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PROGRESS REPORT

BURNABLE POISON ADDITIONS TO UO_2

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BURNABLE POISON ADDITIONS TO UO_2

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INTRODUCTION

The United States and the European Atomic Energy Community (EURATOM) on May 29 and June 18, 1958, signed an agreement which provides a basis for cooperation in programs for the advancement of the peaceful applications of atomic energy. This agreement, in part, provides for the establishment of a Joint U.S. -Euratom research and development program which is aimed at reactors to be constructed in Europe under the Joint Program.

The work described in this report represents the Joint U.S. -Euratom effort which is in keeping with the spirit of cooperation in contributing to the common good by the sharing of scientific and technical information and minimizing the duplication of effort by the limited pool of technical talent available in Western Europe and the United States.

ACKNOWLEDGMENT

We wish to express our appreciation to both Mr. MacGurdy and Mr. Collins of the General Electric Company - Nuclear Materials and Propulsion Operation in Cincinnati, Ohio, for their assistance in providing the facilities for performing the high temperature thermal tests of the tungsten encapsulated $\text{UO}_2\text{-B}_4\text{C}$ mixtures.

BURNABLE POISON ADDITIONS TO UO_2

By

R. C. Brayer and W. P. Chernock

ABSTRACT

The problem of severe axial boron segregation produced by the migration of large (20/25 mesh) self shielded B_4C particles through the vibrating bed during vibratory compaction of fuel rods has been resolved by a combination of incremental loading and incremental compaction. Rods have been incrementally compacted to densities of 87.3 and 88% of theoretical density and the local boron concentration along the rod was maintained within the desired range of plus or minus 20% of the mean boron concentration.

Two tungsten clad UO_2 -0.05 wt% B_4C capsules have been thermally tested for a period of 100 hours each at a maximum axial temperature of 1800 and 2050 to 2200°C. An axial thermal gradient of about 16 and 21°C/cm was maintained on each capsule. These capsules will be evaluated for evidence of UO_2 - B_4C reaction, boron migration and gas release in order to verify the stability of UO_2 - B_4C mixtures in a closed element.

No significant axial or radial boron migration has been observed in a test element containing UO_2 -0.05 wt% B_4C which was operated in an open system (slowly flowing helium gas) under combined axial and radial thermal gradients of about 4500°C/cm and about 15°C/cm with a fuel centerline temperature of 2400°C.

Arrangements have been completed for the irradiation testing of two fuel rods in Saxton. Tentative plans call for the simultaneous irradiation of two full length rods in a 2 x 2 test assembly to burnups of about 2000 and 5000 MWD/MTU at a fuel centerline temperature of 2350°C. Rods, having a geometry similar to that anticipated for use in the irradiation program (1.4 cm diameter by 84 cm long) have been vibratory compacted to 87.7% of theoretical density and the B_4C distribution was maintained within +20% of the nominal loading.

I. SUMMARY

Difficulties previously encountered in producing a uniform distribution of large self-shielded B_4C particles in UO_2 have been resolved through use of a combination of incremental loading and incremental compaction. An evaluation of the local boron concentration at six positions equally spaced along the compacted rod showed that the boron concentration was within $\pm 20\%$ of the average value and that the concentration of the larger particles near the upper end of the rod, observed in previous investigations was absent in these incrementally compacted rods.

Boron migration could not be induced in a compacted UO_2 fuel element containing 0.05 wt% B_4C which was held for 30 hours at a centerline temperature in excess of $2400^\circ C$. Both ends of the fuel column were opened to a chamber containing slowly flowing helium in an attempt to remove the gaseous products of the postulated UO_2 - B_4C reaction. A radial gradient of about $4500^\circ C/cm$ was maintained by water cooling directly on the stainless steel cladding and an axial gradient was introduced through the design of the fuel element cladding which incorporated a region of varying cladding thickness. The resulting ratio of radial to axial thermal gradient per unit length of about 300 was typical of values encountered in large power reactors. Significant boron migration in either the axial or radial direction did not occur.

