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UNRESTRAINED SWELLING OF URANIUM-NITRIDE FUEL IRRADIATED AT TEMPERATURES RANGING FROM 1100 TO 1400 K (1980° TO 2520° R)

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16. Abstract

Six fuel pins were assembled, encapsulated, and irradiated in the Plum Brook Reactor. The fuel pins employed uranium mononitride (UN) in a stainless steel (type 304L) clad. The pins were irradiated for approximately 4000 hours to burnups of about 2.0 atom percent uranium. The average clad surface temperature during irradiation was about 1100 K (1980° R). Since stainless steel has a very low creep strength relative to that of UN at this temperature, these tests simulated unrestrained swelling of UN. The tests indicated that at 1 percent uranium atom burnup the unrestrained diametrial swelling of UN is about 0.5, 0.8, and 1.0 percent at 1223, 1264, and 1306 K (2200°, 2273°, and 2350° R), respectively. The tests also indicated that the irradiation induced swelling of unrestrained UN fuel pellets appears to be isotropic.

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SUMMARY

Six fuel pins employing uranium mononitride (UN) as the fuel and 304L stainless steel as the clad material were assembled in six capsules. These fuel pins were irradiated in the Plum Brook Reactor for approximately 4000 hours to burnups ranging from 1.0 to 1.8 atom percent uranium at an average clad surface temperature of about 1100 K (1980^0 R). At this average clad temperature the stainless steel offers very little restraint to the irradiation induced swelling of the UN fuel. Therefore, under these conditions the UN will swell with very little restraint from the stainless steel.

Post-irradiation examination of the fuel pins revealed that they experienced some swelling. Some of the fuel pins released fission gases into the capsule. It is believed that this resulted from irradiating the stainless steel clad at a relatively high temperature. The unrestrained diametrial swelling of all the fuel pellets examined was less than 3 percent and appeared to be isotropic.

INTRODUCTION

As part of NASA's investigation of space power conversion systems, there exists a need for a program to provide technology for compact, fast-spectrum reactors capable of operating at high temperatures and high powers for long periods of time. To fill this need, a program was initiated at the Lewis Research Center to develop the technology needed to build and operate a reliable compact reactor suitable for use as a heat source in conjunction with a power conversion system. Various aspects of this reactor concept have been described previously. The nuclear design is described in reference 1. The mechanical design, fluid flow and heat transfer, fuel swelling, control, and system dynamics are described in reference 2. The materials studies and the irradiation tests related to the reactor are described in reference 3.

Irradiation experiments were undertaken to evaluate the in-pile performance of the fuel elements. In addition, analytical work was undertaken in order to predict the fuel element performance for off-design conditions. Unrestrained fuel swelling information was desired to check fuel swelling models.

This report describes a set of experiments that were performed to determine the magnitude of the unrestrained fuel swelling of the uranium mononitride (UN). Unrestrained swelling was approached by using a stainless steel clad which has a very low creep strength relative to the creep strength of the fuel at the temperatures of interest. The cross-sectional dimensions of the fuel pins investigated in these tests were approximately one-fourth the cross-sectional dimensions of the fuel pins considered in the reactor described in reference 1. The fuel pins were irradiated in the Plum Brook Reactor at burnup rates 6 to 10 times those of the reactor described in reference 1. Burnups equivalent to those to be experienced in the space power reactor fuel could therefore be obtained in one-sixth to one-tenth the time. A hydraulic capsule facility designed to handle six capsules at a time was used. Instrumentation was limited to one thermocouple per capsule. The facility is described in detail in reference 4.

After irradiation the fuel pins were examined in the Plum Brook Hot Laboratory to evaluate the magnitude of the unrestrained fuel swelling. The details and results of the irradiation are discussed in this report. All the fuel pins were not examined because the program was unexpectedly terminated.

FUEL-PIN AND CAPSULE DESCRIPTION AND ASSEMBLY PROCEDURES

Fuel-Pin Description

A sketch of a typical fuel pin is shown in figure 1. A typical fuel pin contained four UN pellets, each pellet having a length of 0.635 centimeter (0.250 in.) and an outside diameter of 0.381 centimeter (0.150 in.). The pellets were contained in a 304L stainless steel clad tube with an outside diameter of 0.534 centimeter (0.210 in.) and an inside diameter of 0.383 centimeter (0.151 in.). A tungsten cone-shaped spacer was placed at each end of the fueled section. These spacers maintained the fuel position and were designed to deform if the length of the fueled section increased because of axial swelling. A 304L stainless steel tube was electron beam welded to one end cap of the fuel pin. A 304L stainless steel sheath of a grounded junction Chromel-Alumel (type K) thermocouple was electron beam welded to the other end cap of the fuel pin. Both end caps were electron beam welded to the clad tube.

