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AEC FUEL CYCLE PROGRAM
DESIGN AND FABRICATION OF SPECIAL ASSEMBLY 9-L

IRRADIATION PERFORMANCE TEST OF UO_2-CERMET FUEL

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SUMMARY

A UO_2-Mo cermet fuel assembly was fabricated for long-term irradiation performance testing in the Vallecitos Boiling water Reactor. The design and fabrication histories of this assembly are described and pre-irradiation data on each individual rod are presented.

Molybdenum was added to improve the bulk thermal conductivity of the fuel. so that fuel temperatures would remain comparatively low during high-power level operation of the fuel element. The molybdenum was incorporated into the compacts either as fibers or as a thin coating on individual UO_2 particles. Fuel pellets were produced from these materials by vacuum hot pressing. Pellets having the fibers contained 20 vol % (~20 wt %) molybdenum and had densities from 94 to 95% theoretical. The pellets made from the coated UO_2 particles had a metal content of about 16 vol % (~17 wt %) and had densities that ranged from 84 to 96% of theoretical and averaged 89%.

The distribution of the molybdenum in both types of cermet fuels appeared favorable to good heat transfer. The fibers were oriented predominantly in the radial planes of the pellet as a result of the uni-directional compaction during the hot-pressing operation. In the pellets made from the coated particles. a continuous network of molybdenum occurred as a result of the coating welding together during the hot-pressing operation.

The test assembly contains eight fuel rods; three contain the UO_2-Mo fiber cermet, three contain the cermet produced from the coated particles, and two are for reference and contain the conventional sintered UO_2 pellet fuel. The nominal outside diameter of the fuel rods is 1.308 cm (0.515 inch), and the clad wall thickness is 0.051 cm (0.020 inch). The cladding material is Type-304 stainless steel.

The fuel pellets were all centerless ground to achieve a uniform outside diameter and thereby control the pellet-to-clad diametral clearance within a range of 0.076 to 0.102 mm (0.003 to 0.004 inch).

Operation of the fuel rods will be at high specific power levels with surface heat fluxes of about 157 W/cm^2 (~ 500,000 $Btu/h\text{-}ft^2$). The assembly was designed for a lifetime of 4.1×10^{20} fission/cc (15,000 MWD/T) exposure.

I. INTRODUCTION

The operation of bulk UO_2 in a fuel element could be restricted from high levels of specific power generation by the low thermal conductivity of the oxide. The fuel temperatures reached at these high power levels can be objectionably high from the standpoint of fuel element design. Two important temperature-dependent occurrences in this respect are fission gas release from, and thermal expansion of, the UO_2. An extreme case of thermal expansion results from the melting of the UO_2 in the central region, where a volume increase of about 9.6% can be expected.[1] Fuel rods are normally designed to operate at conservative specific power levels at which the UO_2 melting point is avoided and other temperature effects are small and can be accommodated.

To operate a fuel element in increased rating, or higher specific power density, without causing the melting point of the UO_2 to be reached, one method is to improve the thermal conductivity of the bulk fuel. Substantial improvements in the bulk thermal conductivity can be made by additions to the bulk fuel. One such means involves the addition of a refractory metal which is dispersed throughout the oxide matrix. By using such a metal-oxide mixture which is made into dense cermet fuel, improvements in the thermal conductivity of about 300% have been achieved over the pure UO_2 system. Molybdenum and niobium metals have been successfully incorporated into urania and thoria-urania fuels.[2, 3] The performance testing of cermet fuels containing these thermal conductivity improvers had not been conducted at high-power levels for long irradiation periods.

Further testing of this fuel concept was started in a Vallecitos Boiling Water Reactor (VBWR) test fuel assembly. This fuel assembly was fabricated for the AEC Fuel Cycle Program, Contract No. AT(04-3)-189, Project Agreement 11. In one phase of this program, fuel concepts that show potentials for improving fuel cycle economy through increased performance or lower fabrication costs are being irradiation tested in 12 special assemblies in the VBWR. Performance capabilities of these fuel concepts will be assessed in relation to those from the basic fuel assemblies which represent current fuel design and fabrication processes.[4] The assembly for demonstrating the performance of the thermal conductivity improvers is one of these 12 assemblies and is designated Special Assembly 9-L.

The objectives of the test were to operate the cermet fuels at high specific power levels for extended periods and to compare and evaluate their performances with those from the conventional sintered UO_2 fuels. Periodic surveillance inspections of the fuel rods will be performed at convenient intervals during reactor shutdowns. Destructive examination of selected rods will be conducted at an intermediate exposure and the

remaining rods continued to be irradiated to high exposures up to the design limit of 4.1×10^{20} fissions/cc (15,000 MWD/T) before they are also destructively examined. Irradiation which was started in the VBWR in September 1962, was prematurely terminated by shutdown of that facility in December 1963. The results of post-irradiation examinations will be presented in a subsequent report.

II. FUEL COMPACT DESIGN

A PREVIOUS WORK

Experimental work on improving the bulk thermal conductivity of urania and thoria-urania matrices by adding molybdenum or niobium metals were originally conducted by Paprocki, et al., [2] at Batelle Memorial Institute (BMI) and by Baskin et al., [3] at Argonne National Laboratory (ANL). The molybdenum and niobium metals used were in the form of fibers, fine powder, or as a thin coating on individual fuel particles. The amount of metal in the mixtures ranged from 10 to 30 vol %. Out-of-pile measurements of the thermal conductivity of such compacts demonstrated the vast improvements that could be achieved over unadulterated, sintered UO_2 compacts. These improvements were in the order of 300% and greater.

Subsequent irradiation tests conducted at ANL showed that niobium reacted with the UO_2 at elevated temperatures. [5] Because of this reaction, the scope of the testing to be conducted in Special Assembly 9-L included only the molybdenum additives to the UO_2 fuel.

The design and fabrication of the UO_2-Mo cermets for this irradiation experiment were conducted to take full advantage of the results obtained from the work described above. This, in addition to the experience on coated particles available commercially, minimized the selection and development procedures necessary to obtain the cermets for testing in this particular application.

B. MOLYBDENUM ADDITIONS

1. Metal Content

The molybdenum content of the UO_2-Mo fuel compacts used in this program was chosen as 20 wt %. This amount is equivalent to 20 vol % in a compact with a density of 95% of theoretical. It is about the same amount of metal used in the cermets fabricated and tested by Paprocki, et al. [2]

By this duplication, it was possible to use the thermal conductivity data available in estimating the temperature distributions in the fuel compacts for a range of operating power generation levels. These estimates are useful in determining the optimum level at which the assembly should be operated to achieve the test conditions.

2. Form and Distribution of the Metal Phase

Two types of cermet compacts were made. In one type, the molybdenum was added as fibers, and in the other, as a thin coating on individual UO_2 particles. Of the three forms in which the molybdenum was added and tested previously, [1, 2] the two forms chosen for performance testing in this experiment were considered to represent the widest physical difference in the distribution of the metal phase.

In comparing the two forms of addition, it was seen that the molybdenum deposited originally as a coating on individual UO_2 particles was distributed more uniformly throughout the final matrix. But, for a given amount of metal, this distribution is achieved at the cost of losing the wider metal paths. In contrast, the fibers each have a larger cross-sectional area, but larger volumes of UO_2 without the metal are left between them.

It was intended that the fibers be randomly oriented in the mixture, as the cost of pre-orienting them in a radial direction before incorporating them into the matrix would have been prohibitive.

The use of coated particles has a possible additional advantage in retaining fission gases in each of the cells formed by the surrounding metal shell. However, this feature may be insignificant if the molybdenum additions in either form successfully keep the UO_2 temperatures at levels where the fission gas release rates are inherently low.

3. Shape of the Fuel Compacts

The UO_2-Mo fuel compacts were made into right cylindrical pellets so conventional rod-loading practices could be followed. The outside diameters of the pellets were specified to be centerless ground to give a diametral gap of 0.051 to 0.102 mm (0.002 to 0.004 inch). These clearances are within the nominal range used in current fuel rod design practices for cladding which is free standing.

4. Reference Fuels

Regular sintered UO_2 pellets fabricated by conventional fuel fabrication methods were included in this test. These pellets were also centerless ground to give gap clearances that were the same as those for the cermet pellets. A direct comparison of their performances will be made on the basis of identical initial conditions.

In addition to these reference fuel rods in the assembly, the fuel rods being irradiated in Special Assembly 1-L, [6] will also be used for comparison. Conventional sintered UO_2 pellets are being operated to high power levels in the 1-L assembly. Actually, rod outside diameters and the clad wall thickness were purposely made identical in both assemblies to facilitate comparing the fuel performances.

5. Fuel Temperature Profiles

Estimates of the temperatures to be attained within each of the three types of fuels used in this experiment were made. Radial and axial temperature profiles were determined in each case. Three peak heat flux conditions were considered: 141.8, 157.5, and 173.2 W/cm^2. A summary of the calculations is presented in the Appendix. It should be noted that while the best available data were used in these calculations, there are still uncertainties present in them, and the temperatures calculated should be considered as approximations.

Figure 1 shows the axial temperature profiles. Their general shape conforms to the power generation profile of fuel rods operated in the VBWR. A peak-to-average ratio of 1.5 to 1 was assumed. The profiles for the cermet fuels are shown to terminate short of the total fuel column. In these rods, the cermet fuel sections constitute about two-thirds of the column. The balance is made up of regular sintered UO_2 pellets of a lower U-235 enrichment. The temperatures in each fuel section were calculated independently. Thus, transition profiles across the interfaces between the different types of fuels are not shown.

Figure 2 shows the radial temperature profiles determined for the three peak heat flux conditions. It can be seen from these two figures that the improvement in the bulk thermal conductivity, if brought about by the molybdenum additions as anticipated, would cause significant differences in the temperature reached in the sintered UO_2 and cermet pellet fuels.

For the three peak heat flux conditions, the temperatures calculated to be reached in the sintered UO_2 fuel should result in appreciable grain growth extending from the center to about mid-radius. Melting can occur if the rods are operated at surface heat