In an attempt to verify the conclusions relating to the performance of UO_2 - B_4C mixtures in a closed system, samples were encapsulated in tungsten tubing and heat treated at elevated temperatures for a period of 100 hours.

One element was tested at a maximum temperature of $1810^\circ C$ with an induced

axial thermal gradient of about $16^{\circ}\text{C}/\text{cm}$. The second rod was tested at a maximum temperature of 2050 to 2200°C with a temperature gradient of $21^{\circ}\text{C}/\text{cm}$. These test capsules will be punctured and the gases will be collected and identified. The nature of the migrating boron species, if any, will also be identified.

Arrangements have been made for irradiation testing of two fuel rods in a removable 2×2 assembly in Saxton. The fuel will be UO_2 -0.05 wt% B_4C compacted to $88 \pm 1\%$ of theoretical density. Target burnups are 2000 and 5000 MWD/MTU for these test rods.

Two rods having a geometry similar to that of the fuel elements to be irradiated in Saxton have been compacted to 87.7% of theoretical density and the boron concentration, evaluated at four-inch intervals along the rod, was within $\pm 20\%$ of the nominal loading. On this basis no problems are anticipated in the compaction of the enriched fuel elements to be used in the irradiation program.

II. INTRODUCTION

This program is aimed at developing methods for fabricating fuel elements containing burnable poisons homogeneously distributed in UO_2 .

The principal objectives of the program are:

- A. To develop vibratory powder compaction methods for producing a uniform distribution of a burnable poison in high density UO_2 fuel elements.
- B. To investigate the potential for redistribution of the burnable poison within the fuel element by means of out-of-pile thermal gradient tests.
- C. To irradiate test rods containing burnable poison to determine the potential in-pile boron redistribution.
- D. To develop fabrication procedures for fuel elements containing large self-shielded poison particles.

During the first year's effort, electromechanical vibratory compaction methods were utilized to produce UO_2 fuel rods containing 0.05 wt% B_4C additions to densities of 88 to 89% of theoretical. The local boron contents were maintained within $\pm 20\%$ of the nominal loading.

The method for boron analysis was developed and was based on fusion of UO_2 - B_4C mixtures in sodium carbonate at 1000°C in order to transform the contained boron to a water-soluble salt which was then used to produce boron quinalizarin complex solutions. These solutions were subsequently analyzed colorimetrically for boron.

The potential for axial and radial boron redistribution has been evaluated with an axial thermal gradient from 8 to 12°C/cm and at a centerline temperature up to 2000°C for approximately two hours. The results of these tests indicated that significant axial or radial boron migration had not occurred.

Earlier in this program, a thermodynamic evaluation of $\text{UO}_2\text{-B}_4\text{C}$ reactions indicated that, in a closed system, the amount of B_4C which will be reacted and the pressure of the released reaction product gases will be negligible. An experimental effort to verify these findings was initiated in the last quarter. The stability of the $\text{UO}_2\text{-B}_4\text{C}$ mixture is being evaluated in sealed tungsten capsules which have been heated for approximately 100 hours with an axial gradient from 16 to 21°C/cm and no imposed radial gradient.

In addition to investigations of potential boron redistribution in thermally tested fuel elements, a fabrication program was directed toward applying previously developed methods to produce fuel elements of a geometry similar to those anticipated for use in the Saxton irradiation program. Fabrication methods for introducing self-shielded B_4C particles in fuel elements containing $\text{UO}_2\text{-B}_4\text{C}$ mixtures have been developed and this effort was concluded during this reporting period.

III. FABRICATION OF FUEL ELEMENTS CONTAINING SELF-SHIELDING B₄C

During the last reporting period, difficulty was encountered in producing a uniform distribution of large, self-shielded B₄C in UO₂. At that time, it was suggested that the problem of boron migration during compaction may be resolved through use of incremental compaction. The effort during this reporting period was concentrated on this approach.

