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FINAL REPORT:

TEMPERATURE MEASUREMENT OF
URANIUM SWELLING CAPSULE
PT-1P-200-A

AUTHOR

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FINAL REPORT:
TEMPERATURE MEASUREMENT OF URANIUM
SWELLING CAPSULE PT-IP-200-A

J. W. Weber

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FINAL REPORT:
TEMPERATURE MEASUREMENT OF URANIUM
SWELLING CAPSULE PT-IP-200-A

J. W. Weber

I. INTRODUCTION

As a vital link in the fuel element development program for the NPR, a series of experiments to obtain data on unalloyed uranium swelling as a function of temperature, exposure, and restraint, has been initiated.⁽¹⁾ These experiments are now being irradiated in process tubes of D reactor. The experimental assemblies consist of a Zr-2 clad coextruded uranium fuel supported concentrically in an aluminum capsule. Surrounding the fuel rod is an annulus of NaK to serve as a liquid heat transfer medium and thermal barrier to raise the temperatures to the desired values.

To provide a check on the operation and temperature calculations of the capsules, a single capsule with a thermocouple located in the axis of the uranium was irradiated in DR reactor for a period of 29 days.⁽²⁾⁽³⁾ Continuous measurements of the uranium central temperature were made and compared with temperatures calculated from adjacent tube powers, rise factor for the experimental fuel rod, and a slug factor obtained from flux distribution measurements. Irradiation of the experiment was to continue until at least 7 days of continuous steady state reactor operation were achieved. Data from this single capsule test was to be used in determining a temperature correction factor that could be applied to the design of the capsules for the full scale series of swelling tests.

II. SUMMARY

A single swelling capsule was irradiated in DR reactor as a test of the operation and design of a series of similar capsules to be charged later in a large scale uranium swelling experiment. The ratio of measured to calculated uranium temperature increased from 0.7 during the first two-thirds of the irradiation to 1.08 during the last one-third. Most of this change can be accounted for by a flux shift toward the rear of the reactor during the last one-third of the irradiation. Because of this flux shift it was impossible to determine an accurate temperature correction factor to be applied to the full scale test to follow.

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- (1) Weber, J. W., "In-Reactor Restrained Swelling Experiments," HW-56132, Secret.
 - (2) Weber, J. W., "Proposal for Irradiation of Uranium Swelling Capsule," HW-56589, Secret.
 - (3) Kratzer, W. K., "PT-IP-200A, Temperature Measurement of Uranium Swelling Capsule, HW-57109, Secret.

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Radiometallurgy examination revealed an asymmetric radial temperature distribution in the fuel. Subsequent capsule tests have shown that this temperature asymmetry was caused by incomplete NaK coverage of the fuel rod. A change in design of the capsules for the subsequent tests will prevent this.

III. DESCRIPTION OF TEST

A. Experimental Assembly

The uranium rod irradiated in this test was cut from one of a series of 1.6 per cent enriched 0.630 inch O.D. Zr-2 clad rods coextruded by Nuclear Metals, Inc. Uranium in the fuel rod was 0.570 inch diameter by 3.6 inches long. Overall dimensions of the fuel rod, with the Zr-2 end cap electron-gun welded to the cladding, were 0.630 inch O.D. by 4.5 inches in length. To measure the temperature of the center of the uranium, a 0.152 inch diameter hole 1.5 inches deep was drilled axially into the uranium at one end. A Zr-2 thimble was inserted into this hole to prevent reaction of the uranium and stainless steel sheath of the thermocouple. The thimble was electron-beam welded to the Zr-2 end cap to prevent contact of the NaK and uranium. A spider assembly on each fuel rod end cap centered it co-axially in the capsule. To check the integrated neutron flux at the fuel rod, an aluminum-0.08 per cent Co flux monitor was attached along the length of the clad fuel rod.