Capsule Description

A sketch of a typical capsule used in these tests is shown in figure 2. The capsule is a static gas type capsule which employs a helium conduction gap to transfer the heat generated in the fuel pin. To assemble the fuel pin in the capsule, it was necessary to make the diameter of the capsule significantly larger than the diameter of the fuel pin. However, to irradiate the small fuel pins at high burnup rates, a very small gas conduction gap was necessary. As a practical compromise, a sleeve was inserted into the capsule to provide this small gap and still permit assembly of the fuel pin into the capsule. The sleeve was fabricated from aluminum because of its low density resulting in low gamma heating. The outer capsule was made of stainless steel.

The negative leg of the thermocouple was grounded to the body of the capsule. Because of the method of measuring temperatures (the hot junction grounded to the fuel pin and one leg grounded to the capsule), it was necessary to electrically insulate the entire fuel-pin assembly from the capsule body. Alumina washers were used to insulate the fuel pin (shown in fig. 2). The positive leg of the thermocouple was brought out through two metal-to-ceramic insulating seals, which are shown in figure 2 and described more completely in reference 5. The leg of the thermocouple was then attached to an insulated commutator spring.

Six capsules were assembled to form a capsule assembly (fig. 3(a)). The capsule assembly was then inserted into a hydraulic capsule test facility (described in ref. 4). The capsule was positioned against the facility stop which houses several insulated rings (fig. 3(b)). Welded to each ring is a lead which travels from the ring to the instrumentation readout equipment. As the capsule assembly comes to rest, a commutator spring from each capsule contacts one of the rings of the stop. Thus, the signal from the thermocouple is transmitted to instrumentation readout equipment. The negative leg of each thermocouple is attached to a common ground through the capsule bodies.

Fuel-Pin Assembly Procedures

The UN fuel pellets were fabricated by Oak Ridge National Laboratory (ORNL). These fuel pellets were uniaxially pressed in dies using camphor as a binder. A detailed description of the fabrication process is presented in reference 6. The chemical composition of the fuel is given in table I. The clad tube was manufactured from commercial grade stainless steel. The clad tube and end caps were cleaned by scrubbing with a household cleanser, rinsing in hot tap water and boiling in distilled water, rinsing in ethyl alcohol, and finally air drying. The tungsten spacers were cleaned by immersing in acetone, rinsing in alcohol, and air drying.

The fuel pins were not assembled in a controlled environment (e.g., glove box), but they were assembled using clean-room techniques. The fuel pins were then helium leak checked to ensure weld integrity. All fuel pins were considered to have acceptable integrity when the leak rate was less than 0.13×10^{-8} cubic centimeter per second (10^{-8} ft^3/hr) of helium at standard temperature and pressure. The thermocouple and support tube were then electron beam welded to the fuel pin, and the fuel pins were stored in clean glass containers until assembly in the capsules. A summary of the pertinent data about the fuel pins is given in table II.

Capsule Assembly Procedures

The capsule parts (except for the alumina insulators and the fuel pins) were cleaned in acetone and rinsed in alcohol. The ceramic insulators were first welded to their housings. The preparation of the ceramic insulators for welding into the housings is similar to that described in reference 5.

After a polarity check of the thermocouple and a prefitting of all the capsule parts, the fuel pin was assembled in the capsule (fig. 2). After assembly each capsule was X-rayed to determine if the capsule parts were assembled correctly. The thermocouple circuit was checked to verify continuity of the thermocouple. Then welds 1 and 2 (shown in fig. 2) were made. Making welds 1 and 2 did not seal the capsules because the helium fill tube was not sealed. After the welds were made on the capsules, they were baked for 1 hour at 473 K (851° R) in a vacuum chamber and sealed by welding the helium fill tubes in a vacuum. After sealing, the capsules were leak checked by placing them in a container and pressurizing with helium to 34.4 newtons per square centimeter (50 psi) for 1/2 hour. The capsule was then placed in a second container that could be attached to a leak detector and checked for helium leaks. The capsules were filled with helium by placing them in a glove box. After the glove box was purged twice, it was filled with helium to atmospheric pressure. The capsules were filled with high purity helium by cutting the fill tubes. After sealing the capsules by gas-tungsten arc welding the fill tubes, the capsules were helium leak checked. The capsules were then assembled in a capsule holder, and the thermocouple positive-leg wires were welded to the spring support plate.