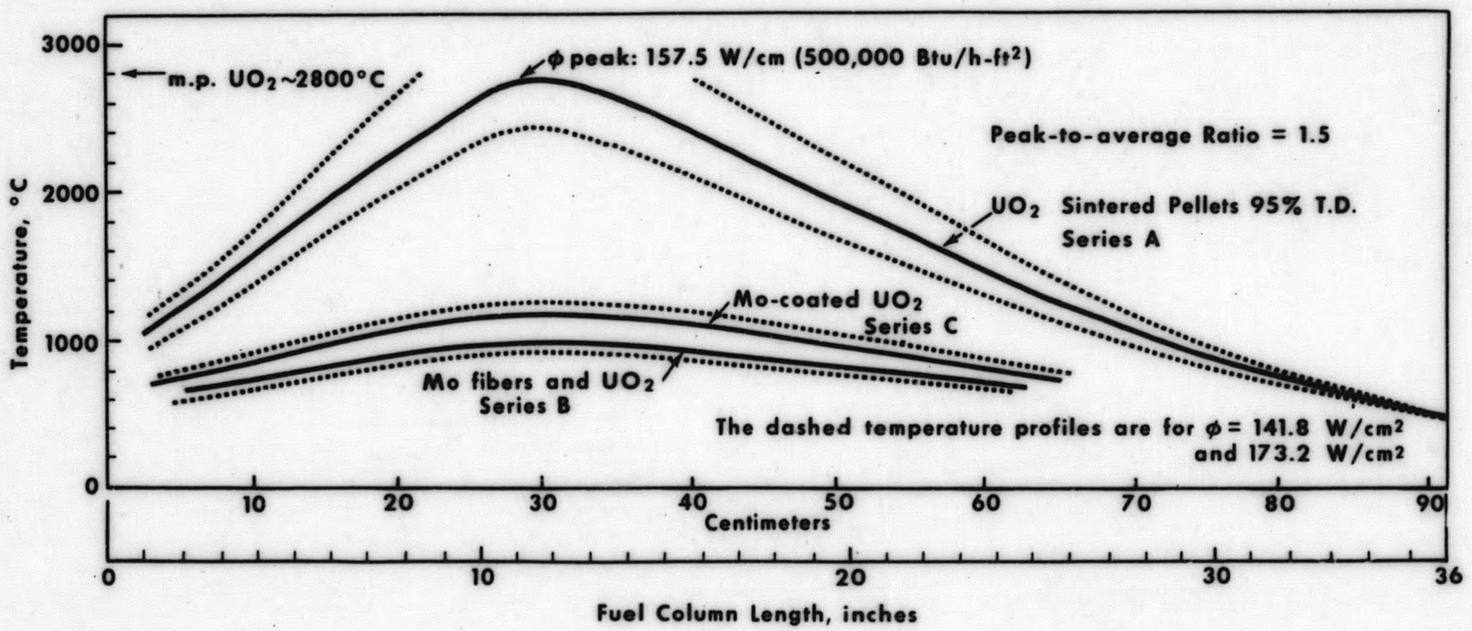


FIGURE 1. AXIAL TEMPERATURE PROFILES IN FUEL RODS OF SPECIAL ASSEMBLY 9-L

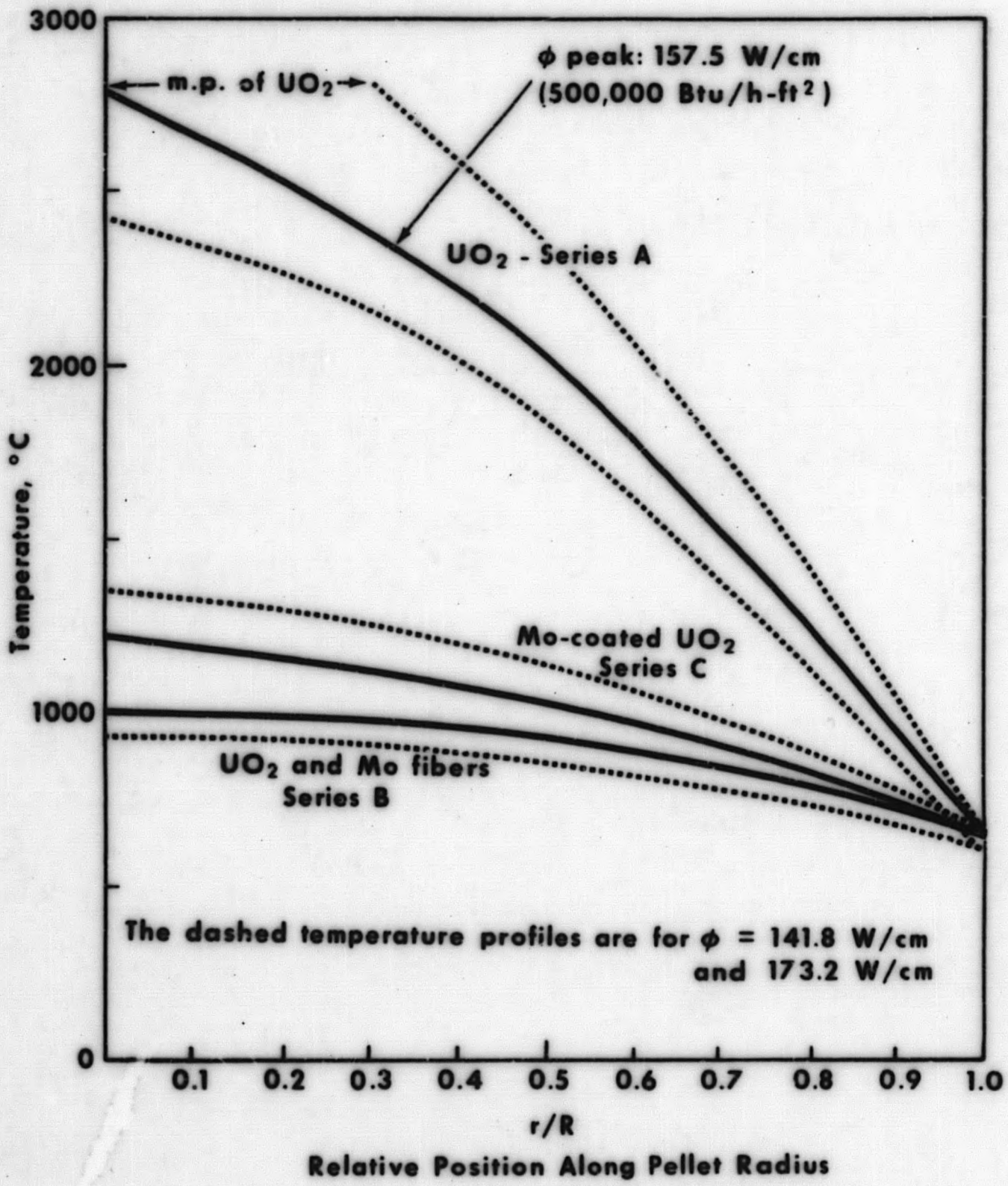


FIGURE 2. RADIAL TEMPERATURE PROFILES IN FUEL RODS OF SPECIAL ASSEMBLY 9-L

fluxes greater than 157.5 W/cm (500,000 Btu/h-ft^2). Under the same operating levels, the temperatures in the cermet fuels, even under the highest level of the three heat fluxes studied, are comparatively low, and little, if any, structural changes are expected in the UO_2 phase.

The evaluation of the performance of the cermet fuels will be based for the most part upon the microstructural differences that exist in the UO_2.

III. ASSEMBLY DESIGN

A. DESIGN CHARACTERISTICS

Figure 3 is an over-all view drawing of Special Assembly 9-L. The characteristics of this bundle are as follows. There are eight fuel rods in a modified 3 by 3 array, in which the center location is taken up by an empty tube. This tube serves to improve the hydraulic characteristics of the bundle so that the fuel rods can be operated at high surface heat fluxes. This tube is also used as the main structural member to which components, such as the bottom tie plate and two spacer plates, are permanently attached. Both ends of the tube are vented to keep it filled with water during operation so that a favorable water-to-fuel ratio is maintained.

The handle extension and top tie plate can be readily disconnected from the frame so that individual fuel rods can be easily removed for inspection or replacement. This feature is illustrated in Figure 4.

FOR REVIEW
NOT FOR CONSTRUCTION

GENERAL ELECTRIC 762D758

TITLE ASSEMBLY
FUEL BUNDLE
FIRST MADE FOR AEC FUEL CYCLE - SPECIAL ASSEMBLY 9L

SHOP	FIELD	QTY	PART NO.	NAME	DRAWING NO. DESCRIPTION MATERIAL WEIGHT
	X	1	1	SUPT FRAME	G2 THIS DWG.
X		1	2	EXTENSION	G3 THIS DWG.
		8	3	FUEL ROD	9A5C89861
		8	4	SPRING	111A3025P1
		1	5	TIE PLATE	117B1594G1
		1	6	DRIFT PIN	149A4957P1
		1	7	WASHER	5/16 O.D. × 5/16 I.D. × 1/16 THK. 304 STN. STL.
		1	8	COTTER PIN	1/8 DIA. × 3/4 LG. 302 or 304 STN. STL.
	1		9	BUNDLE SUPT	9B5C893 G1
	1		10	SPACER	117B1595P1
	1		11	SPACER	117B1595P2
	1		12	TIE PLATE	117B1597P1
	1		13	NUT, HEX	5/16-24-2B REG. 304 STN. STL.
1			14	EXTENSION	1173L5966G1
1			15	HANDLE	885B536 P1
2			16	LOCK PIN	5/32 DIA. × 7/16 LG. 302 STN STL.
1			17	SPRING	115A8799P1

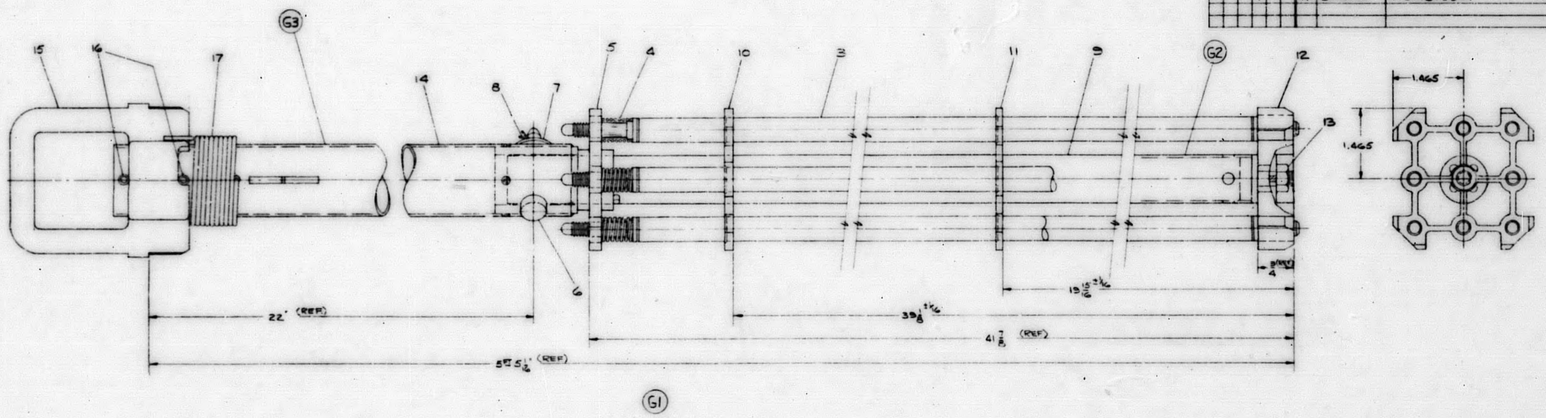
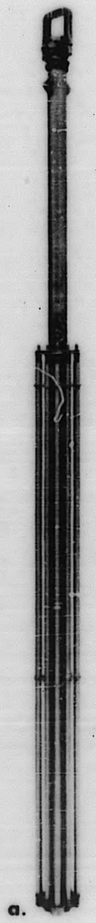
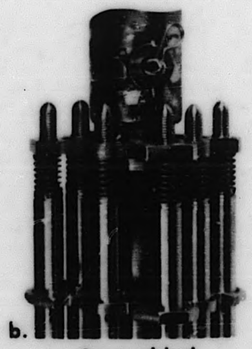


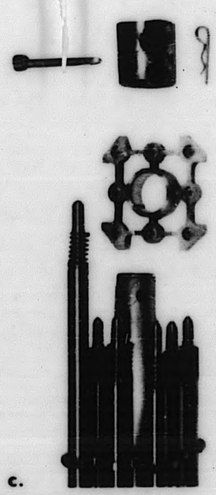
FIGURE 3. DRAWING OF SPECIAL ASSEMBLY 9-L



a.

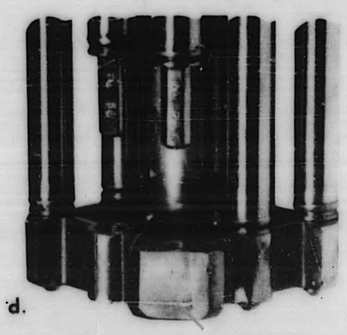


b. Assembled

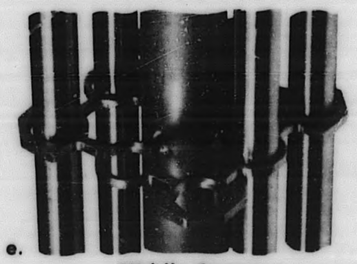


c. Disconnected for easy rod removal

Top Tie Plate and Handle Extension Group



d. Bottom Tie Plate and Rod Identification



e. Middle Spacer

FIGURE 4 PHOTOGRAPHS OF THE COMPLETED ASSEMBLY

B. FUEL ROD CHARACTERISTICS

Externally, all the fuel rods are identical: internally, different types of fuel pellets and arrangements of these pellets are used. Figure 5 illustrates the arrangements of the three different types of fuels used in the rods.

The Type-I rods are the reference rods. The conventional sintered UO_2 pellets only are used. In the Types-II and -III rods, the cermet fuels make up approximately two-thirds of the total fuel column. The middle of the cermet fuel sections were placed in the region where the heat fluxes are expected to peak.

To achieve this condition with the cermets made from the Mo-coated UO_2 particles, it was necessary to use conventional pellets at the bottom to raise these sections. In each of the rods, a gas plenum about 8.9 cm (~3-1/2 inches) was provided above the fuel column to accommodate the fission gases generated and released by the fuel.

