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TESTING OF URANIUM NITRIDE FUEL IN T-111 CLADDING AT 1200 K CLADDING TEMPERATURE

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16. Abstract

Two groups of six fuel pins each were assembled, encapsulated, and irradiated in the Plum Brook Reactor. The fuel pins employed uranium mononitride (UN) in a tantalum alloy (T-111) clad. The first group of fuel pins was irradiated for 1500 hours to a maximum burnup of 0.7-atom-percent uranium. The second group of fuel pins was irradiated for about 3000 hours to a maximum burnup of 1.0-atom-percent uranium. The average clad surface temperature during irradiation of both groups of fuel pins was approximately 1200 K. The postirradiation examination revealed the following: no clad failures or fuel swelling occurred; less than 1 percent of the fission gases escaped from the fuel; and the clad of the first group of fuel pins experienced clad embrittlement whereas the second group, which had modified assembly and fabrication procedures to minimize contamination, had a ductile clad after irradiation.

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SUMMARY

Twelve fuel pins employing uranium mononitride (UN) as the fuel and a tantalum alloy (T-111) as the clad material were assembled in 12 capsules. The first six fuel pins were irradiated in the Plum Brook Reactor for approximately 1500 hours to burnups ranging from 0.4- to 0.7-atom-percent uranium at an average clad surface temperature of about 1200 K (2160° R). Postirradiation examination of these fuel pins revealed that they had not undergone any visible adverse external effects such as swelling, discoloration, corrosion, or rupture. However, further investigation revealed that the T-111 clad had become brittle during irradiation. It was found that vacuum annealing of rings cut from the clad tube at 1589 K (2860° R) for 1 hour restored the ductility of the clad. The clad of one of the irradiated fuel pins was analyzed for nitrogen and found to contain insufficient amounts of nitrogen to cause the embrittlement.

We attempted to resolve this embrittlement problem by irradiating a second group of six fuel pins. The major difference between the two groups was the modification of fabrication and assembly procedures to minimize contamination. The modifications were directed mainly at eliminating contact of dissimilar metals with the T-111 at high temperatures and eliminating all possible sources of water vapor in the capsule.

The second group of fuel pins was irradiated to burnups ranging from 0.5- to 1.0-atom-percent uranium at an average clad surface temperature of 1200 K (2160° R). Postirradiation examination of the second group of fuel pins revealed that they also had undergone no visible adverse external effects such as swelling, discoloration, corrosion, or rupture. Further investigation revealed that the T-111 clad was more ductile than the clad of the first group of fuel pins.

It was therefore concluded that the UN, T-111 combination is a viable system for fuel pins provided extreme care is taken to eliminate sources of contamination during assembly.

INTRODUCTION

As part of NASA's investigation of space power conversion systems, there existed 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 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 irradiation tests related to the reactor are described in reference 3. This report presents a more detailed description of some of the effort covered in reference 3.

Irradiation experiments were undertaken at Lewis in order to evaluate the inpile performance of the fuel elements. This report describes one set of experiments that were run to obtain preliminary information about the UN/T-111 fuel clad system. 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 for a space power reactor. The fuel pins were irradiated in the Plum Brook Reactor at burnup rates 6 to 10 times those of the reference space power reactor. 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 gross effects on the fuel and the clad. Clad swelling, fuel-clad interactions, and clad embrittlement were determined. The details and results of the irradiation are discussed in this report.

FUEL-PIN AND CAPSULE DESCRIPTION AND ASSEMBLY PROCEDURES

Fuel-Pin Description

The first group of fuel pins are referred to as capsule assembly 321. A sketch of a typical fuel pin of this group is shown in figure 1(a). A typical fuel pin contained four UN pellets, each pellet having a length of 0.635 centimeter (0.250 in.), an outside diameter of 0.381 centimeter (0.150 in.), and an inside diameter of 0.119 centimeter (0.047 in.). The pellets were contained in a T-111 clad tube with an outside diameter of 0.460 centimeter (0.181 in.) and an inside diameter of 0.389 centimeter (0.153 in.). A 0.0025-centimeter- (0.001-in.-) thick tungsten (W) foil was wrapped around the pellets. This foil kept the UN from directly contacting the T-111, thus preventing any reaction between the UN and the T-111. A tungsten spacer was placed at each end of the fueled section. These spacers maintained the fuel position and were designed to collapse if the length of the fueled section increased because of swelling. A stainless-steel (type 304) tube was brazed to one end cap of the fuel pin. A stainless-steel (type 304) sheath of a grounded junction Chromel-Alumel (type K) thermocouple was brazed to the other end cap of the fuel pin. The braze used had a nominal composition in weight percent of 19 chromium (Cr), 10 silicon (Si), and 71 nickel (Ni). Both end caps were electron beam welded to the clad tube.

The second group of fuel pins are referred to as capsule assembly 322. A sketch of a typical fuel pin of this group is shown in figure 1(b). These fuel pins are similar to those used in capsule assembly 321. One difference, however, is that fuel pins of capsule assembly 322 employed a liner made of two pieces of tungsten 0.0025 centimeter (0.001 in.) thick. The butt edges of the outer wrap were positioned 180° from the butt edges of the inner wrap. This eliminated any areas where the UN was directly exposed to the T-111 as it was in capsule assembly 321. The extra thickness of liner was accommodated by increasing the inside diameter of the clad by 0.005 centimeter (0.002 in.) to 0.394 cm (0.155 in.). The support tube and thermocouple sheath of the fuel pins of capsule assembly 322 were T-111. This made it possible to election beam weld them to the fuel-pin end cap, and eliminated nonrefractory materials in contact with T-111. The thermocouples used in the fuel pins of capsule assembly 322 were grounded-junction W - 26-percent rhenium (Re)/W - 5-percent Re. Three of the fuel pins of this group contained solid UN fuel pellets, and three contained fuel pellets cored to the same inside diameter as the pellets in capsule-assembly-321 fuel pins.

Capsule Description

A sketch of a typical capsule used in these tests is shown in figure 2. The capsule is a static gas type which employs a helium conduction gap to transfer the heat generated in the fuel pin. In order 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, in order to irradiate the small fuel pins at high burnup rates, a very small gas conduction gap was necessary. A sleeve was inserted into the outer capsule in order to provide this small gap. The sleeve was fabricated from aluminum because its low density resulted 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, as shown in figure 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. This type of capsule was used for both groups of fuel-pin tests.

Six capsules were assembled to form a capsule assembly, as shown in figure 3(a). The capsule assembly was then inserted into a hydraulic capsule test facility described in reference 4. The capsule was positioned against the stop shown in figure 3(b), which houses several insulated rings. Welded to each ring is a lead which travels from the ring to 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 the 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 chemical composition of the T-111 rod used to machine the clad and end caps is given in table II. All T-111 parts for the fuel pin were cleaned before assembly by using cleaning procedures outlined in reference 7. The tungsten liners and spacers were cleaned by immersing in acetone, rinsing in alcohol, and air drying. After undergoing the specified cleaning procedures, the parts were stored in clean glass containers. All tools used to assemble the fuel pins were cleaned by immersion in acetone followed by an alcohol rinse.

Both groups of fuel pins were assembled by using the same procedures. Although the fuel pins were not assembled in a controlled environment (e.g., glove box), they were assembled by using clean-room techniques (e.g., using gloves, clean tools, and clean work surfaces). After assembly the end caps were electron beam welded to the clad tube. The fuel pins were then helium leak checked to ensure weld integrity. All fuel pins were considered to have sufficient integrity when the leak rate was less than 0.13×10^{-8} cm^3/sec (10^{-8} ft^3/hr) of helium at standard temperature and pressure. The thermocouple and support tube were then either electron beam welded or brazed to the fuel pin. The fuel pins were then stored in clean glass containers until assembly into the capsules. A summary of the pertinent data about the fuel pins is given in table III.

