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THE RELATIVE AXIAL EXPANSIONS UNDER IRRADIATION OF STACKS OF UO_2 PELLETS IN ZIRCALOY SHEATHS

CRFD-1092
(Exp-NRX-5603)

by

M.J.F. NOTLEY

Chalk River, Ontario
August, 1962

AECL-1598

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SYNOPSIS

An experiment was performed to measure the relative axial movement of UO_2 fuel pellets inside a Zircaloy sheath. Although the results must be treated with some reservation, the inferences are that there is very little relative movement between the fuel and the sheath when the two are in firm pressure contact. Relative movement was in the range 0.075 ± 0.03 cm for a 30 cm fuel length, and was not greatly affected by the power output, profile of the pellet end-faces or the diametral clearance left between the fuel and the sheath on assembly. However in two elements that had thick sheaths to withstand the coolant pressure and that were assembled with large diametral clearances (2% of the diameter) the available axial clearance for relative fuel/sheath movement (1%) was fully taken up.

The thin sheathed elements showed residual axial expansions of up to 0.17 cm, indicating that the pellets move relative to the sheath only until frictional forces are sufficient for the sheath to grip the fuel; thereafter the sheath is extended. The measurements also indicate that sheath elongation is governed by the temperature at the contact points between adjacent pellets, eg. at the inner edge of a pellet shoulder, as long as that temperature is below approximately $1000^{\circ}C$. At higher temperatures, the UO_2 is too plastic to exert sufficient force to strain the sheath.

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INTRODUCTION:

The deformation of a fuel element sheath may have an adverse affect on the useful lifetime of the element because -

a) it can result in excessive sheath strain and hence failure,

b) distortion can interfere with coolant flows, or

c) relative expansions in a multi-element bundle can cause failure of inter-element connectors, or can assist element bowing with the consequent possibility of preventing bundle removal.

In the CANDU* design of fuel element the sheath is so thin that it has little structural strength, and is therefore susceptible to deformation, either by the external coolant pressure or the fuel expansion. In an attempt to minimise the amount and dependence of length changes on fuel temperature, void spaces have been incorporated into fuel elements, either concentrated at one end or distributed along the fuel stack by dishing the pellet end faces. There is considerable experience to show that these techniques reduce the amount of plastic deformation of fuel elements[1, 2], but there is still uncertainty as to the controlling factors and hence in the prediction of length changes.

The experiment described here was proposed by Robertson[3] to ascertain the amount by which UO_2 fuel pellets could slide relative to a Zircaloy sheath, and hence to determine the amount of axial void that could be taken up by the expanding fuel. This is to be compared with laboratory experiments by Fanjoy et al in which UO_2 pellets were moved in Zircaloy tubes subjected to an external pressure to simulate the reactor conditions (reference 4 abstracted in Appendix 1).

The device used for measuring the relative movement was developed in the laboratory and tested in the Hydraulic Rabbit loop of NRX; since these Rabbit irradiations were only incidental to the results of the loop experiment they are reported in Appendix 2.

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* CANDU - Canadian Deuterium Uranium power reactor, Douglas Point, Ontario.

Four separate irradiations of elements were performed in pressurized water loops of NRX (X-2 and X-6). The variables studied in the experiments were:

a) heat rating
b) fuel/sheath diametral clearance on assembly
c) pellet end profiles
d) sheath thickness

2. DESCRIPTION OF ELEMENTS:

The marker devised for measuring the maximum expansion of the UO_2 pellets relative to the sheath is illustrated in Figure 1. A cylindrical molybdenum stool, resting on a thick molybdenum plate, was placed in the gap between the fuel pellets and the end cap. A molybdenum pin which was a sliding fit in the stool touched the end cap, and was driven into the stool by any relative expansion of the UO_2. This device was tested in Hydraulic Rabbit irradiations (Appendix 2), in which it appeared to operate satisfactorily.

A full description of the fabrication and assembly of the elements has been given by Mizzan et al[5], and is summarised in Table 1 of this report. Each element contained approximately 30 cm (12 in.) length of fuel as UO_2 pellets approximately 1.9 cm (0.75 in.) in diameter. Most of the Zircaloy-2 sheaths were 0.063 cm (0.025 in.) thick, but two elements had sheaths 0.10 cm (0.040 in.) thick. Three different pellet end profiles were tested: flat, spherically dished with a shoulder, and dished with no shoulder. The pellets were loaded into elements with fuel/sheath diametral clearances of 0.005 cm (0.002 in.), 0.015 cm (0.006 in.) or 0.038 cm (0.015 in.).

