MASTER

Argonne National Laboratory

FABRICATION OF SPIKED-CORE FUEL ELEMENTS FOR THE EXPERIMENTAL BOILING WATER REACTOR

by

W. C. Kramer, F. D. McCuaig,
R. A. Beatty, C. H. Bean,
and R. A. Noland

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

ANL-6283
Metals, Ceramics, and
Materials (TID-4500)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

NO. 3.00, R. 50

FABRICATION OF SPIKED-CORE FUEL ELEMENTS
FOR THE
EXPERIMENTAL BOILING WATER REACTOR

by

W. C. Kramer, F. D. McCuaig,
R. A. Beatty, C. H. Bean,
and R. A. Noland

Metallurgy Division

Program 7.9.5

Final Report

A portion of the material contained in this report has been
reported in the following Metallurgy Division Reports:

ANL-6330 (1960) pp. 62-72
ANL-6099 (1959) pp. 32-33

November 1965

Operated by The University of Chicago
under
Contract W-31-109-eng-38
with the
U. S. Atomic Energy Commission

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	9
INTRODUCTION.	9
FUEL DEVELOPMENT	12
FUEL-ELEMENT FABRICATION	21
Fuel Assembly.	22
Frame Assembly	33
Experimental Elements	37
SUMMARY	38
OPERATING EXPERIENCE	40
APPENDICES	
A. Theoretical Annulus Required to Compensate for Thermal-expansion-coefficient Differential in EBWR Spike Fuel Rods Consisting of Al-U ₃ O ₈ Jacketed with Zircaloy-2.	41
B. Drawings of EBWR Spiked-core Fuel Elements	42
C. Contents of U ²³⁵ in EBWR Spike Fuel.	46
ACKNOWLEDGMENTS	64
REFERENCES	65

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission.

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	EBWR Spiked-core Fuel-element Fabrication Flowsheet	13
2.	Extrusion-billet Assembly	14
3.	Effect of Prior Outgassing on Final Density of Extruded and Heat-treated X-8001 Aluminum Powder-product Specimens . . .	14
4.	Rupture in Zircaloy-2 Jacket Tube Caused by Thermal Ratcheting between Jacket and Al-U ₃ O ₈ Fuel	16
5.	Section through Specimen in Which Al-U ₃ O ₈ Fuel Had Melted and Bonded to Zircaloy-2 Jacket	17
6.	Specimen in Which Al-U ₃ O ₈ Fuel Had Melted and Diffused through Zircaloy-2 Jacket	17
7.	Structure of Diffusion Bond between Zircaloy-2 and Al-U ₃ O ₈ . .	18
8.	Fuel-assembly Components before and after Assembly	22
9.	Transverse Section through 0.98-cm (0.385-in.)-OD Zircaloy-2 Tube after Straightening and Annealing	23
10.	Transverse Sections through 0.98-cm (0.385-in.)-OD Zircaloy-2 Tube at 120° Intervals around the Circumference of the Tube Section Shown in Fig. 9	24
11.	Lathe-mounted Eddy-current Equipment for Inspecting Zircaloy-2 Tubing	25
12.	Typical Eddy-current Trace and Corresponding Transverse Sections through a Defective Zircaloy-2 Tube	27
13.	Equipment for Gas Tungsten-arc Welding End Plugs to Jacket Tubing	28
14.	Weld Configuration for Fuel-rod End Plug to Jacket Tubing . . .	29
15.	Glovebox Facility Used to Evacuate and Back-fill Fuel Tubes with Helium Atmosphere	30
16.	Setup for Wet-abrasive Blast Cleaning of Fuel Rods	30
17.	Fuel Rods Being Pickled in Warm 35v/oHNO ₃ -5v/oHF	31
18.	One End of a Completed Fuel Rod and a Fuel Rod with Cut-away Jacket.	31
19.	Fuel-rod End Support before and after Assembly	32
20.	Frame-assembly Components before and after Assembly	33
21.	Corner Angles Being Milled to Design Dimensions	34

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
22.	Corner Angles Being Spot-welded to Lifting Plates to Complete One End of Frame Assembly.	35
23.	Fuel Assembly Being Inserted into Frame Assembly to Complete Fuel Element.	36
24.	Final EBWR 100-MW Core Loading.	40
25.	Ceramic Fuel Pellet.	42
26.	Jacket Tube.	42
27.	End Plug.	42
28.	Fuel Rod.	42
29.	Side Plate.	43
30.	Center Spacer.	43
31.	Lifting Lug.	43
32.	Rod Support.	43
33.	Support Holder.	44
34.	End-support Subassembly.	44
35.	Corner Angle.	44
36.	Lifting Plate.	44
37.	Leaf Spring.	45
38.	End Fitting.	45
39.	Burnable Poison Strip.	45

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	EBWR Fuel-element Design Data	11
II.	Constituents of Three Spike Elements Containing Cermet Fuel	12
III.	Components of Fuel and Frame Assemblies	21
IV.	Summary of Components Fabricated and Used for Assem- bly of 35 EBWR Spiked-core Fuel Elements	39
V.	U ²³⁵ Content by Fuel-element Number	46
VI.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 1 . .	47
VII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 2 . .	47
VIII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 3 . .	48
IX.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 4 . .	48
X.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 5 . .	49
XI.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 6 . .	49
XII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 7 . .	50
XIII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 8 . .	50
XIV.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 9 . .	51
XV.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 10 .	51
XVI.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 11 .	52
XVII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 12 .	52
XVIII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 13 .	53
XIX.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 14 .	53
XX.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 15 .	54
XXI.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 16 .	54
XXII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 17 .	55
XXIII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 18 .	55
XXIV.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 19 .	56
XXV.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 20 .	56
XXVI.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 21 .	57
XXVII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 22 .	57

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
XXVIII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 23	58
XXIX.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 24	58
XXX.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 25	59
XXXI.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 26	59
XXXII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 27	60
XXXIII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 28	60
XXXIV.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 29	61
XXXV.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 30	61
XXXVI.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 31	62
XXXVII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 32	62
XXXVIII.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 33-A: Zircaloy-2 Jacket, Al-U ₃ O ₈ Core with 0.005- 0.008-cm Annulus.	63
XXXIX.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 34-A: Al (A288) Jacket, Al (X-8001)-U ₃ O ₈ Core with No Annulus	63
XL.	U ²³⁵ Content by Fuel-rod Number for Fuel-element No. 35-A: Zircaloy-2 Clad Bonded to Al-U ₃ O ₈ Core	64

FABRICATION OF SPIKED-CORE FUEL ELEMENTS FOR THE EXPERIMENTAL BOILING WATER REACTOR

by

W. C. Kramer, F. D. McCuaig, R. A. Beatty,
C. H. Bean, and R. A. Noland

ABSTRACT

In the modification of the Experimental Boiling Water Reactor (EBWR) to allow for a heat-dissipation capacity of 100 MWt, 28 of the original, slightly enriched, metal-fuel elements¹ were replaced with elements containing highly enriched ceramic fuel. Of 35 fuel elements fabricated for this purpose, 32 contained a solid-solution ceramic fuel composed of 9.01 w/o UO_2 (93% U^{235}), 9.07 w/o CaO , and 81.92 w/o ZrO_2 in the form of cylindrical pellets nominally 0.82 cm (0.322 in.) diam x 1.3 cm (0.5 in.) long.² The three remaining elements contained a cermet fuel composed of a dispersion of 11.83 w/o U_3O_8 (with the uranium being 93% U^{235}) in an 88.17 w/o matrix of X-8001 aluminum. The cermet fuel was nominally 0.82 cm (0.322 in.) diam x 122 cm (48 in.) long. All the fuel was jacketed in Zircaloy-2 tubing, except the rods comprising one cermet fuel element that had A-288 aluminum jackets.

Commercial procurement and/or ANL fabrication of Zircaloy-2, Type 304 stainless steel (304 SS), and aluminum hardware for fuel-element components are discussed. Methods are reviewed covering fuel-rod fabrication, fuel-element assembly, and evaluation procedures.

INTRODUCTION

The original EBWR core loading of 112 fuel elements, 122 cm (48 in.) long, was conservatively designed to operate at a power level of 20 MWt. A series of transfer-function tests was made at progressively higher power outputs. As a result of the analysis of the data secured, it was predicted that the core might be safely operated up to 65 MWt. This prediction was confirmed when EBWR was operated at 61.7 MWt, at which point feedwater pump capacity and excessive moisture carryover became the limiting factors. The power density on this run was 38 kW per liter of core volume.

