CRACK HEALING AND VOID MOVEMENT
DURING IRRADIATION OF ThO₂ - 2 wt% UO₂

by

A. S. BAIN

Chalk River, Ontario
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AECL-3008
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ABSTRACT

Zircaloy sheathed ThO$_2$ - 2 wt% UO$_2$ pellets, which had pre-formed cracks and holes, were irradiated for 69 days at a power rating of $\int \lambda \, d\theta = 61$ W/cm. Central temperatures were 2400 ± 200°C, based on an estimated $\lambda = 0.031$ W/cm deg C. Where circumferential crack widths had been large the diametral expansion of the sheath was low, indicating that the hot fuel was plastic and could move into the voidage. Cracks and axial holes were eliminated above an estimated temperature of 1700 ± 150°C, compared with 1400 ± 100°C for UO$_2$: both temperatures are 0.55 of the absolute melting point. There was no sublimation across any crack; other possible crack healing mechanisms, e.g. creep, surface diffusion, grain boundary sliding have been considered.

Compared with UO$_2$ irradiated at the same power per unit length, the thoria fuel had less diametral expansion, less grain growth: autoradiographs showed essentially no fission product relocation. The presence of a circumferential crack near the periphery throughout the irradiation did not significantly impede heat transfer.

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INTRODUCTION

Solid solutions of UO$_2$ in ThO$_2$ are of interest as fuel for near-breeder reactors$^1$. Examination of experimental elements$^2$ indicate that thoria fuels with a low percentage of UO$_2$ are less subject to grain growth than UO$_2$ irradiated at the same power rating, expressed as

\[ \int_{\theta_s}^{\theta_0} \lambda \, d\theta^* \]

The release of fission product gases, a potential source of performance limitation, may therefore be lower for the ThO$_2$-base fuels. Thermal and densification stresses cause cracking in both materials. Earlier experiments$^4$ showed that cracks in UO$_2$ heal if the temperature is near or above that where appreciable grain growth occurs. Since ThO$_2$ is more refractory than UO$_2$, cracks in the former might be less apt to heal; if so, the resulting higher temperatures could cause higher gas release from the ThO$_2$-base fuels.

The same experiments on UO$_2$ showed that a simulated circumferential crack, present outside the grain growth region throughout the irradiation, caused no measurable effect on the extent of grain growth. The present experiment was therefore undertaken to obtain comparable observations for thoria-base fuels.

Since the behaviour of voids is important to the dimensional changes of ceramic fuels, the movement or elimination of preformed voids was also studied in these experiments. Earlier experiments had shown that, in UO$_2$, large voids near the grain growth limit can close by plastic flow$^4$ and that those within the grain growth region can move inwards by fuel transfer$^5,6$.

* \( \lambda \), the thermal conductivity of the fuel, is integrated between \( \theta_s \), the surface temperature, and \( \theta_0 \), the central temperature. Use of the integral has been described elsewhere$^3$. 
To study the extent of crack healing and the movement or elimination of large voids in ThO$_2$ - 2 wt% UO$_2$, we irradiated two elements composed of pellets in which circumferential and radial cracks were simulated, and in which axial holes were drilled. The design of the test was similar to the design of the previous test on pure UO$_2$.

**ELEMENT SPECIFICATIONS AND IRRADIATION**

Specifications of the fuel and sheath are given in Table 1. The pellets are illustrated in Figure 1, and in Table 2 the loading orders for the pellets in each element are given. In the composite pellets the crack widths were either 0.05 or 0.1 mm, as noted in Table 2. In each pellet with axial holes, dimensions of both ends were taken to ensure that the radial positions of the holes were accurately known. After assembly the diameters of both elements were recorded with linear transducers. Diameter traces are shown in Figure 2. Lengths were recorded and are given in Table 3.

The elements were irradiated in the X-2 pressurized water loop of NRX for 69 days at a time-average power rating of $\int P \, d\theta = 61 \pm 2$ W/cm. Since the elements were at the positions of highest flux in the loop, the maximum power rating i.e. $\approx 62 \pm 2$ W/cm, was little different from the time-average value. Loop operating conditions are given in Table 4.