IRRADIATION

Irradiation Conditions

A summary of the irradiation conditions is given in table III. The thermocouple temperatures given in the table, unless otherwise noted, are time-averaged temperatures. The thermocouple temperatures of the fuel pins, averaged over as many as 3797 hours of irradiation, ranged from 946 to 1089 K (1702° to 1960° R). The average clad temperature and average fuel temperature are calculated values obtained by using a two-dimensional heat-transfer program. The temperatures were calculated for each pin by equating the thermocouple temperature in the heat-transfer calculation to the thermocouple temperature in the actual test.

The heat-transfer gaps in the capsule were designed so that all fuel pins would operate at the same temperature. The variation observed in the thermocouple temperature is attributed primarily to the uncertainties in the local neutron flux data.

Plots of the temperature readouts of the thermocouples for the fuel pins are shown in figure 4. As seen from the figure the fuel pins experienced thermal cycles during the irradiation. Most of the thermal cycles were caused by normal reactor refueling. The temperatures of some thermocouples were relatively steady throughout the irradiation. There were times, however, when the thermocouple readouts were not steady. This unsteady performance was due to film buildup on an electrical contact associated with the thermocouple circuit that was made in water. Whenever this happened noisy readouts resulted. The noisy readouts were not recorded since recording such readouts interfered with the operation of the reactor. This explains the times when some thermocouples appeared not to be reading at all. It is also believed that such a film buildup was responsible for the low readings experienced by thermocouples B, D, and E near the end of the irradiation. Some daily fluctuations in the temperatures are probably due to changes in the neutron flux which was caused by control rod movement.

Fuel-Pin Temperature Distributions

The temperature distribution, fission heating, and gamma heating of the fuel pin were calculated for a given fuel-pin design and irradiation condition. The computer program was developed specifically for the fuel-pin and capsule configuration, and it was checked against existing computer heat-transfer programs for accuracy. The program used a finite difference method to obtain a two-dimensional temperature distribution throughout the fuel pin, with the input being neutron flux, gamma heating, and material characteristics. A map of the temperature distribution for a typical fuel pin is shown in figure 5 for the following conditions:

Fuel material	UN
Fuel weight, g	3.8977
Clad material	304L stainless steel
Capsule inside diameter, cm (in.)	0.610 (0.240)
Perturbation factor	0.720
Fuel pin outside diameter, cm (in.)	0.533 (0.210)
Centerline flux, neutrons/cm^2/sec	2.58×10^{13}
Thermocouple temperature (node 126), K (^{O}R)	1107 (1991)
Maximum capsule surface temperature (node 61), K (^{O}R)	372 (670)
Average clad surface temperature, K (^{O}R)	1262 (2271)
Maximum clad surface temperature, K (^{O}R)	1306 (2351)
Fuel-pin fission heating, W (Btu/hr)	324 (1107)
Capsule gamma heating, W (Btu/hr)	183 (625)
Average gamma heating rate, W/g	0.87

POST-IRRADIATION EXAMINATION

Visual Examination

Visual examination of some of the irradiated fuel pins indicated no severe problems such as clad corrosion, excessive swelling, discoloration, or cracking. Figure 6 shows the fuel pins before irradiation, and figure 7 shows a fuel pin after irradiation. Crystalline surface formations at the center of the fuel pin occurred as a result of the irradiation. These crystalline formations could be attributed to grain growth in the clad. However, these formations were not analyzed to find out why they occurred.

Fuel Swelling Measurements

Some pellets from fuel pins 323A and 323F were removed. The diametrial and length measurements of the pellets before and after irradiation are given in table V. Also listed in table V are the calculated values of pellet operating temperature and burnup. A plot of the percent diametrial swelling for unrestrained irradiated UN pellets is given as a function of burnup for temperatures of 1223 K (2200^O R), 1264 K (2275^O R), and 1306 K (2350^O R) in figure 8. The curves were drawn through the data with the general shape of the curves established from the burnup dependency given in reference 7. From the plot it appears that the diametrial swelling of the UN is about 0.5, 0.8, and 1.0 percent at 1 percent burnup for 1223 K (2200^O R), 1264 K (2275^O R), and 1306 K

(2350° R), respectively. The shaded bands on the plot signify the deviation in the diametrical measurements of the pellets.

Also, it appears from table V that $\Delta L/L$ is approximately equal to $\Delta D/D$, which implies that the swelling of the UN pellets is isotropic.