Loadings of 0.06 wt% B₄C particles with a diameter near 0.076 cm, consistent with a self-shielding factor of about 0.5, were obtained by screening the minus 20, plus 25 mesh fraction from Grade 14F "Norbide", which is a high boron, fused B₄C manufactured by the Norton Company. The powder formulation and blending of UO₂ and B₄C were identical to those previously described.¹ Details of fabrication procedures and analyses of results are presented below.

A. Fabrication*

1. The boron homogeneity was optimized by utilizing a series of twenty-five, 32-gram charges of the UO₂-0.06 wt% B₄C powder mixture. Each charge was prepared by first mixing 30/100 mesh UO₂ particles and 20/25 mesh B₄C particles. This preblended mixture was subsequently blended with the coarse (6/16 mesh) and fine (minus 200 mesh) UO₂ particles.

2. Five charges were spatula-loaded into a one-half inch diameter stainless steel tube. Each individual charge was loaded in the horizontal position. The tube was then placed in an upright position to insure uniform layering of the charge. This sequence of operation was repeated five times

* This fabrication procedure was evolved for laboratory operations to demonstrate a principle. In production, automatic loading hoppers and mechanized compaction rigs would be employed.

prior to compaction.

3. A steel ram was lowered into the loaded tube in direct contact with the fuel column to restrict any gross movement of fuel and to avoid powder segregation during handling.

4. The fuel column was compacted on a Model C-10 vibration exciter unit driven by a Model T-35 power amplifier, manufactured by the M. B. Corporation. An acceleration force of about 45 G with a frequency continuously oscillating between 200 and 500 cycles per second was applied for approximately 15 minutes. The fuel column was restrained axially during compaction by a 7 kg (15 pound) spring loaded ram.

5. The density of the fuel was evaluated after each compaction from the weight of the loaded fuel, the height of the fuel column, and the internal volume of the cladding.

6. Procedures 2, 3, 4 and 5 were repeated five times until all twenty-five fuel charges had been loaded and compacted.

B. Evaluation

The fuel density for the entire tube recorded after each incremental compaction is shown in Figure 1. In each case, the final density is within the desired range of $88 \pm 1\%$ of theoretical.

The axial boron concentration was evaluated at six positions along the 76 cm long rods, as shown in Figure 2. All samples were analyzed by the carbonate fusion quinalizarin technique previously reported.²

The results of boron analyses for these rods are shown in Figure 2. The boron content for each position is within $\pm 20\%$ of the average value. It should be noted that the concentration of the larger boron particles near the

DENSITY OF FUEL CONTAINING SELF-SHIELDED PARTICLES
AFTER EACH INCREMENTAL COMPACTION

Fig. 1

B₄C AXIAL DISTRIBUTION AFTER INCREMENTAL COMPACTION OF SELF-SHIELDED PARTICLES

Fig. 2

upper end of the rod, observed in previous investigations, is absent in these incrementally compacted rods.

The objective of this task, which is to produce a uniform distribution of larger self-shielded B_4C particles in high density UO_2 fuel columns by vibratory compaction techniques, has been achieved through the use of a combination of incremental loading and incremental compaction. No additional work is anticipated on this task.

IV. THERMAL GRADIENT STUDIES

In view of the gross consequences to fuel element performance if axial boron migration were to occur in operating fuel elements, investigation of the potential for such movement during out-of-pile tests has continued. An irradiation test program has been initiated and is described in a later section.

A. Thermal Testing

An attempt was made to induce the formation of volatile boron species in a $\text{UO}_2\text{-B}_4\text{C}$ fuel element. This test was run with an induced radial to axial thermal gradient typical to that anticipated in a large water reactor. The $\text{UO}_2\text{-B}_4\text{C}$ mixture was vibratory compacted around an axial tungsten-rhenium heater. The test was performed at a fuel centerline temperature in excess of 2400°C for a period of approximately thirty hours. Helium was continuously bubbled through the test chamber in an attempt to remove the gaseous products of the $\text{UO}_2\text{-B}_4\text{C}$ reaction, thus providing the equivalent of an open system. The radial gradient of about $4500^\circ\text{C}/\text{cm}$ was maintained by water cooling directly on the stainless steel cladding. An axial gradient was introduced through the design of the fuel element cladding which incorporated a region of varying cladding thickness.¹