Capsule Assembly Procedures

The capsule parts (except for the alumina insulators and the fuel pin) 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, as shown in figure 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 figure 2 were made. For the first group of fuel pins, making these welds sealed the capsules because the fill tube had been sealed beforehand. For the second group of fuel pins, making welds 1 and 2 did not seal the capsules because the helium fill tube was not sealed on these capsules. After the welds were made on the second group of capsules, they were baked out for 1 hour at 473 K (851° R) in a vacuum chamber and sealed off to the atmosphere by welding the helium fill tube shut in a vacuum. After sealing, the capsules were leak checked by placing them in a container and pressurizing with helium to 34.4 N/cm^2 (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 helium by cutting the fill tubes and then sealed by gas-tungsten-arc welding the fill tubes. The capsules were then helium leak checked. The first group of capsules were filled in a glove box where the moisture and oxygen content of the helium was not monitored. The second group of capsules were filled in a glove box where the moisture and oxygen content was monitored and found to be 1.4 ppm H_2O and 2.3 ppm O_2.

The capsules were then assembled in a capsule holder, and the thermocouple positive-leg lead wires were welded to the spring support plate.

IRRADIATION

Irradiation Conditions

A summary of the irradiation conditions is given in table IV. The thermocouple temperatures given in the table, unless otherwise noted, are time-averaged temperatures, averaged over the duration of the test. The thermocouple temperatures of the first group of fuel pins, averaged over the 1498 hours of irradiation, ranged from 1031 K (1856° R) to 1110 K (1998° R). The time-averaged temperatures of the second group of fuel pins ranged from 1026 K (1846° R) to 1157 K (2082° R). Three of the thermocouples of this group of fuel pins did not operate because they were damaged during capsule assembly. 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 capsules were designed so that all fuel pins would operate at the same temperature. The variation observed in the thermocouple temperature is attributed primarily to uncertainties in the local neutron flux data.

Plots of the temperature readouts of the thermocouples for the fuel pins of capsule assemblies 321 and 322 are shown in figures 4 and 5, respectively. In both cases the fuel pins experienced thermal cycling during the irradiation. Most of the thermal cycles were caused by reactor refueling. The temperature readouts of the thermocouples were relatively steady throughout the irradiation. The long-term tendency for the readouts to diverge (comparing thermocouple readings at the start of irradiation to those at the end) is probably a result of different rates of burnup experienced by the fuel pins in a given capsule assembly. The daily fluctuations are probably caused by changes in neutron flux 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 this fuel pin and capsule configuration and 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 6.

POSTIRRADIATION EXAMINATION

Visual Examination

Visual examination of all the irradiated fuel pins indicated no problems such as swelling, corrosion, discoloration, or cracking. Figure 7(a) shows the thermocouple end of the fuel pin after it was irradiated. The dulled areas at the end of the fuel pin are braze material that resulted from the brazing of the thermocouple sheath to the fuel pin. Diametral measurements indicated that the fuel pins had not experienced any swelling.

The fuel pins were then subjected to an examination to determine the extent of fission gas release from the fuel. This was done by placing the fuel pins in a sealed volume container, puncturing the clad tube with a sharp punch-type device, and then recording the pressure rise in the container. However, in the first group of capsules, the clad which was initially ductile underwent a brittle fracture upon impact from the sharp punch. Figure 7(b) shows one end cap of a fuel pin of the first group after such an impact.

Clad Ductility Tests

The center portion of the fuel-pin clad of pin 321D was cut into three rings, each about 0.64 centimeter (0.25 in.) long, with a silicon carbide cutting wheel which used a water spray. The first ring is shown in figure 7(c). The ring was placed in a vise and compressed to determine qualitatively its degree of embrittlement. As soon as the ring compression was started, the ring shattered into the pieces shown in figure 7(d), indicating a very brittle clad.

The two other rings that were cut from the clad of fuel pin 321D were vacuum annealed: one at 1921 K (3460° R) for 1 hour and the other at 1589 K (2860° R) for 1 hour. Each of these rings was compressed in the vise exactly as the first piece. Both of the annealed rings were found to be very ductile after the vacuum anneal. Figure 8 shows the progress of compression on the ring which was annealed at 1589 K (2860° R). The clad ring showed no signs of cracking even when completely compressed.

Fuel pin 321C had its fuel pellets and end caps removed and the resulting clad tube was compressed. The compression caused the clad tube to fracture much like the ring from the clad of fuel pin 321D. This verified that the clad from this fuel pin was in a similar condition of embrittlement as the clad of fuel pin 321D. The pieces resulting from the brittle fracture were saved for a Kjeldahl analysis described in the following section.

Two rings were cut from the clad tube of fuel pin 322B in exactly the same way as was done for fuel pin 321D. The first ring was placed in a vise and compressed. This ring could be compressed to about one-half its diameter before any cracking was observed. Further compression produced cracks in the ring. The progress of this ring compression test is shown in figure 9. This compression indicated that the clad of fuel pin 322B was significantly more ductile than the clad of fuel pin 321D. The second ring from 322B was vacuum annealed at 1311 K (2360° R) for 1 hour. The ring was compressed in a vise; the results of this compression indicated that the ductility of the ring was fully restored.

These clad ductility tests indicated that the most likely cause for embrittlement of the T-111 clad was hydrogen. Hydrogen is highly suspect because vacuum annealing, at the lower temperatures used, will drive off only hydrogen from the T-111.

Kjeldahl Analysis

In order to verify the belief that any nitrogen contamination of the fuel pins was not significant enough to cause embrittlement, the clad tube and one end cap of fuel pin 321C were subjected to a Kjeldahl analysis. The Kjeldahl analysis is described in reference 8. The analysis indicated that the nitrogen contamination in the T-111 was 100.6 ppm (by weight) and that in one of the end caps it was 67.1 ppm (by weight), compared to about 25 ppm (by weight) before irradiation. It is believed that these levels are not high enough to cause embrittlement of the T-111 clad tube.

Photomicrographs

In accordance with usual hot laboratory procedure, samples of the T-111 clad were polished and etched. The photomicrographs did not reveal any unusual formations in the clad material. A typical photomicrograph is shown in figure 10.

Postirradiation Data

Some information obtained in the postirradiation examination is given in table V. The data given in this table are used in some of the discussion which follows.

Discussion of the Clad Embrittlement Problem

The postirradiation examination data obtained and discussed herein do not conclusively indicate the reason for the cladding embrittlement. However, the fact that the photomicrographs did not reveal any unusual formations seems to indicate that the embrittlement was most likely caused by nitrogen, oxygen, or hydrogen. This also indicates that the braze material on the first group of pins was not the reason for their embrittlement. Oxygen and nitrogen were virtually eliminated as the source of embrittlement. The reason for this is that the ductility of the T-111 was restored with vacuum anneals at temperatures too low to drive out the oxygen or nitrogen from the T-111. The results of the Kjeldahl analysis verified that nitrogen was not the cause for embrittlement of the T-111. Thus, we believe that hydrogen caused the embrittlement. This is confirmed to some degree when comparing the results of the ring compression tests for the first and second group of fuel pins. The clad of the second group of fuel pins was more ductile. These fuel pins were assembled in a way to minimize the amount of contamination by hydrogen and oxygen by eliminating as much water vapor from the capsule as possible.

It is important to note, however, that the method of preparation of the rings (cutting, sanding the cut edge, etc.) described herein may produce some degree of embrittlement.