**DIMENSIONAL CHANGES**

Linear transducer traces of the element diameters after irradiation are compared with pre-irradiation traces in Figure 2. In Table 3 the diameter and length changes are given, along with the heights of circumferential ridges in the sheath at pellet interfaces. An average diameter change was not calculated for element JJR because there were two distinct levels of change: over pellets with large circumferential cracks or a large central hole (pellets 4, 6 and 7) the expansion was small, over the other pellets the expansion was similar to that recorded for element JJP.
FUEL DISPOSITION

Each element was cut with a tubing cutter to remove the ring of cobalt wire used to monitor the neutron flux, then cut again in the centre of the top pellet. The remaining sections were impregnated with epoxy resin, and cut with an abrasive cut-off wheel at the centre of each of the special pellets. The cross-sections were metallographically prepared to observe the extent of crack healing and movement or elimination of the axial voids. Photographs are shown in Figures 3 to 7. β-γ autoradiographs were made from each type of pellet; these are illustrated in Figures 3, 4 and 6.

TEMPERATURE DISTRIBUTION IN FUEL

The interpretation of the present results depends on the temperature distribution in the fuel. In tests on unirradiated pellets of the same batch Stoute[8] found that the temperature for discernible grain growth in two weeks was ~ 2000°C; a similar grain growth temperature for ThO₂-10 wt% UO₂ was reported by Harbinson and Walker[9]. By assigning this temperature to the limit of grain growth in an irradiated element, and with knowledge of the integrated conductivity from loop calorimetry, a mean conductivity between 400 and 2000°C of 0.031 W/cm degC was estimated. For comparison Rabin et al.[2] took the conductivity of ThO₂-4.4 wt% UO₂ as 0.029 W/cm degC between 200 and 1400°C; and Rao[2] found that in three minute irradiations the temperature distribution of ThO₂-5.4 wt% UO₂ was similar to that of pure UO₂ (viz. λ ~ 0.03 W/cm degC between 400 and 3000°C). Measurements on unirradiated ThO₂[10] and solid solutions of ThO₂-UO₂[11], at temperatures below 1000°C, indicate a thermal conductivity higher than for UO₂. Initial experimental results indicate that irradiation damage in the lower temperature regions is more significant in thoria-based fuels than in UO₂[12]. Therefore assuming λ ~ 0.031 W/cm degC for ThO₂-2 wt% UO₂ for the present elements, as suggested by the grain growth results, should give a temperature distribution accurate to ± 10%.
DISCUSSION OF RESULTS

(i) Dimensional Changes

The expansions of ceramic fuel elements have been analysed by Notley et al\(^{(13)}\). A model was developed where the diametral sheath expansion was caused by the expansion of an outer cracked, but rigid, annulus of fuel plus the expansion of a plastic core. The model would lead to approximately equal expansions of thoria and urania fuels for a given temperature distribution since the slightly lower expansion coefficient of Th\(\text{O}_2\)\(^{(14)}\) is offset by its higher temperature for plastic deformation\(^{(15)}\). Thus the observations and the model are compatible, since the diametral expansions of the solid Th\(\text{O}_2\)-2\% U\(\text{O}_2\) pellets fall just within the range of measurements for solid U\(\text{O}_2\) pellets, Figure 8. Over pellets with the large circumferential crack width the diametral expansion of the sheath was less than over the other pellets, by about the difference in original clearances; see Figure 2 and Table 3. Presumably this extra internal voidage was being filled by movement of the fuel so that less of the expansion had to be accommodated by sheath strain.

The circumferential ridge heights on the thoria elements were slightly less than for those containing U\(\text{O}_2\) at the same value of \(\int \lambda d\theta\), Figure 9. Possibly this is due to the lower expansion coefficient. However, similar differences in ridge height have been noted on U\(\text{O}_2\) elements at a given value of \(\int \lambda d\theta\) so the present results are not really significant.