These data were extrapolated to predict the potential of a 152-cm (60-in.)-diam core in EBWR, operating with a full loading of 147 elements increased in length to 152 cm (60 in.). The theoretical power level approached 100 MWt. Consequently, the plant and reactor components were altered to permit operation up to 100 MWt.³

To accomplish this objective with the least monetary expenditure for fuel elements, it was decided to "spike" the existing core. This would also permit the maximum utilization and burnup of the existing fuel elements. The EBWR spikes were designed to approximate the Core I plate type elements in terms of heat-transfer area and water-to-metal ratio, yet provide sufficient reactivity and power to approach 100 MW.

Fixed parameters were the length of active fuel, 122 cm (48 in.), and a power level approaching 100 MWt, for the existing lattice structure in EBWR. A rod geometry was selected for the fuel. This was based on ease of fabrication, proper structural capabilities for the selected fuel and cladding, and ready adaptability to a variety of fuel and cladding material selections. Selection of the fuel and jacket materials was based on corrosion-resistance system compatibility and present "state of the art" of the fabrication techniques. The design data for Core I plate type and spike elements are given in Table I.

A spike fuel element consisted of two units: a frame assembly and a fuel-rod assembly. The fuel-rod assembly was removable from the frame but, for use, was inserted into the frame assembly. Features incorporated into the design of the spike elements were: (1) individual axial expansion of the fuel rods, (2) no riveting or fastening of Zircaloy-2 fuel rods to stainless-steel rod supports, (3) a removable and invertible fuel-rod assembly, and (4) a removable frame assembly.

The original reference fuel for the spike elements was enriched U_3O_8 dispersed in an X-8001 aluminum matrix, jacketed in close-fitting Zircaloy-2 tubing. It was repeatedly found, however, that only a few thermal cycles between room temperature and 260°C (the approximate reactor operating temperature) caused severe ratcheting between the aluminum-base fuel and the Zircaloy-2 jacket. This caused the fuel to shorten in length and to increase in diameter, rupturing the jacket in some cases. Although the cause of ratcheting was not firmly established, it logically is associated with the large difference between thermal-expansion values for aluminum (23.6×10^{-6} cm/cm-°C) and Zircaloy-2 (5.4×10^{-6} cm/cm-°C). A series of test cycles on variously prepared specimens established that thermal ratcheting could be eliminated by:

1. Controlling the annulus between the dispersion-type cermet fuel and Zircaloy-2 jacket,

2. Diffusion bonding the cermet fuel to the Zircaloy-2 cladding,
3. Jacketing the cermet fuel in aluminum tubing to negate any effect caused by differences in thermal expansion, or
4. Using a fuel material with a coefficient of thermal expansion $\leq$ that of the cladding material.

TABLE I EBWR Fuel-element Design Data

	Spikes*	Core I Plate Type
Fuel element		
Dimensions (overall)	9.8 cm (3.88 in) sq x 227 cm (89.5 in) long	9.5 cm (3.74 in) sq x 196 cm (77 in) long
Number per core	28	118
Elemental unit	Rod	Plate
Dimensions (overall)	0.95 cm (0.375 in) OD x 130 cm (51 in) long	Thin: 0.548 x 9.2 x 137 cm (0.212 x 3.62 x 54 in) Thick: 0.71 x 9.2 x 137 cm (0.280 x 3.62 x 54 in)
Cladding material	Zircaloy-2	Zircaloy-2
Cladding thickness	0.06 cm (0.025 in)	0.05 cm (0.020 in)
Gap material	Helium	Metallurgical Bond
Fuel material	9w/oUO ₂ -82w/oZrO ₂ - 8w/oCaO Solid Solution Pellets	U-5w/oZr-1.5w/oNb Alloy
U ²³⁵ enrichment	93%	1.44%; natural
Fuel dimensions	0.82 cm (0.322 in) OD x 1.3 cm (0.5 in) long	Thin: 0.44 x 8.4 x 130 cm (0.172 x 3.31 x 51 in) Thick: 0.61 x 8.4 x 130 cm (0.240 x 3.31 x 51 in)
Units/element	49	6
Heat flux		
Ave	42.89 W/cm ² (136,000 Btu/hr-ft ²)	49.52 W/cm ² (157,000 Btu/hr-ft ²)
Max	133.10 W/cm ² (422,000 Btu/hr-ft ²)	152.97 W/cm ² (485,000 Btu/hr-ft ²)
Fuel centerline temp		
Ave.	593°C	304°C
Max.	2480°C	407°C

*These data do not pertain to the three experimental elements fabricated.

Since the fourth alternative was considered the most reliable and easiest to fabricate, 32 elements containing 49 fuel rods each, for use as spike elements in EBWR, were made with zirconia-calcia-urania, solid-solution, ceramic-pellet, fuel material. In addition, three experimental

elements, one each based on the remaining alternatives, were fabricated. The constituents of the three special, 49-rod elements fabricated were as shown in Table II.

TABLE II. Constituents of Three Spike Elements
Containing Cermet Fuel

Element No.	Fuel	Cladding Material	Annulus between Fuel and Cladding
33-A	Al-U ₃ O ₈	Zircaloy-2	0.010-0.015 cm (0.004-0.006 in.) annulus
34-A	Al-U ₃ O ₈	A-288 aluminum	No annulus
35-A	Al-U ₃ O ₈	Zircaloy-2	Metallurgically bonded

Figure 1 is the fabrication flowsheet for the 32 ceramic-pellet fuel elements. Each element consists of a 7 x 7 array of 49 fuel rods. A total of 1,568 rods were fabricated. An additional 147 (49 x 3) fuel rods were manufactured for the three experimental elements.

FUEL DEVELOPMENT

It was originally intended to use a cermet fuel, consisting of an 11.83 w/o U₃O₈ (with the uranium 93% U²³⁵) phase-dispersed in an 88.17 w/o X-8001 aluminum matrix, as the fuel material for the EBWR spike elements. The U²³⁵ content of each fuel rod was fixed by design at 17.64 g. Since U₃O₈ is 84.7 w/o uranium, and the uranium in this case was 93% U²³⁵, 22.35 g of U₃O₈ were required per rod. The fabrication process developed for this fuel involved extruding a dispersion of U₃O₈ in X-8001 Alcoa aluminum* into 0.82-cm (0.322-in.)-diam fuel-rod stock.

The -140 mesh aluminum and U₃O₈ powders were mixed in a stainless-steel ball mill with porcelain grinding balls. After ball milling for 4 hr, the contents of the ball mill were screened into an extrusion can, which was then Syntron-vibrated to increase the packing density. The X-8001 aluminum extrusion can had a wall thickness of 0.32 cm (0.125 in.) and an outer diameter of 11.27 cm (4.43 in.). An extrusion billet as shown in Fig. 2, contained approximately 5.1 kg of mixed powders. Billets were extruded by Precision Extrusion Corporation, Bensenville, Illinois, on a horizontal press fitted with an 11.4-cm (4.5-in.)-diam container. The extrusion temperature, container temperature, and extrusion ratio were 425°C, 365°C, and 186:1, respectively. Billets were preheated in an air-recirculatory furnace at 425°C for 10 hr. An extruded billet produced 34 m (112 ft) of fuel material.

*X-8001 aluminum is 1100 aluminum + 1 w/o nickel, manufactured by Aluminum Company of America.

¹Fabrication and loading of the ceramic fuel is covered in detail in Reference 2.

Fig. 1. EBWR Spiked-core Fuel-element Fabrication Flowsheet

Fig. 2. Extrusion-billet Assembly

The importance of outgassing before extrusion was established through investigations on billets containing only X-8001 aluminum powder. Identical billets were prepared. One billet was loaded and sealed at atmospheric pressure; the other billet was outgassed at 150°C for 16 hr under 10^{-2} Torr pressure, and sealed. The billets were extruded under conditions identical to the fuel-extrusion conditions. Specimens cut from each extruded X-8001 aluminum rod were heated to various temperatures up to 648°C. Densities of the specimens were determined after the heating and cooling cycles, and were found to vary according to the curves plotted in Fig. 3. Appreciably less gas formation occurred in extruded material during subsequent heating above 426°C,

when the original billet was outgassed at 150°C. Between 426 and 648°C, the advantage gained by prior outgassing became greater as temperature was increased.

