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INFLUENCE OF THERMAL RATING AND BULK DENSITY ON IRRADIATION PERFORMANCE OF FUSED UO_2 TUBULAR FUEL ELEMENTS

G. R. COLE

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INFLUENCE OF THERMAL RATING AND BULK DENSITY ON IRRADIATION PERFORMANCE OF FUSED UO_2 TUBULAR FUEL ELEMENTS

by

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August 1966

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ABSTRACT

Mechanically compacted tubes of fused and ground UO_2 in Zircaloy sheaths, with bulk densities between 82 and 90% of theoretical, were irradiated in the Heavy Water Components Test Reactor (HWCTR) to 3500 MWD/Te_u at thermal ratings* up to 50 watts/cm. Fission gas release up to 60% and extensive columnar grain growth occurred in elements operating at thermal ratings of approximately 40 to 50 watts/cm. Gas release was not significantly affected by bulk density. The tubes of lower density, 82 to 87%, that operated at the higher thermal ratings experienced substantial decreases in core volume and formed a lengthwise ridge in the outer sheath.

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* Thermal rating = $\int_{T_s}^{T_c} k\,d\theta$

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INFLUENCE OF THERMAL RATING AND BULK DENSITY ON IRRADIATION PERFORMANCE OF FUSED UO_2 TUBULAR FUEL ELEMENTS

INTRODUCTION

The fabrication and irradiation of tubular uranium dioxide fuel elements at the Savannah River Laboratory was part of the Du Pont development program on heavy-water-moderated power reactors. Emphasis was on a nested tubular fuel element of fused UO_2 mechanically compacted into Zircaloy tubing because of the potential low cost of this element in a reactor fueled with natural or slightly enriched uranium. The performance of tubular elements under power reactor conditions was studied to investigate the effects of thermal rating*, exposure, and material and fabrication variables on fuel stability. A variety of test fuel elements were irradiated in the Heavy Water Components Test Reactor (HWCTR), which was put into service at the Savannah River Plant in October 1962 and was taken out of service in December 1964.

This report gives the results of the postirradiation examination of two assemblies in a test designated as SOT-2.** The primary purpose of this test was to study the irradiation behavior of a UO_2-filled tubular fuel element, 2.1-inch OD and 1.2-inch ID, at thermal ratings up to 50 w/cm in order to define the limiting values of certain fabrication and design parameters, such as allowable core density, nitrogen content of the UO_2, and allowable thermal rating for the particular shape. The two assemblies discussed in this report were discharged from the reactor because of sheath failures after a maximum exposure of 3500 MWD/tonne of contained uranium (MWD/Te_u). Other assemblies containing similar elements with lower thermal ratings (peak $\int k d\theta$'s of 25 to 30 w/cm) reached exposures greater than 11,000 MWD/Te_u without incident.

It is noteworthy that some of the information from this test was a direct result of the highly realistic test conditions in the HWCTR and could not have been obtained, for example, from an irradiation at low coolant pressure.

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* Thermal rating = $\int_{T_s}^{T_c} k d\theta$

** SOT = Segmented Oxide Tubes.

SUMMARY

A group of sixteen Zircaloy-sheathed tubular fuel elements of fused uranium dioxide fabricated by vibration-plus-swaging or by vibrational compaction alone were irradiated at thermal ratings of approximately 5 to 50 w/cm to exposures up to 3500 MWD/Te_u. In four of the sixteen elements, the outer sheath collapsed to form a longitudinal ridge and, in two cases, the sheath cracked at the apex of the ridge. The ridge formed only in fuel elements with low initial core densities, 82 to 87% of theoretical, that operated at thermal ratings of approximately 40 to 50 w/cm.

Fission gas release in the fuel elements ranged from 2 to 62% of that formed; the fractional release increased with thermal rating and rose sharply in the range of 25 to 30 w/cm. The nitrogen released by the UO_2 during irradiation varied from 0.2 to 23 cc/kg of UO_2, which was well below the amount required to collapse the inner sheath of the tubular element. One tube contained a large quantity of deuterium gas, 218 cc/kg, presumably from D_2O that leaked into the element during irradiation; the point of entry was not located.

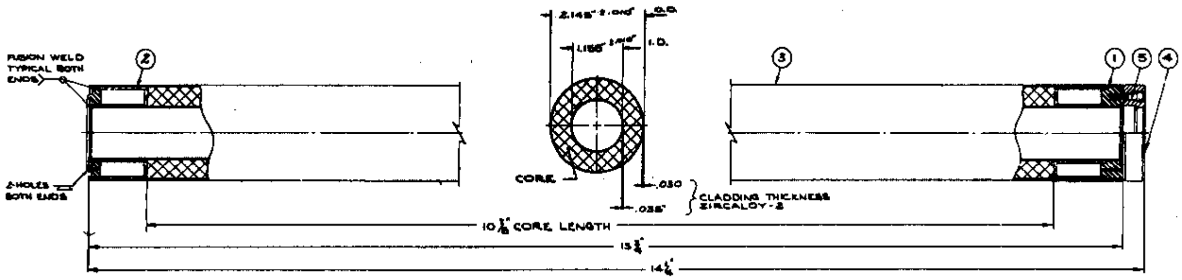
Cross sections of the core showed that weak sintering occurred at thermal ratings as low as about 5 w/cm and that a transition to columnar grain growth occurred at about 25 to 30 w/cm. The transition to columnar grain growth is believed to be responsible for the sharp increase in fission gas release observed at approximately the same thermal rating.

DISCUSSION

DESCRIPTION OF FUEL ELEMENTS

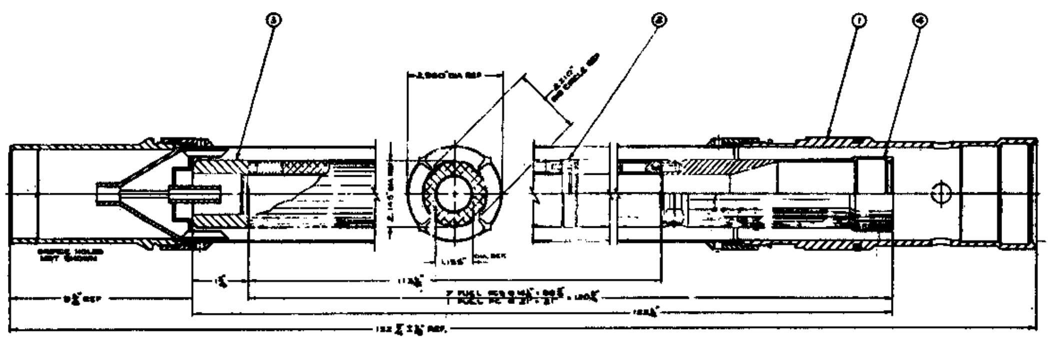
The sixteen fuel elements were mechanically compacted with natural UO_2 in Zircaloy-2 sheaths. Suitably sized particles of fused UO_2 were compacted by vibration alone or vibration-plus-swaging. Nominal overall tube dimensions were 2.145-inch OD by 1.155-inch ID by 14-1/4 inches long; the active core length was 10-7/8 inches (Figure 1). The as-fabricated core density and method of compaction for each tube are listed in Table I. Carbon-steel void chambers were inserted at the ends of each fuel tube to provide additional free volume (Figure 1). Eight 1/32-inch-diameter holes were drilled in the end of the chamber to permit entry of gas generated by the UO_2 in the core. The volume of the two chambers in each fuel element was approximately equal to the free volume in the core.