Prior to autoclaving at 260-400°C (see Table 1), circumferential marks were scribed at 2.5 cm (1 in.) intervals along each element's length. The positions of these were measured before and after irradiation and were used to indicate the strain distribution along the element length.

3. IRRADIATION CONDITIONS:

The elements were irradiated in four separate batches, some being included into composite charges with elements from other experiments.

The loop coolant conditions were similar for all the irradiations, and are summarised together with the details of each separate irradiation in Table 2. No unusual occurrences were note during any of the tests.

4. ELEMENT HEAT RATINGS:

The average heat rating for each element has been calculated from cobalt monitor data, and is presented in Table 3. There is considerable confidence in this method, based on comparisons with the burnups determined by loop calorimetry, Pu/U ratio, Cs/U ratio, and U-235 depletion[6, 7]. For this particular test the burnup determined by chemical analysis of the Pu/U ratio and the Cs/U ratio was also performed on certain specimens. The cobalt monitor readings were fitted to a sine curve, representing the flux distribution at the average moderator height, and these adjusted values of heat rating were used for subsequent calculations. The difference between any individual burnup determination and that used to calculate the adjusted value of heat rating was never greater than 5%. The corrections and constants used in calculations are outlined in references 6 and 8. Peak heat ratings were calculated for every specimen by dividing by the ratio of the time average flux at the specimen position to the maximum instantaneous flux (obtained from the reactor power and moderator height). Curves of flux versus position in the reactor for different moderator heights have been calculated by Webster[9] based on measurements by Bock and Boyd(10).

The overall heat output of the loop was measured, and is compared with the sum of the heat outputs of the individual specimens (as determined from the cobalt monitors) in Table 3. Calculation of the individual heat outputs of the elements in the first two six-element charges on the basis of the known flux distribution in the loop and normalising to the measured total loop output did not agree well with the results from the cobalt monitors. It appears possible that the two six-element loop charges hung approximately 20 cm (8 in.) lower in the loop than the records show. This could be due to the use of too long a hanger rod, the same hanger rod having been used in both the anomalous irradiations. Unfortunately, there is now no way of checking this, but it is felt that the cobalt monitor method has been proved sufficiently reliable not to need other confirmation.

5. POST-IRRADIATION EXAMINATION:

- General Appearance:

The surface of the Zircaloy-2 sheaths was generally clean and in good condition. Small areas of corrosion product were seen at the end caps of elements BVZ and BYW, but contamination was known (5) to have been responsible for enhanced corrosion of some elements on autoclaving.

- Dimensions:

Diametral measurements at 120° intervals were made at three or five places along the element lengths. Length changes were also measured. Both measurements are recorded in Table 4.

The elements were then laid alongside a steel rule calibrated in 0.025 cm(0.010 in.) intervals and the distance between the circumferential scribe marks was estimated under a stereomicroscope. The distance between the marks appeared to be unchanged, within the probable error of measurement of ± 0.012 cm (0.005 in.), but the measurement accuracy was such that it was impossible to determine whether the length change had taken place uniformly along the element length or was concentrated outside the gauge lengths (i.e. near the end plugs).

The elements were then cut open and the marker movement measured by comparison of pre- and post-irradiation readings. These and the estimated limits for measurement errors are detailed in Table 6. Four out of seventeen markers had broken, by cracking of the pin or stool. Subsequently the intact markers were compressed in a pneumatic vice to see whether they were still free to move under load. The load necessary to move them varied between 6.8 and 226 kg (15 and 500 lbs) and two further stools broke during the test.

The end plugs of the elements were examined to see if the marker pin had been pressed against the inside surface of the plug with sufficient force to indent or mark it. In some cases indentations were pronounced, indicating that the marker pin had been exerting a considerably force on the end cap. The most obvious mark was in element CDL which showed the highest amount of marker movement.

All but two (BWC and BWF) of the marker movements observed were greater than those calculated to have taken place on autoclaving (compare Table 1 and Table 6). To some extent these two elements must therefore be regarded with suspicion.

- Oxide Appearance:

Each specimen was sectioned with a tubing cutter at intervals along its length, and the diameter of grain growth estimated from stereo-photographs of these sections. Circumferential and radial cracking, equiaxed and columnar grain-growth and formation of a central void were seen in various elements, as detailed in Table 5.