Fig. 3. Effect of Prior Outgassing on Final Density of Extruded and Heat-treated X-8001 Aluminum Powder-product Specimens

Ten evacuated billets containing mixed U_3O_8 and aluminum powders were extruded. However, thermal-cycling experiments conducted on specially prepared test specimens indicated that the differential thermal-expansion coefficient between the cermet fuel and Zircaloy-2 cladding was too great to determine with any reasonable level of confidence that this type element would perform reliably during reactor operation.

The reference fuel was to have been assembled by inserting the dispersion fuel into a Zircaloy-2 tube, sinking the loaded tube to eliminate the annulus between the fuel and the tube, cutting the tube to length with sufficient internal void space to allow for the differential thermal expansion of fuel and jacket, and sealing the end closures by welding. One rod was assembled in this manner with wrought 1100 aluminum inside a Zircaloy-2 jacket. This dummy fuel rod was thermally cycled by heating to 300°C in oil, followed by quenching in room-temperature water. A radiograph taken after 10 cycles showed the 0.8-cm (0.31-in.)-long expansion space inside the tube to have increased to 4.9 cm (1.94 in.). The rod diameter increased by 0.008 to 0.010 cm (0.003 to 0.004 in.). This thermal-ratcheting phenomenon was investigated further on an extruded dispersion of normal U_3O_8 in X-8001 aluminum. Various methods of heating to 260°C (the approximate reactor operating temperature) and cooling were tried. These consisted of oil heating and water quenching, furnace heating and air cooling, and furnace heating and water quenching. Specimens were heated and cooled in the vertical as well as the horizontal position. Fuel rods or rod sections incorporating various modifications were tested. Some were prepared with sealed end closures, others with open ends. Zirconium alloy tubing was replaced with thinner-wall Type 304 stainless-steel tubing; 0.15-cm (0.06-in.)-deep circumferential grooves were rolled into specimens clad with Zircaloy-2 tubing as well as with the 304 SS tubing; and one specimen contained a fuel slug on which a spray coating of graphite had been applied. In every case, the same results were obtained--shortening of the fuel and increasing of the rod diameter. In two cases, cycling was carried far enough to cause a crack to appear in the jacket tube. Figure 4 is a transverse section through a specimen with such a failed jacket.

Specimens were then prepared in which the annulus between the cermet fuel material and the Zircaloy-2 jacket was varied from 0 to 0.13 cm (0.005 in.) in 0.002-cm (0.001-in.) increments. Ratcheting occurred in all specimens having an annulus less than 0.005 cm (0.002 in.), but was not observed in those specimens having an annulus greater than 0.005 cm (0.002 in.) between fuel and jacket.

One specimen was prepared for a fuel-meltdown experiment. The specimen with Al- U_3O_8 fuel material in a Zircaloy-2 tube with end caps welded into each end was placed vertically in a muffle furnace that had been preset at 750°C. By means of a thermocouple attached to the outside of the

tube, it was determined that the fuel melted at approximately 675°C (i.e., the heating curve leveled off at this temperature). Examination of the specimen after cooling showed the fuel to have diffusion-bonded to the tubing leaving a large amount of void space throughout the center length of the tube. Figure 5 shows a transverse section through the rod after testing. At one point near the top of the vertical specimen, the fuel had diffused completely through the tube, as seen in Fig. 6.

Fig. 4. Rupture in Zircaloy-2 Jacket Tube Caused by Thermal Ratcheting between Jacket and Al- U_3O_8 Fuel

Fig. 5. Section through Specimen in Which Al-U₃O₈ Fuel Had Melted and Bonded to Zircaloy-2 Jacket

Fig. 6. Specimen in Which Al-U₃O₈ Fuel Had Melted and Diffused through Zircaloy-2 Jacket

Another specimen was prepared by zone-melting the fuel material inside Zircaloy-2 tubing to obtain a diffusion bond. Before the bonding treatment, the fuel rod was drawn through a die to minimize the annulus and promote heat transfer between the Al-U₃O₈ fuel and the Zircaloy-2 jacket. The rod was then passed vertically through a three-turn induction coil at approximately 33 cm(13 in.)/min. During the bonding process, the fuel rod was inside a Vycor tube through which helium gas was flowing to provide a protective atmosphere over the rod while it was being heated. The fuel-rod surface temperature, as measured by optical pyrometer, was maintained at 700°C within the zone heated by the induction coil. Under these conditions, only a thin surface layer of the fuel material was melted. Extensive melting of the fuel was avoided to minimize segregation of the U₃O₈ constituent and gas void formation. Figure 7 shows the bond achieved by this process. Other than establishing the hardnesses of the three layers making up the bond zone between the Al-U₃O₈ fuel and the Zircaloy-2 cladding, no attempt was made to determine the nature of the bond.

Fig. 7. Structure of Diffusion Bond between Zircaloy-2 and Al-U₃O₈

The bonded fuel-rod specimen was cycled by slow heating to 300°C and air-cooling, and by subsequent heating to 300°C in oil and water-quenching. The diffusion bond between the fuel and cladding prevented ratcheting or shortening of the fuel in both cases.

Another rod was prepared with ceramic pellets (normal uranium oxide dispersed in zirconium oxide) as fuel material. The annulus between the pellets and the Zircaloy-2 jacket tubing was from 0.008 to 0.010 cm (0.003 to 0.004 in.). Slow heating to 300°C and slow cooling, and heating to 300°C in oil followed by water-quenching, did not alter the original dimensions of the pellets or the tubing.

Finally, a fuel rod consisting of cermet fuel (normal U_3O_8 dispersed in X-8001 aluminum) jacketed with close-fitting (no annulus) A-288 aluminum tubing was prepared and cycled, both slowly and rapidly, between room temperature and 300°C. Original dimensions of the fuel and jacket material were not changed by cycling.

In summary, the development work had shown that thermal ratcheting could be eliminated in at least four ways:

(1) Sufficient annular space could be left between fuel and jacket materials to allow for differential thermal expansion. In the case of the Al- U_3O_8 cermet fuel and Zircaloy-2 jacket materials, it was found experimentally and substantiated by arithmetical calculation (Appendix A) that a 0.005-cm (0.002-in.) annulus is adequate for this purpose.

(2) A diffusion bond could be effected between fuel and cladding. The bond between the Al- U_3O_8 cermet fuel and Zircaloy-2 cladding, which was achieved by zone-melting the core material at a controlled rate, prevented ratcheting during thermal cycling tests.

(3) Aluminum jacket tubing could be used rather than Zircaloy-2. Since the coefficients of thermal expansion for the fuel and jacket materials were so nearly equal, no ratcheting tendencies were observed in an aluminum-jacketed fuel-rod specimen that was thermally cycled.

(4) A fuel material could be used that has a lower thermal-expansion coefficient than that of the jacket material. No thermal ratcheting was observed in a specimen consisting of urania-zirconia ceramic-pellet fuel material in a Zircaloy-2 jacket.

Based on a review of the four proven methods for preventing ratcheting, considerations of fabricability, dependability, and material preferences led to the selection of the fourth stated alternative. The material chosen as the new reference fuel was a solid-solution ceramic composed of 9.01 w/o UO_2 (with the uranium constituent 93% U^{235}), 9.07 w/o CaO, and 81.92 w/o ZrO_2 .

Zircaloy-2 was retained as the choice for jacketing the ceramic fuel. The spike loading required 32 elements containing the reference fuel.

In addition, three elements were fabricated containing the original reference fuel, a cermet of U_3O_8 dispersed in X-8001 aluminum. Each of these elements had a distinguishing feature in that one of the other three methods of preventing thermal ratcheting was incorporated into the design. In one of these elements a controlled annulus of 0.005 to 0.008 cm (0.002 to 0.003 in.) was maintained between the cermet fuel and Zircaloy-2 jacket of each fuel rod. In another element, the cermet fuel and Zircaloy-2 cladding of the rods were diffusion-bonded. A-288 aluminum tubing was used to jacket the cermet fuel in the remaining element.

FUEL-ELEMENT FABRICATION

A spike fuel element consists of a fuel assembly and a frame assembly. The components for each type of assembly are described in Table III. Reference drawings for each component part are included in Appendix B. Fuel-element fabrication involved the procurement of materials, fabrication of components, and assembly of components into the final elements with operations such as cleaning, inspection, and record keeping interspersed between various processing steps.