The tubes were irradiated in two ten-foot assemblies designated SOT-2-2 and SOT-2-3 (Figure 2).



1 Void Chamber End Plug
2 Void Chamber
3 Vibrationally Compacted Tube, or Swaged Tube
4 Chuck Adapter
5 Screw

FIG. 1 FUSED UO_2 TUBE



1 Housing Assembly HWCTR Fuel Elements
2 Segmented Oxide Tube
3 Bottom Spacer
4 Top Fuel Piece Subassembly

FIG. 2 SEGMENTED UO_2 FUEL ASSEMBLY

IRRADIATION CONDITIONS

The tubes were irradiated under power reactor conditions in the HWCTR. The mean temperature of the heavy water coolant ranged from 200 to 250°C; pressure varied between 1000 and 1200 psig.

The maximum conditions experienced by any fuel element in these two assemblies occurred during an exposure of 3500 MWD/Te_u at a thermal rating of 50 w/cm. Maximum surface heat flux was about 600,000 $Btu/(hr)(ft^2)$. Both assemblies underwent seven scrams from power during irradiation. Irradiation conditions calculated from reactor operating data are included in Table I. The values are based on the computed profile of total exposure; they are presented graphically in Figure 3 for Assembly SOT-2-3.

TABLE I

Fuel Element Fabrication Information and Irradiation Conditions

Position	Tube No.	Method of Compaction[a]	Collapse	Core Density, % of TD	$\int kd\theta$,[b] w/cm	Exposure,[b] MWD/Te_u
Assembly SOT-2-2						
1	Z-257C	V+S	No	89	3	200
2	Z-250B	V	No	83	11	800
3	Z-256A	V+S	No	90	25	1800
4	Z-251A	V	Yes	87	42	900
5	Z-251C	V	Yes	82	49	3500
6	Z-255B	V+S	No	90	47	3300
7	Z-257B	V+S	No[c]	89	34	2400
8	Z-252C	V	No	82	16	1100
Assembly SOT-2-3						
1	Z-254A	V+S	No	90	3	200
2	Z-251B	V	No	83	10	700
3	Z-256B	V+S	No	90	23	1500
4	Z-252B	V	Yes	83	39	2600
5	Z-254B	V+S	No	89	48	3200
6	Z-253C	V	Yes	85	45	3000
7	Z-257A	V+S	No	89	32	2100
8	Z-253B	V	No	85	15	1000

(a) V = Vibration alone.
V+S = Vibration plus swaging.

(b) $\int kd\theta$ and burnup estimates are based on reactor operating data and were averaged over the length of the element. The $\int kd\theta$ ratings correspond to the period of highest power generation.

(c) This element suffered incipient collapse at its "cold" end.

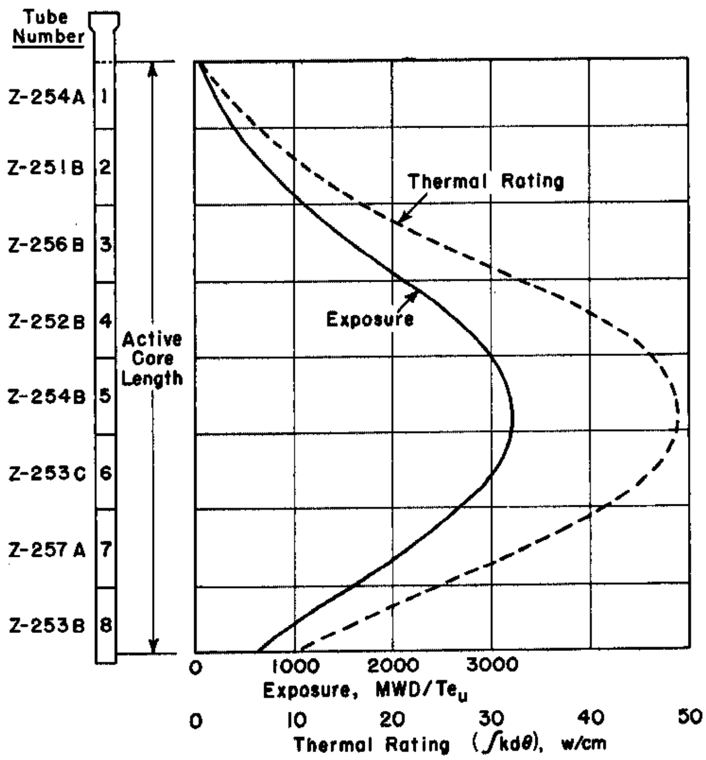


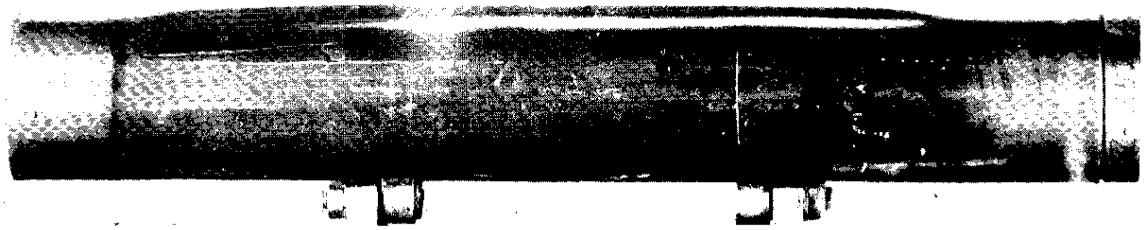
FIG. 3 EXPOSURE AND THERMAL RATING PROFILES
(For Assembly SOT-2-3. SOT-2-2 is similar)

Failure of Assembly SOT-2-2 was signaled during reactor startup; that of Assembly SOT-2-3 four hours after reactor shutdown. In both cases failure was detected by fission gas activity monitors; no particulate matter was released by the failures.

