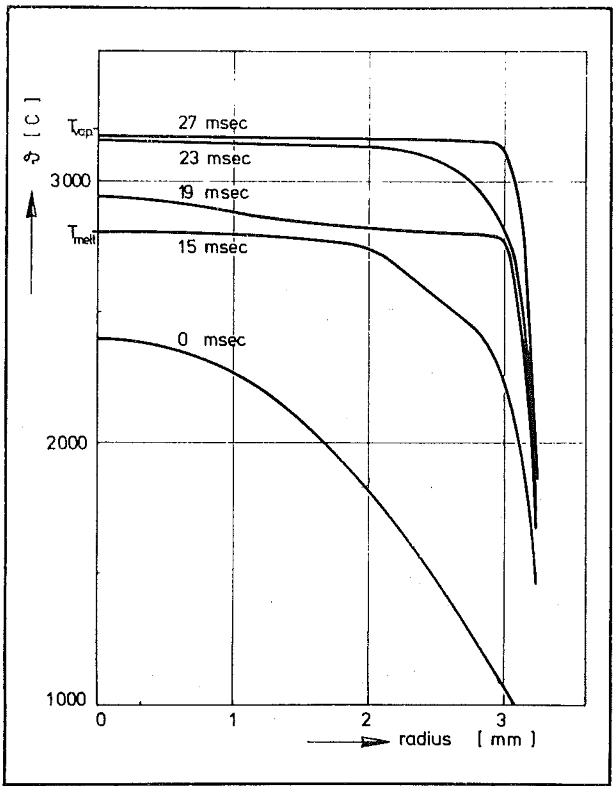

Tangential clad deformation rate versus heat, rating parameter clad temperature | PSB

fig.10



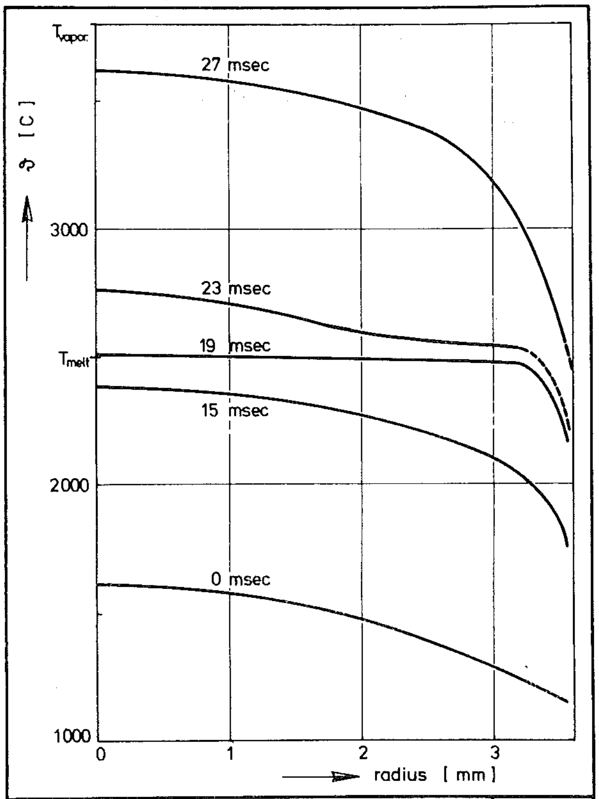

| Residual clad creep deformation due to a power increase of 40% as function of pellets crack length | PSB |
|---|---|

fig.11




Oxid response to power transient

fig.12




Carbid response to power transient

fig.13