Burnup

Three methods were used to determine the average burnup of the fuel pins. A summary of the burnup determinations is given in table VI. In one method the burnup was calculated by finding the burnup rate in the fuel pin necessary to satisfy the heat-transfer requirements.

The burnup was also determined by using the average neutron flux measured with cobalt alloy and tungsten wires to calculate the average burnup in the fuel pins. The average flux was calculated by taking the average flux indication of two wires (see table V), one located at each end of the fuel-pin supports. Finally, the average burnup was again determined by using the mass spectrometer to find the $^{235}U/^{236}U$ ratio before and after the irradiation. The burnups resulting from these three methods varied from ± 10 to ± 25 percent about the average of all methods for capsule assembly 321. The same variance was from ± 12 to ± 19 percent for capsule assembly 322. Generally speaking, the mass spectrometer determination of the burnup gave a significantly lower number for the average burnup than did the burnup calculated by using the flux calculated from heat transfer or the flux obtained from the flux wires. The average burnups as determined by the flux wires and heat-transfer requirements were in good agreement.

Fission Gas Release

Very small amounts of fission gas were released from the UN fuel in the fuel pins irradiated. The amount released was determined in two ways. One method consisted of puncturing the fuel pin and then determining the pressure rise in a fixed volume because of gas escape from the interior of the fuel pin. The second method consisted of taking a sample of the gas released from the fuel pin after it was punctured and determining the disintegration rates of xenon-133 (Xe^{133}) and krypton-88 (Kr^{88}). The results of both methods are given in table V. In the first method the range of the pressure transducers was not low enough to detect any rise in pressure caused by fission gas release. The pressure transducers were chosen to measure as little as approximately 1-percent fission gas release. Therefore, we can say that this method indicated the fission gas release from the fuel was less than 1 percent. A few of the gas samples taken from the fuel pins of capsule assembly 321 had detectable levels of Xe^{133} and Kr^{88}. The gas samples taken from fuel pins of capsule assembly 322 also had detectable levels of Xe^{133} and Kr^{88}. A simple calculation was made to estimate what fraction of fission gas was released from the fuel. It was found that only about 0.05 percent of the gas produced by fission was released from the fuel. The surface-volume ratio of the fuel in these fuel pins was 9.19 cm^{-1} (23.32 $in.^{-1}$).

CONCLUSIONS

The following conclusions can be drawn from tests of uranium mononitride fuel in T-111 cladding at 1200 K cladding temperature:

1. Fuel pins employing the design described in this report can operate for 3000 hours, to a burnup of 1-atom-percent uranium (equivalent to 18 000 hours of burnup in the reference space power reactor), at 1200 K with no evidence of fuel-pin swelling or any incompatibility between the materials of the fuel pins.

2. UN fuel can operate at about 1200 K, with fission power densities of approximately 1 kW/cm^3, to burnups of at least 1-atom-percent uranium with release of only about 0.05 percent of the fission gas produced. The surface-volume ratio of the fuel was 9.19 cm^{-1} (22.32 $in.^{-1}$).

3. The T-111 clad maintains some degree of ductility after the irradiation. However, such ductility depends on the assembly and fabrication procedures to minimize contamination and on use of a tungsten liner to prevent contact between UN and T-111. This conclusion assumes the T-111 material has a low impurity level at the outset of the experiment since original impurities can affect the ductility of the clad.

4. Based on the Kjeldahl analysis for nitrogen and annealing of samples, which completely restored ductility, the loss in ductility of the T-111 clad appears to be caused by hydrogen contamination. The levels of nitrogen in the T-111 clad during irradiation are not believed to be sufficient to cause embrittlement. There is a possibility also that the cutting techniques (water-cooled silicon carbide wheel) may have contributed to the embrittlement.

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National Aeronautics and Space Administration,
Cleveland, Ohio, November 17, 1972,
503-25.

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TABLE I. - CHEMICAL ANALYSIS OF UN 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. - CHEMICAL ANALYSIS OF T-111 CLAD AND END CAP MATERIAL[a]

(a) Composition

Element	Composition by weight percent	
	Top	Bottom
W	8.4	8.2
Hf	2.1	2.1
Ta	Balance	Balance

(b) Impurities

Element	Composition by weight, ppm	
	Top	Bottom
Al	<10	<10
C	45	40
Cb	640	640
Co	<5	<5
Cu	<20	<20
Fe	40	40
H	2.5	6.1
Mo	15	15
N	30	20
Ni	<10	<10
O	90	100
Si	<20	<20
Ti	<20	<20
V	<10	<10

[a]T-111 tantalum alloy rod 0.803 cm diam by 67.945 cm long (0.316 in. by 26.75 in.); heat 650028-T-111. Brinell hardness number: range, 207 to 217; average, 215. ASTM grain size: 7.5 to 8.5.

TABLE III. - FUEL-PIN FABRICATION SUMMARY

[Cladding: material, T-111; outside diameter, 0.460 cm (0.181 in.). Fuel: material, UN; outside diameter, 0.381 cm (0.150 in.); length, 2.54 cm (1.00 in.); enrichment, 10 percent.]

Capsule	Cladding wall thickness		Thickness of tungsten liner		Fuel			
					Inside diameter		Percent theoretical density	Weight of UN, g
	cm	in.	cm	in.	cm	in.		
321A	0.036	0.014	0.0025	0.001	0.120	0.047	97.6	3.61
321B	0.036	0.014	0.0025	0.001	0.120	0.047	96.4	3.58
321C	0.036	0.014	0.0025	0.001	0.120	0.047	96.9	3.58
321D	0.036	0.014	0.0025	0.001	0.120	0.047	94.2	3.51
321E	0.036	0.014	0.0025	0.001	0.120	0.047	95.0	3.52
321F	0.036	0.014	0.0025	0.001	0.120	0.047	95.3	3.50
322A	0.033	0.013	0.0050	0.002	0.120	0.047	95.2	3.53
322B	0.033	0.013	0.0050	0.002	0	0	95.0	3.90
322C	0.033	0.013	0.0050	0.002	0.120	0.047	94.3	3.50
322D	0.033	0.013	0.0050	0.002	0	0	94.9	3.87
322E	0.033	0.013	0.0050	0.002	0.120	0.047	95.9	3.52
322F	0.033	0.013	0.0050	0.002	0	0	95.0	3.87
Control	0.033	0.013	0.0050	0.002	0	0	95.0	3.88

TABLE IV. - CAPSULE IRRADIATION CONDITIONS

Capsule	Time at temperature, hr	Temperature, K			Power density, kW/cm^3
		Thermocouple	Average clad	Average fuel	
321A	1498	1031	1119	1131	0.614
321B	1498	1100	1202	1224	1.002
321C	1498	1044	1125	1154	.923
321D	1498	1102	1196	1213	.803
321E	1498	1110	1220	1236	.675
321F	1498	1054	1150	1163	.581
322A	1369	[a]1160	[a]1284	[a]1298	.740
322B	2278	1133	1230	1251	.956
322C	2888	1026	1112	1143	.980
322D	2888	1157	1247	1263	.770
322E	2888	[a]1160	[a]1258	[a]1272	.580
322F	1160	[a]1160	[a]1258	[a]1272	.598

[a]Calculated values.