RESULTS OF THE POSTIRRADIATION EXAMINATION

Outer Sheath Collapse

Four of the sixteen fuel elements experienced outer sheath collapse, forming a ridge along the entire length of the core. Typical collapse and ridge appearance is shown in Figures 4A and B. Cross sections of the collapsed tubes showed that the UO_2 core filled the ridge and was in close contact with the sheath. The extent of the columnar grains, which were present in the ridge and elsewhere, indicated that the ridge was formed and filled with UO_2 for some appreciable time before nuclear shutdown. Two of these four elements developed small cracks in the Zircaloy sheath at the apex of the ridge, as shown in Figure 5. One of the four tubes formed a second ridge approximately 165° away from the larger ridge (Figure 6); it was smaller than the principal ridge in height (1/16 inch versus 5/32 inch) and in length (2 inches versus 10 inches).



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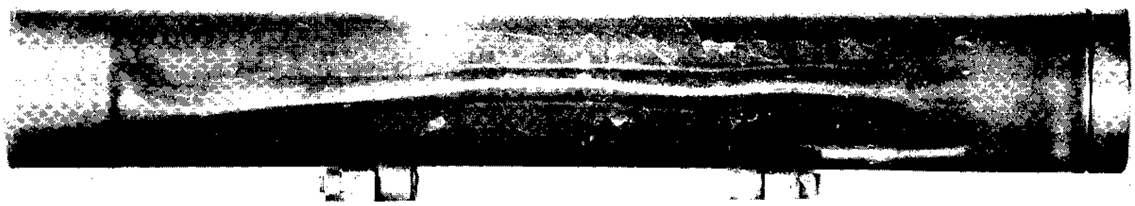

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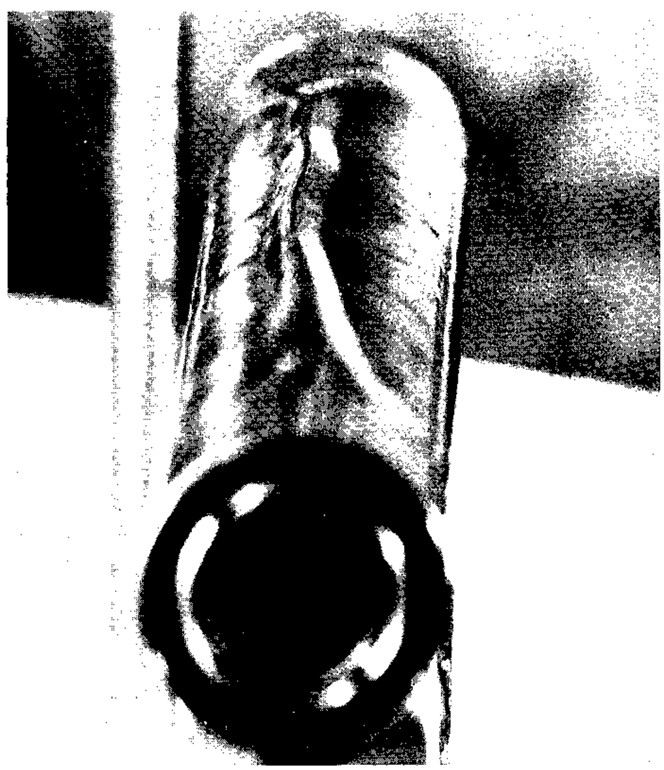
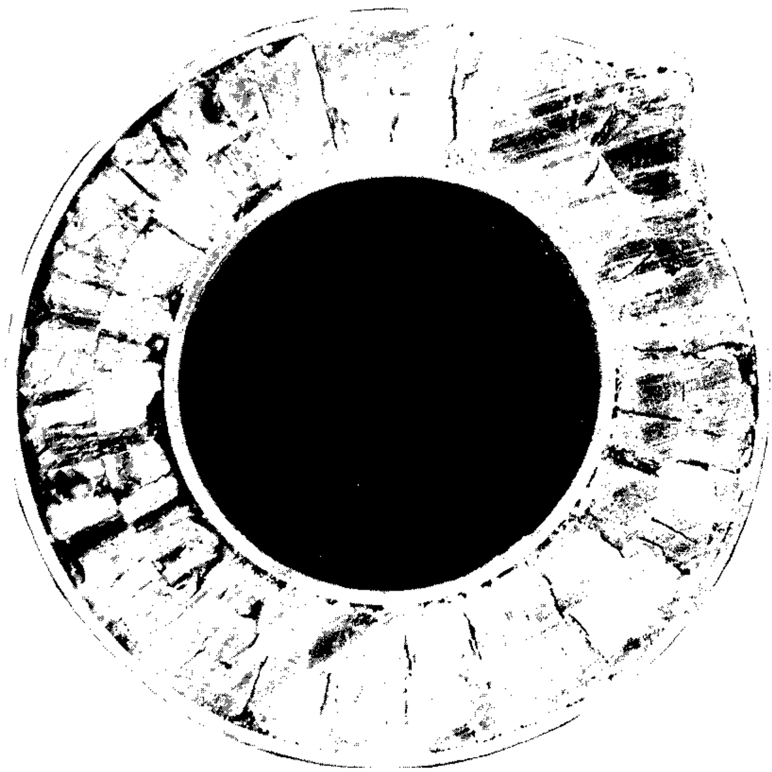


FIG. 4A SURFACE APPEARANCE OF COLLAPSED TUBE Z-252B



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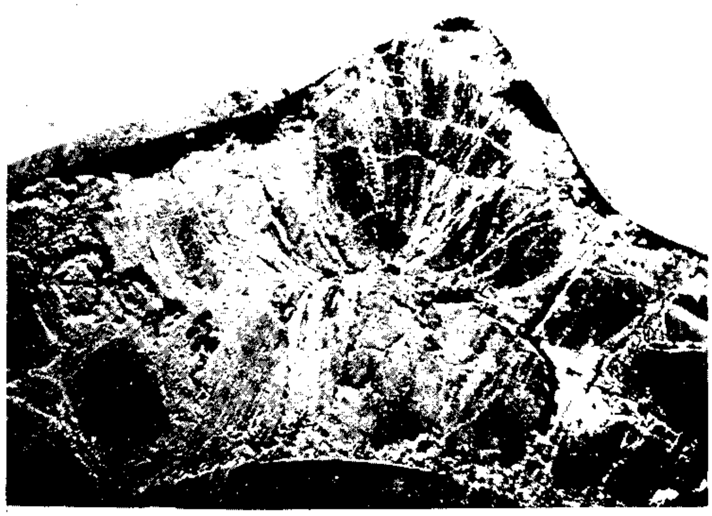

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FIG. 4B CROSS SECTIONS OF COLLAPSED TUBE Z-252B
Note extent of columnar grain growth and the migration of UO_2 into the ridge.