(ii) Crack Healing

The cross-sections of the special pellets showed that simulated circumferential and radial cracks can be healed leaving no trace of their former position at

\[
\int_{\theta_s}^{\theta_{ch}} \lambda d\theta = 39.5\ \text{W/cm}
\]

where \(\theta\) is the temperature above which cracks were healed. With \(\theta_s = 410^\circ\ C\), and \(\lambda = 0.031\ \text{W/cm degC}\), \(\theta_{ch} \approx 1700 \pm 150^\circ\ C\) for radial cracks in Th\(\text{O}_2\)-2 wt\% U\(\text{O}_2\). This temperature could possibly change with duration of irradiation and contact pressure between the surfaces. In U\(\text{O}_2\) irradiated under similar conditions\(^{(4)}\), \(\theta_{ch} \approx 1400 \pm 100^\circ\ C\). Each temperature
is 0.55 of the absolute melting point.

The radial crack healing may have been initiated or enhanced by surface tension forces at the points of contact on the relatively flat surfaces; e.g. the surface tension stresses $\frac{2\gamma}{r}$ are about 400 kg/cm$^2$ (5600 lb/in.$^2$) if the surface energy $\gamma$ is taken as 1000 ergs/cm$^2$ and 2r, the diameter of the contact points, is $10^{-5}$ cm. This is comparable with the restraint from the fuel sheath and loop coolant pressure. As the contact diameter increased to $10^{-3}$ cm the surface tension forces would become negligible compared with the restraint of the sheath plus coolant.

The complete elimination of the radial cracks could be similar to final densification in large grain ceramic bodies. Rossi and Fulrath studied this in $\text{Al}_2\text{O}_3$ by vacuum hot pressing between 1100 and 1300$^\circ$C. They found that densification occurred by particle re-arrangement and by diffusional creep according to the Nabarro-Herring model. The densification was controlled by aluminum diffusion in the oxide. Similarly Coble and Ellis and Vasilos and Spriggs concluded that final-stage densification of alumina was by a diffusion-controlled process. In hot pressing studies with $\text{UO}_2$, Amato et al suggested that final densification may not be by the Nabarro-Herring model, because of the importance of the surface tension forces in their $1 \mu$m material; they suggested that densification was more likely by the plastic flow model of Mackenzie and Shuttleworth. In the present fuel, no plastic flow into the void, was observed even though the internal forces due to sheath and coolant restraint, at the position of crack healing, were possibly up to 400 kg/cm$^2$. Also the grain size was large (15 $\mu$m), and once crack healing had started the surface tension forces would be negligible. In $\text{UO}_2$ and $\text{ThO}_2$ the crack healing temperatures are both 0.55 of the absolute melting temperature. According to Tammann and others bulk diffusion becomes appreciable in ionic solids at approximately this homologous temperature.

We consider, therefore, that when the crack surfaces are forced into contact by the compressive load of the coolant and sheath, the surfaces are sintered together, most likely by a bulk diffusion process. Above the temperature for grain growth (2000$^\circ$C), crack healing should be more rapid due to the greater mobility of the atoms.
In UO₂, healing of circumferential cracks was enhanced by sublimation across the crack because of a temperature difference (⁴). But ThO₂ has lower evaporation rates (²²), therefore this mechanism should not be significant until a much higher temperature than for UO₂: no evidence of it was observed in the present elements.

(iii) Fuel Disposition

The extent of grain growth in the ThO₂-2 wt% UO₂ could not be measured accurately because of difficulty in etching the material. Estimates of the extent of grain growth regions in each element showed no difference between pellets with a simulated circumferential crack and those with originally solid pellets. When possible errors of measurement were taken into account, this indicated a heat transfer coefficient between the two surfaces of at least 1.5 W/cm² degC. The same result was found in irradiations of pure UO₂ (⁴).