TABLE V. - CAPSULE FLUENCES, GAS SAMPLE, AND BURNUP DETERMINATION

Capsule	Fluences from flux wires,[a] nvt				Fuel-pin gas sample			Burnup, percent at 2σ			
	Near core		Away from core		Pressure[b]	Xe^{133}[c]	Kr^{88}	Pellet 1	Pellet 2	Pellet 3	Pellet 4
	Co	W	Co	W							
321B	5.4×10^{20}	--------	1.1×10^{20}	1.0×10^{20}	(d)	1.8×10^{10}	(e)	0.715±0.026	0.681+0.026	0.631±0.05	0.594±0.03
321D	2.9	2.7×10^{20}	.98	.98	(d)	1.2×10^{9}	(e)	.682±0.02	(f)	(f)	(f)
321A	2.4	2.6	.79	.83	(d)	(d)	(d)	.463±0.035	(f)	(f)	(f)
321C	3.7	4.1	1.4	1.4	(d)	(d)	(d)	.758±0.035	(f)	(f)	(f)
322A	2.5	2.7	.89	.9	(d)	[g]1×10^{9}	(d)	.560±0.026	(f)	(f)	(f)
322B	5.5	6.3	2.2	2.2	(d)	[h]2.8×10^{6}	(d)	1.156±0.033	(f)	(f)	(f)

[a]±20 Percent at 2σ level. These are final fluences based on Co^{60} and W^{185} activities.

[b]0- to 5-psia transducer used for measurement. Minimum sensitivity of transmitter, ±0.02 psia.

[c]Corrected to time capsule is removed from reactor. Numbers may be in error because of background contamination on sample vial. Counting uncertainty is unknown.

[d]Not detectable.

[e]Detectable only by counting the gas chromatograph separation column. Because there is no established geometry for the separation column, no quantative number can be applied.

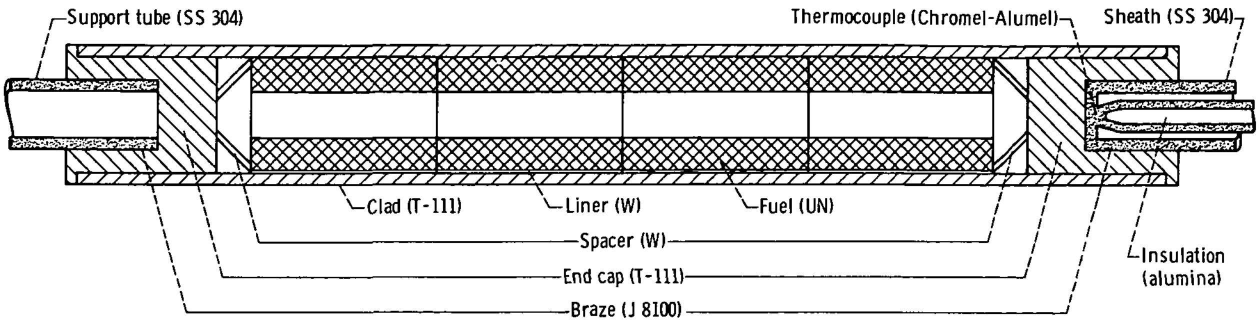
[f]Not analyzed.

[g]Not detectable. Based on direct counting of a 4-milliliter plastic vial (representative sample). Estimated uncertainty, ±30 percent at the 2σ level.

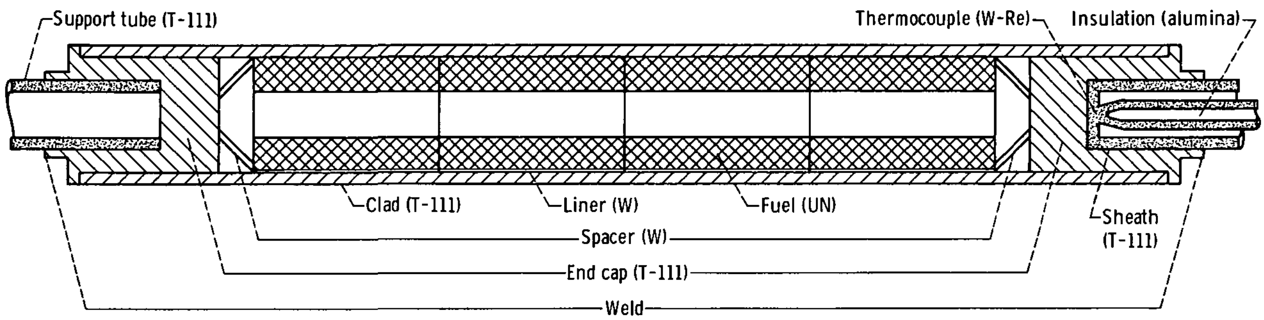
[h]Not detectable. Detected after separation of a 150-milliliter sample on a gas chromatograph column. Estimated uncertainty, ±50 percent at the 2σ level. Largest uncertainties are in the separation and sampling efficiency.

TABLE VI. - SUMMARY OF BURNUP RESULTS

Capsule	Burnup, percent			
	As determined by heat-transfer requirement (calculated)	As determined by flux wires		As determined by mass spectrometer
		Cobalt	Tungsten	
321A	0.708	0.57±0.11	0.60±0.12	0.425
321B	.925	1.15±0.23	---------	.655
321C	.925	.91±0.18	.97±0.19	.695
321D	.708	.69±0.14	.66±0.13	.626
321E	.560	---------	---------	-----
321F	.560	---------	---------	-----
322A	.539	.60±0.12	.64±0.13	.514
322B	1.192	1.19±0.24	1.51±0.30	1.06
322C	1.498	---------	---------	-----
322D	1.162	---------	---------	-----
322E	.885	---------	---------	-----
322F	.890	---------	---------	-----



(a) Capsule assembly 321.



(b) Capsule assembly 322.

Figure 1. - Fuel pins.

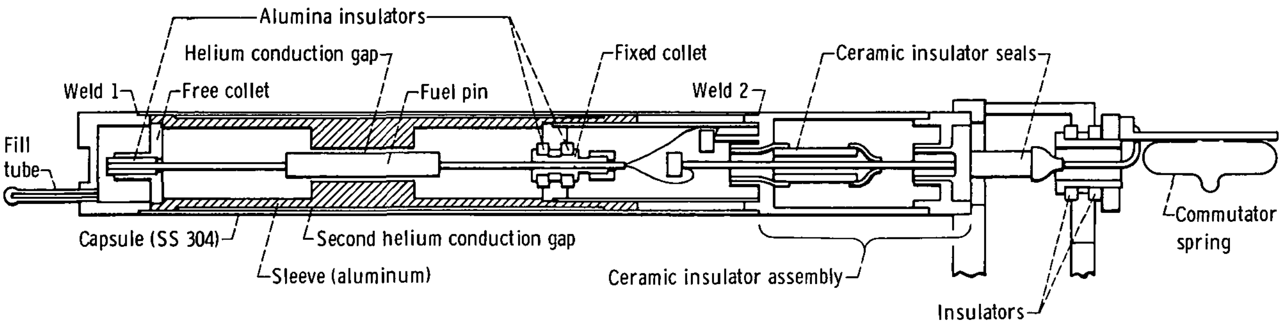
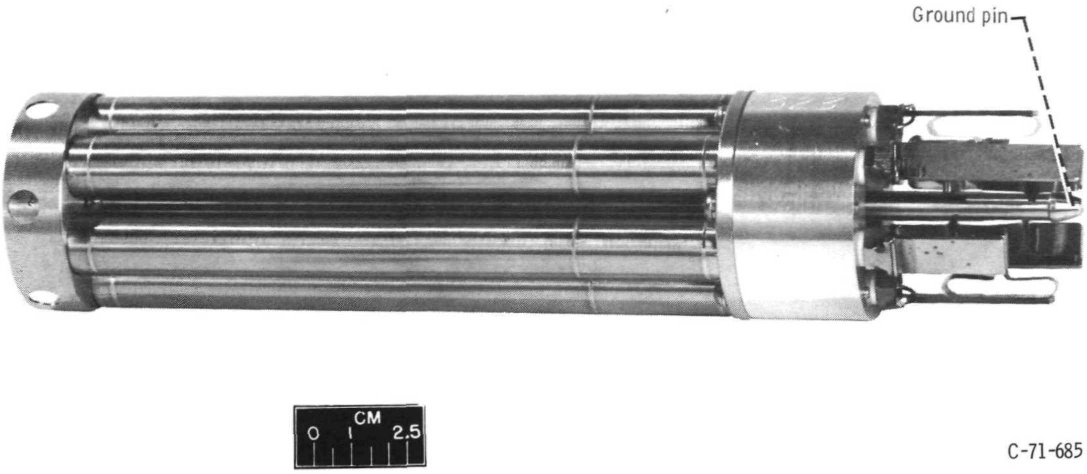
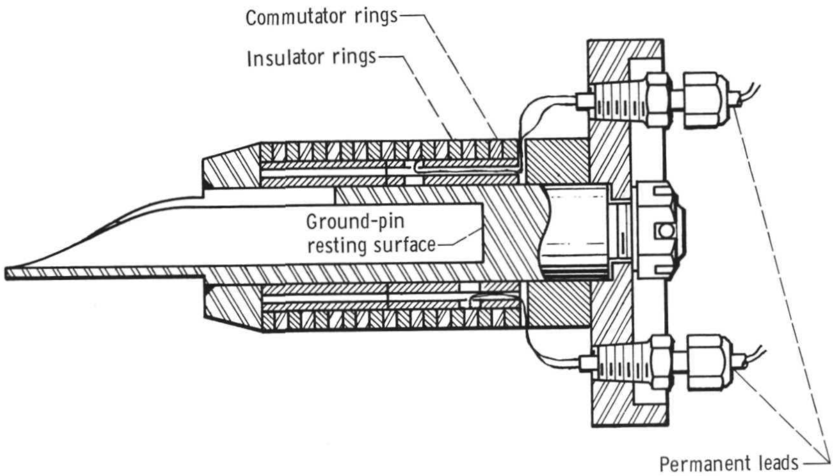