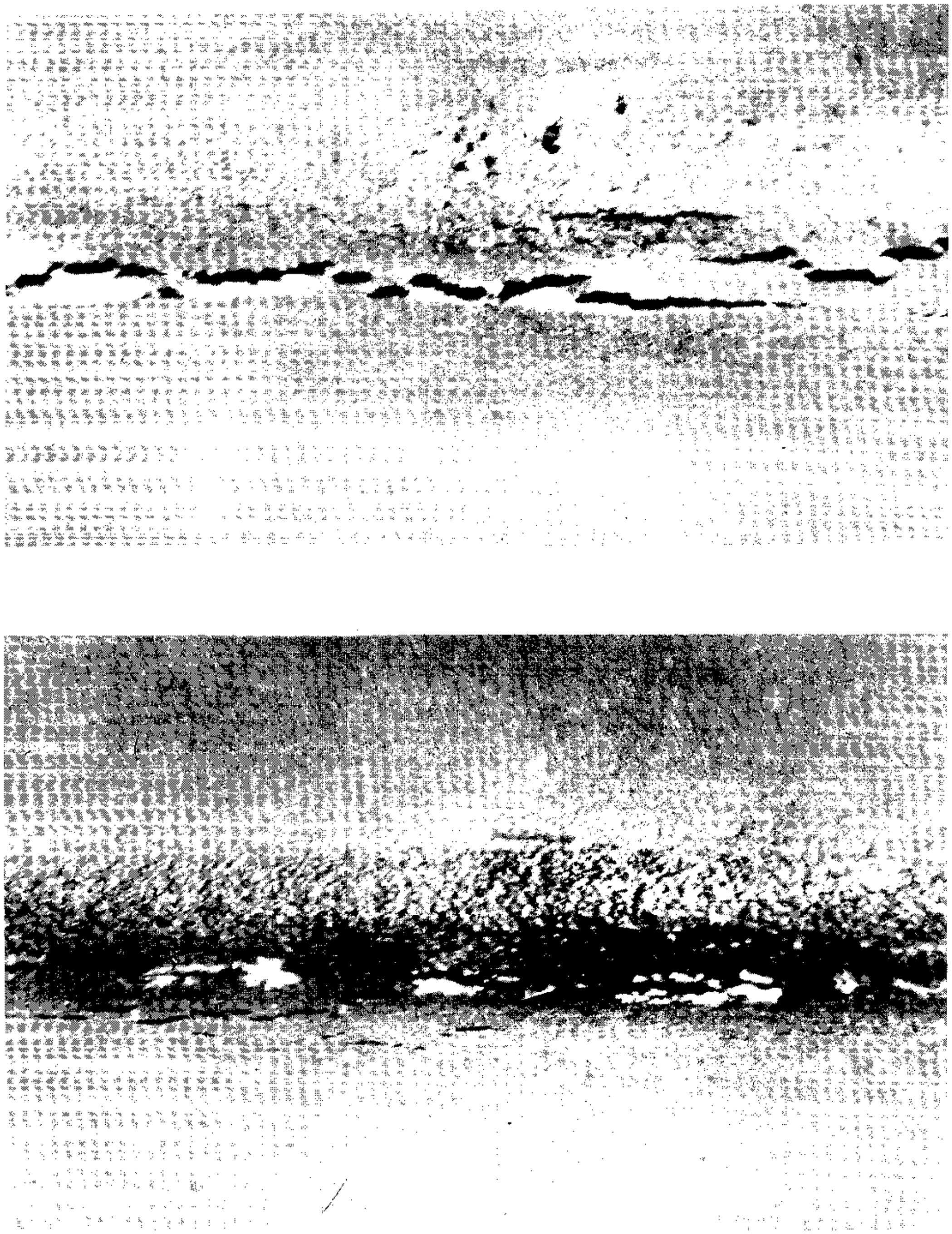


FIG. 5 SHEATH CRACKS AT THE APEX OF THE RIDGE (Z-253C)

40X

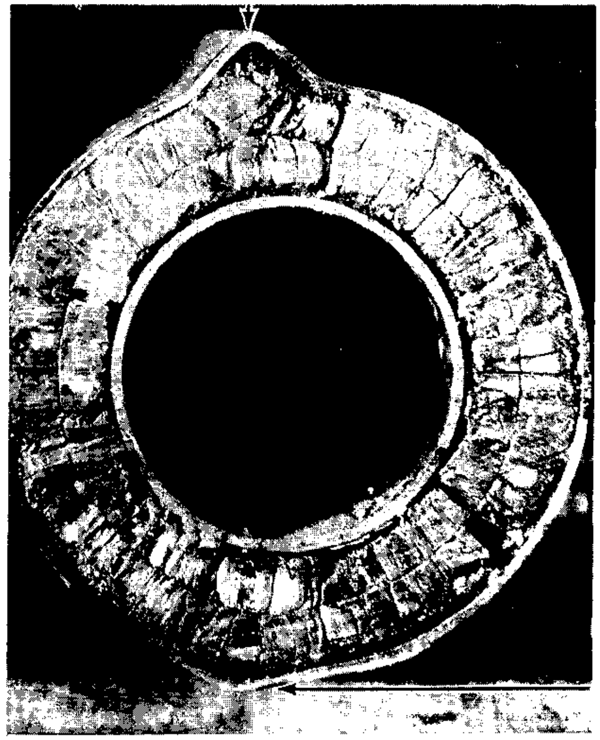


FIG. 6 COLLAPSED. TUBE WITH TWO RIDGES
(Center section of Z - 252B)

The extensive outer sheath collapse occurred only in fuel elements of low initial core density that operated at high thermal rating (approximately 40 to 50 w/cm). Each of the collapsed tubes was compacted by vibration alone to 82 to 87% of theoretical density. The lower the initial core density, the larger the volume decrease on collapse (Table II) and the sharper the ridge that was formed. The final core densities of the collapsed tubes ranged from 87 to 89% of theoretical if it is assumed that the volume decreases were due solely to core densification.