In the ThO₂-2 wt% UO₂ there was no significant difference in structural changes when the original diametral clearance of the simulated circumferential crack was 0.05 or 0.1 mm. Presumably the larger clearances were adjusted by thermal expansion and internal movement of the thoria, resulting in the same effective crack width in both types of pellets during operation. The polished cross-sections of the ThO₂ did not show any more voidage in pellets with large original cracks. Experimental work on the plastic behaviour of ThO₂ (¹⁵), indicates that above 1400°C (the estimated temperature at the simulated crack, Figure 5) the creep rate is sufficient for the material to have flowed significantly during a period comparable to the whole irradiation. However, the polished cross-section (Figure 5) shows two concentric cracks, the simulated one and one formed during the irradiation with the annulus of fuel between them broken into approximately equal segments. On first startup the strain rate is rapid and apparently the annulus was not sufficiently plastic to yield, so it broke when the inner core expanded and the segments were pushed outwards into the simulated crack.

At the mid-radius position (where the temperature was ~1800°C) the axial holes were not being closed appreciably due to plastic flow. (The holes were slightly elliptical before irradiation, as shown in Figure 1). The work on
unirradiated ThO₂(16), however, indicates that some creep had 
probably occurred. On the hotter side of these holes (T ≈ 
1900°C) there were many voids, some spherical and others 
flatter (Figure 4). However, with one possible exception, 
where the temperature was about 2300°C, see Figure 10, we did 
not observe long columnar grains similar to those seen in 
UO₂ of ~ 95% theoretical density irradiated with similar cen-
tral temperatures(4). The flat voids around the holes (Figure 
4) were probably not associated with a sublimation mechanism. 
Possibly at temperatures > 1900°C, the compressive forces 
caused intergranular voids and shearing of grain boundaries, 
as noted by Poteat and Yust(15). The voids would then support 
the suggestion that some creep had occurred. At the centre of 
the fuel element the axial holes were partially filled and the 
surrounding oxide was very porous (Figures 4, 7 and 10).

The majority of the pores were on grain boundaries, 
usually at triple points; whereas in the original material, 
and near the periphery in the irradiated fuel, the pores were 
smaller and more randomly distributed; see Figure 11. The 
same type of pore movement has been seen in the equiaxed 
growth region of UO₂. In discussing similar observations 
Kingery and Francois(23) noted that during grain growth the 
pores remain on the boundaries, more commonly at intersections 
(triple points), and that the pores must therefore migrate 
along with the boundaries. This causes a restraint on the 
boundary movement. For a given pore shape the migration 
rate is inversely proportional to the pore diameter. Pore 
migration during grown growth results in larger pores, as 
depicted graphically and confirmed metallographically in 
Figure 12.

(iv) Autoradiographs

The most striking difference between the ThO₂-2 wt% UO₂ 
and pure UO₂ was in the autoradiographs. The thoria elements 
gave a mottled appearance over almost the entire cross-section 
because of the inhomogeneous mixing of the ThO₂ and UO₂ powders 
(Figures 3, 4 and 6). UO₂ irradiated with the same \( \lambda \mathrm{d} \) has 
several distinct bands of activity (Figures 13 and 14). In 
UO₂ some of the autoradiographic features are due to outward 
movement of volatile fission products (or compounds of the 
elements) such as cesium, iodine, barium-lanthanum, and ruthen-
nium. Possibly the lack of movement in the present ThO₂ 
elements is because of the relatively small atomic mobility,
even in the hottest regions. If similar elements were irradiated with central temperatures sufficient to give greater atomic mobility, as evidenced by extensive grain growth, fission product movement might be observed.