Figure 2. - UN fuel-pin irradiation capsule.



(a) Capsule assembly



(b) Facility stop.

Figure 3. - Capsule assembly and facility stop.

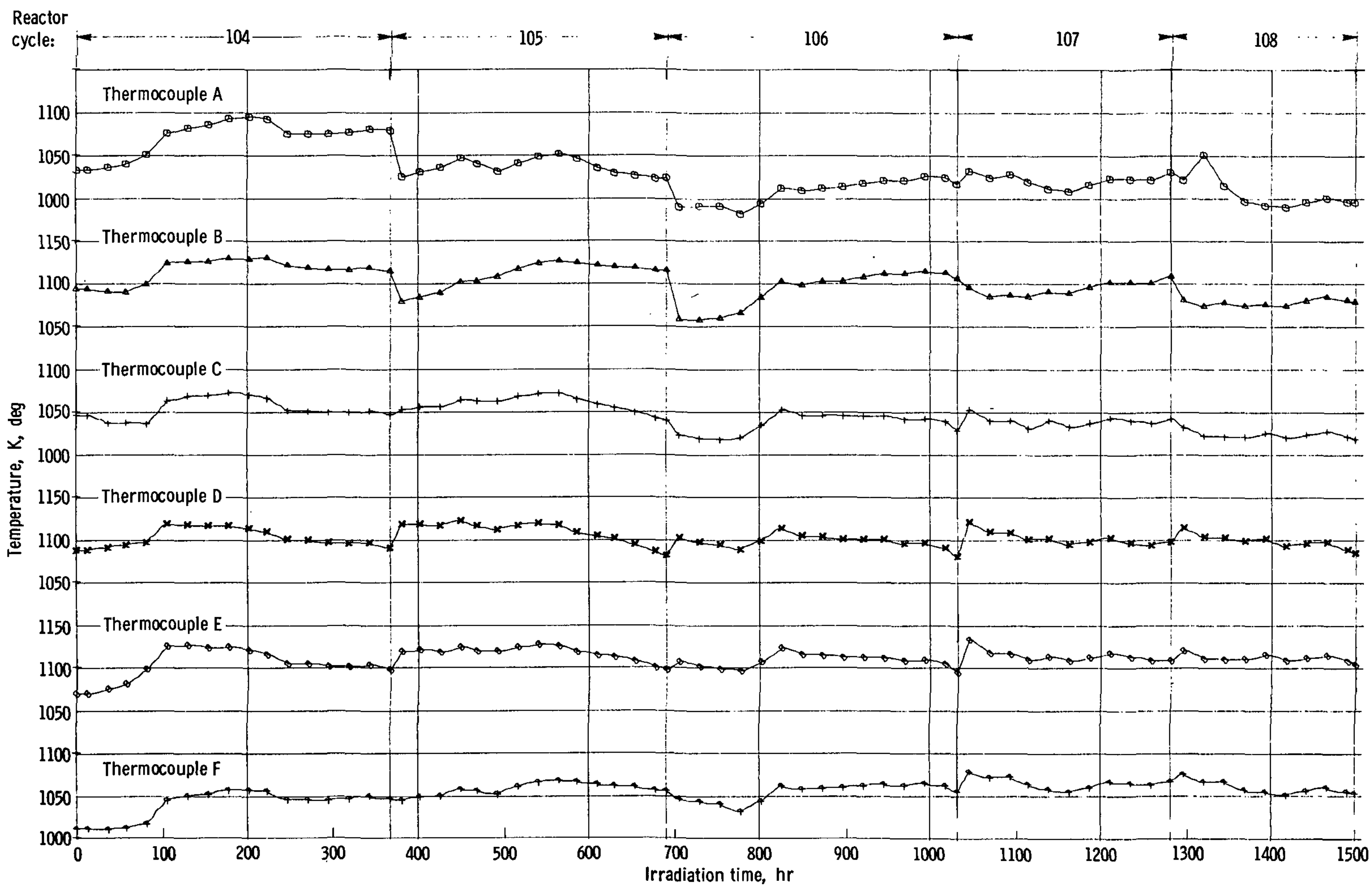


Figure 4. - Daily averaged thermocouple readings for capsule assembly 321.