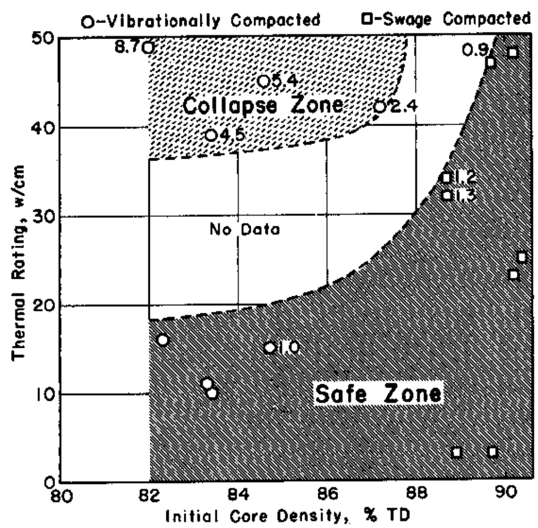
TABLE II

Core Volume Changes and Final Densities in the Collapsed Tubes

Tube No.	Volume Changes, %	Calculated Core Density, % TD	
		Preirradiated	Postirradiated
Z-251A	-2.4	87	89
Z-251C	-8.7	82	89
Z-252B	-4.5	83	87
Z-253C	-5.4[a]	85	88

(a) Estimated from OD and ID measurements.

A plot of initial core density versus thermal rating, with volume change during irradiation as a parameter, groups the tubes into distinct zones (Figure 7) to give a convenient visual presentation of a "Collapse Zone" and a "Safe Zone." There is a fairly large "No Data" region separating the two zones, but the presentation is helpful in establishing conservative design limits. The figure indicates that core densities of 90% of theoretical or higher are required for elements of this type to operate safely at thermal ratings of 40 to 50 w/cm. Because the mechanism is believed to be one of collapse due to external coolant pressure, fuel element diameter is an influential parameter; the results reported here apply specifically to tubes of approximately 2-inch OD, but analogous results should be obtained for other diameters.

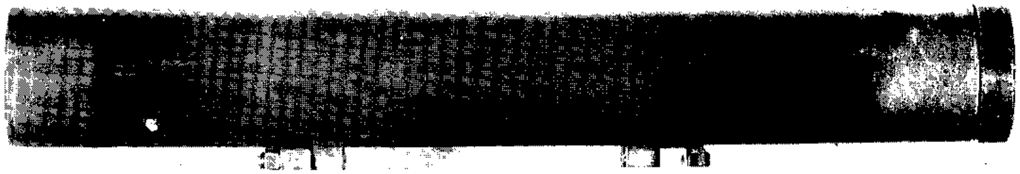


Each point represents an irradiated tube; the number beside each point is the percent decrease in core volume during irradiation. Volume changes less than one-half percent are not shown.

Tubes that experienced outer sheath collapse fall in a region shown as the "Collapse Zone". Its boundary is uncertain because of the "No Data" region between the "Collapse" and the "Safe Zones".

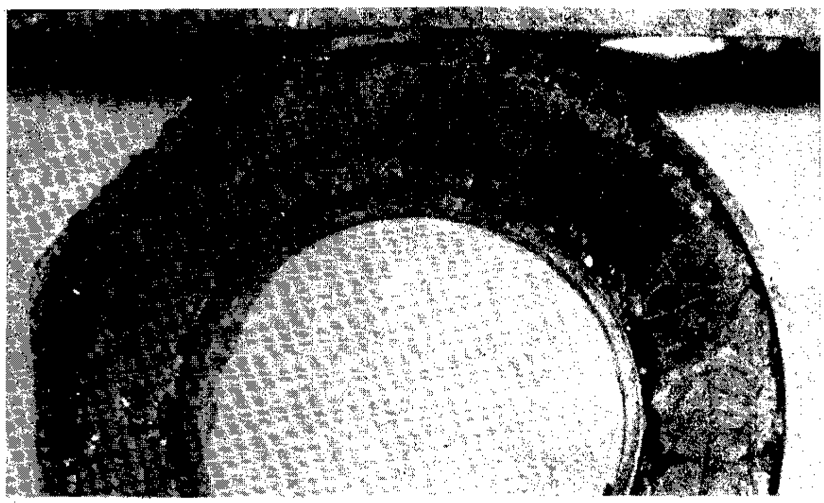
FIG. 7 EFFECT OF THERMAL RATING ($\int k d\theta$) AND CORE DENSITY ON IN-PILE VOLUME CHANGES AND OUTER SHEATH COLLAPSE OF SOT-2 TUBES

A short ridge, about two inches long, formed on the outer sheath of tube Z-257B (Figure 8). This tube had an average initial core density of 89% and operated at a mean thermal rating of 34 w/cm. The collapse occurred at the cooler end of the tube and is believed to have resulted from an unexpectedly low local density. Low core densities at the ends of the elements can be produced during fabrication when a portion of the core is removed mechanically to insert the end void chamber. There was a central cavity in the core under the highest part of the ridge, as shown in Figure 8B. There was no such cavity under the ridge in any of the four collapsed tubes discussed above.



A. Exterior view --- collapse region near left end

0.35X



2X

6.6X

B. Transverse section at collapse region

FIG. 8 LIMITED OUTER SHEATH COLLAPSE (Z-257B)

Flow of UO_2 in End Chambers

During irradiation, the UO_2 core forced the end of the steel insert aside and flowed into the void chamber in line with the outer sheath ridge in two of the tubes. The penetration was most extensive in the tube of lowest initial core density, Z-251C; the UO_2 entered the void chambers at both end of the tube (Figure 9). At the upper (and hotter) end of this tube, the core material filled about 75% of the chamber. The flange was later redesigned to provide additional support.

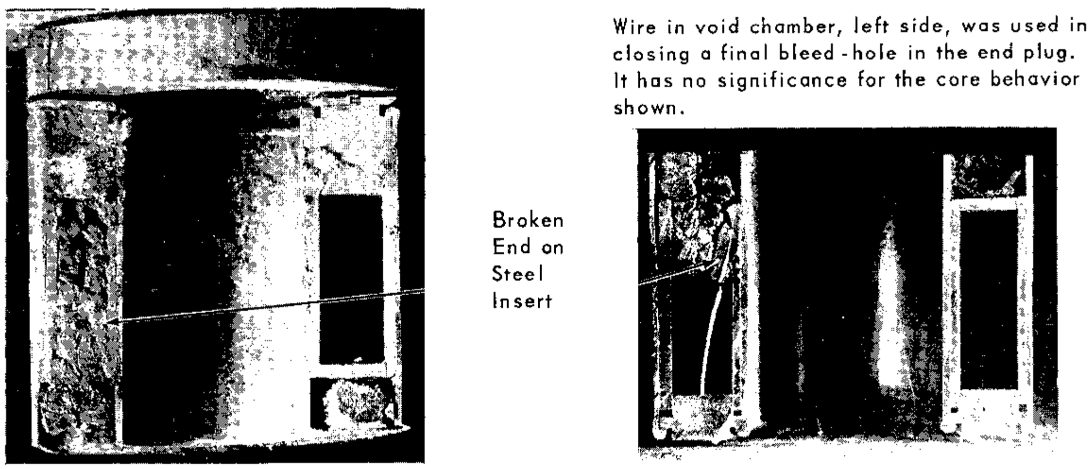


FIG. 9 UO_2 PENETRATION INTO END VOID CHAMBERS IN LINE WITH OUTER SHEATH RIDGE (Z-251C). The tube assembly drawing, Figure 1A, shows the relationship of void chamber to tube. (1X)

Dimensional Changes

Dimensional changes were significant only in the collapsed tubes. The mean decrease in OD of the collapsed tubes ranged from 0.014 to 0.054 inch, but the OD at the ridge increased as much as 0.105 inch. Changes in mean OD and ID for the remaining tubes were less than 0.002 inch.