The lack of fission product movement could be important in a thoria-fuelled reactor, for at least two reasons: firstly, if a fuel element became defective the release of fission products to the coolant might be less than for comparably rated UO$_2$. Such an effect was noted previously by Robertson\(^{(24)}\). During a failure of a ThO$_2$-2 wt% UO$_2$ element irradiated at $\lambda d\theta = 57$ W/cm at CRNL\(^{(25)}\), activity levels were generally low, and with a Ge(Li) detector no change was noted in the Mo-99 and Te-132 activity on deposition traps installed in the loop. The defect in this element was, however, very small, so a direct comparison of release rates of fission products could not be made between ThO$_2$ and UO$_2$ fuels. Secondly, in UO$_2$ elements, where fission product iodine can move to the fuel surface, there is a potential iodine-zirconium cyclic reaction\(^{(26)}\), although no defects have been positively attributed to such a reaction. With lower fission product mobility such a reaction is less likely to occur.

CONCLUSIONS

The behaviour of ThO$_2$-2 wt% UO$_2$ was in some aspects similar to UO$_2$ irradiated at the same $\lambda d\theta$, but in other aspects the behaviour was different:

Similar aspects were:

1. Radial and circumferential cracks were healed at temperatures above 0.55 of the absolute melting temperature.

2. In cooler regions cracks and holes were unchanged.

3. Both materials moved into voidage at positions where the fuel was plastic. Where there was internal voidage the diametral expansions of the sheath were lower than over solid pellets.

4. Over the solid pellets of the two materials the diametral expansions of the sheath agreed with the "rigid-annulus, plastic core" model, when the differences in linear expansion coefficient and temperature of plasticity are
Different aspects were:

1. For similar power ratings the structural changes (grain growth and lenticular void migration) were less in the ThO$_2$-2 wt% UO$_2$ than in UO$_2$.

2. For similar power ratings (or central temperatures) there was much less fission product relocation in ThO$_2$-2 wt% UO$_2$, than in pure UO$_2$. 
REFERENCES


   Rao S.V.K., "Investigations of ThO\textsubscript{2} - UO\textsubscript{2} as a Nuclear Fuel", J. Nuc. Mat. 12 No. 3 (1964) p. 323.


25. Palmer J.F., CRNL work to be published.

26. GEAP - 3771 - 13, June 1964
    GEAP - 3771 - 14, September 1964
    GEAP - 3771 - 17, June 1965

TABLE 1

ELEMENT SPECIFICATIONS

| Fuel | - Stoichiometric ThO$_2$-2.2 wt% UO$_2$
|      | Uranium is 91.7 wt% U-235 (by mass spectroscopy). As received powders dry blended for 2 hours, prepressed at 1400 kg/cm$^2$ (20,000 lb/in$^2$), then granulated to - 20 mesh. This powder was then dry blended with 0.2 wt% Sterotex and the pellets pressed at 2800 kg/cm$^2$ (40,000 lb/in$^2$) the green pellets were sintered for 3 hours in hydrogen at 1750°C, then centreless ground to size. |
|      | - pellet dishing  
|      |   - one end 0.5 
|      |   - one end flat  
|      |   - land width 0.38 mm |
| Sheathing | - Zircaloy-2  
|          | - outer diameter 20 mm  
|          | - wall thickness 0.63 mm |
| Fuel/Sheath Clearances | - diametral 0.1 mm  
|                   | - axial <0.25 mm  
|                   | - distributed axial clearance <0.25 mm |
| End Fittings and Wire Wrap | - standard X-2 end fittings  
|                         | - no wire wrap needed |
| Monitor | - A cobalt monitor was fitted in a groove around the fifth pellet from the top of each element. |
| Autoclave Treatment | - Water at 300°C and 100 kg/cm$^2$ for three days. |
TABLE 2
ASSEMBLY DATA