TABLE III. Components of Fuel and Frame Assemblies

Item	Number per Assembly	Dimensions	Material
Fuel Assembly			
Fuel rods	49	0.95 cm (0.375 in.) diam x 130 cm (51 in.) long	Ceramic fuel pellets in Zircaloy-2 jacket tubing with Zircaloy-2 end plugs
Side plates	2	141 cm (55.5 in.) long x 7.6 cm (3 in.) wide x 0.16 cm (0.062 in.) thick	Zircaloy-2
Center spacer	1	9.05 cm (3.562 in.) sq x 0.64 cm (0.250 in.) thick	Zircaloy-2
End supports	2	9.05 cm (3.562 in.) sq x 13.02 cm (5.125 in.) long	Type 304 SS
Frame Assembly			
Corner angles	4	1.9 cm x 1.9 cm (0.750 in. x 0.750 in.) angles, 0.21 cm (0.08 in.) thick x 203 cm (80 in.) long	Zircaloy-2
Lifting plates	4	46.04 cm (18.125 in.) long x 6.03 cm (2.375 in.) wide x 0.21 cm (0.081 in.) thick	Zircaloy-2
Leaf springs	4	9.53 cm (3.750 in.) long x 2.86 cm (1.125 in.) wide x 0.08 cm (0.031 in.) thick	Zircaloy-2
End fitting	1	9.84 cm (3.875 in.) sq x 28 cm (11 in.) long	Type 304 SS
Burnable poison strips	2	155.89 cm x 5.79 cm x 0.16 cm (61.375 in. x 2.281 in. x 0.062 in.)	Type 304 SS with 1.1 w/o natural boron

Fuel Assembly

A single fuel assembly consists of (as shown in Table III) 49 fuel rods, two side plates, one center spacer, and two end supports. All the components, except the 304 SS end supports and the ceramic-pellet fuel material, were Zircaloy-2. For one of the experimental elements, aluminum parts were used instead of the Zircaloy-2 parts used in the other 34 fuel assemblies. One of the Zircaloy-2 clad fuel assemblies is shown in Fig. 8 before and after assembly.

106-5282-A

Fig. 8. Fuel-assembly Components before and after Assembly

All Zircaloy-2 tubing for fuel-rod jacketing was fabricated commercially from ingot material furnished by ANL. The 0.95-cm (0.375-in.)-OD x 0.06-cm (0.025-in.)-wall-thickness tubing was received from the fabricator in 147- to 157-cm (58- to 62-in.) lengths. Surface finish both inside and outside was to be smooth and free from such defects as laps, seams, and longitudinal striations. The tubing was also to be free of longitudinal cracks originating on the inside wall such as had been found in some 0.98-cm (0.385-in.)-OD evaluation tubing that had been previously procured. One anomaly observed in this 0.98-cm (0.385-in.)-OD evaluation tubing was a spiral pattern on the tube ID surface. This tubing had been sized over a hardened-steel mandrel. The mandrel was later removed in a riffling operation with a multiroll straightener. This expanded the tube slightly to facilitate mandrel removal. The spiral pattern, caused by contact with the straightener rolls, was not observed on the OD surface of delivered tubing as it had been removed by belt-sanding and acid-pickling.

Variations in tube-wall thickness associated with the spiral pattern were negligible, well within specified dimensional tolerances. It was possible that alternating bending stresses and additional cold work introduced by the riffling operating could contribute to tube cracks. Although this procedure was not considered a problem in commercial tube-mill practice, a detailed metallographic examination was made of the Zircaloy tubing. The metallographic structure of finished tubing confirmed the existence of severe and uneven amounts of cold work in this portion of the tubing. The tubing had been annealed to produce a fine-grained recrystallized structure.

The metallographic structure of a transverse section of annealed tubing (Fig. 9) shows that both the inside and outside tube surfaces in areas that had contacted the straightener rolls had undergone extensive cold work as indicated by the grain growth following recrystallization. This coarse-grain structure was almost completely absent from the two transverse sections of the same tube at 120° intervals from the previous section, as illustrated in Fig. 10. The coarse-grain structure was not always observed in all tubes that exhibited the spiral pattern on the ID surface.

Visual inspection of 20-cm (8-in.)-long segments from approximately 100 of the first 152 lengths of 0.95-cm (0.375-in.)-OD tubing received indicated that 40% of the material received had undesirable ID or material defects such as scratches, gouges, pock marks, galled spots, imbedded foreign particles, and spiral markings from cross-roll straightening and mandrel-removing operations. These defects could not be effectively removed, even by extensive pickling. Cracks deeper than 0.01 cm (0.004 in.) were detected in approximately 27% of all tubing tested with a dual-frequency, probe-type, eddy-current, testing unit developed at ANL.⁴ Oscillograph recordings provided permanent tube-inspection records with pen excursions representing flaws in tube walls at particular locations.

Fig. 9

Transverse Section through 0.98-cm (0.385-in.)-OD Zircaloy-2 Tube after Straightening and Annealing. The coarse-grain structure is in an area of severe bending stresses; the fine-grain structure along the neutral axis was not stressed in bending.

28625

Polarized Light

100X

28626

Polarized Light

100X

28627

Polarized Light

100X

Fig. 10. Transverse Sections through 0.98-cm (0.385-in.)-OD Zircaloy-2 Tube at 120° Intervals around the Circumference of the Tube Section Shown in Fig. 9. Severe bending stresses were almost completely absent from this portion of the tube wall.

As shown in Fig. 11, the eddy-current probe was mounted on a long-bed lathe in which tubes were rotated at 187 rpm. The probe moved with the lathe carriage at a feed of 0.16 cm (0.062 in.)/revolution. This arrangement and the need for a permanent recording of inspection results on each tube permitted an inspection rate of 9.7 cm (3.8 in.)/sec. Including setup time, approximately 3 min were required to inspect each tube length. Defect indications from the eddy-current device showed good correlation with both the location and the depth of actual cracks.

106-5236

Fig. 11. Lathe-mounted Eddy-current Equipment
for Inspecting Zircaloy-2 Tubing

When conclusive inspection and evaluation data first became available, it was decided that available jacket tubing with some ID inclusions and roughness must be accepted. This decision was based primarily on the following information:

- a) Tubing quality showed little or no improvement as subsequent batches were received.
- b) The vendor could foresee no process modifications that would improve the quality of future batches.
- c) The deadline for completion of the fuel loading did not allow time for further process development by the vendor.

Sufficient material for the loading could only be obtained if tubing was accepted with ID cracks or defects up to 0.01 cm (0.004 in.) deep. No application requirements or conditions could be determined to preclude the use of tubing having ID defects of the character indicated.

Measurement of the permanent trace of the eddy-current signal was the method used to select material to be accepted. Tubes were accepted if the trace deflection within a 124-cm (49-in.)-long section was 0.6 cm (0.25 in.) or less. The average background signal produced a deflection of 0.16 to 0.32 cm (0.062 to 0.125 in.). Most of the acceptable tubing contained crack-type or other defects as deep as 0.01 cm (0.004 in.). The eddy-current trace of a rejected tube, shown in Fig. 12, is indicative of deflections caused by wall imperfections emanating from the inside diameters of tubes.

The reference design for EBWR spiked fuel called for an aluminum- U_3O_8 dispersion fuel loaded into 0.98-cm (0.385-in.)-OD x 0.06-cm (0.025-in.)-wall Zircaloy-2 tubes. The fuel rods would then be drawn to 0.95-cm (0.375-in.) OD as a final sizing operation, which would also reduce the annulus between the fuel and the tube ID. Tubing was originally ordered to 0.98-cm (0.385-in.) OD. After the reference design was changed to incorporate the ceramic fuel, the tubing stock size was changed to 0.95-cm (0.375-in.) OD x 0.06-cm (0.025-in.) wall. The tube vendor was notified, and the fabrication process was changed accordingly. Some fabricated 0.98-cm (0.385-in.)-OD tubing and some 0.95-cm (0.375-in.)-OD tubing, which was too small for oversize ceramic pellets, were resized at ANL by various methods including die-sinking, drawing over a mandrel, stretching over a mandrel, and expanding over a pin. A total of 740 tubes were resized and inspected.

The following procedures were used in evaluation and inspection of the Zircaloy-2 tubing prior to machining to length. The tubes were cleaned by degreasing in hot trichlorethylene upon receipt, plug-gaged to assure that pellets could be inserted, and eddy-current-inspected for crack-type defects. Tubes were consecutively numbered after eddy-current inspection, and the following records were maintained:

- a) Tube number.
- b) Eddy-current trace on acceptable tubes.
- c) Size of largest plug gage which would pass through the tube.