IV. MATERIALS

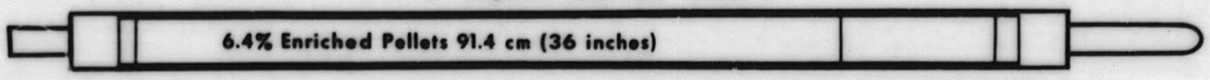
A. CLADDING

Type-304 stainless steel tubing was used as the cladding. The chemical analyses and mechanical properties data for this tubing are given in Table 1.

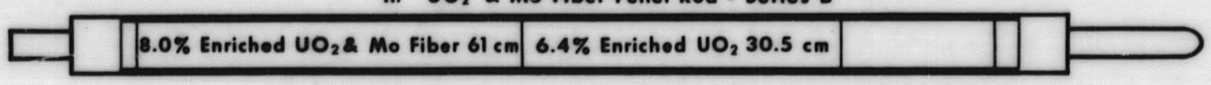
B. MOLYBDENUM FIBERS

The fibers were made from pure molybdenum wire 0.076 and 0.152 mm (0.003 and 0.006 inch) in diameter and cut to 0.8 cm (5/16) in length. Equal amounts of each size fiber were randomly mixed. Chemical analyses of the wires are shown in Table 2.

I. Regular Pellet Rod - Series A



II. UO_2 & Mo Fiber Pellet Rod - Series B



III. UO_2 - Coated Particle Pellet Rod - Series C

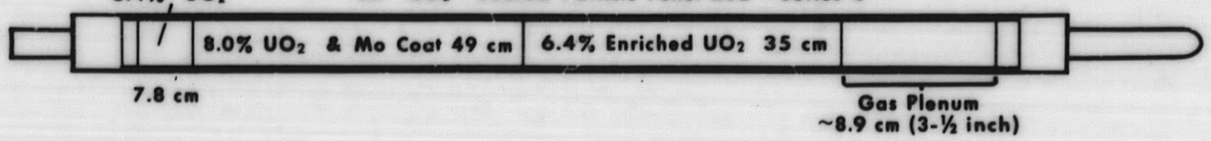


FIGURE 5. ARRANGEMENT OF FUEL IN THE THREE GROUPS OF FUEL RODS USED

TABLE 1. Description of Tubing Material

Material: Type-304 stainless steel, welded and drawn.

Dimensions: 1.308 cm (0.515 inch) o.d.
0.508 mm (0.020 inch) wall.

Mechanical Properties: Tensile test results.

	0.2% Yield Strength		Ultimate Tensile Strength			
Results	kg/cm^2	psi	kg/cm^2	psi	Elongation, %	
Vendor	5,857	83,200	8,222	116,800	32	room temperature
	5,794	82,300	8,096	115,000	34	
APED	6,399	90,900	8,082	114,800	32	room temperature
	6,090	86,500	8,082	114,800	32	
	6,174	87,700	8,061	114,500	35.5	
	4,632	65,800	6,090	86,500	15	650° F
	4,541	64,500	5,949	84,500	18.5	

Chemical Analysis

C	0.056 %	Ni	9.14 %
Mn	1.19	Cr	18.41
P	0.016	Cu	0.15
S	0.01	Mo	0.22
Si	0.53	Co	0.064

TABLE 2. Chemical Analyses* of Molybdenum Fibers

	Diameter, 0.076 mm (0.003 in.)	Diameter, 0.152 mm (0.006 in.)
Al	200 ppm	200 ppm
B	< 1.0	< 1.0
Cd	< 100	< 100
Ca	50	50
Cr	500	500
Co	50	50
Cu	500	500
Fe	1000	1000
Pb	10	10
Mg	10	10
Mn	10	10
Mo	Major	Major
Si	200	200
Ag	< 10	< 10
Na	< 1000	< 1000
Sn	1000	1000
V	< 100	< 100
Zn	< 100	< 100
Ba	< 10	< 10
Ni	1000	500
W	500	500
Ti	< 10	< 10

*Spectrographic Analyses

C. UO_2

Ceramic grade UO_2 was used for both the conventional sintered pellets and the cermet pellets. The UO_2 enrichments were 6.4 and 8.0%, respectively. The higher enrichment compensates for the parasitic neutron absorption by the molybdenum in the cermet fuels, so that about equal power generation levels are achieved in both the pure UO_2 and the cermet fuel pellets during irradiation. The high levels of U-235 enrichment were specified to provide sufficient reactivity so that the desired power levels could be reached in the rods when the bundle was placed in the outer regions of the VBWR core.

D. COATED PARTICLES

The specifications for the coated particles were based on an evaluation of data available in the literature. The particle size range was selected to be between 100 and 140 meshe, to achieve about the same degree of metal distribution throughout the final cermet compact. Since much of the development of coated UO_2 fuel particles was in this size range, commercial capabilities to handle such particles was presumed to be good so that procurement of this material would be facilitated. It was decided to use essentially one particle size instead of a wider range of sizes, so that better control of the metal content and its distribution could be achieved.

The size range selected was also acceptable from the standpoint of the coating thickness required to obtain the desired metal content of 20 wt %. Calculations performed for estimating were based on the spherical configuration and showed that a coating thickness about 5 microns would be required.

The shape of the UO_2 particles was taken into consideration. Either spherical or angular particles could be used. While the deposits on spherical particles tend to be more uniform in thickness and their integrity much better. a higher cost is associated with the manufacture of the spherical particles. It was felt that the small variation in the thickness of the coating on angular particles would not seriously affect the objective of distributing the metal phase uniformly in the final cermet compact. Furthermore. it was believed that any discontinuities present in the deposit on the angular particle would weld shut during the hot pressing operation at elevated temperatures. Because it appeared that the use of the coated angular particles would be technically acceptable. it was decided to use them and to take advantage of their lower cost.

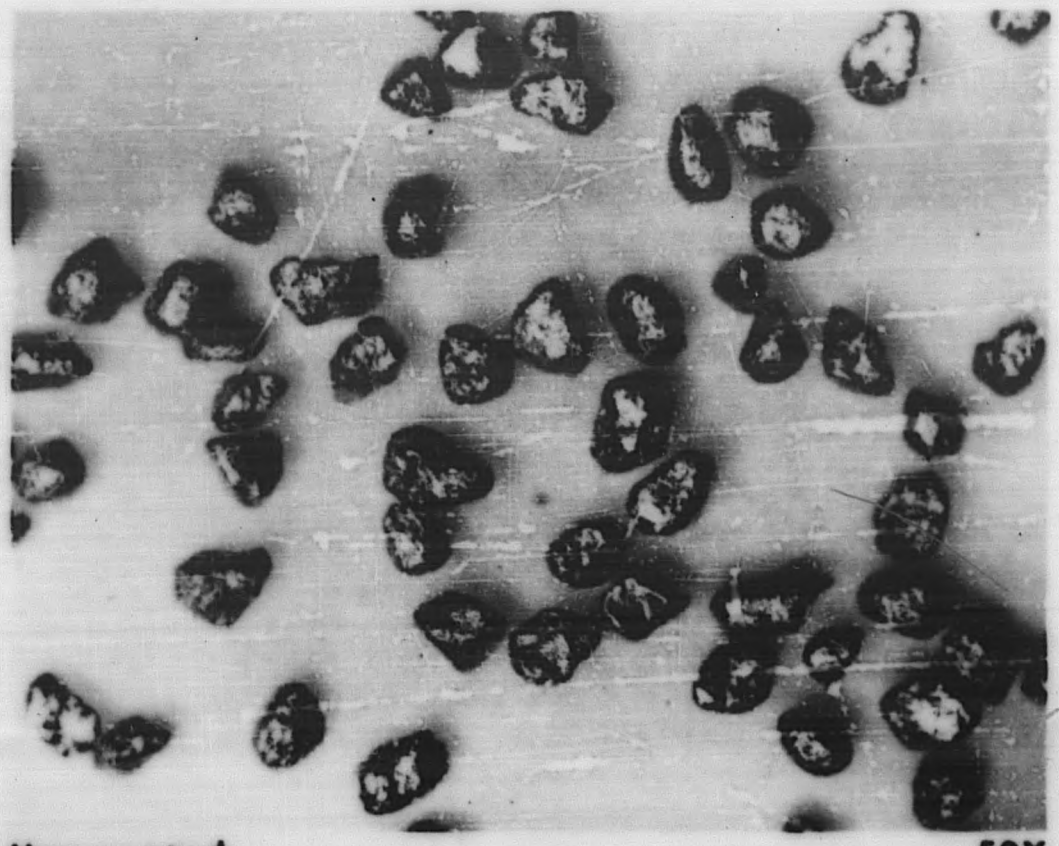
The coated particles were prepared from the 8% enriched ceramic-grade UO_2 powder. Nuclear Materials and Equipment Corporation (NUMEC) of Appollo, Pennsylvania, was contracted to agglomerate the UO_2 into dense particles and to coat them with molybdenum.

Figure 6 shows the appearance of the individual coated particles. The thickness of the film was measured to range from 1 to 3.3 microns, which was less than the thickness desired. By chemical analysis. the metal content was determined to be 16.7% by weight. The substrate UO_2 had a density ranging from 95 to 97% of theoretical.

V. FABRICATION PROCEDURE - FUEL COMPACTS

A. METHOD OF COMPACTION

The UO_2-Mo mixtures were compacted in a vacuum induction hot press. It was necessary to use this method of compaction rather than the conventional sintering procedure on pressed green compacts. because previous tests by Paprocki. et al.. [2]



Unmounted 50X

Mounted and Sectioned 150X

Substrate particle size, 0.149 to 0.105 mm (100 to 140 mesh); Mo coating thickness, 1 to 3 microns UO_2 density, 95 to 97% of theoretical; UO_2 enrichment, 8.0%

FIGURE 6. INDIVIDUAL MOLYBDENUM-COATED UO_2 PARTICLES

showed that a dynamic compression on the mixture held at an elevated temperature was required to achieve the high bulk densities.

A description of the apparatus used for this compaction is presented by Hoyt.[7] Graphite dies were used in which compacts measuring 12.7 mm (0.5 inch) in diameter and from 2.54 to 3.81 cm (1 to 1-1/2 inches) long were produced.

B. HOT-PRESSING

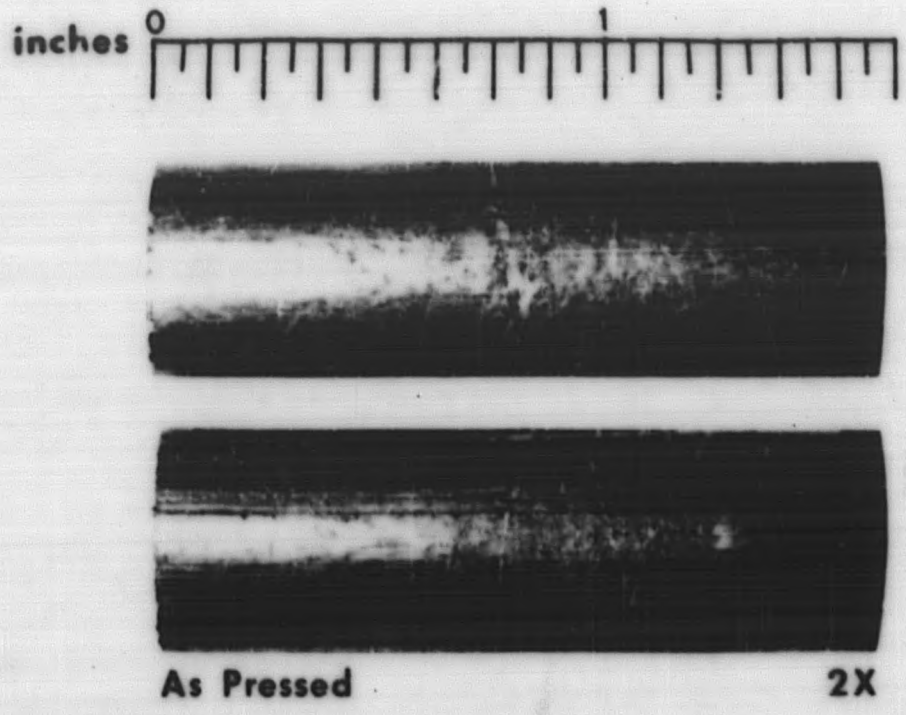
1. UO_2-Molybdenum Pellets

The fuel pellets containing the molybdenum fibers were fabricated by weighing and mixing required amounts of fibers and UO_2 powder for each charge (pellet) and loading them into the die cavity. The pressing was carried out at 1500° C (2732° F) at 5,000 psi for 30 minutes at temperature. The vacuum stabilized to 10^{-5} torr during this operation.