CONCLUSIONS

The following conclusions can be drawn from the tests on unrestrained swelling of UN fuel irradiated for up to about 3800 hours:

1. At 1-percent uranium atom burnup, the unrestrained diametrial swelling of the UN is about 0.5, 0.8, and 1.0 percent at 1223 K (2200° R), 1264 K (2275° R), and 1306 K (2350° R), respectively.

2. The irradiation induced swelling of the unrestrained UN fuel pellets appears to be isotropic.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 27, 1973,
503-25.

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TABLE I. - CHEMICAL ANALYSIS

OF URANIUM-NITRIDE FUEL[a]

Element	Composition, wt. %
Uranium	94.44 to 94.85
Nitrogen	5.13 to 5.53
Oxygen	0.098 to 0.190
Carbon	0.021 to 0.046

[a] Fuel grain size, approximately 0.0025 cm (0.001 in.) in diameter.

TABLE II. - FUEL-PIN FABRICATION SUMMARY

Cladding:	
Material	304 stainless steel
Outside diameter, cm (in.)	0.533 (0.210)
Wall thickness, cm (in.)	0.076 (0.030)
Fuel:	
Material	uranium nitride
Inside diameter, cm (in.)	0 (0)
Outside diameter, cm (in.)	0.381 (0.150)
Length, cm (in.)	2.54 (1.00)
Theoretical density, percent	94.3
Weight of uranium nitride, g, for capsule -	
323A	3.91
323B, 323C, 323D, 323E	3.90 (each)
323F	3.89
Enrichment, percent	10

TABLE III. - CAPSULE IRRADIATION CONDITIONS

Capsule	Time at temperature, hr	Temperature, K (^{O}R)			Power density, kW/cm^3
		Thermocouple	Average clad	Average fuel	
323A	3797	1052 (1883)	1185 (2132)	1219 (2194)	0.930
323B		946 (1703)	1113 (2002)	1155 (2079)	1.178
323C		1089 (1960)	1262 (2271)	1306 (2350)	1.218
232D		1021 (1837)	1155 (2079)	1189 (2140)	.944
323E		975 (1755)	1079 (1942)	1106 (1990)	.735
323F	2844	1039 (1871)	1142 (2054)	1168 (2103)	.724

TABLE IV. - SUMMARY OF BURNUP RESULTS

Capsule	Burnup, percent (as determined by heat-transfer requirement (calculated))
323A	1.703
323B	2.155
323C	2.230
323D	1.729
323E	1.347
323F	.993

TABLE V. - FUEL PELLET SWELLING DATA

Fuel pellet	Calculated burnup, at. %	Diameter before, max/min		Length before		Pellet temperature	
		cm	in.	cm	in.	K	^{o}R
323F(3)	0.948 (measured 0.838)	0.3808/0.3806	0.1499/0.1498	0.6363	0.2505	1222±28	2200±50
323A(1)	1.858	0.3808/0.3806	0.1499/0.1498	.6375	.2510	1265±28	2275±50
323A(2)	1.755	0.3808/0.3806	0.1499/0.1498	.6325	.2490	1306±14	2350±25

Fuel pellet	Diameter after, max/min		Length after		Percent change in diameter, % ΔD/D, max/min	Percent change in length, % ΔL/L
	cm	in.	cm	in.		
323F(3)	0.3828/0.3818	0.1507/0.1503	0.6411	0.2524	0.60/0.33	0.76
323A(1)	0.3886/0.3886	0.1530/0.1530	------	------	2.14/2.07	----
323A(2)	0.3901/0.3899	0.1536/0.1535	------	------	2.53/2.40	----