End-plug stock was hot-rolled at ANL from 4.13-cm (1.625-in.)-diam bars forged at Anderson Schumaker and Company, Chicago. The starting material was 30-cm (12-in.)-diam, atmosphere-melted, Zircaloy-2 ingot. To provide end plugs for weld closure of tubes, approximately 14.3 m (47 ft) of the 4.13-cm (1.625-in.)-diam forged-bar stock was machine-conditioned, dye-penetrant inspected, and hot-rolled at 850°C to 1.9-cm (0.75-in.) diam. Subsequent rolling to 1.02-cm (0.402-in.) diam was done at a temperature of 600°C. Yield from forged bar to 1.02-cm (0.402-in.)-diam rod was 78% minimum. After centerless grinding to finished diameter, the rod

Fig. 12

Typical Eddy-current Trace and Corresponding Transverse Sections through a Defective Zircaloy-2 Tube

stock was ultrasonic through-transmission tested for material defects. Of 183 m (600 ft) tested, 4% was rejected due to suspected internal defects.

End-plug stock was finish-machined after development of the arc-welding method had fixed the design of the end closures. A total of 3600 end plugs, representing approximately 80 w/o of the stock supplied, were made. Acceptable Zircaloy-2 tubes, which had been cut to final length of 124.46 ± 0.03 cm (49.00 ± 0.010 in.) and plug-gaged to determine the exact ID size, were matched with end plugs which had been stamped with numbers corresponding to their respective identifying tube numbers. The matched end plugs were inert-gas shielded-arc welded into one end of the corresponding tubes, and the welds were checked with a mass-spectrometer helium-leak detector. The fuel rods were lathe-mounted in a horizontal position and rotated automatically during the programmed welding cycle while a stationary torch effected a continuous circumferential weld.

The welding equipment is shown in Fig. 13. The power supply was a 300-Amp d.c. rectified welder operating at 30 Amp and approximately 12 V. The power remained constant during the weld cycle until, after 360° of completed weld, the current was reduced before being completely shut down. In this manner, weld crater formation was avoided. The automatic weld cycle included a 10-sec helium purge at 0.56 cu m (20 cu ft)/hr before and after welding. The rotation of the work was varied from 5 rpm at the start to 15 rpm at the completion of the weld. Speed variation during the single 360° rotation was necessary to compensate for the heat buildup in the end

106-4991

Fig. 13. Equipment for Gas Tungsten-arc Welding End Plugs to Jacket Tubing

plug. The only manual operation of the automatic cycle was the positioning of the electrode. The configuration of the end-plug weld is shown in Fig. 14.

106-5391-A

Fig. 14. Weld Configuration for Fuel-rod End Plug to Jacket Tubing

A noteworthy feature, which typifies the weld of the end plug to the jacket tubing, is that the metal thickness at the weld is greater than that of the tube wall. This is accomplished through proper end-plug design.

After the first end-plug weld enclosure was tested, the tubes were manually loaded with the ceramic-pellet fuel material.² The loaded fuel tubes were evacuated and back-filled with an atmosphere of approximately 98 v/o helium, 1 v/o nitrogen, 1 v/o hydrogen, and the second end plug was welded into the open ends of the fuel rods. The glovebox and related equipment that were used for evacuation and backfilling of the fuel tubes prior to final end-plug closure-welding are shown in Fig. 15. This equipment was constructed for processing of EBR-II blanket rods⁵ and proved to be convenient for accomplishing this part of the fuel-rod manufacturing operations. The

helium atmosphere enabled the checking of the final end-plug closure welds, and served as an efficient medium for heat transfer across the 0.008- to 0.010-cm (0.003- to 0.004-in.) annulus between the ceramic fuel and the Zircaloy cladding. Of the number of welds required in fabricating 1,568 fuel rods of this type, less than 1.0% were found to be incompletely sealed.

After 0.18-cm (0.070-in.)-wide x 1.3-cm (0.5-in.)-deep positioning slots were machined into both end plugs of each loaded and sealed rod, the rods were wet-abrasive blasted at 3.5 to 4.2 kg/cm² (50 to 60 psi) with 400-mesh Al₂O₃ grit. Fuel rods were traversed through the center of a metal ring to which were attached three grit-blasting nozzles. The nozzles were positioned to focus the Al₂O₃-H₂O slurry at the traversing fuel rod as the slurry was air blasted from the nozzles. The relative positions of nozzles and fuel rod during cleaning are shown in Fig. 16. A chain-belt-driven, screw-type, driving rod was used to mechanically pass the fuel rod through the focal point of the abrasive grit blast so that the rod was rotated at 120 rpm during a 10-min traversing interval. The rods were then pickled in a 35v/oHNO₃-5v/oHF solution maintained at 35 to 50°C to enhance the corrosion resistance of the rod surface. Five fuel rods are shown being

pickled in Fig. 17. The vapor-blasting and pickling operations removed above 0.005 cm (0.002 in.) from the OD of the rods.

106-4975

Fig. 15. Glovebox Facility Used to Evacuate and Back-fill Fuel Tubes with Helium Atmosphere

Fig. 16

Setup for Wet-abrasive Blast Cleaning of Fuel Rods

106-5280

Fig. 17. Fuel Rods Being Pickled in
Warm $35\text{v}/\text{oHNO}_3$ - $5\text{v}/\text{oHF}$

Figure 18 is a view of one end of a completed fuel rod and a fuel rod with the jacket cut away. The rods were nominally 0.95 cm (0.373 in.) diam x 130 cm (51 in.) long. Each fuel rod contained nominally 17.64 g

106-5281-A

Fig. 18. One End of a Completed Fuel Rod and a Fuel Rod
with Cutaway Jacket

of U^{235} . Each element contained 864.36 g (17.64 x 49) of U^{235} . Based on the weight of fuel loaded into each fuel rod (217 to 258 g), the percentage of UO_2 in the fuel (9.01 w/o), the percentage of uranium in the UO_2 (~88 w/o), and the percentage of U^{235} in the uranium (~93 w/o), the amount of U^{235} in each fuel rod was calculated. These calculated values, for each rod and as totaled on a per-element basis, are tabulated in Appendix C.

Center spacers for 34 elements (one per element) were cut from 0.6-cm (0.25-in.) Zircaloy-2 plate. The plate was sheared to about 9.5-cm (3.75-in.) squares. The squares were drilled to accept 49 fuel rods in a 7 x 7 array, and machined to allow for maximum coolant flow between fuel rods. Completed spacers were wet-abrasive blasted and pickled in warm 35v/oHNO₃-5v/oHF solution, to a final nominal size of 9.05 cm (3.562 in.) sq.

Sheet stock of Zircaloy-2 fabricated from vacuum-melted ingots was inspected, wet-abrasive blast-cleaned to remove rolled-in dirt, and acid-pickled in the 40°C 35v/oHNO₃-5v/oHF solution.

Side plates (two per element, or 68 total) were sheared to size, cold die-formed to final shape, and again warm-acid dipped. The 0.16-cm (0.064-in.)-thick side plates were roughly 7.6 cm (3 in.) wide x 141 cm (55.5 in.) long.

Fuel-rod end supports as shown in Fig. 19 were fabricated from Type 304 SS. Support holders were made by cold-forming 0.21-cm (0.081-in.)-thick sheet into channel shapes, and inert-gas shielded-arc welding two mated channel seams. Rod supports were sheared from 0.16-cm (0.062-in.)-thick stock and gang-milled to final shape. Seven rod

106-5239-A

Fig. 19. Fuel-rod End Support before and after Assembly

supports were welded in place on each support holder. Lifting lugs were sheared to size from 0.32-cm (0.125-in.)-thick stock and welded in place at the opposite end of the support holder to complete the end supports. A total of 70 end supports were made, since two were needed for each of the 35 fuel elements fabricated. End supports were given an electrolytic polish as a final cleaning operation. End supports were 9.05 cm (3.562 in.) sq x 13.02 cm (5.125 in.) long.