The average temperature profile on the inside diameter of the cladding was calculated from an average of temperature measurements recorded by thermocouples on the surface of the cladding and the calculated temperature drop across the thickness of the cladding. Temperature measurements were made periodically during the thirty-hour test. The power input, Q , used in the ΔT calculations was determined experimentally and typical calculations are

shown in Table I. The average centerline temperature of the fuel (2425°C) was calculated from resistivity measurements of the tungsten-rhenium heater. A typical fuel centerline temperature profile is shown in Figure 3.

The ratio of radial to axial thermal gradient per unit length was 290 on one taper and 360 on the other taper. These values are reasonably close to typical values encountered in large power reactors.

B. Boron Distribution

The radial and axial distribution of boron in the fuel mixture after thermal testing has been evaluated. The axial and radial sampling plans are shown in Figures 3 and 4. Analytical results obtained by the carbonate fusion-quinalizarin method² are shown in Table II. There was no discernible trend in the variation in local boron concentration with either radial or axial position in the test element. The large variations in local boron concentrations from sample to sample were not surprising since each sample represented an average volume slightly greater than 0.1 cm^3 , or only approximately five times the volume of the largest UO_2 particle size fraction used in the compacted fuel formulation. It is for this reason that the most significant results are those shown in Table II for the average of two samples in each region of the fuel.

These results have reaffirmed previous conclusions concerning boron migration. There is no evidence of significant boron migration in either a radial or an axial direction. These results are particularly significant in light of the concerted attempt to induce boron migration by operating this test element in an open* system, at fuel centerline temperatures in excess of 2400°C and with a radial thermal gradient of about $4500^{\circ}\text{C}/\text{cm}$.

* A discussion of this open system is presented in Section V.

NOTE:
1. NUMBERS INDICATE POSITION OF THERMOCOUPLES ON CLADDING
2. LETTERS INDICATE AREAS WHERE FUEL SAMPLES WERE SECTIONED

ESTIMATED CENTER TEMPERATURE PROFILE ON THERMAL TEST ELEMENT
NUMBER 89 (T.D. = 86.8 %) and RADIAL POSITION OF CHEMICAL SAMPLES

II. TEMPERATURE PROFILE

I. RADIAL SAMPLING

RADIAL SAMPLING and TEMPERATURE PROFILE
Fig. 4

TABLE I

Thermal Gradient Studies
Clad Temperature (ID)

Thermocouple Position (Figure 3)	T _{OD} (°C)	d _i (cm)	d _o (cm)	$\frac{d_o}{d_i}$	$\ln \frac{d_o}{d_i}$	K (Watt/cm ² / cm/°C)	$\frac{Q}{2 \pi l}$ (Watt/cm)	ΔT_r (°C)	T _{ID} (°C)
1	41.7								126.1
2	44.6								129.0
9	55.6		1.9050	1.596	0.4675			56.4	140.0
10	52.6								137.0
		1.1938				0.173	20.52		
3	36.2		2.3280	1.950	0.6678			80.6	144.8
8	65.9								174.5
4	41.8		2.7520	2.305	0.8351			100.8	170.6
7	53.5								182.3
5	36.2		3.1760	2.659	0.9780			118.0	182.2
6	40.6								186.6

$$T_{ID} = T_{OD} + \Delta T_r$$

$$T_{ID} = \text{Average ID Clad Temperature (°C)}$$

$$T_{OD} = \text{Average OD Clad Temperature (°C)}$$

$$\Delta T_r = \text{Radial Temperature Drop (°C)}$$

$$\Delta T_r = \frac{Q}{2 \pi l} \ln \frac{d_o}{d_i} \frac{1}{K}$$

$$Q = \text{input power} = 2540 \text{ Watts}$$

$$l = \text{length of heated zone} = 19.7 \text{ cm}$$

$$d_o = \text{outside diameter of the clad (cm)}$$

$$d_i = \text{inside diameter of the clad (cm)}$$

TABLE II

Thermal Gradient Studies
B₄C Distribution (wt%)