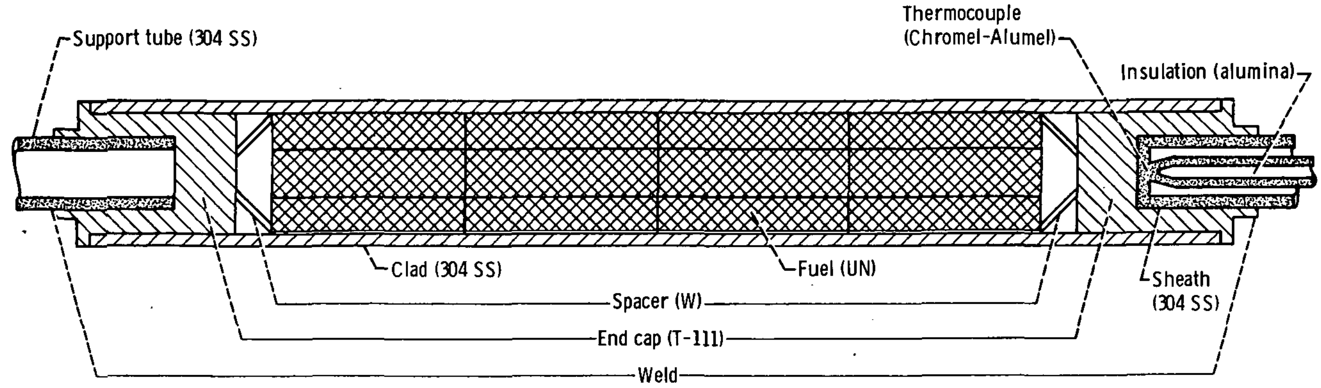


Figure 1. - Fuel pins.

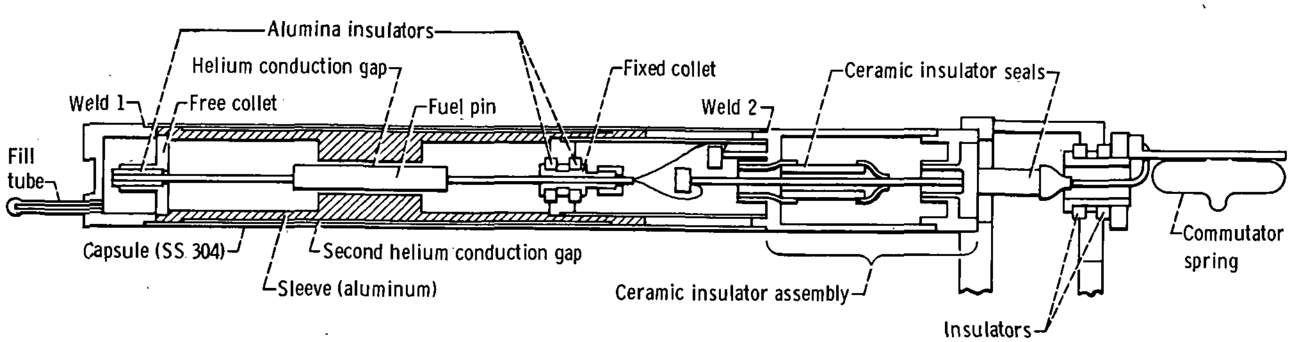
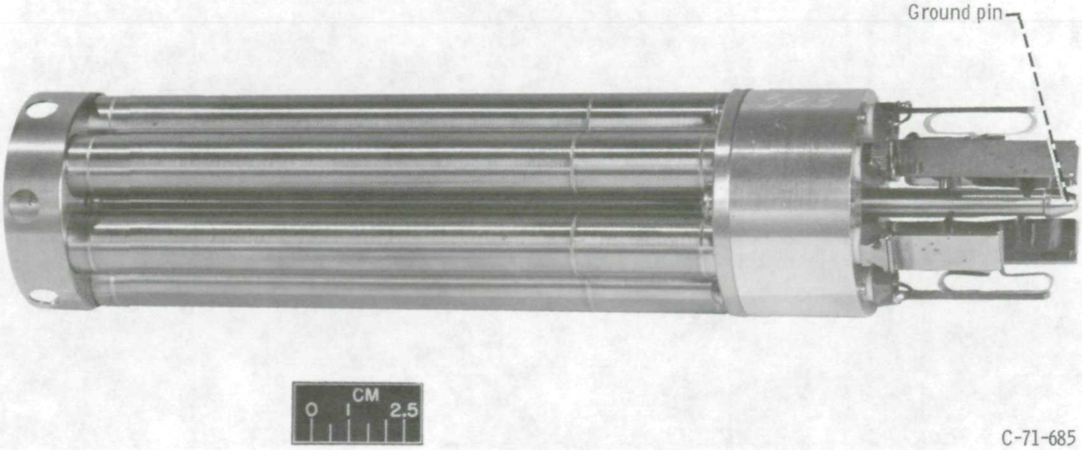
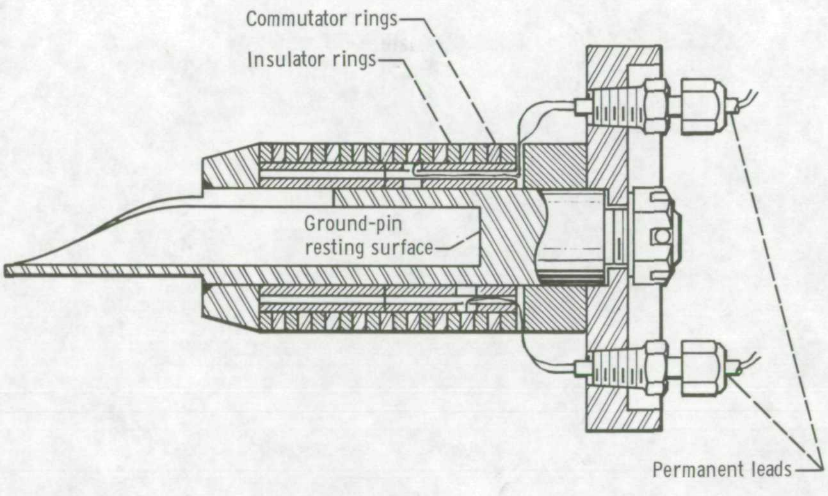