To provide low neutron absorbing, corrosion resistant containers for the fuel rod and the NaK, cylindrical capsules 1.44 inch O.D. x 10.4 inch long were machined from ALCOA C-64 aluminum alloy. At design temperatures, the volume expansion of the NaK amounts to 10 per cent. To limit the internal pressure imposed on the capsule by this NaK expansion and the volume increase in the uranium to 150 psi, expansion chambers were provided at both ends of the capsule. These expansion chambers at the top of the capsule were filled with Helium at 1 atmosphere pressure. They connect to the NaK annulus in the fuel chamber as shown in Figure I. If the capsule were rotated 180° from the orientation shown in the figure, the NaK would flow into the expansion chamber uncovering a portion of the fuel rod, resulting in excessive temperatures in the cladding and uranium. To retain the expansion chamber in the proper orientation, rails which rest on the ribs of the process tube, were welded to the outside of the capsule.

A 1/8 inch O.D. swaged chromel-alumel thermocouple with MgO insulation and stainless steel sheath was used to monitor the uranium temperature. The thermocouple was sealed into the capsule body through two stainless steel Swageloks. In the reactor, the thermocouple was led through a train of dummies and out a modified rear face nozzle. Lead wires then carried the temperature signal to a recorder in the reactor control room.

B. Test Conditions and Procedure

By selecting combinations of NaK annulus thickness and power generation in the fuel rod, various uranium axial and cladding surface temperatures can be achieved. Restrictions imposed by the allowable thickness of the NaK annulus, as dictated by the size of expansion chamber required and

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available reactor tube powers, limit the range of temperatures. Conditions selected for this test were:

Power generation 23 kw/ft.
Uranium core temperature 513 C.
Cladding surface temperature 233 C.
NaK annulus thickness 0.122 inch.

The ratio of specific power in the test capsule to the specific power in the fuel elements of adjacent process tubes is 0.569. Using this factor and assuming that the experimental fuel rod would be opposite the maximum powered fuel element in the adjacent tubes, the adjacent tube power required was 900 KW.

The capsule and thermocouple train were charged through the rear face nozzle into tube number 2763 of DR reactor. The distance from the rear face nozzle cap to the thermocouple bead in the fuel rod was 240 inches. Numbered natural uranium fuel elements for a front to rear flux traverse in tube number 2764 were charged and discharged concurrently with the capsule.

Data to calculate the average adjacent tube power was taken each reactor shift. From this information, the ratio of specific power generation in the capsule and adjacent fuel elements, and the flux distribution obtained from the adjacent tube, a "calculated uranium temperature" was obtained with which to compare the measured temperature.

After discharge the capsule was sent to Radiometallurgy Operation for examination.

IV. IN-REACTOR PERFORMANCE

A. Comparison of Calculation and Measured Temperatures

Figure II shows the average central uranium temperature for each hour on the dashed lines and the temperature measured at each hour on the solid line. The numbered circles with the time indicated correspond to the times at which data was taken for calculating temperatures. Calculated temperatures are shown on Figure II as crosses. Table I lists pertinent times, temperature, and power values for each data point. During the first two-thirds of the irradiation the measured temperature varied from 75 to 200 C below the calculated temperature. However, during the last five days the measured temperature was 25 to 50 C higher than the calculated temperature.

B. Flux Traverse Measurements

After discharge the numbered fuel elements in the adjacent tube were sent to the examination basin at C reactor for activity measurements. Two sets of measurements were made approximately five days after discharge, with a third set made three days later. The relative activities are plotted in Figure III for each set of measurements. From this activity data a slug factor was determined which was used in calculating the uranium temperature. This factor of necessity, was assumed to be constant, but actually varied during the irradiation, as described in the discussion to follow.

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V. POST-IRRADIATION EXAMINATION

No visible signs of corrosion could be found on the external surface of the capsule. The capsule was opened in the radiometallurgy facility and a careful visual examination made of its internal surface. There was no indication of NaK reaction with the aluminum. Temperature of the NaK-aluminum interface was approximately 100 C.

Examination of the fuel rod revealed that the aluminum flux monitor had disintegrated and all that remained was isolated regions of a brittle metallic material covered by a black oxide. (Figure IV.)