<table>
<thead>
<tr>
<th>Pellet No. from ball end</th>
<th>Specimen JJP</th>
<th>Specimen JJR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solid cylindrical pellet.</td>
<td>As for Specimen JJP.</td>
</tr>
<tr>
<td>2</td>
<td>A pellet with a longitudinal crack. This was simulated by cutting two pellets longitudinally and grinding the flat surface of the two larger halves to make one pellet of the proper diameter.</td>
<td>As for Specimen JJP.</td>
</tr>
<tr>
<td>3</td>
<td>For porosity, four 1.27 mm diameter holes were drilled diametral opposite, on four pitch circle diameters -</td>
<td>As for Specimen JJP except the diameter of the holes was 0.63 mm.</td>
</tr>
<tr>
<td></td>
<td>(1) 1.27 mm from the center at 0°</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(2) 2.54 mm &quot; &quot; &quot; at 180°</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(3) 5.01 mm &quot; &quot; &quot; at 90°</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4) 7.6 mm &quot; &quot; &quot; at 270°</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>A circumferential crack near the periphery of the pellet, was simulated by removing a 12.7 mm diameter core from the centre of the pellet. An additional pellet was centerless ground to fit the axial hole with a diametral clearance of 0.05 mm.</td>
<td>As for Specimen JJP except the diametral clearance was 0.1 mm.</td>
</tr>
<tr>
<td>5</td>
<td>Solid cylindrical pellet containing a groove 0.81 mm wide x 0.63 mm deep for the cobalt monitor.</td>
<td>As for Specimen JJP.</td>
</tr>
<tr>
<td>6</td>
<td>Contained a simulated circumferential crack near the center, as for No. 4 pellet with 6.3 mm diameter hole. The fitted pellet left a diametral clearance of 0.05 mm.</td>
<td>As for Specimen JJP except the diametral clearance was 0.1 mm.</td>
</tr>
<tr>
<td>7</td>
<td>A 1.27 mm diameter axial hole was drilled through the center of the pellet.</td>
<td>As for Specimen JJP except hole diameter was 2.54 mm.</td>
</tr>
</tbody>
</table>

**NOTE**
All simulated cracks and porosity holes were done on solid cylindrical pellets.
TABLE 3
DIMENSIONAL CHANGES (in mm)

<table>
<thead>
<tr>
<th>Element</th>
<th>JJP</th>
<th>JJP</th>
<th>JJR</th>
<th>JJR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter Change</td>
<td>Ridge Height</td>
<td>Diameter Change</td>
<td>Ridge Height</td>
</tr>
<tr>
<td>Pellet 1</td>
<td>0.04</td>
<td>0.55</td>
<td>0.05</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>0.3</td>
<td>0.04</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>0.5</td>
<td>0.05</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>0.5</td>
<td>0.01</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>0.04</td>
<td>0.65</td>
<td>0.06</td>
<td>0.75</td>
</tr>
<tr>
<td>6</td>
<td>0.05</td>
<td>0.55</td>
<td>0.01</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>0.05</td>
<td></td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

Averages 0.05 0.51

Total diametral expansion of fuel:
= Sheath thermal expn. = 0.19%
+ Sheath elastic expn. = 0.20%
+ Diametral clearance = 0.5%
+ Residual expansion = 0.26%

\[ \text{Total diametral expansion} = 0.19\% + 0.20\% + 0.5\% + 0.26\% = 1.15\% \text{ of fuel diameter} \]

<table>
<thead>
<tr>
<th></th>
<th>JJP</th>
<th>JJR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length Expansion: [ \frac{0.25}{1326} \times 100 = 0.2% \text{ of fuel stack length} ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>Pressure (kg/cm²)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Water inlet temperature (°C)</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Loop Flow (1/s)</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>Oxygen content of water (ppm)</td>
<td>&lt;0.1</td>
<td></td>
</tr>
<tr>
<td>pH (maintained with LiOH)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Irradiation started</td>
<td>December 14, 1965</td>
<td></td>
</tr>
<tr>
<td>Irradiation finished</td>
<td>March 14, 1966</td>
<td></td>
</tr>
<tr>
<td>Time at power (d)</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>Linear power output (W/cm)</td>
<td>810 ± 25</td>
<td></td>
</tr>
<tr>
<td>Surface heat flux - sheath to coolant (W/cm²)</td>
<td>127 ± 5</td>
<td></td>
</tr>
<tr>
<td>Power rating $\int \lambda d\theta$ (W/cm)</td>
<td>61 ± 2</td>
<td></td>
</tr>
<tr>
<td>Fuel surface temperature (°C)</td>
<td>410 * ± 50*</td>
<td></td>
</tr>
</tbody>
</table>