6. DISCUSSION:

There is doubt as to whether the markers are a reliable indication of the relative movement, or whether, by seizing, they reduced fuel/sheath slip. Four out of seventeen markers fractured, undoubtedly after seizing, and the load required to move some of the pins in their stools after irradiation was high, though it can be calculated that this load is insufficient to strain the sheath plastically. The strongest argument for believing that marker seizure did not affect relative movement significantly stems from the observations of indentation of the marker pin in the end caps. Element CDL, which showed almost complete marker movement, had a very obvious indentation in the end cap - indicating that there was considerable marker friction. The absence of indentations in other elements infers that fuel/sheath movement was not significantly restrained by the marker.

- Length Changes:

The following condition governing sheath deformation holds for any fuel element :

Fuel expansion = sheath thermal expansion + sheath elastic expansion + residual sheath plastic expansion* + fuel/sheath clearance + fuel internal clearance (if appropriate).

It is therefore possible to calculate the effective fuel temperature to cause any given amount of plastic expansion of the sheath* (see Appendix 3 for a sample calculation). Marker movement can be

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* Provided that no negative plastic strain (reduction in length of the sheath) takes place at shutdown due to the external coolant pressure or tensile stresses exerted by the contracting fuel.

considered as a measure of the amount of fuel/sheath axial clearance taken up by the fuel. The effective fuel temperatures calculated to produce the measured amounts of:-

a) marker movement (with no associated sheath strain)
b) marker movement plus sheath strain

are presented in Table 6. They can be compared with the actual fuel temperatures calculated from the element heat ratings, given in the same table. Within the limits of experimental error quoted this comparison shows the following:-

a) The fuel temperature to cause marker movement in the thin-sheathed elements is remarkably constant (470 ± 100°C) and not affected greatly by pellet profile, heat rating, or fuel/sheath diametral clearance.

b) The fuel temperature necessary to cause marker movement plus sheath expansion agrees reasonably closely with the calculated pellet shoulder temperature, with the reservation discussed in (d) below.

c) The spherically dished elements (no shoulder) showed less expansion plus movement than the shouldered dished elements at comparable heat ratings, though rather more than if they were expanding an amount equivalent to the surface temperature of the fuel. The length expansion of a UO_2 pellet is expected to follow closely the parabolic temperature distribution between surface and center; it is suggested that provision of a spherical dish at the pellet end faces still allows some overall pellet elongation.

d) The highest observed expansion plus movement was equivalent to a fuel temperature of 1170°C, for a stack of flat-ended pellets. The remainder of the equivalent fuel temperatures for flat pellet stacks were in the range 970 - 1030°C. It is thought that the pellet stack has a plastic core which is not capable of exerting sufficient force to strain the sheath, provided there are internal voids, and that sheath strain is governed by the thermal expansion of the innermost non-plastic ring. This explanation could also account for the yielding of the inner edge of a shoulder on a dished pellet, resulting in a less-than-expected expansion.

Recent laboratory work by Armstrong and Irvine[11] has shown that UO_2 is measurably plastic under stresses of 50 kg/cm^2 (690 psi) at 1300°C. Fission spikes would be expected to enhance plasticity further, due to generation of internal stresses. It is therefore not unreasonable that, in this experiment, the UO_2 above 1000°C is apparently incapable of exerting sufficient axial force (approximately 1100 kgf) to strain the sheath plastically.

- Comparison of Fuel/Sheath Slip in and out of the Reactor:

The load required to cause the pellets to move in the sheaths in the laboratory experiments (Appendix 1) was in the range 18 - 410 kg.

The reactor experiments reported here show little relative movement and some sheath strain. Therefore the pellets must have been exerting an axial force of approximately 1100 kgf on the sheath. There are a number of possible explanations why this force was insufficient to cause relative movement in the reactor.

a) The coolant pressure and hence the fuel/sheath interfacial pressure was higher in the loop irradiations than for the laboratory tests (105 kg/cm^2 versus 81 kg/cm^2). Although this might increase the load required for slip it would be unlikely to increase it by the factor of 10 required.

b) The fuel expands more than the sheath and the cessation of movement might correspond to the point where the sheath is beginning to be strained elastically around its circumference by fuel expansion. However, if this were so, one might expect a greater amount of relative axial movement for those elements having an assembled diametral clearance of 0.015 cm (0.006 in.) than those with a clearance of 0.005 cm (0.002 in.). Comparison of Tables 1 and 6 shows that the difference, if any, is very small, and it is thought improbable that this effect is the complete answer. If it were the reason, then increasing the diametral clearance over a certain critical value should result in complete slip of pellets. This is obviously a matter which should be investigated further.

c) The fuel pellets crack under thermal stress and the small segments and wedges of fuel might dig into the sheath and increase the resistance to relative movement.