The 130-cm (51-in.)-long fuel rods were held in the fuel assembly by fitting the positioning slots in each end plug onto the rod supports at both ends. Comb-type positioning fixtures were used to hold the fuel rods in position until the end support was fully seated. The rods were also supported at their centers by the center spacer. The fuel assemblies were completed by fastening the side plates to the end supports with two 0.6-cm (0.25-in.)-diam stainless-steel rivets at each end of both side plates, and resistance-spot-welding the side plates to the center spacer. During assembly of the rod bundles, records were maintained as to the number of the assembly into which each rod was loaded. These numbers, which are the same as the fuel-element numbers, are part of Appendix C. The length of a completed fuel assembly, as seen in Fig. 8, is 154.3 cm (60.75 in.).

Frame Assembly

As given in Table III, a frame assembly consists of four corner angles, four lifting plates, four leaf springs, one end fitting, and two natural-boron poison strips. Figure 20 is a photograph showing all components except the boron poison strips, before and after assembly. With the exception of the Type 304 SS end fitting and the Type 304 SS strips containing 1.1 w/o boron, all frame components were Zircaloy-2.

106-5283-A

Fig. 20. Frame-assembly Components before and after Assembly

Corner angles were made from 0.021-cm (0.081-in.)-thick Zircaloy-2 sheet. The sheet was sheared into 3.8-cm (1.5-in.)-wide strips. Right angles with 1.9-cm (0.75-in.) sides were formed from these strips on a press brake, after resistance-heating the strips to approximately 700°C by means of a 600-Amp Hobart welder. The angles were then wet-abrasive blasted to remove surface contamination which occurred during heating for forming. The abrasive-cleaned angles were cut to final length of 203 cm (80 in.). For the first 48 cm (19 in.) along their lengths, the outer 0.95 cm (0.375 in.) of the angle sides was milled to 0.10-cm (0.040-in.) thickness as shown in Fig. 21. Finally, the angles were degreased and given the standard warm-acid pickle. A total of 136 corner angles, or four for each of 34 frame assemblies, were fabricated.

106-5232

Fig. 21. Corner Angles Being Milled to Design Dimensions

Lifting plates were sheared to final nominal dimensions of 46.04 x 6.03 cm (18.125 x 2.375 in.) from 0.21-cm (0.081-in.) Zircaloy-2 sheet stock. Holes were punched into each plate near one end to accommodate the free end of a leaf spring and lifting devices, which were to be used to

position the fuel element in its reactor location. Finished plates were given the usual wet-abrasive blast cleaning and acid pickle. A total of 136 lifting plates were fabricated.

Leaf springs measuring 0.95 x 2.86 cm (0.375 x 1.125 in.) were sheared and cold-formed from 0.08-cm (0.031-in.)-thick Zircaloy-2 strip, after which they were degreased and pickled. Since each lifting plate required a companion leaf spring, 136 were made.

A single-leaf spring was resistance-spot-welded to each lifting plate to aid in spacing the fuel elements in the reactor. Milled corner angle sides were lapped over, and resistance-spot-welded to, milled lifting-plate edges to form a square cross section at one end of the frame assembly. The welding operation and Sciaky equipment are shown in Fig. 22.

106-5231

Fig. 22. Corner Angles Being Spot-welded to Lifting Plates to Complete One End of Frame Assembly

A single Type 304 SS end fitting was used for each of the 35 frame assemblies. These end fittings were sand-cast at Watertown Arsenal. After formed Type 304 SS crosspieces, 0.32 cm (0.125 in.) thick, were gas tungsten-arc welded onto the end fittings, the fittings were machined to final dimensions of 9.84 cm (3.875 in.) sq x 28 cm (11 in.) long. A completed end fitting was attached to the free ends of the corner angles with 0.6-cm (0.25-in.)-diam flathead screws.

Burnable-poison strips of Type 304 SS containing 1.1 w/o natural boron were purchased from Universal-Cyclops Steel Company, Bridgeville, Pennsylvania. Strips were received in final dimensional form, 155.89 cm (61.375 in.) long x 5.79 cm (2.281 in.) wide x 0.16 cm (0.062 in.) thick. Punching and shearing operations were done at ANL. Two poison strips were attached to each frame assembly--one on each of two opposite and parallel sides. The strips were tack-welded to the end fitting at one end and "tucked" inside the lifting plates at the other end of the assembly. The welds could be easily broken enabling remote removal of selected poison strips to restore reactivity as required during reactor service.

A completely assembled frame, as shown in Fig. 20, was 9.84 cm (3.875 in.) sq x 227.3 cm (89.5 in.) long. The poison strips are not shown in this photograph.

A fuel assembly, invertible with respect to its ends, was inserted into a frame assembly, as shown in Fig. 23, to complete each fuel element.

106-5284

Fig. 23. Fuel Assembly Being Inserted into Frame Assembly to Complete Fuel Element

Experimental Elements

In addition to 32 ceramic fuel elements, three elements were made containing a dispersion of 11.83 w/o highly enriched U_3O_8 in X-8001 aluminum. The dispersion-type cermet fuel material for the three elements was made by mixing a predetermined amount of -140 mesh enriched U_3O_8 with -140 mesh X-8001 Alcoa aluminum powder, sealing the mixed powders in a 0.32-cm (0.125-in.)-wall-thickness x 11.3-cm (4.5-in.)-diam X-8001 aluminum can, and extruding the sealed billet (Fig. 2) through a 0.82-cm (0.322-in.)-diam die with conditions as previously described (page 12). The extruded material was cut into core lengths, and density measurements were made on each core section. Since the density of any given core section used in a fuel rod did not vary from the density of any other fuel-rod core section by more than 1%, it appears that good homogeneity of U_3O_8 content was achieved in the cermet extrusions. Aluminum jacket tubing for one of these elements was extruded through a porthole die from machined A-288 aluminum* cast billets, 15 cm (6 in.) diam x 51 cm (20 in.) long. The cast billets were procured from Aluminum Company of America. The 0.95-cm (0.375-in.)-OD tubing was given an eddy-current test for internal wall defects. Of 640 m (2100 ft) inspected, approximately 47% was considered acceptable.

The side plates and center spacer for the aluminum-jacketed element were fabricated by hot-rolling an Alcoa A-288 billet at 260°C, cold-finishing to final thickness, and shearing, forming, and machining as described previously for the Zircaloy-2 components. A-288 aluminum end-plug stock was fabricated by hot-rolling at 260°C, cold-swaging, grinding, and machining to final dimensions.

Zircaloy-2 tubing for one of the special elements was selected so that 0.005- to 0.008-cm (0.002- to 0.003-in.) annuli remained between the fuel and jacket of each rod. The rods for another element were passed through an induction coil to melt only the outer layer of the cermet fuel causing diffusion bonding to occur between the fuel and cladding. The bonding process was briefly described earlier (page 18). Aluminum tubing for the remaining element was expanded to enable insertion of fuel sections, and then drawn down over the fuel to achieve best possible contact between the tubing and fuel. All other assembly steps for these three elements were as described previously, except that aluminum components for one fuel assembly were not abrasive-blasted or acid-pickled and the tubes were cut to final length after the fuel sections were loaded.

The net U^{235} content of each fuel rod in these three experimental elements is tabulated, on a per-rod and per-element basis, in Appendix C. The lower than nominal amounts of U^{235} in most of the fuel rods in these three elements stems from the fact that the fuel sections were sheared or

*A-288 aluminum is high-purity (99.999 w/o) aluminum + 1 w/o nickel and 0.5 w/o iron.

snipped slightly undersize in length from the extruded cermet rods, rather than being precisely machined to length.

SUMMARY

The original reference fuel for the EBWR spiked-core loading was a cermet composed of 11.83 w/o U_3O_8 (fully enriched), dispersed in an 88.17 w/o matrix of X-8001 aluminum, jacketed in close-fitting Zircaloy-2 tubing. However, in fuel sections of this design, ratcheting (successive shortening of cermet-fuel lengths and increasing of outer-jacket diameters) was found to occur upon thermal cycling between the reactor operating temperature (260°C) and room temperature. This condition progressed with each additional thermal cycle and, in some cases, resulted in rupture (longitudinal splitting) of the jacket tubing.

It was determined that ratcheting could be prevented in at least four ways. One of these was to substitute a solid-solution ceramic fuel for the cermet fuel. The particular ceramic, which was chosen as the new reference fuel, consisted of 9.01 w/o UO_2 (fully enriched), 9.07 w/o CaO, and 81.92 w/o ZrO_2 . A total of 32 elements were fabricated with this fuel jacketed in Zircaloy-2 tubing. In addition, three experimental elements were fabricated, each with the original cermet fuel and each incorporating a different design feature to prevent ratcheting. In one case, controlled annuli were maintained between fuel and jacket; in another case, fuel was metallurgically bonded to jacket material; and in a third case, close-fitting A-288 aluminum tubing was substituted for Zircaloy-2 as jacketing.