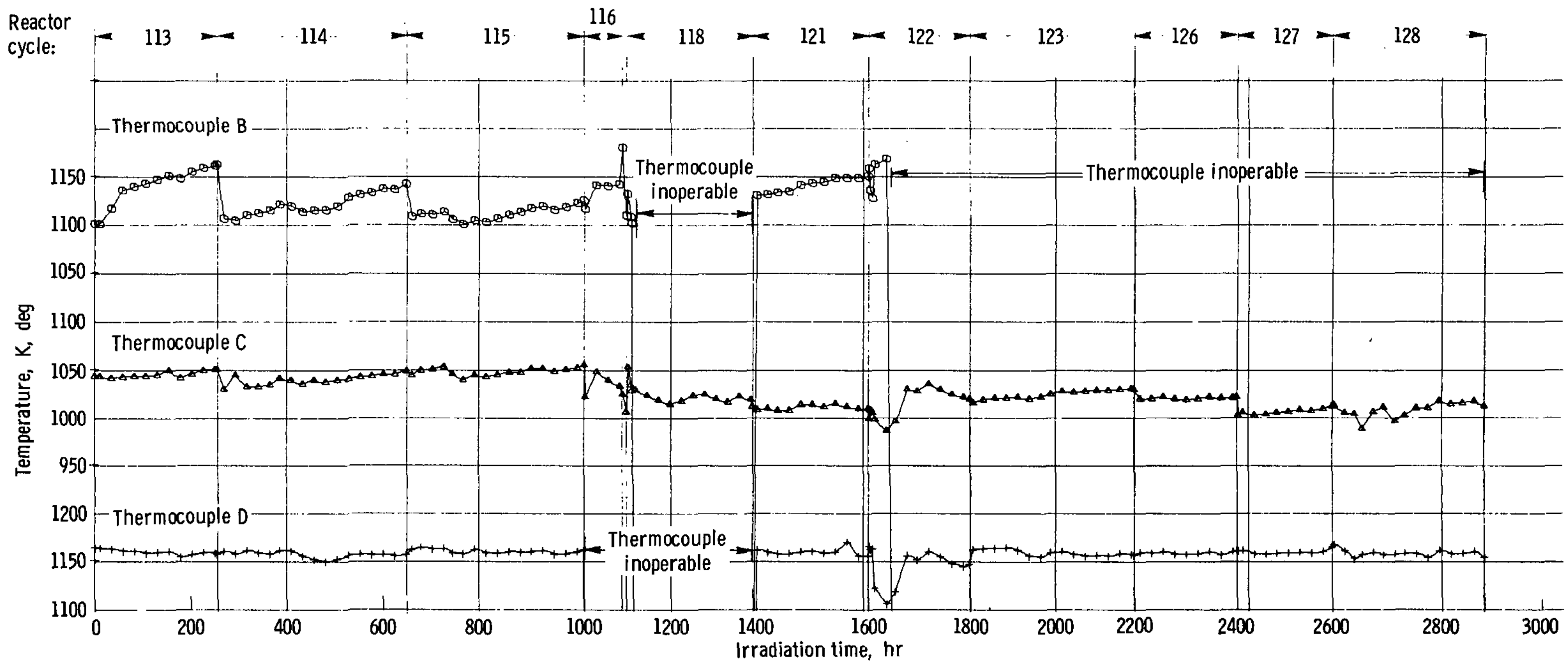


Figure 5. - Daily averaged thermocouple readings for capsule assembly 322.

Fuel material	UN
Fuel weight, g	3.58818
Clad material	T-111
Capsule inside diameter, cm (in.)	0.536 (0.211)
Perturbation factor	0.7200
Fuel-pin outside diameter, cm (in.)	0.460 (0.1810)
Centerline flux, neutrons/cm^2/sec	0.3155x10^{14}
Thermocouple temperature (node 126), K (^oR)	1106 (1990)
Maximum capsule surface temperature (node 61), K (^oR)	367 (660)
Average clad surface temperature, K (^oR)	1203 (2164)
Maximum clad surface temperature, K (^oR)	1248 (2246)
Fuel-pin fission heating, W (Btu/hr)	264.5 (902.5)
Capsule gamma heating, W (Btu/hr)	200.3 (683.7)
Average gamma heating rate, W/g	0.95

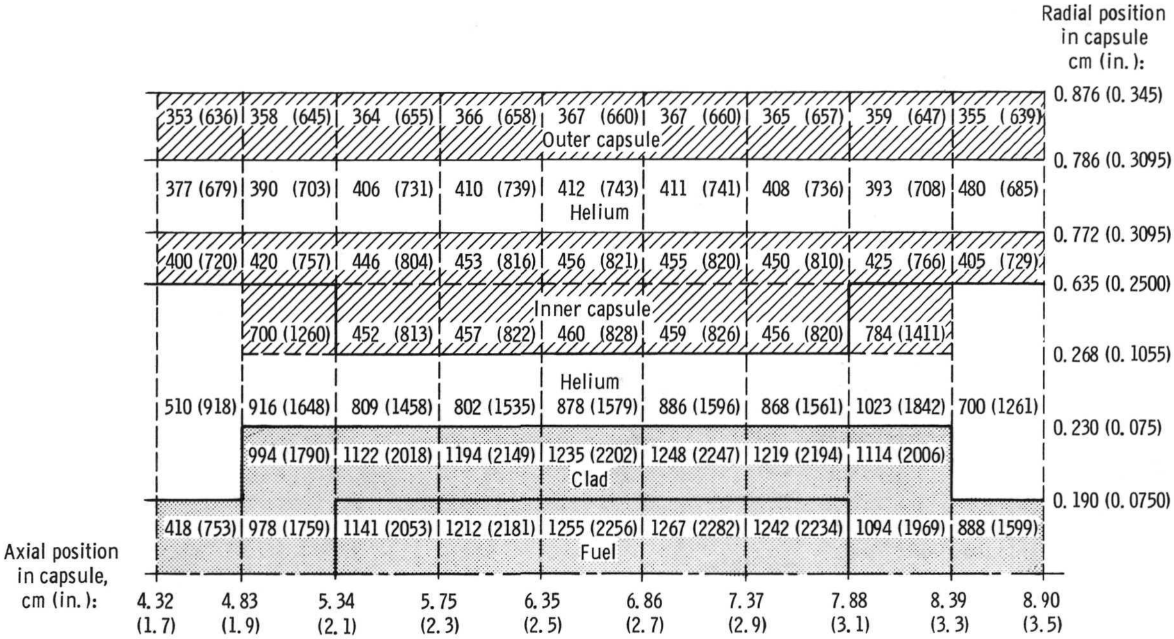
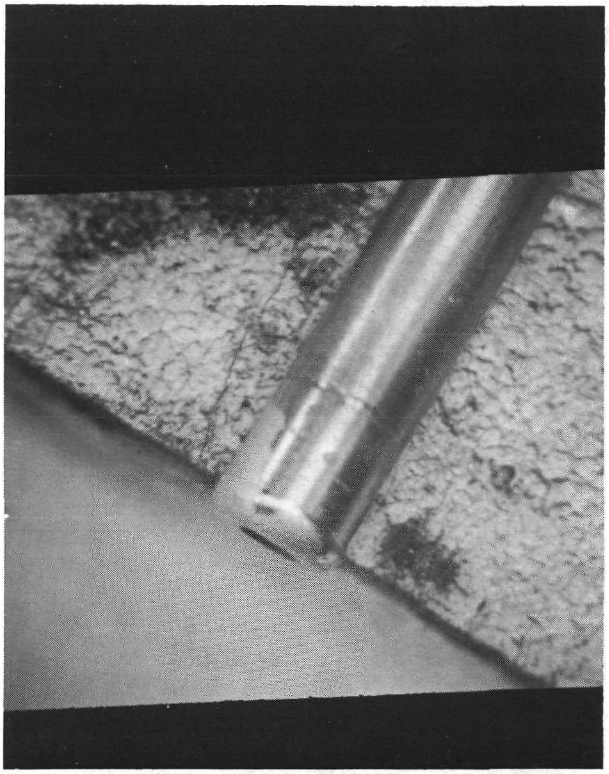
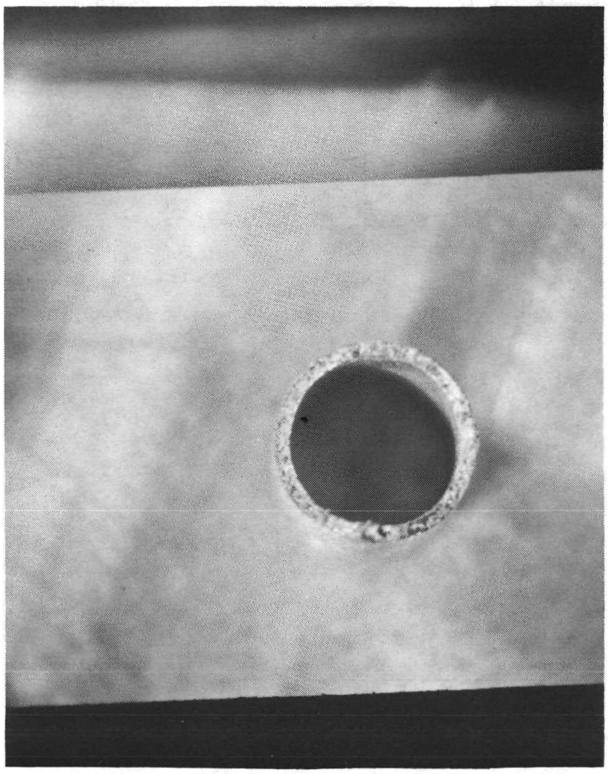


Figure 6. - Heat-transfer results for a typical capsule and fuel pin. Temperatures at various locations are given by numbers on sketch in K (^oR).