- Comparison with Work by Other Authors:

Spalaris at APED has done a series of experiments using various marker devices. These are described in a preprint(12) which was considerably amplified in a paper available at the meeting(13). The experimental uncertainties associated with the measurements described in reference 12 (with free-standing sheaths) were probably sufficiently large to mask any indications of relative fuel/sheath movement, but a further series of irradiations with a different marker proved more satisfactory(13). These elements were of the annular superheat type in which it was calculated that the sheath would have been collapsed into contact with the fuel, the marker being a coiled-spring maximum and minimum device. Contractions of the UO_2 pellet stack of approximately 0.25 cm were seen, with no significant change in length of the sheath. Spalaris attributes this contraction to densification and plastic flow of the UO_2, and to some extent the present results agree with his hypothesis. Thus his figure of 900°C for UO_2 plasticity(13) is confirmed by the value of 1000°C deduced from the present work. However, it is thought unlikely that the pellet stack contractions observed by Spalaris could arise from the mechanism proposed, namely UO_2 densification or plastic flow under the restraining forces exerted by the sheath. It is extremely unlikely that a sintered UO_2 pellet of density 10.3 g/cm^3 would have decreased in overall length in the experiment, the surface of the pellets being at a temperature of 450° - 750°C. It is probable that pellet stack contraction took place as a result of elimination of "distributed axial clearance", a term used to describe the clearance incorporated in loading pellet stacks due to chips at interfaces, pellet tilting or the oblique angle of end faces to the pellet axis. It is improbable that the pellet stack shrank and registered negative marker movement while the elements were subjected to the external coolant pressure, since in this state the collapsed sheath would grip the pellets. It is suggested that the observed movement took place when the elements were removed from the reactor.

Of more significance is the disagreement with Spalaris' conclusion that UO_2 in fuel elements with free-standing sheaths expands little, if at all, relative to the sheath. Elements CDL and CDM showed considerable relative movement when contact pressure between the fuel and the sheath was low.

In laboratory thermal simulation experiments Martin and Weir(14) have shown that the expansion of a stack of UO_2 flat pellets in a sheath is a function of the maximum temperature of the pellet (up to $1500^{o}C$), or for dished pellets the temperature of the inside edge of the pellet shoulder. These observations are similar to those from the present work. The absence of UO_2 plasticity at $1500^{o}C$, compared with Armstrong's observations of plasticity at $1300^{o}C$ (11) is probably because the axial stress on the pellet stack in Martin's experiments was low and the duration of the experiment short.

- Grain Growth:

Observations of the type and extent of grain growth are given in Table 5. The comparison between elements with high and low assembled diametral clearances is particularly interesting. CDL and CDM had clearances of 0.038 cm, the remainder of the elements being in the range 0.006 - 0.015 cm. The average $\int_{T_s}^{T} g k d\theta$ value for CDL and CDM is 34.2 W/cm, in contrast with that for the other elements of 37.9 W/cm. Due to the small number of samples the difference between the two groups can only be regarded as significant at the 90% confidence level. However, assuming a difference of 3.7 W/cm it can be calculated that the difference in fuel surface temperature between the high and low clearance elements was approximately $110^{o}C$ for a fuel/sheath heat flux of 100 W/cm^2. Again, assuming that the fuel pellets expand as a perfect, elastic solid without cracking, it can be calculated that for the high clearance elements, a large diametral clearance would exist between fuel and sheath at power. This is not compatible with the observed fuel surface temperature, and leads to the conclusion that the fuel pellets must expand to fill the diametral clearance, presumably by cracking and relocation of the fragments.