Figure 2. - Uranium-nitride fuel-pin irradiation capsule.



(a) Capsule assembly.



(b) Facility stop.

Figure 3. - Capsule assembly and facility stop.

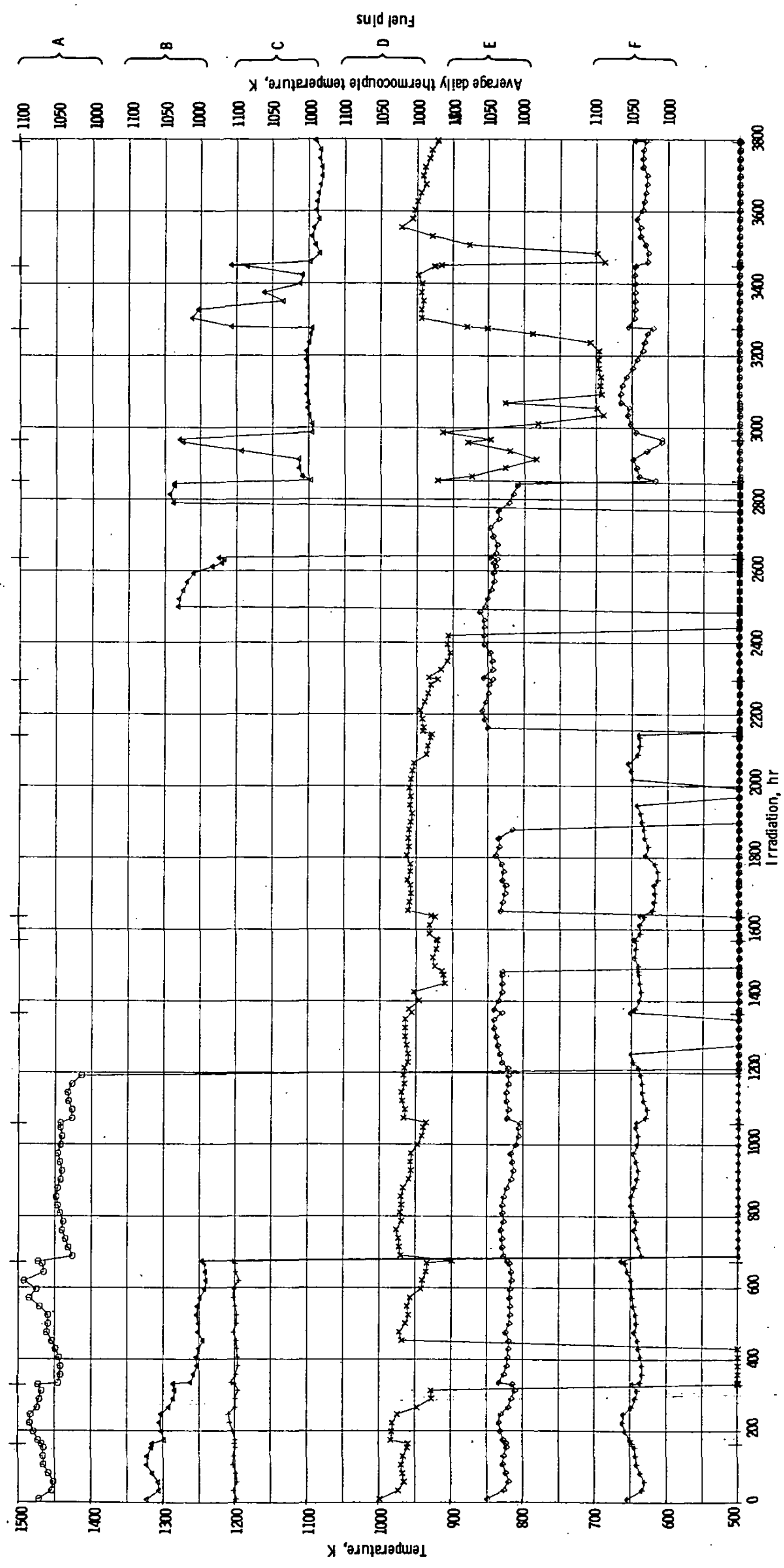


Figure 4. - Daily averaged thermocouple readings for fuel pins.