Figure 7 shows the condition of the pellet surfaces in the as-pressed and centerless ground conditions. The distribution of the exposed ends of the fibers on the ground surfaces was uniform and indicates that the fiber distribution in the matrix was also uniform.

Confirmation of the favorable distribution and orientation of the fibers was obtained when sample pellets were sectioned. Figure 8 shows a cross section and a longitudinal section from a typical pellet. It can be seen that the fibers are oriented predominantly in the planes perpendicular to the pellet axis. The excellent contact between fibers and the UO_2 should contribute favorably to good heat transfer (Figure 9).

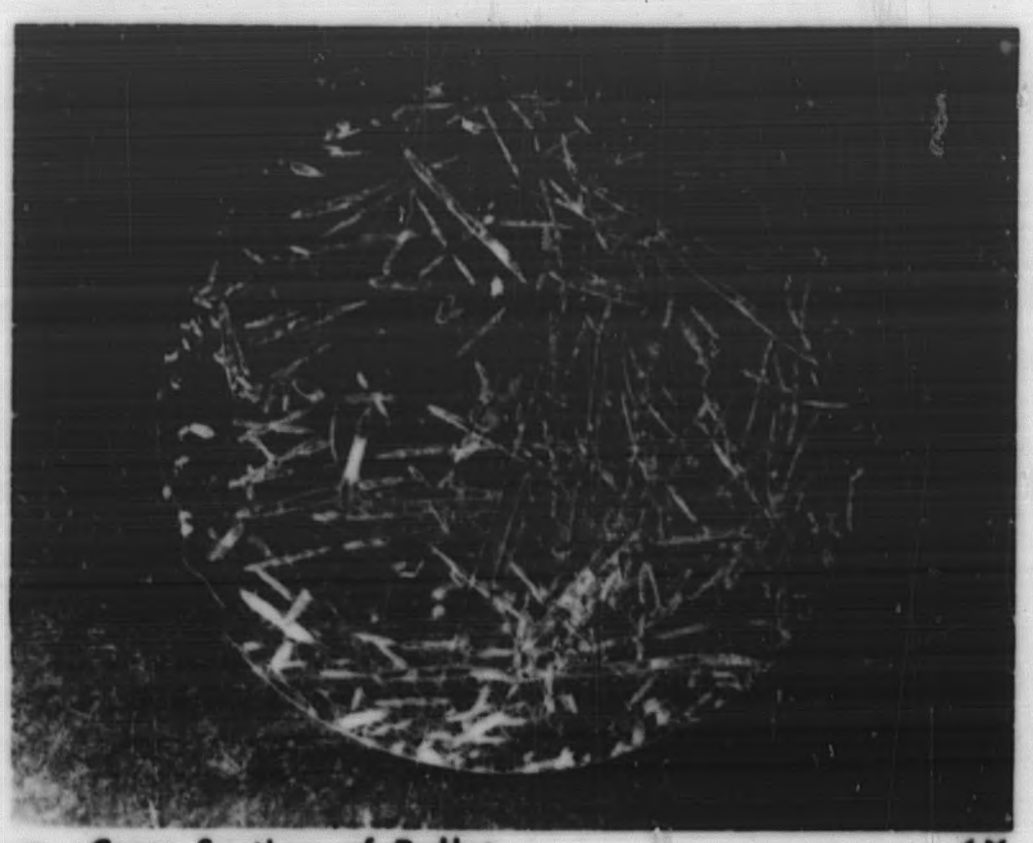
The pellet structure was permeated with a network of fine cracks, which are clearly visible in the preceding photographs. The fibers served to reinforce this structure and



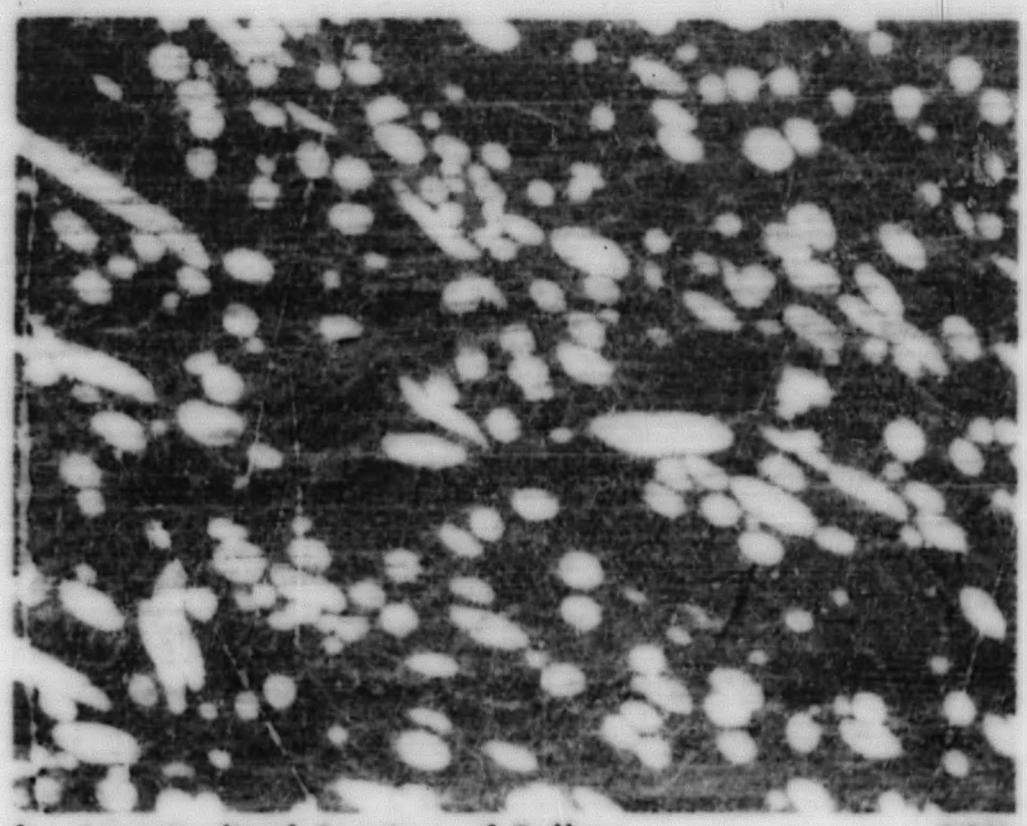
As Pressed 2X

Centerless Ground 4X

FIGURE 7. HOT-PRESSED PELLETS MADE FROM A MIXTURE OF UO_2 POWDER AND MOLYBDENUM FIBERS



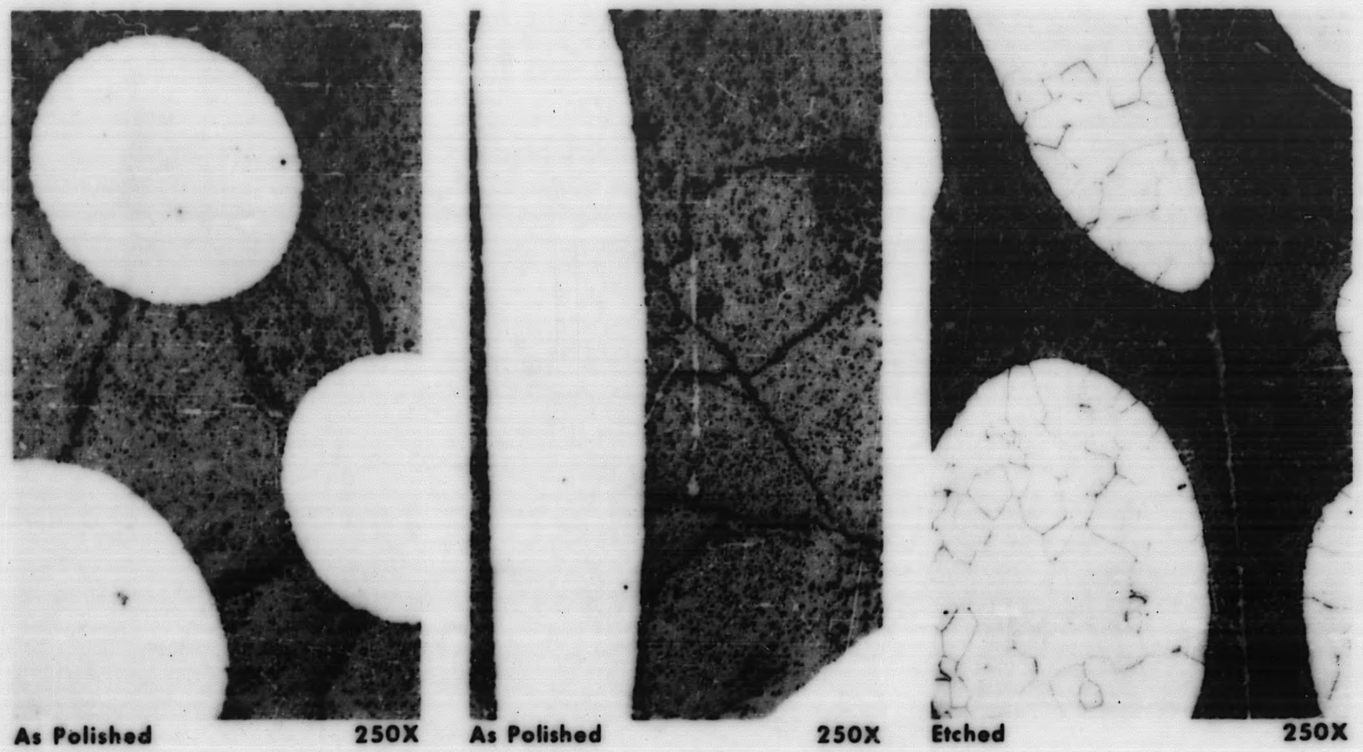
a. Cross Section of Pellet 6X



b. Longitudinal Section of Pellet 20X

8% UO_2 containing 20 wt % Mo

FIGURE 8. SECTIONS THROUGH HOT PRESSED PELLETS SHOWING FIBER ORIENTATION



As Polished 250X As Polished 250X Etched 250X

FIGURE 9. SECTIONS SHOWING GOOD MOLYBDENUM FIBER - UO_2 INTERFACIAL CONTACT

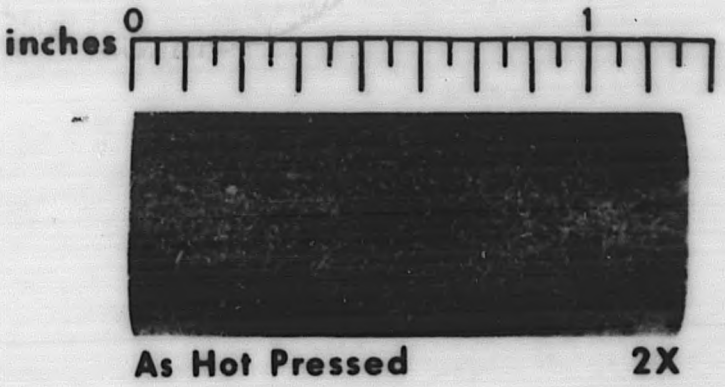
to hold the integrity of the pellet. There were no problems of the pellets disintegrating during the centerless grinding operation. The density of these pellets was a uniform 94 to 95% of theoretical, corrected for the molybdenum content.

2. Coated-Particle Pellets

The hot pressing of the coated particles into compacts proved to be somewhat more difficult. It was found that high densities could not be achieved in the compacts pressed at 1500° C. As a corrective measure, the temperature was raised to 2200° C (3992° F). This change in practice increased the bulk density to 96% of theoretical. However, at this higher temperature, the pellet surface reacted with the graphite dies and made it impossible to remove the pellet except by breaking the dies. Therefore, further compaction at this temperature was stopped. A compromise temperature of 1700° C (3092° F) was chosen to permit a higher pellet yield per set of dies, although the bulk density of the pellets was lowered to an average of 89% of theoretical. The die pressure was 5000 psi and the duration of the pressing operation was 30 minutes at temperature. A vacuum of 10^{-5} torr was maintained during this period.