7. PROPOSED MODEL FOR THE AXIAL EXPANSION OF UO_2 FUEL ELEMENTS:

If thin-walled, the sheath of a fuel element is collapsed into contact with the UO_2 pellets by the external coolant pressure. As the element is brought to power the pellets expand and slide slightly in the longitudinal direction relative to the sheath. When diametral expansion of the fuel causes the frictional force between the fuel and the sheath to be sufficiently high, the sheath is elongated, first elastically and then plastically. The axial stress in the fuel is such that the hot central core becomes plastic and deforms more readily than the sheath. The fuel expansion is therefore a function of the expansion of the highest temperature non-plastic ring of fuel, provided there is sufficient voidage to accommodate expansion of the plastic core. Modifications to the pellet end face profile will alter the point of contact of the hot pellets, and hence the amount of fuel expansion.

8. CONCLUSIONS:

Subject to the qualifications made in Section 6,

a) There is little relative longitudinal movement between a stack of UO_2 pellets and a thin Zircaloy sheath under irradiation in a high pressure coolant. Movement is not greatly affected by element heat rating, pellet profile or fuel/sheath diametral clearance.

b) The elongation of a stack of UO_2 pellets in a fuel element is governed by the temperature of the inner edge of the pellet shoulder, or by the thermal expansion of the innermost non-plastic ring of UO_2 (approximately $1000^{\circ}C$ for this irradiation test).

c) The fuel/sheath interface temperature drop for elements assembled with large diametral clearances and free-standing sheaths is considerably less than that calculated by assuming that the pellet expands as an ideal elastic solid. The most probable explanation is that pellet cracking and the subsequent relocation of fragments reduces the diametral clearance, and hence the interface temperature drop.

ACKNOWLEDGEMENTS:

Many individuals contributed to the investigation. In particular, acknowledgement is made to the personnel in NRX Reactor Branch and Reactor Loops Branch, who irradiated the elements, to R. D. MacDonald and those in Fuel Development Branch for post-irradiation examination, and to A. S. Bain and J. A. L. Robertson for many stimulating discussions. The original idea for the marker device was due to G. MacGregor; E. Mizzan and J. D. Craigie performed the development.

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TABLE 1

Element Description[5]

Element Identification	Sheath Thickness (cm)	Diametral Clearance (cm)	Profile	Dish Depth (cm)	Shoulder Width (cm)	Autoclave Temperature (^oC)	Calculated* Marker Movement Due to Autoclaving (cm)
BVV	0.063	0.0153	S	0.0305	0.198	260	0.043
BVR	"	0.0063	"	"	0.207	"	"
BVW	"	0.0153	"	"	0.198	"	"
BVS	"	0.0051	"	"	0.207	"	"
BVX	"	0.0153	"	"	0.198	"	"
BVT	"	0.0051	"	"	0.207	"	"
BWA	"	0.0051	D	0.0318	nil	400	0.066
BWE	"	"	F	nil	-	"	"
BWB	"	"	D	0.0318	nil	"	"
BVP	"	"	S	0.0305	0.207	"	"
BWF	"	"	F	nil	-	"	"
BWC	"	"	D	0.0318	nil	"	"
BYU	"	0.0153	F	nil	-	"	"
BYW	"	0.0165	F	nil	-	"	"
BVZ	"	0.0076	D	0.0318	nil	260	0.043
CDL	0.094	0.038	F	nil	-	-	-
CDM	"	0.038	F	nil	-	-	-

F = flat ends to pellet
S = one end face dished (with shoulder)
D = one end face dished (no shoulder)

UO_2 enrichment - 1.876 ± 0.005 w/o U-235 in total U
Average pellet density - 10.60-10.65 g/cm^3
Fuel length per element approximately 29.9 cm
Element length and diameter - see Table 4.

* Calculated for relative thermal expansions, with expansion coefficients as follows:-

UO_2 = $11 \times 10^{-6}/^oC$

Zircaloy = $6.5 \times 10^{-6}/^oC$

TABLE 2

Irradiation Conditions

	Element Identification	Nominal Distance from Flux Centerline* (cm)	Loop Flow Rate (ml/sec)	Average Moderator Height (cm)
1st Loading	BVV	+90	750	283
	BVR	+54		
21 October, 1960	BVW	+18		
-	BVS	-18		
21 November, 1960	BVX	-54		
	BVT	-90		
X-2 Loop				
2nd Loading	BWA	+90	750	279
	BWE	+54		
25 November, 1960	BWB	+18		
-	BVP	-18		
18 December, 1960	BWF	-54		
	BWC	-90		
X-6 Loop				
3rd Loading	BYU	+90	750	285
	BYW	+18		
26 December, 1960	BVZ	-117		
-				
3 January, 1961				
X-6 Loop				
4th Loading	CDL	-28	630	282
	CDM	-64		
2 March, 1961				
-				
3 April, 1961				
X-2 Loop				

Loop Inlet Temperature	250°C
Loop Inlet Pressure	105 kg/cm^2 (1500 psi)
Loop Coolant pH	9.5-10.5, maintained by LiOH resin
Oxygen Content	<0.1 ppm

* See also Section 4.