* sheath/coolant heat transfer coefficient 5 W/cm² - deg.C
  fuel/sheath heat transfer coefficient 1.3 W/cm² - deg.C
  conductivity of Zircaloy 0.15 W/cm - deg.C
FIGURE 1 SPECIAL PELLETS FOR ELEMENTS OF TEST X-23701
FIGURE 2  DIAMETERS OF ELEMENTS BEFORE AND AFTER IRRADIATION
FIGURE 3
CROSS SECTION AND AUTORADIOGRAPH OF PELLET 2, ELEMENT JJR, SHOWING EXTENT OF HEALING OF DIAMETRAL CRACK
LINE DRAWING SHOWING ORIGINAL HOLE LOCATIONS MEASURED FROM PRE-IRRADIATION PHOTOGRAPH OF DRILLED PELLET

FIGURE 4 CROSS SECTIONS AND AUTORADIOGRAPH OF PELLET 3, ELEMENT JJP, SHOWING VOID ELIMINATION
FIGURE 5

CROSS SECTION OF PELLET 4, ELEMENT JJP, SHOWING SIMULATED CIRCUMFERENTIAL CRACK STILL VISIBLE NEAR PERIPHERY, AND GRAIN BOUNDARY POROSITY NEAR CENTER
FIGURE 6  CROSS SECTION AND AUTORADIOGRAPH OF PELLET 6, ELEMENT JJP, SHOWING THAT THE SIMULATED CIRCUMFERENTIAL CRACK NEAR THE CENTRE WAS COMPLETELY ELIMINATED
CROSS SECTION OF PELLET 7, ELEMENT JJR,
SHOWING PARTIAL FILLING OF CENTRAL HOLE,
AND ROUNDED PORES IN THE FUEL
Figure 8: Diametral expansions of ThO₂ - 2 wt% UO₂ and UO₂ deduced from irradiation of elements in water-cooled loops.

- MOLTEN NO MELTING
- TEST X-23701 - ThO₂ - 2 wt% UO₂

Calculated diametral expansion of an unrestrained UO₂ pellet.

Central melting for UO₂.
DIAMETRAL CLEARANCES - .08 mm TO .12 mm
SHEATH THICKNESS .61 mm TO .64 mm ZIRCALOY-2

\[
\int_{T_0}^{T} \lambda_{de} \text{ (w/cm)}
\]

FIGURE 9 CIRCUMFERENTIAL RIDGE HEIGHT VS \( \int \lambda d\theta \)
FIGURE 10

POSSIBLE LENTICULAR VOID MOVEMENT AND COLUMNAR GRAINS IN CENTER OF PELLET 3, ELEMENT JJP
FIGURE II

PORE SIZE AND LOCATION IN ThO$_2$ - 2wt. % UO$_2$
NEAR THE PERIPHERY OF THE IRRADIATED PELLETS
FIGURE 12

PORE LOCATIONS IN GRAIN GROWTH REGIONS IN ThO₂ - 2 wt. % UO₂ AFTER IRRADIATION

[DIAGRAMS AFTER KINGERY AND FRANCOIS (23)]
FIGURE 13

AUTORADIOGRAPH OF UO$_2$ IRRADIATED AT $\int \lambda d\theta = 56$ W/cm. IN ELEMENT LFX OF TEST X-51520 (27)
FIGURE 14 POLISHED CROSS SECTIONS AND CORRESPONDING AUTORADIOGRAPH SHOWING ELIMINATION OF LARGE HOLES AND TRACES OF VOID MOVEMENT IN IRRADIATED UO₂

(SUPPLIED BY J. CHRISTENSEN, B.M.I. RICHLAND WASHINGTON)

DARK INDICATES ACTIVITY