Radial
Position
(Figure 4)

Axial Position (Figure 3)

	A	B	A+B Avg	C	D	C+D Avg	E	F	E+F Avg	A+B+E+F Avg
a	0.030	0.032	0.031	0.038	0.052	0.045	0.037	0.034	0.036	0.034
b	0.052	0.098	0.075	0.055	0.046	0.051	0.052	0.031	0.042	0.059
c	0.048	0.040	0.044	0.041	0.036	0.039	0.031	0.052	0.042	0.043
d	0.042	0.041	0.042	0.055	0.055	0.055	0.034	0.050	0.042	0.042
e	0.032	---*	(0.032)	0.038	(0.092)**	(0.065)	0.031	0.052	0.042	0.037
Average for Axial Position			0.045			0.051			0.041	0.043
General Position	Low Temperature			High Temperature			Low Temperature			Low Temperature

* Samples lost during analysis.

** Value for sample D_e is cumulative value for boron and impurities. Separation was attempted without success.

V. B₄C-UO₂ STABILITY

Results of previous efforts³ on this program indicated that UO₂-B₄C reactions occurred at temperatures as low as 1600°C. In fact, the results of these investigations in a flowing argon system led to a postulated reaction,

Dissociation of UB₄ to UB₂, with the formation of a volatile boron species was postulated for an open system.

In experiments in which large quantities (up to 3 wt%) of B₄C were reacted with UO₂, in a flowing argon system, boron losses were observed. An analysis of the boron and specimen weight loss indicated that the postulated mechanism was compatible with the experimental data; a similar analysis based on B₄C dissociation was found to be incompatible. It was further shown,^{1, 3, 4} on the basis of thermodynamic calculations, that the postulated reaction would be negligible in a closed system. On the basis of this previous analysis, boron migration should be observed in an open system; no migration should be observed in a closed system. This conclusion, appears to be inconsistent with results reported in Section IV which indicated no evidence of boron migration, even with a radial thermal gradient of 4500°C/cm with fuel centerline temperatures in excess of 2400°C, in what was believed to be an open system. These results do not remain incompatible when an analysis is made of the degree to which this latter system was really open. Previous work at CEND has indicated significant applied pressures were necessary to push helium through a vibratory compacted fuel bed with a density around 88% of theoretical.

On this basis, it is likely that gaseous reaction products from $\text{UO}_2\text{-B}_4\text{C}$ reactions, in the high temperature region of the fuel, were retained in regions from which they were generated in sufficient concentrations to inhibit additional reaction. Thus, although an attempt was made to provide an open system on a gross scale, it is likely that conditions consistent with a closed system were achieved on a local scale. These results again reaffirm the stability of $\text{UO}_2\text{-B}_4\text{C}$ mixtures in a closed system operated under severe thermal gradient conditions. These results appear to indicate the subtle conclusion that, in an out-of-pile test, a truly open system may not be possible in a rod containing $\text{UO}_2\text{-B}_4\text{C}$ mixtures which were compacted to high densities. However, the influence of dynamic grain growth and void redistribution in an operating fuel element must be assessed.

In an attempt to verify the conclusions relating to performance in closed systems, $\text{UO}_2\text{-B}_4\text{C}$ mixtures have been encapsulated in tungsten tubes and heat treated at elevated temperatures for a period of 100 hours. Element A was tested for 100 hours at a maximum temperature of 1810°C with an induced axial temperature gradient of about $16^\circ\text{C}/\text{cm}$, as shown in Figure 5. Element B was tested at a maximum temperature of 2200°C with a temperature profile of $21^\circ\text{C}/\text{cm}$, as shown in Figure 6. These test capsules will be sectioned to identify the gases produced, evaluate boron migration and, if migration is observed, identify the migrating species.