TABLE 3

Power Generated in the Fuel (W/cm)*

	Element Identification	Method: Cobalt Monitor	Method: Pu/U Ratio	Method: Cs/U Ratio	Time Average**	Peak***	Date of Peak	Moderator Height (cm)
1st Charge	BVV	426			428	445	20 Nov. '60	292
	BVR	576			580	580	-	-
	BVW	645	659	635	645	676	23 Nov. '60	270
	BVS	618			615	670	21 Nov. '60	240
	BVX	501			506	618	"	"
	BVT	333			333	445	"	"
	Estimated heat output to loop (from average above)					95 kW		
	Measured heat output to loop(15)					96.0 kW		
2nd Charge	BWA	460			470	490	13 Dec. '60	292
	BWE	657			650	650	-	-
	BWB	747	787	743	752	782	28 Dec. '60	275
	BVP	740			720	770	"	240
	BWF	599			595	690	"	"
	BWC	369			370	475	"	230
	Estimated heat output to loop (from average above)					108 kW		
	Measured heat output to loop(15)					103 kW		
3rd Charge	BYU	440			440	465	30 Dec.'60	295
	BYW	683	736	673	697	700	-	-
	BVZ	195			200	240	26 Dec. '60	250
4th Charge	CDL	680	696	642	678	732	4 Mar. '61	270
	CDM	487	505	508	500	570	3 Mar. '60	230

* Figures quoted refer to an average along the element length.

** Used for temperature calculations. Obtained by fitting a sine curve of flux distribution to the experimental points.

*** See Section 4. Calculated from reactor power and moderator height data using information from references 9 and 10.

TABLE 4

Pre- and Post-Irradiation Dimensions

Element Identification	Length (cm)*			Diameter (cm)**		
	Pre	Post	Change	Pre	Post	Change
BVV	33.890	33.936	0.046	2.032	2.032	0.000
BVR	33.890	33.969	0.079	2.032	2.042	0.010
BVW	33.890	33.956	0.066	2.032	2.034	0.002
BVS	33.900	34.007	0.107	2.028	2.038	0.010
BVX	33.885	33.951	0.066	2.032	2.032	0.000
BVT	33.900	33.958	0.058	2.030	2.033	0.003
BWA	33.895	33.895	0.000	2.025	2.032	0.007
BWE	33.680	33.853	0.173	2.028	2.038	0.010
BWB	33.920	33.966	0.046	2.023	2.035	0.012
BVP	33.905	34.014	0.109	2.025	2.037	0.012
BWF	33.690	33.865	0.175	2.030	2.042	0.012
BWC	33.880	33.875	-0.005	2.023	2.028	0.005
BYU	33.905	34.047	0.142	2.023	2.028	0.005
BYW	33.887	34.024	0.137	2.030	2.032	0.002
BVZ	33.902	33.900	-0.002	2.030	2.030	0.000
CDL	33.180	33.182	0.002	2.020	2.020	0.000
CDM	32.890	32.892	0.002	2.020	2.020	0.000

* Average of three readings at 120° intervals

** Average of three readings at 120° intervals at each of five places along the length of the element.

Measurement error limits:

Diameter ± 0.002 cm
Length ± 0.01 cm

TABLE 5

Uranium Oxide Appearance

Element	Diameter of Grain Growth (cm)	Type of Cracking	Remarks on Grain Growth	$\int_{T_s}^{T_g} k d\theta$ * (W/cm)
BVV	nil	Random		>32.5
BVR	0.55	Random	Equiaxed	40.5
BVW	0.93	Radial, circumferential	"	37.5
BVS	0.81	" "	"	38.5
BVX	0.53	Random	"	35.5
BVT	nil	Random	"	>25
BWA	nil	Random		>35.5
BWE	0.98	Radial, circumferential	Equiaxed, columnar	36.5
BWB	1.06	" "	" " void	38.5
BVP	1.00	" "	Equiaxed, columnar	39.5
BWF	0.76	" "	"	38
BWC	nil	Random		>28
BYU	<0.5	Random	Equiaxed (high flux end)	>33
BYW	1.06	Radial, circumferential	Equiaxed, columnar void	36.5
BVZ	nil	Random		>15
CDL	0.99	Radial, circumferential	Equiaxed, columnar	32
CDM	0.77	" "	Equiaxed	36.5

* Based on the average heat rating, Table 3.