Figure 10 shows the appearance of the pellet surface in the as-pressed and centerless gound conditions. The ground surfaces were smooth and the UO_2 exposed by the grinding remained intact.

Internally, the structure consisted of continuous networks of metal heat paths, as shown in Figure 11 and 12. The continuity in the heat paths was enhanced by the molybdenum coating welding together. The large voids present in the UO_2 shown (Figures 11 and 12) are pull-outs from the mount preparation and not voids in the original UO_2 particles. Voids between the particles are also present and varied in amount among



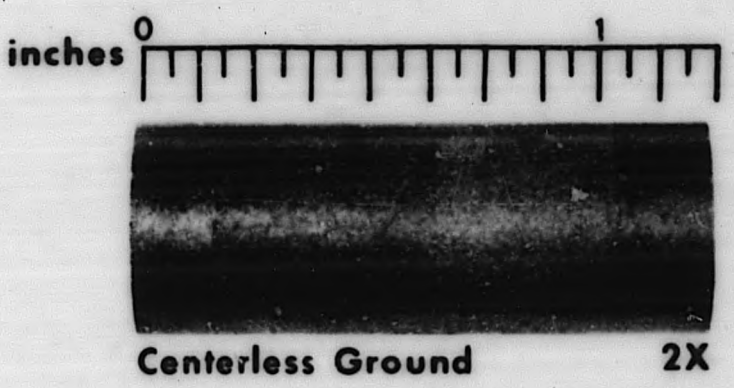
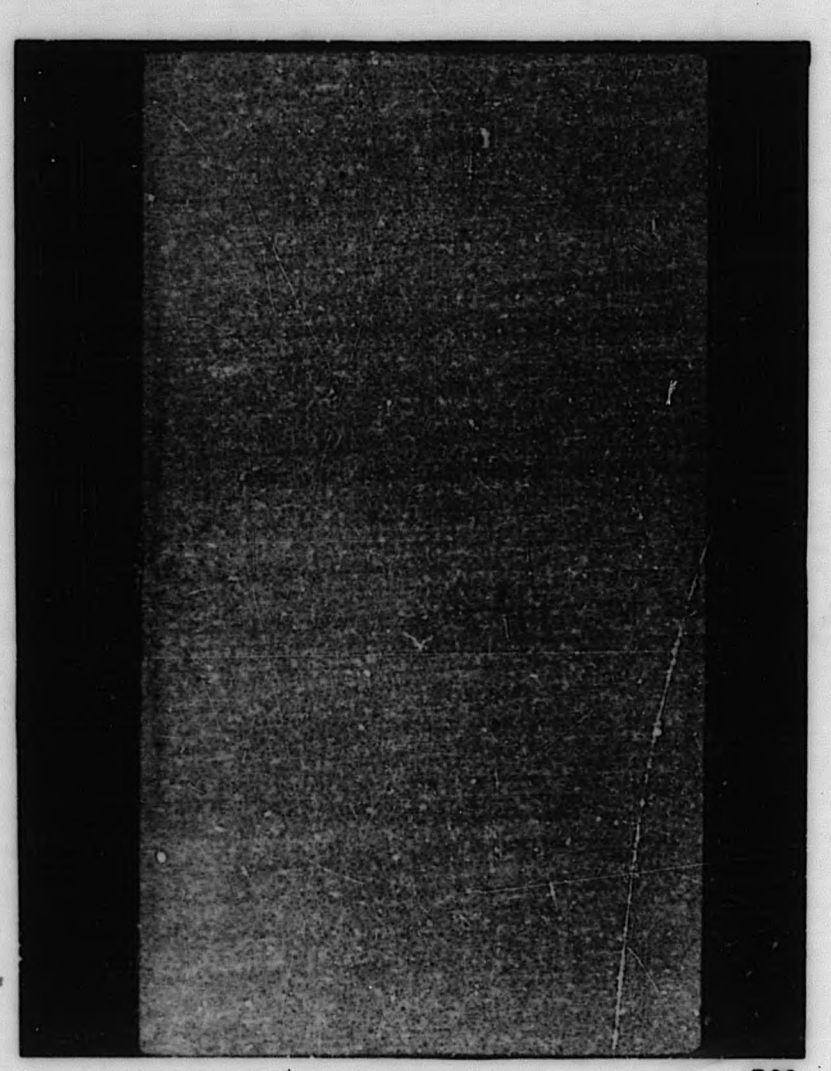
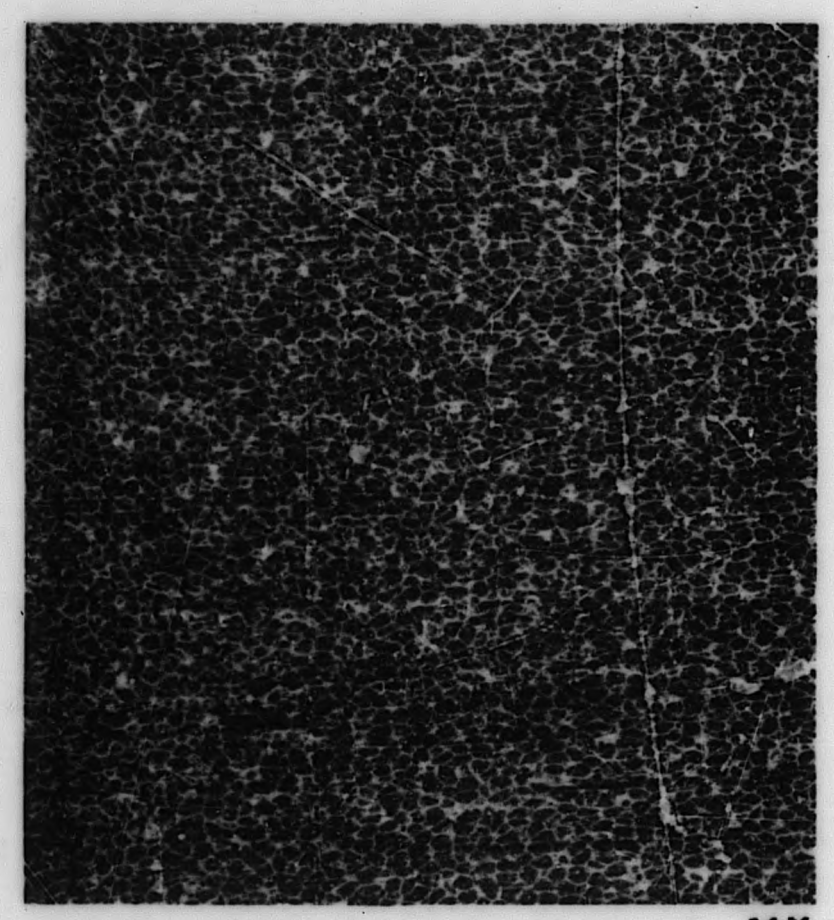


FIGURE 10. HOT-PRESSED PELLETS MADE FROM Mo-COATED UO_2 PARTICLES



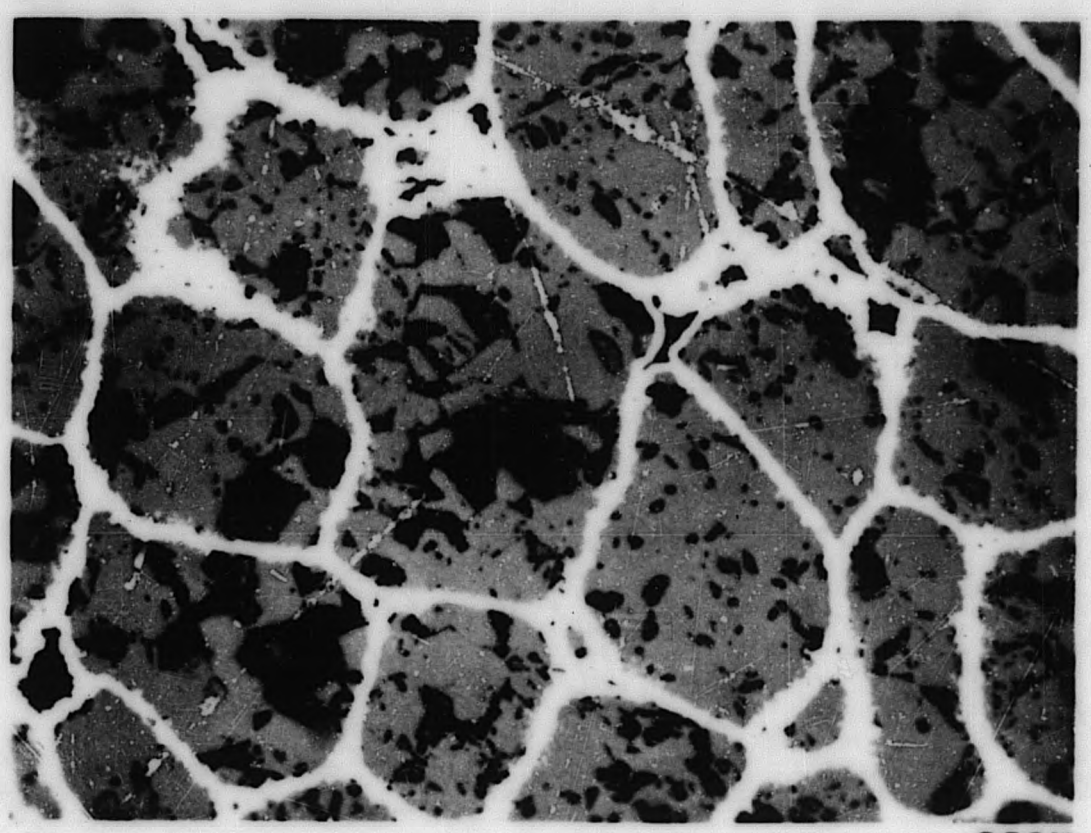
5X



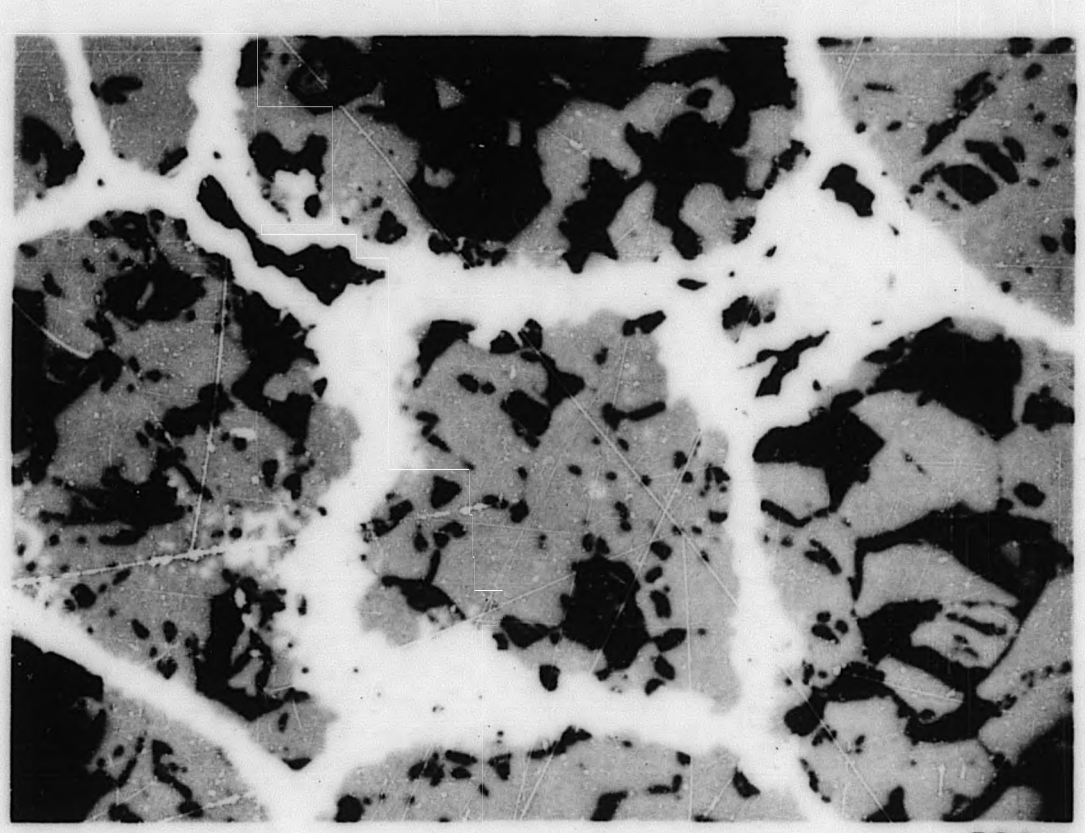
16X

Note: Low density area near left edge.