The $\text{UO}_2\text{-B}_4\text{C}$ reaction mechanism, postulated at the beginning of this section, involves the production of UB_2 . Another potential mechanism⁵ involves the production of volatile boron species without the possibility of

ELEMENT "A" TEMPERATURE PROFILE
Fig. 5

ELEMENT "B" TEMPERATURE PROFILE
Fig. 6

forming UB_2 . An X-ray diffraction photogram taken from the reaction product of a mixture containing 3 wt% B_4C - UO_2 , which was held for two hours at $2000^{\circ}C$ in flowing purified argon, is shown in Figure 7. Schematic indications of the positions and relative intensities of diffraction lines from UO_2 , UB_2 and UB_4 are also shown in Figure 7. Table III contains "d" spacings for all of the lines on the film down to a "d" value of 1.05. Included also, are "d" spacings for UO_2 , UB_2 , and UB_4 obtained from the ASTM Card Index. The Figure and Table indicate that all lines on the film can be accounted for on the basis of $UO_2 + UB_2$. Two of the three most intense lines and six of the nine most intense lines (relative intensity greater than 39) for UB_4 are missing. On the bases of these data the presence of UB_2 as the prime reaction product between UO_2 and B_4C at $2000^{\circ}C$ in flowing argon has been established. This is further verification both for the UO_2 - B_4C reaction mechanism proposed at the beginning of this Section and for the contention that this reaction will be inhibited in a closed system.

Fig. 7 MIXTURE CONTAINING 3 W/O B₄C 97 W/O UO₂ HELD FOR TWO HOURS IN FLOWING, PURIFIED ARGON AT 2000°C. THE SAMPLE WAS HELD ON A TUNGSTEN SHEET. B₄C WAS IN THE FORM OF -325 MESH SIZE AND UO₂ CONTAINED 60 W/O: 6-16 MESH 15 W/O: 30-100 MESH 25 W/O: <200 MESH

TABLE III

X-ray
"d" Spacings

Film		UO ₂ (Card #5-0550)		UB ₂ (Card #11-228)		UB ₄ (Card #5-0663)	
"d"	Relative Intensity*	"d"	Relative Intensity	"d"	Relative Intensity	"d"	Relative Intensity
3.99	W			3.99	85	3.99#	47
						3.55#	46**
3.15	S	3.16	100			3.17#	73
2.72	M	2.74	48	2.71	80		
						2.64#	71**
						2.48#	100**
2.24	MW			2.24	100	2.24	19
						2.12	27**
1.99	W			1.99	15	1.99	19
1.93	M	1.93	49			1.95	24
						1.76	11**
						1.73	26**
						1.72#	49**
						1.68#	40**
						1.67	18**
1.64	M	1.65	47				
1.60	W			1.61	30		
1.58	MW	1.58	13			1.58#	61
1.56	VW			1.57	15	1.56	9
						1.54	19**
						1.49	8**
1.45	VW			1.46	25		
						1.41	4**
						1.39	5**
1.36	W	1.37	9				
1.35	VW			1.36	10		
1.32	VW			1.33	5	1.33	9
						1.31	11**
						1.30#	39**
1.28	VW			1.28	10	1.28	16
1.25	M	1.26	18			1.24	16
1.23	MW			1.23	10	1.22	16
1.22	VW	1.22	15			1.21	14
1.19	VW			1.19	10	1.18	8
						1.17	6**
						1.16	28**
						1.14	8**
1.12	M	1.12	13	1.12	10	1.13	7**
						1.11	9
1.05	M	1.05	15				

TABLE III (Continued)

* S = Strong.
 M = Medium
 MW = Medium-Weak
 W = Weak
 VW = Very Weak

** Spacings which are not present on the X-ray diffraction photogram.

UB_4 spacings which have relative intensities of 39 or greater.