T_g = Temperature for discernible grain growth

T_s = Fuel surface temperature

TABLE 6

Equivalent Fuel Temperatures to Cause Expansion and Calculated[a] Temperature Distribution Through the Elements

Element	Marker Movement	Overall Length Change	Calculated Equivalent Fuel Temperature (°C) For Marker Movement	Length Change + Marker Movement	Pellet Profile	$\int_{T_s}^{T_o} kd\theta$	T_s[b]	T_o[d]	$T_{shoulder}$[d]	$\int_{T_s}^{T_o} kd\theta$	T_s[b]	T_o[d]	$T_{shoulder}$[d]
	(cm)	(cm)				(W/cm)	(°C)	(°C)	(°C)	(W/cm)	(°C)	(°C)	(°C)
BVV	0.069	0.046	440	710	S	32.5	370	1400	740	34	375	1490	760
BVR	0.061	0.079	440	870	S	44	410	1850	940	44	410	1850	940
BVW	0.069	0.066	460	850	S	49	410	2000	1000	51.5	415	2050	1030
BVS	0.053	0.107	410	910	S	46.5	400	1900	950	50.5	410	2020	1020
BVX	broken	0.066	-	>630	S	38	370	1610	820	46.5	395	1900	940
BVT	broken	0.058	-	>590	S	25	320	1100	600	33.5	350	1430	730
BWA	0.063	0.000	430	<620	D	35.5	390	1570	-	37	395	1610	-
BWE	broken	0.173	-	>980	F	49	420	2000	-	49	420	2000	-
BWB	0.063	0.046	450	830	D	55	440	2200	-	57	445	2230	-
BVP	0.063	0.109	450	980	S	54	420	2150	1100	58	430	2270	1160
BWF	0.046	0.175	380	1030	F	45	390	1860	-	52	410	2060	-
BWC	0.046	-0.005	380	<540	D	28	340	1270	-	36	370	1550	-
BYU	0.069	0.142	420	970	F	33	350	1420	-	35	355	1490	-
BYW	0.102	0.137	570	1170	F	52	420	2080	-	52	420	2100	-
BVZ	broken	-0.002	-	-	D	15	310	740	-	18	320	860	-
CDL	0.295**	0.002	>1070	<1270	F	50	420[c]	2030	-	54	435[c]	2140	-
CDM	0.255**	0.002	950	<1140	F	38	370[c]	1610	-	43.5	385[c]	1800	-

* See Appendix 3 for calculations
** All available marker movement taken up

Pellet Profile (see also Table 1)

F = Flat ends to pellet
S = One end face dished (with shoulder)
D = One end face dished (no shoulder)

Errors in dimensional changes -
Marker movement ± 0.005 cm
Length change ± 0.010 cm

a) Calculated on the basis of the curve of $\int_{0^\circ C}^{T} kd\theta$ versus T given in reference 17.
b) Fuel/sheath heat transfer coefficient taken as 1.2 W/cm^2 °C (see reference 17).
c) Since these elements have a large assembled diametral clearance the fuel/sheath heat transfer coefficient used in calculation is almost certainly too high. These temperatures are therefore minimum temperatures.
d) Errors are estimated to a 95% probability on the basis of error limits in a) above and in heat rating -