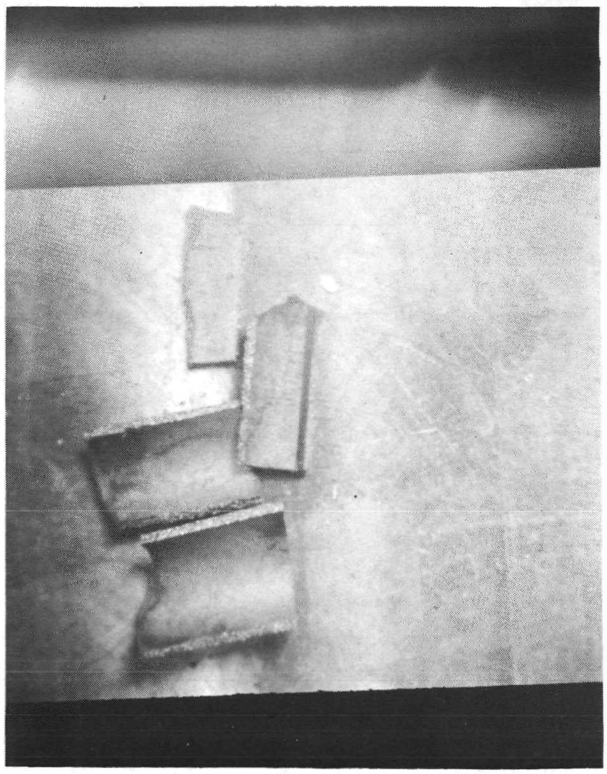


(a) Fuel-pin appearance.

(b) End cap of fuel pin after point impact.

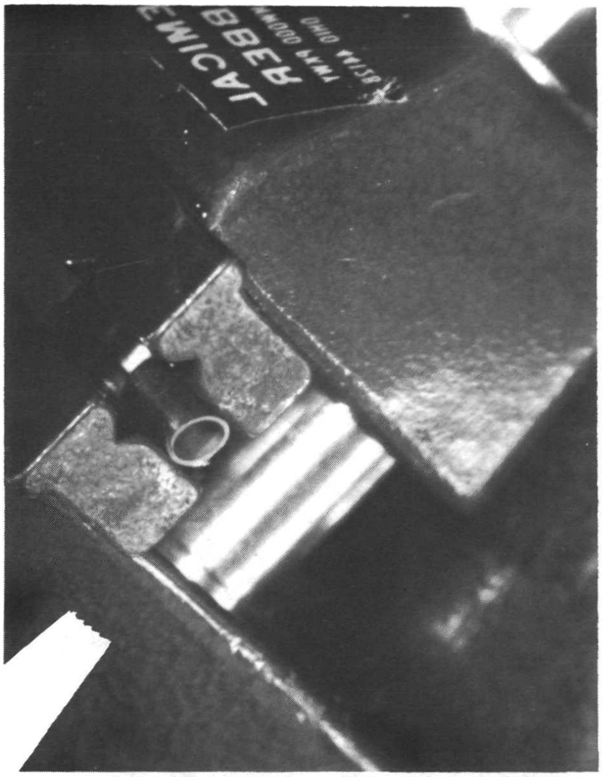


(c) Fuel-pin ring before compression test.

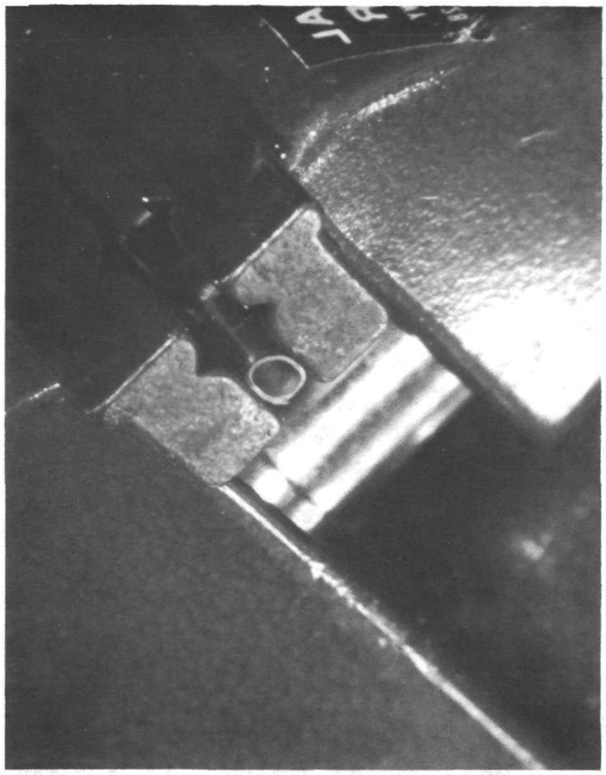


(d) Fuel-pin ring after compression test.

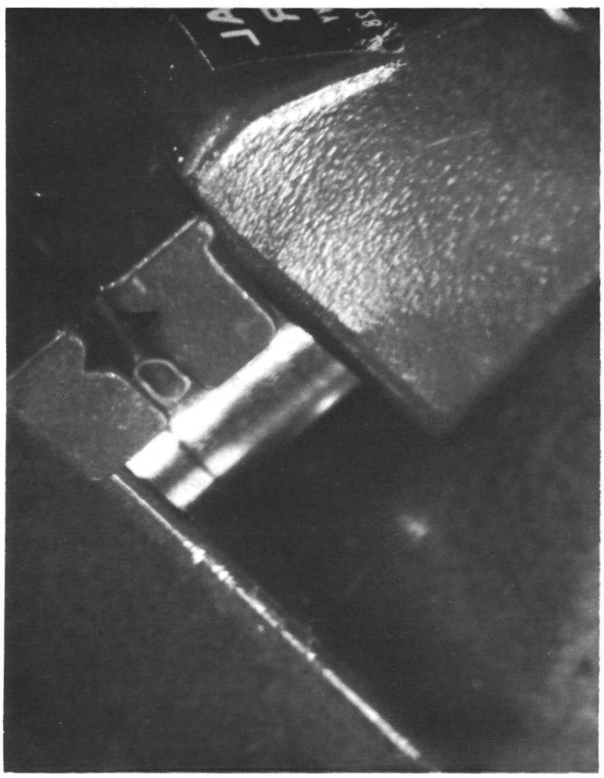
Figure 7. - Postirradiation examination of fuel pin 321D.