This material was lightly adhered to the Zr-2 cladding. A light brushing removed the black oxide uncovering the shiny remnants of the flux monitors as shown in Figure VA. In some areas the flux monitor had reacted or oxidized to a powder and only a thin layer remained on the cladding. The appearance of the Zr-2 in Figure VA and the thinning of the cladding to 0.015 inch as shown in Figure VB suggest that the flux monitor reacted with the Zr-2. An out-of-reactor test was conducted in which a piece of aluminum flux wire was attached to a Zr-2 tube and immersed in NaK for 25 days at 500 C. The aluminum reacted with the Zr-2 producing a product very similar to that found in the irradiation test (Figure VIB.) A brittle diffusion zone was found in the Zr-2 (Figure VIIB). A similar test run at 400 C for approximately one-third the time showed no tendency for the aluminum and Zr-2 to react.

A series of longitudinal cracks was found in the cladding in the region of the flux monitor. These cracks penetrated into the uranium.

At the end of the fuel rod opposite the thermocouple a bulge in the cladding was found. Metallography revealed severe circumferential and radial cracking in the uranium (Figure VII). The circumferential crack occurred a short distance from the U-Zr bond and remained in the uranium except at the very ends of Figure VIII. A wide U-Zr diffusion zone can be seen on the cladding side of the crack. Elongated grains, indicating that at some time during the irradiation the uranium was above the α - β transformation temperature, radiate from a point on the radial crack (Figure VII) approximately 0.160 inch from the cladding.

VI. DISCUSSION

To determine a correction factor that could be applied to the subsequent capsule irradiations, the ratio of measured to calculated temperatures was calculated for each data point during the irradiation. This ratio, plotted in Figure IX averages approximately 0.7 for the first 600 hours, then increases rather abruptly to approximately 1.08 for the last 100 hours of the test. This difference in ratio of T_m and T_c can be attributed to

- (1) Change in front to rear flux distribution,
- (2) Change in the radial temperature distribution of the uranium rod.
- (3) Some combination of both the above.

An analysis of changes in the amount and location of control poison in the

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reactor during the irradiation showed that the maximum flux peaks were shifted toward the rear of the reactor the last 100 hours. This shift is confirmed by data showing a shift of the adjacent column activity peaks toward the front slugs with each subsequent weasel reading. Therefore a larger slug factor should be applied for the data points 30 through 37. A larger slug factor would reduce the ratio $\frac{T_m}{T_c}$. Also

if a smaller slug factor were applied to the earlier data points the ratio $\frac{T_m}{T_c}$ would

be increased during that time period. Another possible cause of flux shifting could be the amount of water in the graphite which was known to be greater during the first two-thirds of the irradiation than during the last one-third. From this information then, it appears highly probable that a shift in flux toward the rear face of the reactor did occur during the last days of the irradiation.

Evidence of an asymmetric temperature distribution is shown in the radiometallurgy observations of the overheated flux wire, the thick diffusion zone along a segment of the U-Zr bond, and the orientation of the elongated grains.

Existence of this asymmetric temperature could account for part of the low $\frac{T_m}{T_c}$ ratio

during the early portion of the irradiation by shifting the region of maximum uranium temperature toward the edge of the fuel. The time of the occurrence of the large circumferential crack is unknown, but the wide U-Zr diffusion band at the top of the rod indicates high temperatures existed at this location for some period of time. A high temperature would only exist before the crack separated the diffusion layer from the uranium proper. What the effects on temperature distribution would be as a result of the crack is difficult to analyze. Radiographic examination of several capsules made subsequent to this test revealed NaK in the expansion chambers and a bubble of He gas above the fuel rod. This is undoubtedly the cause of the asymmetric temperatures observed in this test.

VII. CONCLUSIONS

The changes in flux distribution and the lack of knowledge of the flux at a given slug at any one time during the irradiation makes the determination of an accurate temperature correction factor impossible. Therefore, based on the apparent correlation of reactor poison charging and discharging operations with changes in $\frac{T_m}{T_c}$ and

on the radiometallurgy examination, the design of the subsequent capsule experiments was not altered except to place the expansion chamber at one end. An incomplete coverage of the fuel rod with NaK was the cause of the asymmetric temperatures.