for T_o (UO_2 central temperature) error is $\pm (T_o - T_s) \times 0.09$°C

$T_{shoulder}$ " is $\pm (T_{shoulder} - T_s) \times 0.09$°C

TABLE 7

Hydraulic Rabbit Tests of Axial Expansion Markers

Specimen	VY	VZ	XA	XB	XV	XW
Marker type (see Appendix 2)	b	b	a	a	c	d
Uranium Oxide batch	P111	P111	P111	P111	P104	P104
Sheath			Zircaloy-2			
Outside diameter (cm)			1.8			
Thickness (cm)			0.063			
Fuel/Sheath						
Diametral clearance (cm)			0.011			
Axial clearance (cm)	0.380	0.374	0.374	0.378	0.250	0.262
Diameter of melting (cm)	0.46	0.48	0.48	0.48	0.33	0.28
Diameter of grain growth (cm)	0.99	1.02	0.99	0.99	0.92	0.91
Post-irradiation diametral expansion (cm)	0.015	0.013	0.013	0.013	0.030	0.025
Axial expansion (cm)	-0.015	-0.015	-0.008	-0.008	0.013	0.010
Fuel axial expansion within sheath (cm)	0.125	0.032	0.084	0.070	0.180	0.250
$\int_{T_s}^{T_o} k d\theta^*$ (W/cm)	89.0	88.0	88.4	88.6	84.8	84.0
$\int_{400^oC}^{T_m} k d\theta^*$ (W/cm)	80.8	79.4	79.7	80.1	82.4	82.2
$\int_{400^oC}^{T_g} k d\theta^*$ (W/cm)	59.1	56.2	57.6	58.0	63.0	62.5

* Heat ratings calculated from cobalt monitor activation(16)

APPENDIX 1

Experiment to Measure the Movement of UO_2 Pellets Inside Zircaloy Sheaths Under Out-of-Pile Conditions

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Abstracted from C.G.E. Internal Reports[4]

This experiment was performed to determine the load required to move UO_2 pellets inside 2.5 cm (1.0 in.) O.D. x 0.065 cm (0.025 in.) wall thickness and 1.5 cm (0.6 in.) x 0.04 cm (0.015 in.) wall thickness Zircaloy sheaths at NPD-2* coolant pressure and temperature (81 kg/cm^2 and 260°C).

Diametral clearances were kept near the maximum permissible for the NPD production fuel. The assembled elements were first pressurised to 127 kg/cm^2 (1800 psi) in cold water and examined for longitudinal ridging, none being found. The test temperature and pressure were then applied and the load required to move the pellet stack inside the sheath was measured. This axial load remained substantially constant throughout the sliding, rising sharply when all the axial clearance had been taken up. Results are summarised as follows:

TABLE 8

Sheath Outside Diameter (cm)	Diametral Clearance (cm)	Load Required (kg)
2.5	0.0089 - 0.0107	120 - 410
1.5	0.010 - 0.0132	18 - 75

* Nuclear Power Demonstration reactor, Rolphton, Ontario.

APPENDIX 2

Hydraulic Rabbit Tests

The design finally adopted for the marker to measure relative movement of the fuel and the sheath is shown in Figure 1. It was arrived at after a series of Hydraulic Rabbit irradiations, in which the following variations were tried:

a) Zircaloy pin and stool)
) no wafer
b) Molybdenum pin and stool)

c) As (b) but a 0.063 cm (0.025 in.) thick wafer

d) As (b) but a 0.127 cm (0.050 in.) thick wafer

When there was no wafer the UO_2 bulged and expanded within the stool, and in case (a) melted the Zircaloy pin. A wafer of 0.063 cm thick molybdenum was insufficient, since the pressure of the expanding oxide bulged the center, but a 0.127 cm thick wafer gave satisfactory results. Details of the irradiations, heat ratings etc. are given in Table 7.

APPENDIX 3

Calculation of Equivalent Fuel Temperatures (Table 6)

Fuel expansion = sheath thermal expansion + elastic expansion + plastic expansion + fuel/sheath clearance + fuel internal clearance

Expansion coefficient UO_2	=	$11 \times 10^{-6}/^{\circ}C$
Zircaloy-2	=	$6.5 \times 10^{-6}/^{\circ}C$
Elastic limit Zircaloy-2		0.2%
UO_2 stack length		30 cm
Zircaloy sheath length (between end plug welds)		32 cm

Equivalent fuel temperature for marker movement °C

$$= \frac{30 \times 6.5 \times 10^{-6}\, T_i + m}{30 \times 11 \times 10^{-6}}$$

where T_i = sheath temperature °C

m = marker movement (cm)

Equivalent fuel temperature for sheath expansion °C

$$= \frac{30 \times 6.5 \times 10^{-6}\, T_i + m + e + 2 \times 10^{-3} \times 32}{30 \times 11 \times 10^{-6}}$$

where e = sheath plastic expansion (cm)

FIG. 1

MARKER FOR MEASUREMENT OF RELATIVE AXIAL EXPANSIONS