VI. IRRADIATION TESTING

The objective of the irradiation program is to determine the potential for boron migration under typical power reactor conditions. Two fuel rods, 0.599 inch (1.52 cm) in diameter and 41.03 inches (1.1 meter) long will be irradiated as removable rods in a 2 x 2 assembly in the Saxton Reactor. The irradiation is scheduled to start early in January 1965. One rod will be irradiated from 1500 to 2500 MWD/MTU while the second rod will accumulate a burnup of about 5000 MWD/MTU.

The fuel element design is typical of that used for the Saxton fuel and includes a fuel column which is 0.552 inch (1.40 cm) in diameter and 33.24 inches (0.85 meter) in length. The fuel composition selected is $\text{UO}_2 + 0.05 \text{ wt\% B}_4\text{C}$ mixture compacted to $88 \pm 1\%$ of theoretical density.

Welded and cold drawn (10% cold work) Type 304 stainless steel tubing, to be used as clad material in this program, has been ordered. Attempts are being made to obtain 6% enriched compaction grade fused crystalline uranium dioxide for this program. Use of this enrichment will provide a peak rod power of 18 kw/ft and a maximum centerline temperature of $2250 \pm 200^\circ\text{C}$. The 6.48% enriched fuel, which is available from one vendor, has been held as an alternate and will be used if the procurement of the 6% enriched fuel produces an unrealistic schedule.* The higher enrichment fuel will produce a peak rod power of 19.5 kw/ft and a maximum centerline temperature of $2350 \pm 250^\circ\text{C}$.

Two rods, having a geometry similar to that of the fuel elements to be irradiated, have been fabricated using compaction methods similar to those

* Scheduling is of great concern at this time as a result of the impending plutonium loading for Saxton.

developed previously on this program. The density obtained in those rods (87.7% of theoretical density) was comparable to the densities previously obtained in the compaction of rods containing 0.460 inch (1.17 cm) in diameter by 36 inch (0.95 meter) long fuel columns.

The axial boron distribution in these two rods was evaluated in 1 inch long (3/4 inch long for rod 95) transverse sections. The position of the sections is shown in Figure 8. The boron was analyzed by the carbonate fusion-quinalizarin technique previously reported, and the boron concentration for each increment is shown on the Figure. In both rods, the boron concentration for each position is within the $\pm 20\%$ of the nominal loading. On this basis, no problems are anticipated in the compaction of the enriched fuel elements.

AXIAL BORON DISTRIBUTION IN 0.550 in. Dia. x 33 in. LONG CYLINDRICAL FUEL COLUMNS

Fig. 8

VII. PLANNED EFFORT DURING THE NEXT REPORTING PERIOD

A. Evaluation of compatibility tests of $\text{UO}_2\text{-B}_4\text{C}$ in a closed system will be completed.

B. A number of additional rods, typical of those to be irradiated in Saxton, will be vibratory compacted and analyzed for local density and boron variations to provide better statistical data concerning these parameters in as-fabricated rods. These data will be vital in the post-irradiation evaluations.

C. Fabrication of enriched fuel rods for the irradiation test program will be completed and the rods will be shipped to Saxton.

REFERENCES

1. Brayer, R. C. and W. P. Chernock, "Burnable Poison Additions to UO_2 ," USAEC Report CEND-3107-216, Combustion Engineering, Inc., Nuclear Division, July 1964.
2. Zuromsky, G., R. C. Brayer, and W. P. Chernock, "Burnable Poison Additions to UO_2 ," USAEC Report CEND-181, Combustion Engineering, Inc., Nuclear Division, November 1963.
3. Brayer, R. C. and W. P. Chernock, "Burnable Poison Additions to UO_2 ," USAEC Report CEND-203, Combustion Engineering, Inc., Nuclear Division, January 1964.
4. Brayer, R. C. and W. P. Chernock, "Burnable Poison Additions to UO_2 ," USAEC Report CEND-3107-210, Combustion Engineering, Inc., Nuclear Division, April 1964.
5. Versteeg, G. and P. F. Sens, "The Reaction Between UO_2 and B_4C at High Temperatures," RCN-1616, Reactor Centrum Nederland, Institute for the Development of Peaceful Applications of Nuclear Sciences, September 1964.