Gas Release

The free gas contained in fourteen of the test fuel elements was collected, measured, and analyzed (Table III); the gas in the two cracked tubes was lost during operation. Each tube was punc-

TABLE III

Postirradiation Gas Content of SOT-2 Tubes

Tube No.	Gas Release (Major Constituents Only), cc/kg UO_2: Total	Xe	N_2	D_2	He	A	Volume of He + A, cc at STP	Initial Free Volume, cc	Xenon Release, % of that produced by fission
Assembly SOT-2-2									
Z-257C	23.5	0.05	0.7	ND	23	0.1	86	96	1.4
Z-250B	31.0	1.1	0.3	ND	29	0.6	107	122	7.6
Z-256A	48.8	4.8	16	ND	26	0.1	97	90	15
Z-251A	69.2	31	5.6	ND	28	1.3	111	107	57
Z-251C	Gas lost via sheath cracks								
Z-255B	69.2	39	0.2	ND	26	0.1	94	92	62
Z-257B	40.2	14	5.0	ND	16	0.2	56	96	33
Z-252C	31.5	ND	1.0	ND	30	0.03	109	126	0
Assembly SOT-2-3									
Z-254A	30.4	0.06	6.0	ND	24	0.3	86	92	1.8
Z-251B	30.3	0.3	1.5	ND	27	1.3	104	122	2.2
Z-256B	29.6	0.9	4.5	ND	24	0.1	88	91	3.0
Z-252B	76.4	29	11	ND	32	0.2	117	118	59
Z-254B	302	27	23	218	30	0.2	112	91	46
Z-253C	Gas lost via sheath cracks								
Z-257A	50.0	13	5.7	ND	28	0.3	102	96	33
Z-253B	26.6	0.3	5.9	ND	16	2.5	71	117	1.8

tured inside an evacuated system, and the free gas in the core was allowed to expand into the known volume of the closed system.[1] An aliquot of the gas was then analyzed by mass spectrography.

The fractional release of fission gas increased with increasing thermal rating, and ranged from 2 to 62% of that formed. The percent release of xenon is plotted in Figure 10 against the thermal rating; the correspondence of exposure to thermal rating is shown in Table I. Both fission xenon and krypton were detected, but for convenience only xenon, which was more than 80% of the fission gas, was plotted. A sharp increase in xenon release occurred in elements operating in the range of 25 to 30 w/cm. This increase is believed to be associated with the onset of columnar grain growth. There was no significant correlation of fission gas release with UO_2 bulk density.

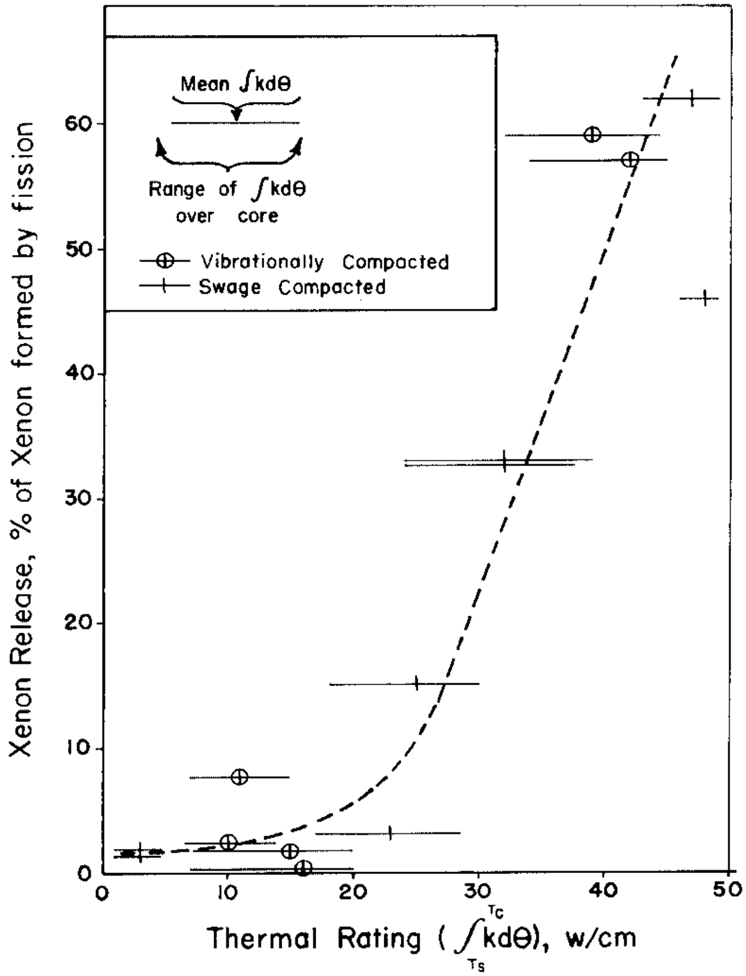


FIG. 10 INCREASE IN FISSION XENON RELEASE WITH INCREASE IN THERMAL RATING

The amount of nitrogen released by the core during irradiation was low, and indicated that nitrogen release from the UO_2 would not be an operational problem. The low values of nitrogen released in the present test confirmed the effectiveness of the treatment (4 hours in vacuum at 1200°C) used to outgas the UO_2. The average and maximum releases were 6 and 23 cc/kg, respectively (cc of gas at STP per kg of UO_2). The results for all the tubes (Figure 11) have a wide scatter, but a rising trend with thermal rating is evident. In previous irradiations of similar fuel tubes of fused UO_2, outgassed by different procedures, nitrogen release by the core was much greater, an average of 53 and a maximum of 118 cc/kg in nine tubes.[2,3]

The large quantity of deuterium in tube Z-254B was apparently due to a sheath failure that was not detected by routine post-irradiation examination.