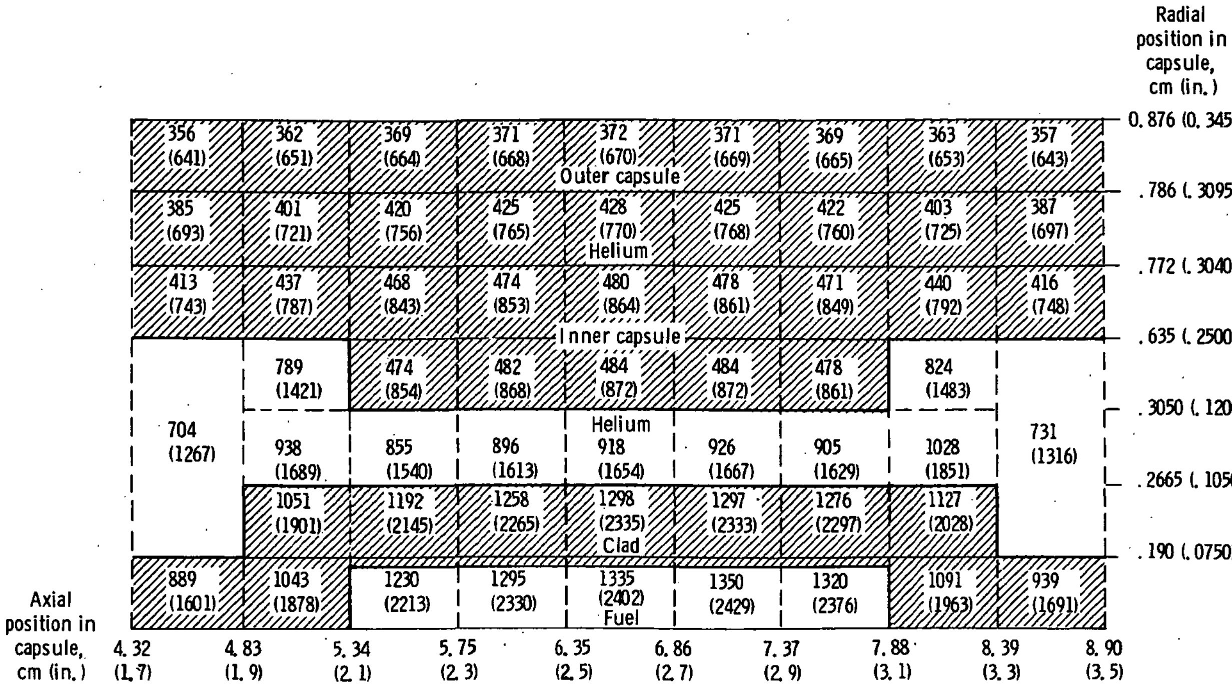


Figure 5. - Heat-transfer results for typical capsule and fuel pin. Temperatures at various locations are given in kelvin degrees (°R).

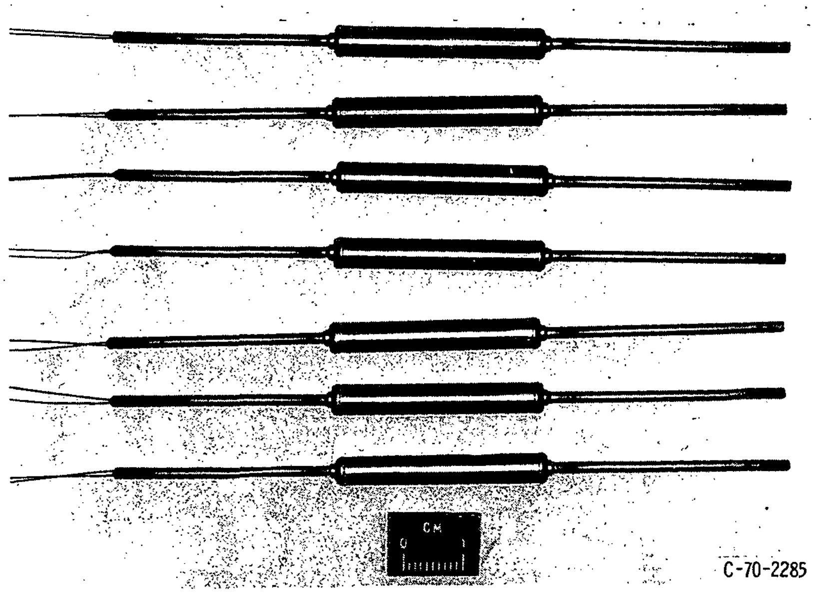


Figure 6. - Fuel pins before irradiation.