FIGURE 11. LONGITUDINAL SECTION OF PELLET MADE FROM Mo-COATED UO_2 PARTICLES



250X



500X

FIGURE 12. REGION OF HIGH DENSITY IN PELLET MADE FROM HOT-PRESSED COATED UO_2 PARTICLES

the pellets; these voids were the chief reasons for the variation in the pellet densities. Figure 13 shows an area where the density is low.

C. CONVENTIONAL SINTERED UO_2 PELLETS

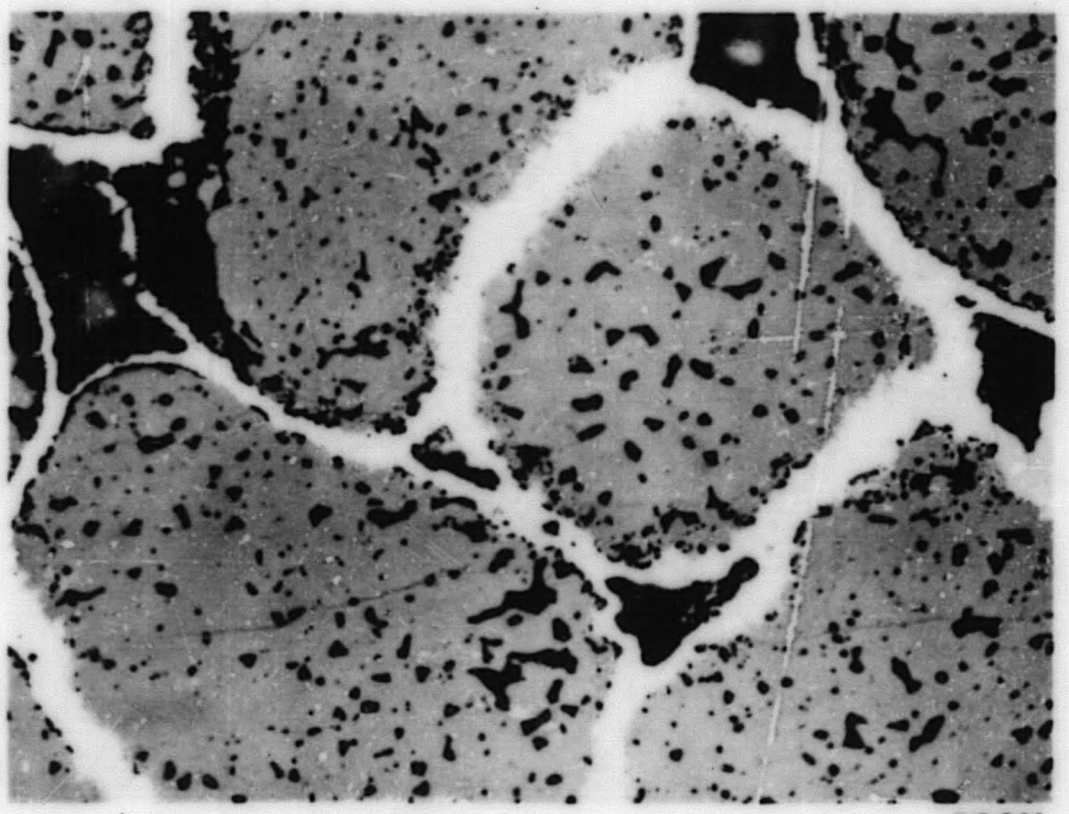
The conventional sintered UO_2 pellets were fabricated by the standard procedure in which green compacts were sintered at 1650° C in a hydrogen atmosphere. The density of these pellets was from 95 to 97% of theoretical. The chemical analyses of these pellets are shown in Table 3.

TABLE 3. Chemical Analyses of 6.4% Enriched UO_2 Pellets

Isotopic Content: 6.45 ± 0.06%
Oxygen-to-Uranium Ratio 2.008

Ag	< 0.1 ppm	F^-	15 ppm
Al	25	Mg	2
B	< 0.2	Mo	4
Bi	1	Mn	< 3
C	10	Na	< 35
Ca	10	Ni	50
Cd	< 1	Pb	< 1
Cl^-	< 5	Sb	< 2
Co	< 2	Si	60
Cr	50	Sn	1
Cu	< 1	V	< 15
Fe	200	Zn	< 10

150X



500X

FIGURE 13. REGION OF HIGH VOID CONTENT IN LOW DENSITY HOT-PRESSED PELLET MADE FROM COATED PARTICLES

D. GENERAL DESCRIPTION OF THE RODS

Each of the three different types of fuel was kept separated in individual rods. The arrangement of these fuels within the rods was slightly different (Figure 5). The reason for shortening the cermet fuel column was to conserve the high cost fuel containing the molybdenum. For the tests. it was sufficient to place a short fuel column of this type fuel in the peak heat flux region. In the following sections the fabrication procedure followed and the data recorded for each of these fuel rods are described.

1. Reference Fuel Rods

The two reference (Series A) fuel rods were filled with conventional, sintered, 6.4% enriched UO_2 pellets. Each fuel rod was identified by metal stamping a letter-number combination on the bottom end plug stud (Figure 4a). The outside diameter of the pellets used in these rods was ground to within the tolerance of 1. 194 to 1. 196 cm (0.470 to 0.471 inch). Before loading the pellets into the tubes for each rod, they were placed in a V-trough; the diameter of the first or bottom pellet and of every tenth pellet was measured. Two measurements, 90 degrees apart, were made on each of these pellets: the length of the fuel column was also measured. The measurements are given in Table 4.

TABLE 4. Diameter Measurements of UO_2 Pellets in Series A Rods

Pellet	Rod A-1	Rod A-2
1	0.4705	0.4702
10	0.4705	0.4702
20	0.4705	0.4708
30	0.4705	0.4715
40	0.4698	0.4710
50	0.4698	0.4709
60	0.4705	0.4708
70	0.4712	0.4712
Fuel Column Length, inches		
	37-7/8	35-3/4

The inside diameter of the tubing was actually 1.204 cm (0.474 inch). The diametral clearance between the pellet surface and the inside surface of the clad was 0.076 to 0.102 mm (0.003 to 0.004 inch). All the pellets used were free from cracks and chips. Additional details on the rods are given in a tabulated summary at the end of this report.

2. Rods Containing the Fuel with the Fibers

The three Series B rods contain the pellets with the molybdenum fibers. Only two-thirds of the fuel column in each of these rods is filled with the UO_2-molybdenum pellets. The remaining upper third is filled with conventional. sintered 6.4% enriched UO_2 pellets.

Each rod contains 16 molybdenum-bearing pellets and 23 conventional pellets. Diameter measurements were taken of each of the cermet fuel pellets. and of the first and then of every tenth conventional pellet. The location or elevation of the pellet interfaces of the cermet fuel with respect to the bottom of the fuel column was also measured. The results are given in Table 5.

The diametral clearance between the pellet surface and the inside surface of the cladding was between 0.05 to 0.07 mm (0.002 to 0.003 inch) over the cermet fuel column, and 0.05 to 0.102 mm (0.002 to 0.004 inch) over the conventional fuel column. Additional details on these rods are given in a tabulated summary at the end of this report.

3. Rods Containing the Coated Particle Fuel

The three Series C rods* contain the pellets made from the coated particles. The fuel column in each of these rods also contains both the special and conventional

*Rod C-3 was fabricated as a substitute for Rod C-4. which was not completed when the assembly was inserted into the VBWR core. The C-3 was subsequently replaced by C-4 in late December. 1962 after operation at a low power level for one VBWR cycle. Rod C-3 contained conventional sintered UO_2 pellets of 5.46% enrichment. Since C-3 is not part of the test program. it will not be described further.

TABLE 5. Diameters and Locations of Fuel Pellets. Series B Rods
(All measurements are given in inches.)

	Pellet	Rod B-1		Rod B-2		Rod B-3	
		Interface*	Diameter	Interface	Diameter	Interface	Diameter
Bottom		- 0		- 0		- 0	
UO_2-Mo Fiber Pellets	1	- 1-9/16	0.4713-0.4724	- 2	0.4712-0.4720	- 1-5/8	0.4715-0.4720
	2	- 3-1/16	0.4715-0.4718	- 3-7/16	0.4700-0.4715	- 3-1/8	0.4712-0.4720
	3	- 4-5/8	0.4715-0.4715	- 4-15/16	0.4721-0.4728	- 4-11/16	0.4712-0.4715
	4	- 6-3/16	0.4715-0.4721	- 6-7/16	0.4711-0.4715	- 6-1/4	0.4705-0.4710
	5	- 7-5/8	0.4719-0.4719	- 8	0.4710-0.4710	- 7-3/4	0.4708-0.4720
	6	- 9-1/8	0.4715-0.4719	- 9-9/16	0.4715-0.4718	- 9-5/16	0.4712-0.4715
	7	-10-9/16	0.4711-0.4718	-11-1/16	0.4715-0.4718	-10-13/16	0.4712-0.4712
	8	-12-1/8	0.4708-0.4718	-12-1/2	0.4712-0.4715	-12-3/8	0.4700-0.4715
	9	-13-5/8	0.4700-0.4715	-13-15/16	0.4712-0.4715	-13-7/8	0.4710-0.4715
	10	-15-1/8	0.4715-0.4718	-15-1/2	0.4690-0.4710	-15-7/16	0.4709-0.4709
	11	-16-5/8	0.4700-0.4712	-17-1/16	0.4715-0.4718	-16-15/16	0.4712-0.4716
	12	-18-1/8	0.4711-0.4717	-18-1/2	0.4715-0.4718	-18-1/2	0.4703-0.4713
	13	-19-3/4	0.4712-0.4722	-20	0.4708-0.4716	-20-1/16	0.4705-0.4705
	14	-21-1/4	0.4712-0.4715	-21-1/2	0.4712-0.4722	-21-1/2	0.4711-0.4715
	15	-22-7/8	0.4712-0.4717	-23-1/16	0.4712-0.4718	-23	0.4708-0.4710
	16	-24	0.4712-0.4712	-24	0.4712-0.4718	-24	-
Regular Pellets	17		0.4702		0.4702		0.4705
	26		0.4708		0.4715		0.4706
	36	-36-1/8	0.4705	-35-5/16	0.4708	-36-1/8	0.4708

*Pellet interface location measured from bottom of fuel column.

fuels. As shown previously in Figure 5. the bottom 7.8 cm (~3 inches) is filled with the conventional fuel to raise the cermet fuel column so that the midpoint of this section is in the peak heat flux region of the rod.

Since their densities were not uniform. the pellets made from the coated particles were segregated according to their bulk densities and then distributed among the three rods so that in each of the three cermet fuel zones formed. the pellets could be arranged in a cosine-type density distribution. The middle of each zone had the highest density pellets and was placed in the peak heat flux region. The pellet diameters and interface locations were measured. These measurements and the pellet densities are presented in Table 6.

The outside diameters of all the pellets in these three rods were within the tolerance of 0.470 to 0.471 inch leaving a pellet-to-clad diametral clearance of 0.07 to 0.102 mm (0.003 to 0.004 inch). There were three undersized molybdenum-bearing pellets which could not be ground uniformly. The dimensions of these pellets are referenced in Table 7 by an asterisk. Additional details on these rods are given in the tabulated summary.

4. Final End Closure

All the loaded tubes were evacuated in a weld chamber to less than 10^{-3} torr and back-filled with reactor grade helium to 1 atm. The top end plugs were then welded to complete the fabrication. The completed rods were tested for leaks in a helium mass spectrometer leak detector and x-rayed as a final check before they were assembled into the fuel bundle. Figure 14 shows the arrangement of the fuel rods in the assembly.