(a)



(b)



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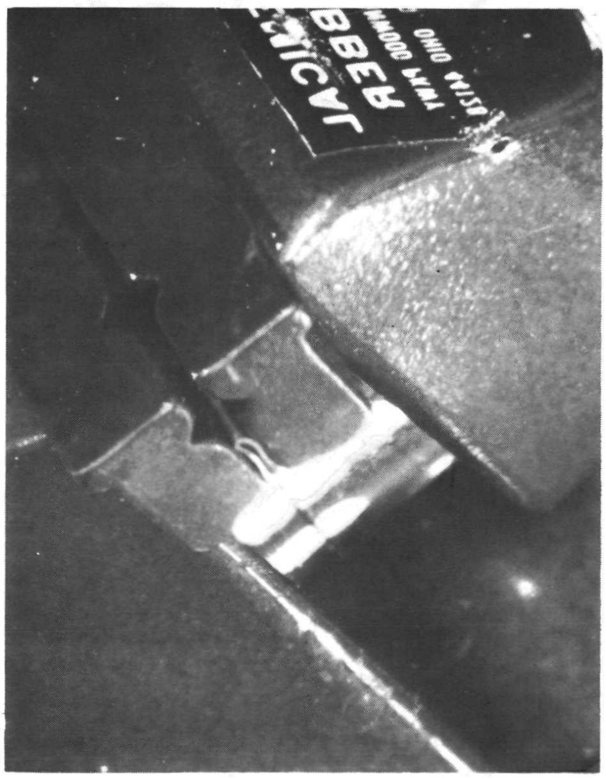
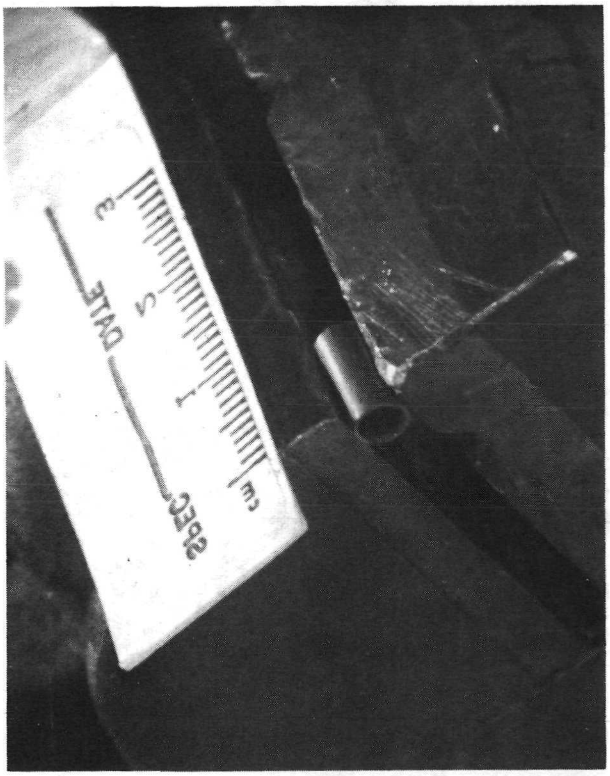
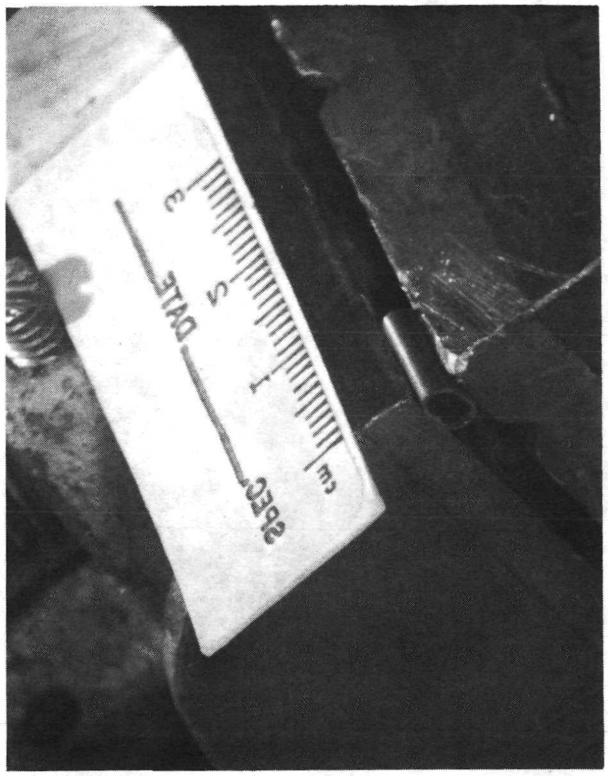


(d)

Figure 8. - Progression of compression test on ring from capsule 321D after it had been annealed for 1 hour at 1589 K (2860° R).



(a)



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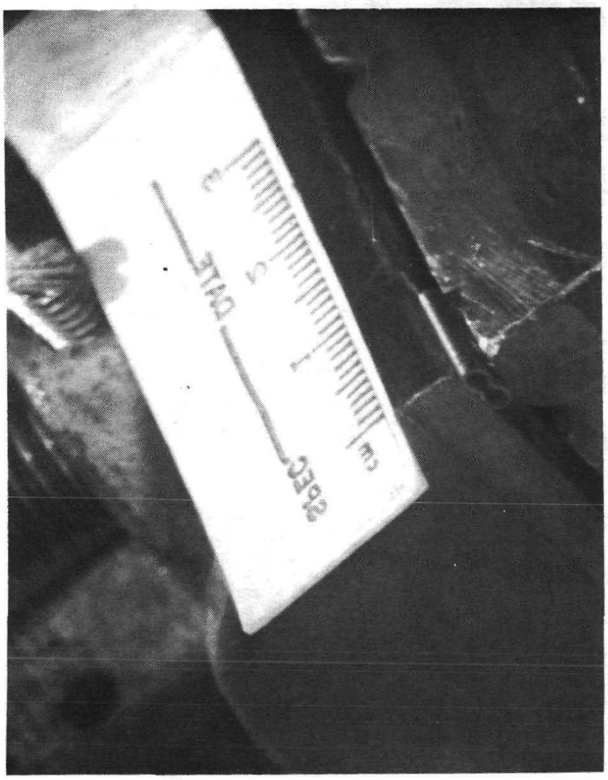
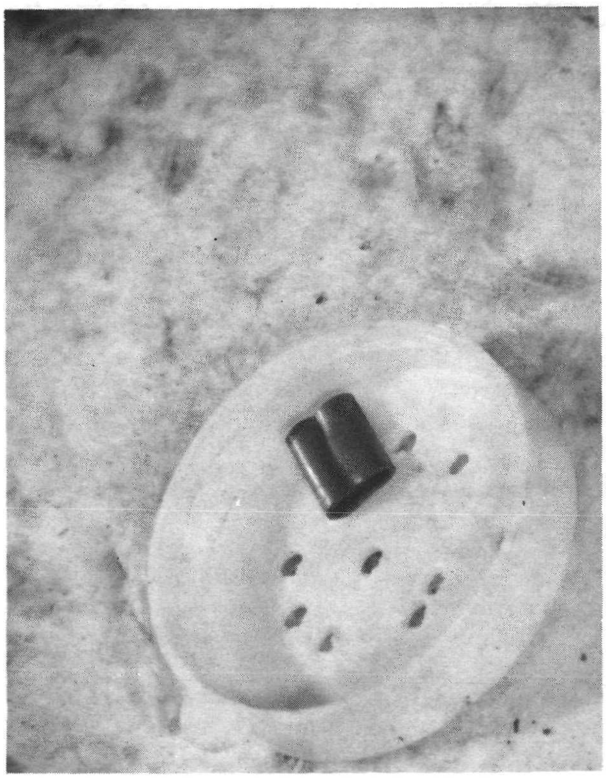


(c)



(d)

Figure 9. - Progression of compression test of ring from fuel pin 322B.

Figure 10. - Photomicrograph of a section of T-111 clad (fuel pin 321B at X250).

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