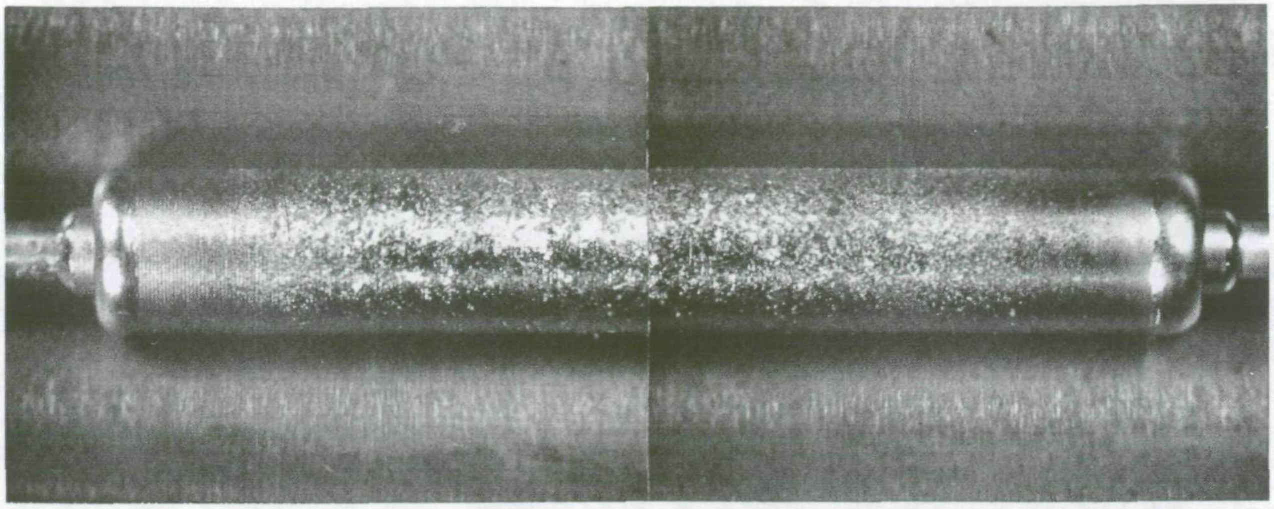


Figure 7. - Fuel pin after irradiation.

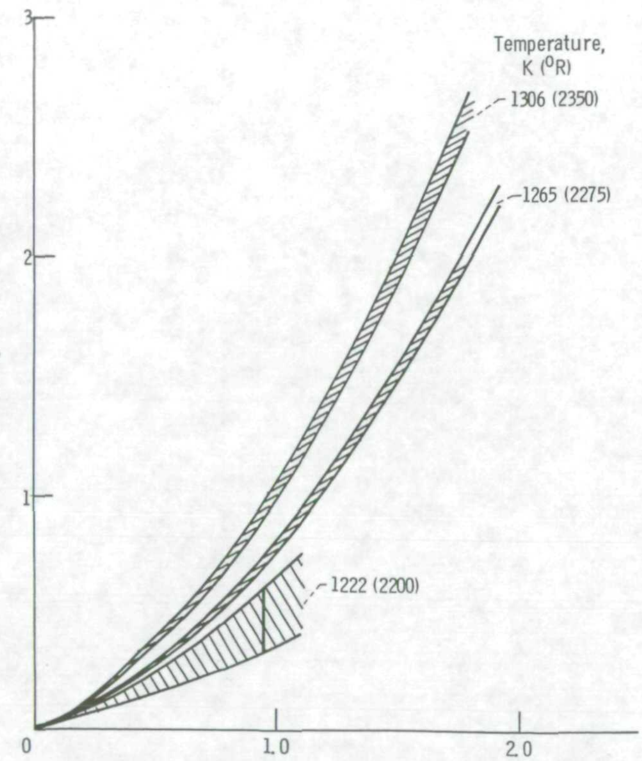


Figure 8. - Percent diametrial growth for unrestrained uranium-nitride fuel pellets as function of burnup.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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