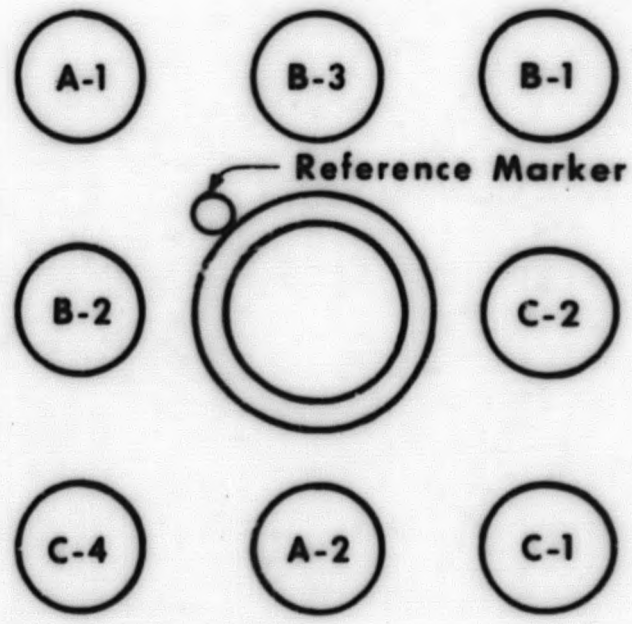
TABLE 6. Diameters, Locations, and Densities of Fuel Pellets, Series C Rods
(All measurements are given in inches.)

	Pellet	Rod C-1 Interface	Rod C-1 Diameter	Rod C-1 Density	Rod C-2 Interface	Rod C-2 Diameter	Rod C-2 Density	Rod C-4 Interface	Rod C-4 Diameter	Rod C-4 Density
	1	- 3-1/16	0.4705	>95	- 3-1/16	0.4705	>95		0.4701-0.4707	>95
Coated-Particle Pellets	7	- 4-1/8	0.4700-0.4702	88.7	- 4	0.4700-0.4702	88.9		-	-
	8	- 5-1/4	0.4706-0.4708	88.9	- 5-3/16	0.4700-0.4702	88.9	- 4-1/16		
	9	- 6-5/16	0.4702-0.4704	89.1	- 6-1/4	0.4702-0.4706	89.1	- 5-1/4	0.4701-0.4703	84.8
	10	- 7-3/8	0.4700-0.4705	89.2	- 7-3/16	0.4702-0.4704	89.4	- 6-1/16	0.4703-0.4704	88.4
	11	- 8-5/16	0.4706-0.4704	90.0	- 8-9/32*	0.4698-0.4702	90.4	- 7-1/2	0.4700-0.4702	88.6
	12	- 9-5/16	0.4702-0.4704	90.5	- 9-7/16	0.4660-0.470	90.8	- 8-1/2	0.4702	89.1
	13	-10-1/16	0.4700-0.4705	90.7	-12-1/8	0.4700-0.4702	96.5	- 9-9/16	0.4703	90.1
	14	-11-1/16	0.4702-0.4705	91.8	-13-5/16	0.4700-0.4702	88.6	10-9/16	0.4704-0.4705	90.3
	15	-12-1/16	0.4704	94.6	-14-1/2	0.4700-0.4706	88.3	-12-3/16	0.4702-0.4704	90.6
	16	-12-7/16	0.4705	90.0	-15-5/8	0.4700-0.4702	88.2	-13-1/32	0.4704	94.5
	17	-13-9/16	0.4702	88.5	-16-7/8	0.4700-0.4702	88.1	-14-1/32	0.4705	90.7
	18	-14-3/4	0.4705	88.3	-18-1/8	0.4700-0.4704	88.0	-15-1/4	0.4702-0.4703	90.5
	19	-15-1/16	0.4705	88.2	-19-1/4	0.4700-0.4704	87.9	-17-7/16	0.4703-0.4704	90.1
	20	-16-3/32	0.4705	88.1	-20-9/16*	.455	87.7	-19-1/4	0.4700	89.2
	21	-17-7/32	0.4704	88.0	-21-1/2	0.4705	86.9	-20-1/2	0.4702-0.4703	87.7
	22	-18-15/16	0.4700	87.7	-22-3/8	0.4702-0.4705	85.8	-21-9/16	0.4702	86.4
	23	-20-1/8	0.4702-0.4704	87.5	↑	0.4705	>95	-22-5/8	0.4704	84.6
	24	-21-5/16	0.4705	86.2		↕	↕	-23-5/8	0.4702-0.4705	84.2
	25	-22-1/4	0.4702-0.4706	85.7	↓			-23-5/8	0.4707	>95
*Regular Pellets	26	-22-1/4	0.4705	>95	-22-3/8	0.4705	>95	-23-5/8	0.4707	>95
	52	-36	0.4705	>95	-36-1/16	0.4705	>95	-36-5/16	0.4707	>95

Note: Rod No. C-3 was a substitute rod later replaced by C-4.

Summary of Fuel Rod Fabrication Data
(All measurements are given in inches.)

Identification	I - Series A Rods Regular Pellet A-1	I - Series A Rods Regular Pellet A-2	II - Series B Rod UO_2 + Mo Fiber Pellet B-1	II - Series B Rod UO_2 + Mo Fiber Pellet B-2	II - Series B Rod UO_2 + Mo Fiber Pellet B-3	III - Series C Rod Coated UO_2 Pellet C-1	III - Series C Rod Coated UO_2 Pellet C-2	III - Series C Rod Coated UO_2 Pellet C-4
Net Fuel Weight, gm								
Regular Pellets, UO_2	1054.2	1051.4	350.3	344.5	359.2	493.9	492.6	493.3
Cermet Pellets, including molybdenum	-	-	683.3	684.0 (20 wt % Mo)	672.4	487.3	483.9 (16.7 wt % Mo)	465.2
Enrichment								
Regular Pellets	6.4 →							
Cermet Pellets			8.0	Same for Rods in both groups, B & C →				
Pellet Density								
Regular Pellets	96.0	Same in all groups →						
Cermet Pellets			94.4% →			Various - See Table 5.		
Fuel-Column Length, inches								
Regular Pellets	35-7/8	35-3/4	12-1/8	11-5/16	12-1/8	3-1/16 & 13-3/4	3-1/16 & 13-11/16	4-1/16 & 12-11/16
Cermet Pellets	-	-	24-0	24-0	24-0	19-3/16	19-5/16	19-9/16
Total	35-7/8	35-3/4	36-1/8	35-5/16	36-1/8	36-0	36-1/16	36-5/16
No. of Pellets								
Regular Pellets	70	70	23	23	23	6 & 27	6 & 27	8 & 25
Cermet Pellets			16	16	16	19	16	16
O.D. of Pellets								
Regular Pellets	0.470-0.471	Same in all groups →						
Cermet Pellets			0.470-0.472 →			0.470-0.471 →		
Tube								
I.D., inch	0.474 →							
O.D., inch	0.514-0.515 →							
Plenum Length, inches	3-5/8	3-7/8	3-5/8	3-7/8	3-3/8	3-1/2	3-1/2	3-1/4
Over-All Length, inches (measured from shoulder of bottom end plug to tip of stud of top end plug)	41-25/32	41-25/32	41-25/32	41-25/32	41-13/16	41-13/16	41-25/32	41-3/4



Series A Reference rods
Series B Mo fiber & UO_2
Series C Mo-coated UO_2

FIGURE 14. ARRANGEMENT OF FUEL RODS IN SPECIAL ASSEMBLY 9-L

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ACKNOWLEDGMENTS

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APPENDIX

CALCULATIONS PERFORMED TO ESTIMATE OPERATION TEMPERATURES OF CERMET FUELS USED IN SPECIAL ASSEMBLY 9-L

Estimates of the operating temperatures to be reached in the UO_2 and the cermet fuels used in Special Assembly 9-L were calculated. A summary of the calculations performed is presented.

The radial temperature profiles at the peak heat flux region of the fuel rods and the axial centerline temperature profiles were calculated for three peak heat flux conditions: ϕ = 141.8. 157.5. and 173.2 W/cm^2. The profiles were determined for the sintered UO_2 pellets in the reference rods. the UO_2-molybdenum fiber mixture. and the pellets made from the UO_2 particles coated with molybdenum.

The calculations were performed in two parts. In Part 1 calculations for estimating the thermal conductivity of the cermet fuels were made. In Part 2 calculations were made of the temperature distribution. Each part is summarized in the following paragraphs.

THERMAL CONDUCTIVITY FOR THE UO_2-MO CERMET FUELS

Thermal conductivity values of UO_2-Mo cermet fuels up through the temperature of about 1600° C were not available. A suitable theoretical model for calculating the thermal conductivity values for such mixtures also was not available. In the absence of a model. and because of the dependence of the thermal conductivity upon the metal content and the structure of the mixture. accurate values of thermal conductivity can be obtained only by actual measurement of the mixtures in each particular case.

Thermal conductivity measurements of the cermet fuels used in this experiment were not included in this program. In lieu of these measurements, it was planned to use the values reported by Paprocki, et al.,* for similar UO_2-molybdenum mixtures. The molybdenum contents in the fuel compacts were thus specified to be the same as the BMI compacts, i.e., 20 vol % molybdenum.

In actual practice. however, this target amount of molybdenum was not achieved, particularly in the compacts made from the coated particles. Because of this condition and the need to obtain conductivity values for temperatures beyond those reported, it was decided tc calculate the thermal conductivity based on a weighted average procedure. A homogeneous mixture of the UO_2 and molybdenum components was assumed. In this case, the effects of the two different forms in which the molybdenum was added. i.e., as fibers and as coating, were not differentiated. Variations in the metal content only were then taken into account by this procedure.

The curves obtained by plotting the results of calculation from this procedure were modified further to bring them into conformance with the reported values for the lower temperature range. In effect this adjustment was an arbitrary means to compensate for deviations from the ideal case of a perfectly homogeneous mixture.

The thermal conductivities were calculated by

$$k_{mixture} = k_{UO_2} \times \text{vol \% } UO_2 + k_{Mo} \times \text{vol \% Mo.}$$

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*Paprocki, S. J., et al., "Preparation and Properties of UO_2 Cermet Fuels," BMI-1487, December 19. 1960.

Thermal conductivity values of pure molybdenum were obtained from the "Rare Metals Handbook."* Thermal conductivity values of 95% T.D. sintered UO_2 were obtained from M. F. Lyons.**

Figure A-1 shows the thermal conductivity curves for the Series B and C fuel compacts used in this experiement. The Series B compacts contain 20 vol % molybdenum, and the Series C, 15.8 vol % molybdenum.

Two curves taken from Paprocki are shown in Figure A-1. These curves were for compacts having 20 vol % molybdenum. The B′ and C′ curves show the adjustments made: the referenced curves were used as guides.

A sharp rise in the thermal conductivity at the higher temperatures is shown for one of the reference curves. A similar kind of trend, though not as pronounced, was reported by Baskin, et al.,*** for thoria-molybdenum fiber compacts. A possible reason given for this behavior was the closing of gaps between the metal and oxide phases and also the closing of cracks in the UO_2 to increase the heat transfer through the compact. This behavior would probably raise the B′ and C′ curves from 1000° C. In the traces shown, curves B′ and C′ do not account for this trend and therefore are believed to be conservative estimates in this respect.

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* "Rare Metals Handbook," C. A. Hamper, editor, 2nd Ed., Reinhold Publishing Corporation, 1961. p. 291.

** Lyons, M. F., et al., "UO_2 Thermal Conductivity at Elevated Temperatures." paper presented at ANS Meeting, June 17, 1963, Salt Lake City, Utah.

*** Baskin, Y., Harada, Y., and Handwerk, J. H., "Some Physical Properties of Thoria Reinforced by Metal Fibers," Journal of American Ceramic Society, Ceramic Abstracts, Vol. 43, pp. 489-492, September, 1960.