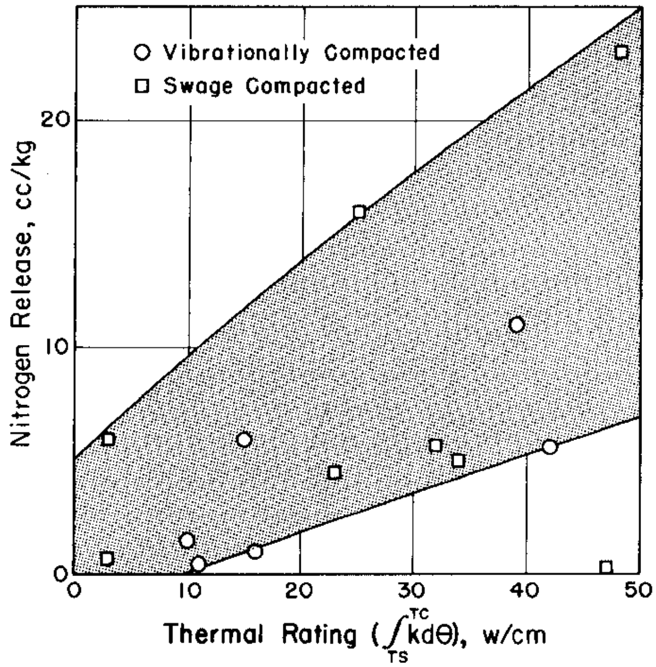


FIG. 11 INCREASE IN NITROGEN RELEASE WITH INCREASE IN THERMAL RATING

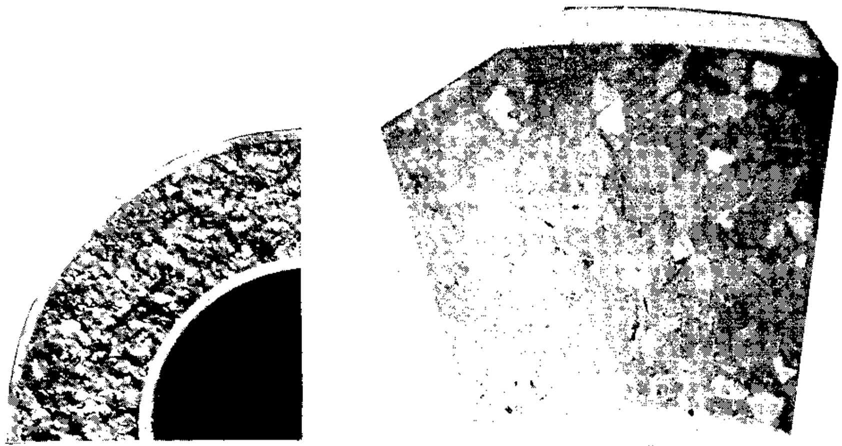
Core Structure versus Thermal Rating

The appearance of the as-cut core sections progressed from "weak sintering" to "extensive columnar grain growth" as the specific thermal rating increased from approximately 4 to 50 w/cm. The influence of thermal rating on core structure is of interest because of expected relationships between core structure and gas release, and because of possible contributions to a better understanding of core temperatures and in-pile thermal conductivities of powder-packed fuel elements.

The extent of in-pile sintering increased from weak to moderate as the thermal rating increased from 4 to 18 w/cm (Figure 12). The section from Z-256B, at approximately 18 w/cm, experienced sufficient sintering to exhibit core cracks in the as-cut section. The difference in particle sizes of the UO_2 powder used in swaged and in vibrated fuel tubes can be seen by comparing tubes Z-254A and Z-251B.

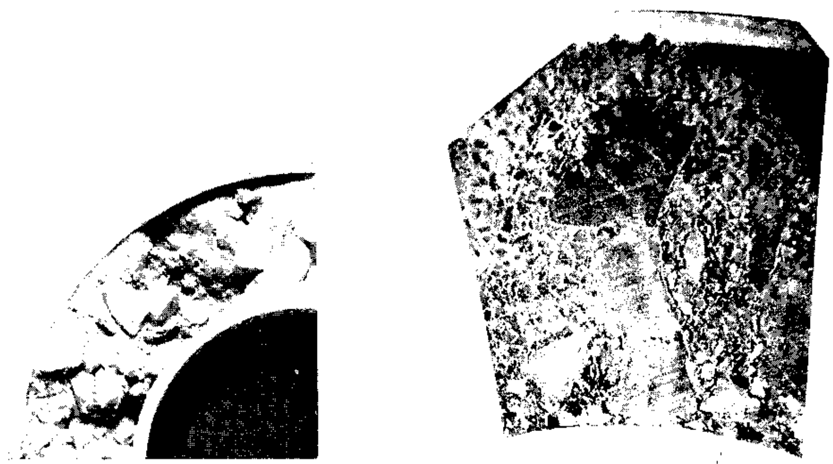
A transition to columnar grain growth occurred at a thermal rating between 25 and 30 w/cm. Examples of the transition are shown in Figure 13, where a section of tube Z-256B rated at approximately 28 w/cm shows strong sintering but no grain growth; two sections of tube Z-257A, one at approximately 27 w/cm and one

AS - CUT GROUND



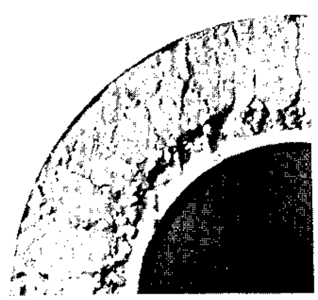
2X 5X

A. Transverse section of swaged tube Z-254A rated at approximately 4 w/cm. Weak in-pile sintering provides slight cohesion of core.



2X 5X

B. Transverse section of vibrated tube Z-251B rated at approximately 10 w/cm showing some core cohesion, but obvious washout during sectioning.



2X

C. Transverse section of swaged tube Z-256B rated at approximately 18 w/cm showing moderate in-pile sintering and some cracking of the core.

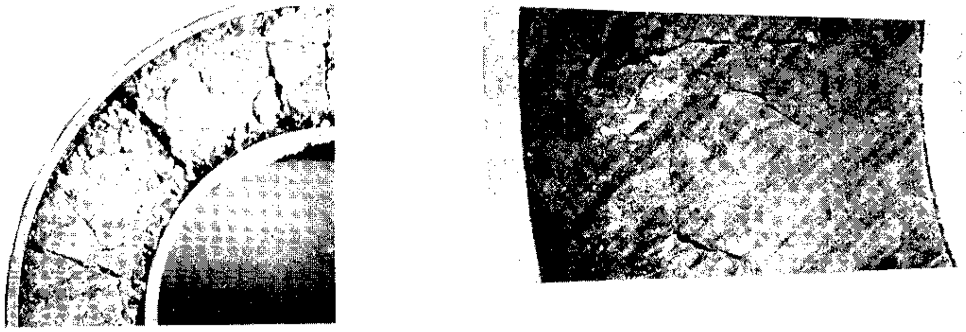
FIG. 12 CORE STRUCTURE versus THERMAL RATING at approximately 37 w/cm show columnar grain growth. The difference in structure in the two sections of similar rating can probably be ascribed to one of two causes:

(a) The fuel elements in question were in positions 3 and 7 in the assembly (Figure 3), and an error in the assumed axial flux shape could throw the estimated thermal ratings off by several watts per centimeter.