Zircaloy-2 jacket tubing, strip stock for frame components, and an arc-cast forging billet for end-plug stock were commercially procured. Cast Type 304 SS end fittings and Type 304 SS poison strips containing natural boron, atomized X-8001 aluminum powder for cermet-fuel matrix, and A-288 aluminum castings (from which were made tubing, end plugs, and selected fuel-assembly components for one experimental element) were also purchased from commercial suppliers. Commercial facilities were used for aluminum tube and fuel extrusion, and for forging of Zircaloy-2 end-plug stock.

Evaluation of materials, fabrication of fuel- and frame-assembly components, and assembly of fuel elements, were done at ANL. Table IV is a summary of components fabricated and used for the spiked-core fuel elements. Although 4,900 m (16,000 ft) of Zircaloy-2 tubing in approximately 152-cm (60-in.) lengths were procured, it was necessary to accept ID cracks or defects up to 0.01 cm (0.004 in.) in depth to provide enough lengths of tubing for the 34 Zircaloy-2 jacketed fuel elements. Approximately 50% of the lengths of tubing inspected by a dual-frequency, eddy-current testing unit were rejected as having defects of larger magnitude than this specified minimum.

TABLE IV. Summary of Components Fabricated and Used for
Assembly of 35 EBWR Spiked-core Fuel Elements

Item	Material	Amount or Number Used
Ceramic pellet fuel	9.01w/oUO ₂ (93% enriched)- 9.07w/oCaO-81.92w/oZrO ₂	379,755.6 g (242.2 g mean per fuel rod)
Cermet fuel	11.83 w/o U ₃ O ₈ (93% enriched), dispersed in an 88.17 w/o matrix of X-8001 aluminum	26,379.6 g (179.5 g mean per fuel rod)
Fuel tubes	Zircaloy-2	2,073.5 m (6,802.8 ft) in 1,666 lengths of 124.5 cm (49 in)
	A-288 aluminum	61.0 m (200 ft) in 49 lengths of 124.5 cm (49 in.)
End plugs	Zircaloy-2	3,332 (two each for 1,666 fuel rods)
	A-288 aluminum	98 (two each for 49 fuel rods)
Side plates	Zircaloy-2	68 (two each for 34 fuel assemblies)
	A-288 aluminum	Two (for one fuel assembly)
Center spacers	Zircaloy-2	34 (one each for 34 fuel assemblies)
	A-288 aluminum	One (for one fuel assembly)
End supports	Type 304 SS	70 (two each for 35 fuel assemblies)
Corner angles	Zircaloy-2	140 (four each for 35 frame assemblies)
Lifting plates	Zircaloy-2	140 (four each for 35 frame assemblies)
Leaf springs	Zircaloy-2	140 (four each for 35 frame assemblies)
End fittings	Type 304 SS	35 (one each for 35 frame assemblies)
Burnable poison strips	Type 304 SS + 1.1 w/o natural boron	70 (two each for 35 frame assemblies)

Some development was required to optimize the fuel-rod end-plug design and parameters associated with welding and forming of Zircaloy-2 components. For the most part, however, the fabrication of components and assembly of fuel elements progressed quite smoothly. Zircaloy-2 tubing and strip stock were received at ANL in January to March 1960. The first 32 elements were completed by May 1960. Aluminum fuel and components were processed and the remaining three experimental elements completed by August 1960.

OPERATING EXPERIENCE

Loading of the EBWR spiked core was started February 29, 1960. The first spike elements were loaded during April 1960. Beginning at this time and continuing until December 6, 1962, a series of experiments and tests⁶ was conducted, with 100-MWt operation being achieved on November 15, 1962. The arrangement of the final EBWR spiked core is shown in Fig. 24. The spike elements had undergone approximately 5 a/o U^{235} burnup before reactor shutdown in December 1962. Other than the typical water-corrosion product covering the Zircaloy-2 and stainless-steel components, the physical appearance of the spike elements upon removal from the reactor was no different from when they were originally loaded. Fuel-rod dimensions were essentially unchanged, and postirradiation examination of one element has given no indication that the fuel did not perform satisfactorily during its critical reactor lifetime.

EBWR-CORE 1A; LOADING #63 (REV).

52-EH = ENRICHED HEAVY
 54-ET = ENRICHED THIN
 8-NH = NATURAL HEAVY
 1-NT = NATURAL THIN
 32-S = SPIKE
 1-N* = SOURCE

Fig. 24

Final EBWR 100-MW Core Loading

112-2621

Only the 32 ceramic-pellet-fueled elements were used in the spiked-core configurations during critical operation. Although the three cermet-fueled experimental elements were available, the limited time available for carrying out the testing program, the fact that 100-MW operation was achieved using the ceramic-fueled elements, and the de-emphasis taking place in the water-reactor program at ANL, were factors that led to abandonment of plans for their use as part of an EBWR spiked-core loading.

APPENDIX A

Theoretical Annulus Required to Compensate for Thermal-expansion-
coefficient Differential in EBWR Spike Fuel Rods Consisting
of Al-U₃O₈ Jacketed with Zircaloy-2

E_Z = Thermal-expansion coefficient of Zircaloy-2 from 25 to 250°C*

$$= 5.4 \times 10^{-6} \text{ cm/cm-}^\circ\text{C}.$$

E_A = Thermal-expansion coefficient of pure aluminum** from 20 to 100°C*

$$= 23.9 \times 10^{-6} \text{ cm/cm-}^\circ\text{C}.$$

T_R = Reactor operating temperature = 260°C.

T_A = Ambient temperature = ~20°C.

D = Core diameter = 0.83 cm (0.325 in.).

$(T_R - T_A) \times (E_A - E_Z) \times D$ = Thermal-expansion differential for fuel
relative to jacket,

$$= (260 - 20) \times (23.9 - 5.4) \times 10^{-6} \times 0.83$$

$$= 0.004 \text{ cm}.$$

$$\text{Minimum annulus required} = \frac{0.004}{2} = 0.002 \text{ cm}.$$

Since it is difficult to control annulus size to increments of <0.0025 cm (0.001 in.), an annulus of ≥ 0.0051 cm (0.002 in.) would be required to ensure elimination of thermal ratcheting between fuel and jacket.

*Although temperatures covered by the coefficients used do not satisfy the total range (20 to 260°C) of interest, the error incurred by using these values would not be so great as to invalidate this calculation.

**The expansion coefficient of the cermet fuel material has not been determined, but is not likely to be greater than the coefficient for pure aluminum that was used for this calculation. Therefore, any inherent error resulting from this substitution of coefficients would not make the calculated minimum annulus smaller than the actual minimum annulus.

APPENDIX B

Drawings of EBWR Spiked-core Fuel Elements
(all dimensions in centimeters)

Fig. 25
Ceramic Fuel Pellet

Fig. 26. Jacket Tube

Fig. 27
End Plug

Fig. 28. Fuel Rod

Fig. 29. Side Plate

Fig. 30
Center Spacer

Fig. 31. Lifting Lug

Fig. 32. Rod Support

Fig. 34
End-support
Subassembly

APPENDIX C
Contents of U²³⁵ in EBWR Spike Fuel

TABLE V. U²³⁵ Content by Fuel-element Number

Fuel-element No.	(A) Total Net U ²³⁵ , g	Total Over (Under) Nominal,* g	(A ÷ 49) Mean U ²³⁵ per Fuel Rod, g	Total Over (Under) Nominal,** g
1	861.91	(2.45)	17.59	(0.05)
2	858.35	(6.01)	17.52	(0.12)
3	864.66	0.30	17.64	-
4	875.04	10.68	17.86	0.22
5	880.07	15.71	17.96	0.32
6	886.42	22.06	18.09	0.45
7	895.24	30.88	18.27	0.63
8	898.93	34.57	18.34	0.70
9	900.78	36.42	18.38	0.74
10	893.33	28.97	18.23	0.59
11	895.91	31.55	18.28	0.64
12	908.25	43.89	18.53	0.89
13	868.28	3.92	17.72	0.08
14	911.99	47.63	18.61	0.97
15	891.03	26.67	18.18	0.54
16	924.61	60.25	18.87	1.23
17	883.83	19.47	18.04	0.40
18	877.42	13.06	17.91	0.27
19	917.21	52.85	18.72	1.08
20	883.99	19.13	18.04	0.40
21	901.78	37.42	18.40	0.76
22	893.16	28.80	18.23	0.59
23	887.20	22.84	18.11	0.47
24	886.22	21.86	18.09	0.45
25	864.27	(0.09)	17.64	-
26	879.99	15.63	17.96	0.32
27	879.81	15.45	17.95	0.31
28	871.78	7.42	17.79	0.15
29	857.29	(7.07)	17.50	(0.14)
30	868.22	3.86	17.72	0.08
31	858.80	(5.56)	17.53	(0.11)
32	873.36	9.00	17.82	0.18
33-A	810.48	(53.88)	16.54	(1.09)
34-A	819.06	(45.30)	16.72	(0.92)
35-A	764.53	(99.83)	15.60	(2.04)

*Nominal net U²³⁵ per element = 864.36 g.