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TABLE I

TIME, TEMPERATURE, AND RATIO T_m FOR EACH DATA POINT
 T_c

Point	Date Time	Av Tube Power kw	Measured Temp °C	Water Temp °C	$\Delta T_{cal.}$ °C	Calculated Temp °C	$\frac{T_m}{T_c}$	Reactor Power MW
1	4 1235	591	--	19.2	394	413	--	1100
2	5 0840	744	343	19.4	496	515	0.666	1190
3	6 0845	783	363	18.9	522	541	0.695	1210
8	11 0915	742	314	17.3	494	511	0.614	1075
10	13 0845	768	390	17.3	512	529	0.737	1300
11	14 0845	794	392	18.0	529	547	0.717	1345
12	15 0845	878	500	18.2	585	603	0.829	1385
13	16 0545	898	438	13.8	598	617	0.710	1390
14	16 0830	863	432	18.6	575	594	0.727	1385
15	17 0430	909	376	18.9	606	615	0.611	1400
16	17 0800	908	390	18.5	605	623	0.626	1400
17	17 1610	905	393	18.3	603	621	0.633	1400
18	18 0220	905	400	18.8	603	622	0.643	1410
19	18 0800	898	405	18.2	598	616	0.657	1415
20	18 1615	917	393	17.9	611	629	0.625	1415
29	27 0900	524	307	15.9	349	365	0.841	1000
30	28 0845	640	500	16.8	426	442	1.131	1160
31	29 1020	770	550	15.2	513	528	1.042	1300
32	29 1700	713	559	15.7	475	491	1.138	1320
33	30 0155	809	609	15.8	539	555	1.130	1340
34								
35	30 1620	850	587	15.9	566	582	1.009	1345
36	31 1200	868	614	16.0	578	594	1.034	1365
37	31 0845	872	638	15.7	581	597	1.069	1375

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FIGURE 1

Uranium Swelling Capsule with Thermocouple to Measure Central Uranium Temperature of Zr-2 Clad Fuel Rod. The Capsule Used in the Test Described in this Document had Expansion Chambers at Both Ends.

FIGURE 2

Hourly Maximum and Average Measured Uranium Temperatures,
Temperatures Calculated from Reactor Data.

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FIGURE 3

Front to Rear Relative Flux Distribution Curves for the Adjacent Tube

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A. Disturbed Longitudinal Band on Cladding Shows Location of Aluminum Flux Monitor. - 3/4X.

B. One of Many Longitudinal Cracks Found in the Zr-2 Cladding Under the Flux Monitor. - 2X.

FIGURE 4

Fuel Rod Irradiated in Swelling Capsule

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A. Remains of the Aluminum Flux Monitor
with Most of the Black Oxide Removed.
3X

B. The Cladding was Thinned to 0.016" by
Reaction with the Flux Monitor. 50X.

FIGURE 5

Fuel Rod Irradiated in Swelling Capsule

A. Surface of Zr-2 Tube with Remains of Aluminum Flux Monitor. 8X.

B. Brittle Diffusion Band on Zr-2 Tube where the Aluminum Flux Monitor was Located. 250X.

FIGURE 6

Results of Ex-Reactor Zr-Al-NaK Compatibility Test After Heating to 500°C for 20 Days.

3.5X

FIGURE 7

Cross Section of Fuel Rod Through the Bulge in the Cladding. The Circumferential and Radial Cracking are Shown as are the Elongated Grains Indicating Temperatures at Sometime Above the α - β Transformation.

50X

FIGURE 8

The Wide U-Zr Diffusion Zone is Shown on the Cladding Side of the Large Circumferential Crack which Entered the Cladding Only at its Ends. The Uranium is at the Bottom.

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FIGURE 9

Ratio of $\frac{T_M}{T_C}$ for Each Data Point During the Irradiation

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