(b) The history of the remainder of the core might have had an influence on the sections shown in Figure 13A and B. For example, the sintered section came from the hot end of a relatively cool tube; element Z-256B operated at a mean thermal rating of approximately 23 w/cm and released only 3% of its fission xenon. The section that showed grain growth came from the cool end of a relatively hot tube; element Z-257A operated at a mean thermal rating of approximately 32 w/cm and released 33% of its fission xenon. Thus, the true operating temperature along the tube that showed grain growth may have been higher than expected, because the greater fission gas release may have reduced the heat removal capability of this tube.

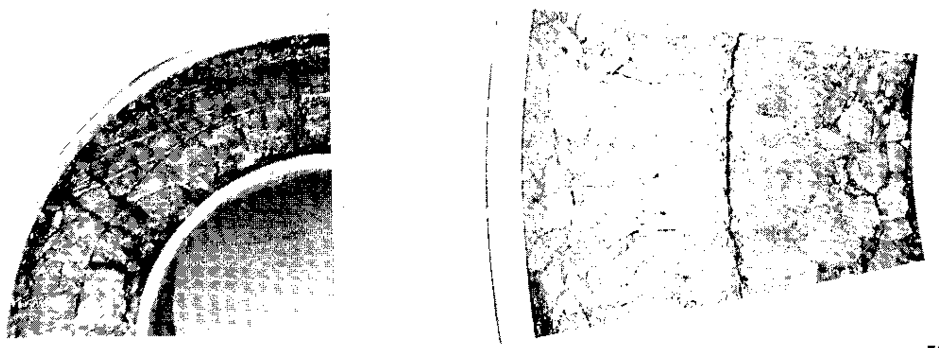
There was little change in the structure of the core as the thermal rating increased from about 37 to 50 w/cm (Figures 13 and 14); long columnar grains were formed in all cases. The columnar grains in the vibrated tubes are quite similar in size and general appearance to those in the swaged tubes (Figure 14). Grain growth extended over 40 to 60% of the core at 37 w/cm and 80 to 90% of the core at 45 w/cm, as estimated from ground sections.

AS - CUT GROUND



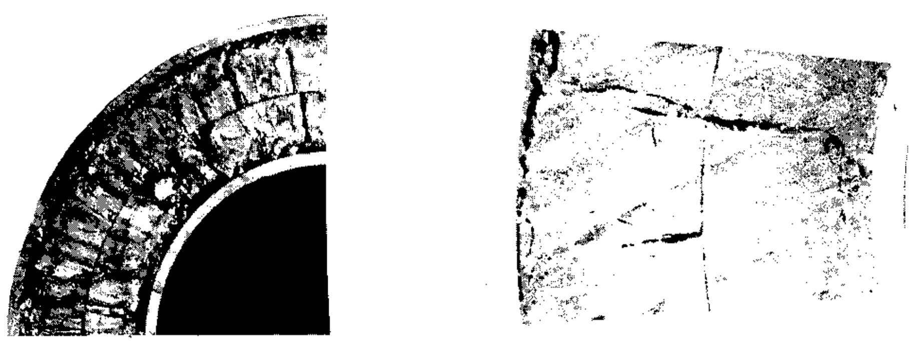
2X 5X

A. Transverse section of swaged tube Z-256B rated at approximately 28 w/cm showing extensive sintering, but no columnar grain growth.



2X 5X

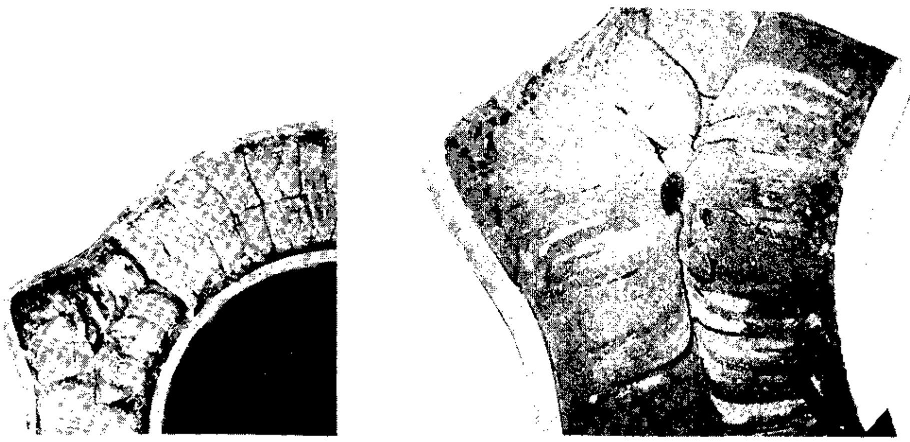
B. Transverse section of swaged tube Z-257A rated at approximately 27 w/cm showing extensive sintering with circumferential as well as radial cracking. Beginning of radial columnar grain growth.



2X 5X

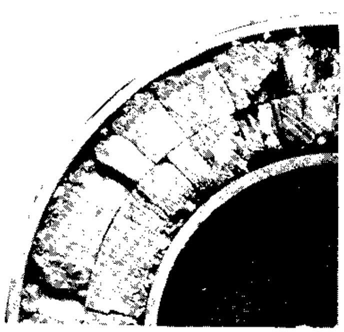
C. Transverse section of swaged tube Z-257A rated at approximately 37 w/cm showing long radial columnar grains.

FIG. 13 CORE STRUCTURE versus THERMAL RATING



As - Cut 2X Ground 5X

A. Transverse section of vibrated tube Z-252B rated at approximately 39 w/cm. Grain directions under the ridge are believed to indicate mass flow or heat flow.



As - Cut 2X

B. Transverse section through swaged tube Z-255B rated at approximately 45 w/cm.

As - Cut 2X

C. Transverse section through vibrated tube Z-251C rated at approximately 49 w/cm.

FIG. 14 CORE STRUCTURE versus THERMAL RATING
(Large columnar grains are present.)

REFERENCES

1. P. H. Chismar. Fission Gas Sampler. USAEC Report DP-814, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1963).

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3. D. F. Babcock. Heavy Water Moderated Power Reactors - Progress Report July 1962. USAEC Report DP-765, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1962).