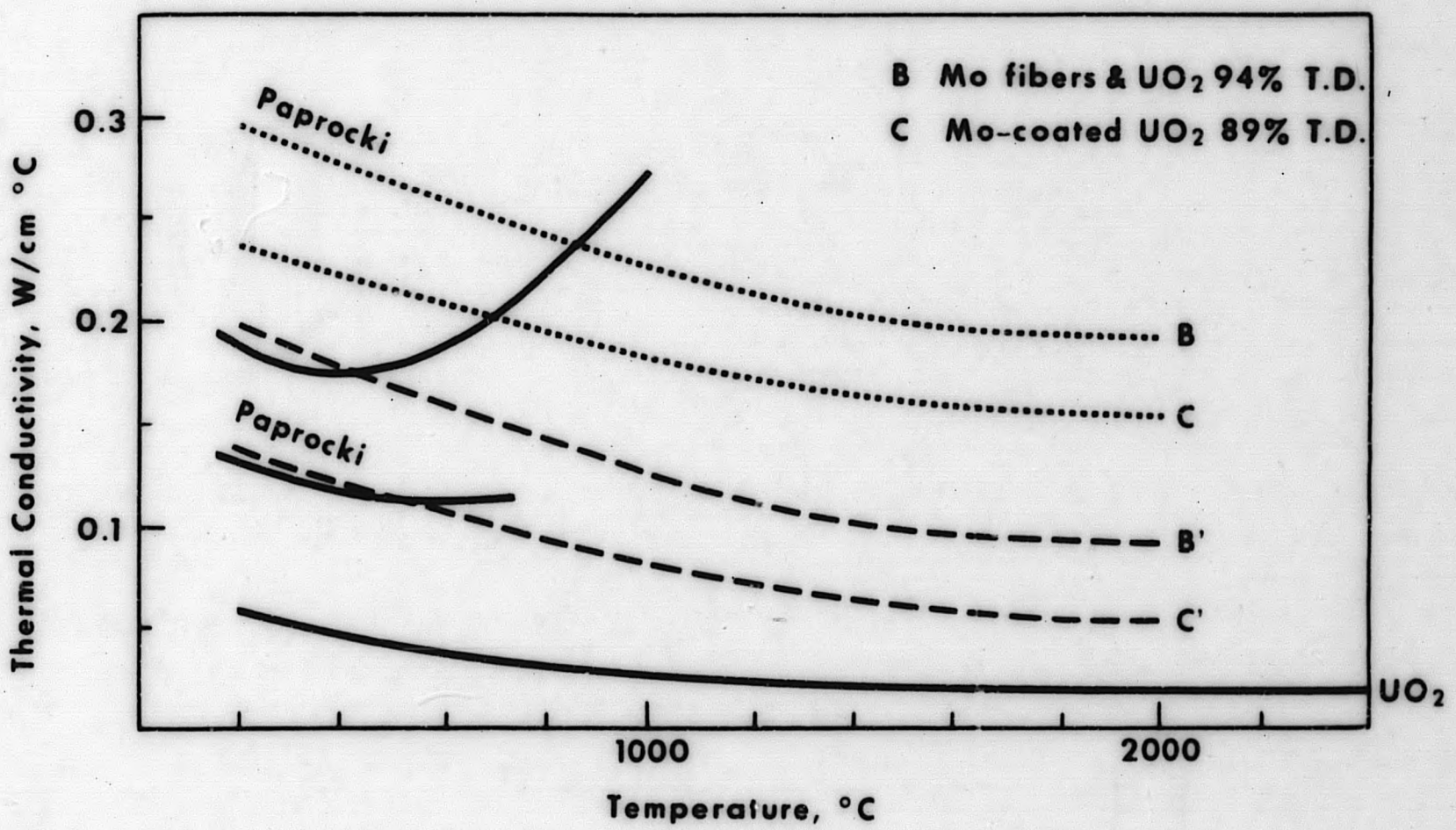


FIGURE A-1. ESTIMATED THERMAL CONDUCTIVITIES OF UO_2 - Mo CERMETS

The B′ and C′ curves were replotted on semilog paper and expressions of the thermal conductivity were derived in terms of temperature. For simplification, a straight line function was fitted up to about 1600° C. Preliminary calculations showed that the maximum temperature in these cermet fuels would not exceed this temperature at the operating surface heat fluxes of the rods. The

$$\int_0^T k\,dT$$

for T = 0 to T = 1600 values were calculated using these expressions and plotted as shown in Figure A-2. The $\int k\,dT$ curve for pure UO_2 is plotted also.* These were the curves used to calculate the tmperature distribution in the fuels.

TEMPERATURE PROFILE CALCULATIONS

Axial Profiles

Gross power distribution from the fuel rod was assumed to be as shown in Figure A-3. A peak-to-average ratio of 1.5 to 1 was assumed. The axial profile was determined by calculating the average centerline temperature of 12 equal segments of the fuel rod. The average heat flux in each of these 12 segments was determined by proportion using the gross power distribution assumed. This procedure was repeated for each of the three peak heat flux conditions investigated.

The fuel surface temperatures were calculated using the following thermal resistances. The calculations were performed in English units; sample calculations shown here are shown in these same units. The final results were converted into metric units for plotting in graphs.

*Op. cit. Lyons, et al.

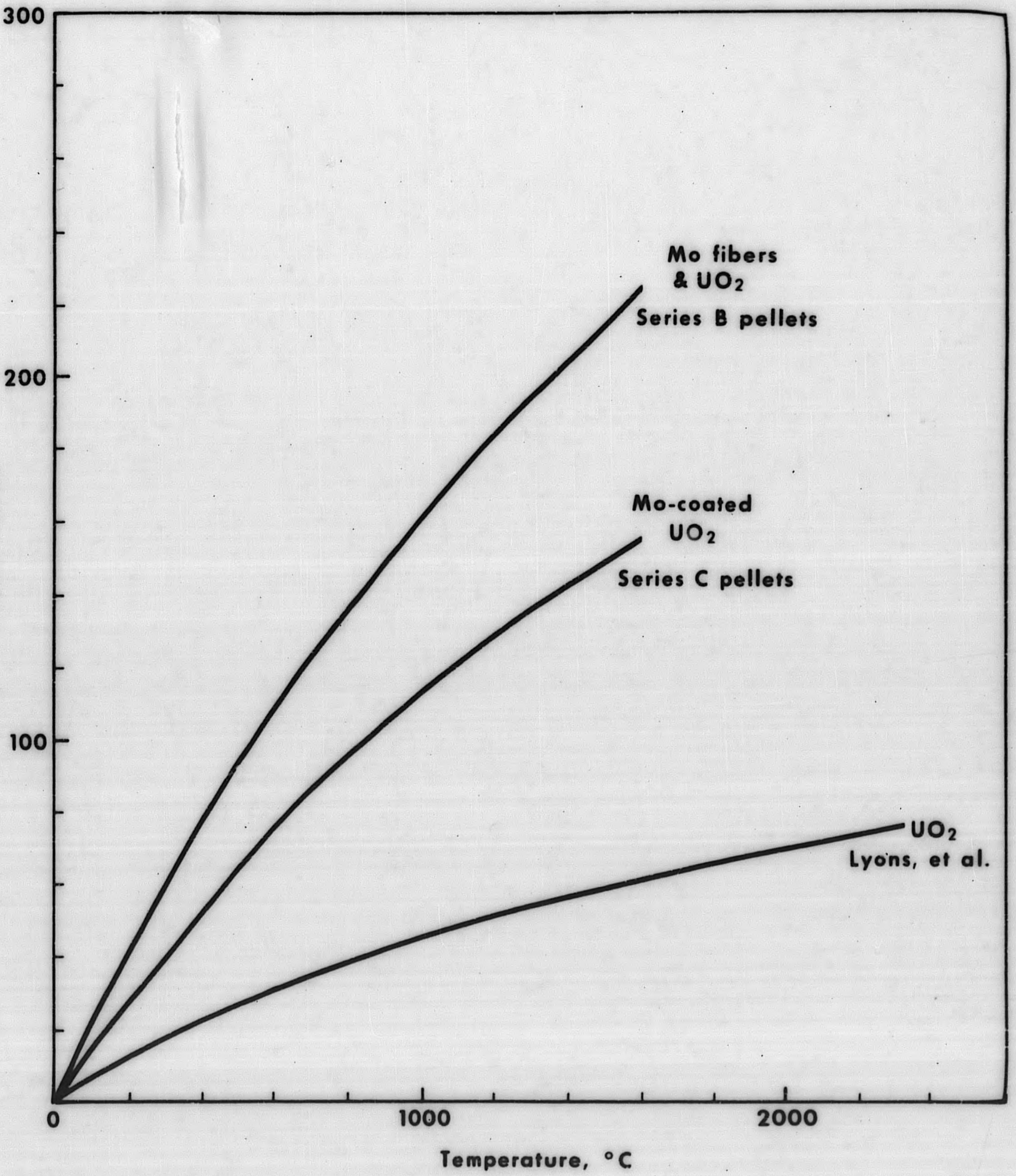
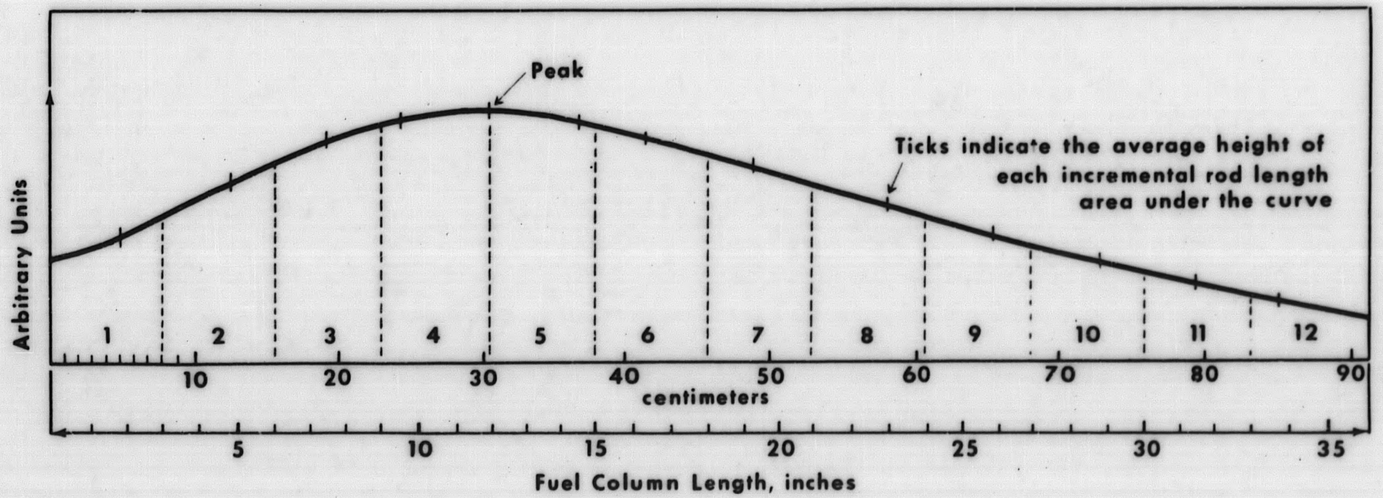


FIGURE A-2. ∫ kdT VERSUS TEMPERATURE OF THREE FUELS USED IN SPECIAL ASSEMBLY 9-L

VAL 5015



Peak-to-Average Ratio = 1.5

FIGURE A-3. GROSS POWER DISTRIBUTION ALONG ROD USED IN SPECIAL ASSEMBLY 9-L

$$R_{film} = 1/hA_o$$
$$= 7.42 \times 10^{-4} \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$$

where h is film conductance (10^{-4} Btu/h-ft^2) and A_o is fuel rod surface area (ft^2/ft).

$$R \text{ clad} = m\,(ro_o/r_i)/2\pi k$$
$$= 11.58 \times 10^{-4} \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$$

where r is clad radius and k is thermal conductivity of stainless steel equal to 11.1 Btu/h-ft^2-$^\circ$F.

$$R \text{ gap} = 1/hA_i$$
$$= 80.70 \times 10^{-4} \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$$

where h is gap conductance equal to 1000 Btu/h-ft^2-$^\circ$F.

$$T_{\text{fuel surface}} = 546 + A\Sigma R\phi$$
$$= 546 + 13.45 \times 10^{-4}$$

where ϕ is heat flux (Btu/h-ft^2).

Power generation was assumed to be the same in both the sintered UO_2 and cermet pellets. A parabolic distribution within the fuel was considered. The centerline temperatures determined for each incremental length were plotted for each of the three heat flux conditions. The axial temperatures are shown in Figure 1.

Radial Profiles

The radial profiles were calculated for the three peak heat flux conditions only in each type of fuel. A parabolic distribution of the power was considered. The temperatures are plotted in Figure 2.

END