**Nominal net U²³⁵ per rod = 17.64 g.

TABLE VI. U^{235} Content by Fuel-rod Number for Fuel-element No. 1

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
28	17.53	(0.11)	259	18.07	0.43
47	17.49	(0.15)	264	18.04	0.40
54	17.07	(0.57)	272	17.91	0.27
65	17.46	(0.18)	275	17.52	(0.12)
69	17.27	(0.37)	276	17.99	0.35
75	17.83	0.19	283	17.50	(0.14)
76	17.32	(0.32)	289	18.03	0.39
89	17.59	(0.05)	298	17.74	0.10
94	17.28	(0.36)	306	17.59	(0.05)
100	17.90	0.26	313	18.03	0.39
103	17.38	(0.26)	321	17.71	0.07
104	17.19	(0.45)	327	17.52	(0.12)
113	17.03	(0.61)	331	17.67	0.03
118	17.61	(0.03)	332	17.73	0.09
119	17.20	(0.44)	352	17.45	(0.19)
139	17.66	0.02	353	17.91	0.27
142	17.07	(0.57)	363	17.37	(0.27)
155	17.35	(0.29)	373	17.88	0.24
164	17.22	(0.42)	389	17.86	0.22
231	17.90	0.26	407	17.53	(0.11)
235	17.88	0.24	1160	17.54	(0.10)
241	17.78	0.14	121	17.36	(0.28)
242	17.50	(0.14)	122	17.20	(0.44)
247	17.71	0.07			
251	17.86	0.22	TOTAL	861.91	(2.45)
256	17.68	0.04			

TABLE VII. U^{235} Content by Fuel-rod Number for Fuel-element No. 2

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
83	17.26	(0.38)	1137	17.55	(0.09)
96	17.41	(0.23)	1142	17.58	(0.06)
120	17.47	(0.17)	1144	17.57	(0.07)
271	17.98	0.34	1145	17.77	0.13
274	17.75	0.11	1156	17.22	(0.42)
1090	17.70	0.06	1164	17.91	0.27
1092	17.07	(0.57)	1166	17.64	-
1093	17.76	0.12	1167	16.51	(1.13)
1094	17.76	0.12	1170	17.61	(0.03)
1095	17.85	0.21	1174	17.20	(0.44)
1098	17.90	0.26	1202	17.25	(0.39)
1100	17.09	(0.55)	1204	17.29	(0.35)
1103	17.36	(0.28)	1205	17.77	0.13
1104	17.87	0.23	1206	17.12	(0.52)
1106	17.79	0.15	1210	17.25	(0.39)
1107	16.21	(1.43)	1211	17.41	(0.23)
1109	17.10	(0.54)	1218	17.65	0.01
1112	17.70	0.06	1224	17.82	0.18
1114	17.79	0.15	1230	17.32	(0.32)
1118	17.91	0.27	1233	17.68	0.04
1120	17.78	0.14	1234	17.41	(0.23)
1121	17.53	(0.11)	1264	17.54	(0.10)
1124	17.79	0.15	1352	17.62	(0.02)
1126	17.87	0.23			
1127	17.77	0.13	TOTAL	858.35	(6.01)
1130	17.19	(0.45)			

TABLE VIII. U^{235} Content by Fuel-rod Number for Fuel-element No. 3

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
1091	17.80	0.16	1222	17.65	0.01
1097	17.83	0.19	1225	17.61	(0.03)
1099	17.81	0.17	1226	17.77	0.13
1108	17.83	0.19	1227	17.85	0.21
1111	17.00	(0.64)	1228	17.47	(0.17)
1116	17.61	(0.03)	1231	17.94	0.30
1117	17.10	(0.54)	1235	17.81	0.17
1129	16.98	(0.66)	1239	17.68	0.04
1136	17.03	(0.61)	1244	17.83	0.19
1146	17.85	0.21	1245	17.65	0.01
1147	17.55	(0.09)	1246	17.67	0.03
1151	17.85	0.21	1248	17.70	0.06
1157	17.74	0.10	1250	17.84	0.20
1162	17.68	0.04	1257	17.79	0.15
1169	17.81	0.17	1259	17.80	0.16
1171	17.84	0.20	1262	17.71	0.07
1176	17.82	0.18	1273	17.70	0.06
1178	17.58	(0.06)	1286	17.66	0.02
1180	17.69	0.05	1296	17.68	0.04
1183	17.54	(0.10)	1299	17.64	-
1190	17.74	0.10	1317	17.65	0.01
1208	17.44	(0.20)	1322	17.68	0.04
1213	17.78	0.14	1460	17.90	0.26
1219	17.24	(0.40)			
1220	17.61	(0.03)	TOTAL	864.66	0.30
1221	17.23	(0.41)			

TABLE IX. U^{235} Content by Fuel-rod Number for Fuel-element No. 4

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
1138	17.58	(0.06)	1353	18.27	0.63
1141	17.80	0.16	1354	17.69	0.05
1143	17.91	0.27	1371	18.23	0.59
1158	17.75	0.11	1391	18.02	0.38
1165	17.82	0.18	1392	17.87	0.23
1188	17.16	(0.48)	1401	17.80	0.16
1215	17.60	(0.04)	1402	17.88	0.24
1238	17.70	0.06	1403	17.66	0.02
1240	17.50	(0.14)	1406	18.33	0.69
1255	17.69	0.05	1408	18.26	0.62
1295	17.98	0.34	1409	17.83	0.19
1301	18.03	0.39	1411	17.89	0.25
1303	17.96	0.32	1412	18.18	0.54
1308	17.71	0.07	1414	17.77	0.13
1315	17.66	0.02	1417	18.10	0.46
1318	17.85	0.21	1418	18.09	0.45
1321	17.60	(0.04)	1422	17.73	0.09
1325	17.67	0.03	1424	18.16	0.52
1331	17.86	0.22	1425	18.07	0.43
1333	18.07	0.43	1426	18.06	0.42
1338	18.14	0.50	1459	17.04	(0.60)
1340	18.00	0.36	1512	17.65	0.01
1343	17.68	0.04	1513	18.16	0.52
1346	18.14	0.50			
1348	17.69	0.05	TOTAL	875.04	10.68
1349	17.75	0.11			

TABLE X. U^{235} Content by Fuel-rod Number for Fuel-element No. 5

Fuel-rod No	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
425	19.11	1.47	1575	18.08	0.44
426	19.32	1.68	1583	17.94	0.30
433	18.67	1.03	1584	18.13	0.49
446	19.24	1.60	1585	17.80	0.16
454	18.23	0.59	1590	17.83	0.19
457	18.73	1.09	1615	18.23	0.59
469	17.85	0.21	1618	18.04	0.40
482	18.87	1.23	1627	17.83	0.19
491	18.71	1.07	1628	17.88	0.24
502	18.87	1.23	1633	16.43	(1.21)
535	17.68	0.04	1638	16.51	(1.13)
539	17.86	0.22	1646	16.44	(1.20)
542	18.96	1.32	1652	17.68	0.04
544	17.08	(0.56)	1657	16.40	(1.24)
553	19.24	1.60	1658	18.08	0.44
573	18.23	0.59	1663	18.15	0.51
582	17.92	0.28	1667	17.93	0.29
621	16.68	(0.96)	1679	17.98	0.34
1528	17.89	0.25	1695	17.81	0.17
1530	17.98	0.34	1698	17.28	(0.36)
1537	18.17	0.53	1701	17.85	0.21
1538	18.16	0.52	1715	19.18	1.54
1540	18.16	0.52	1716	16.38	(1.26)
1550	18.20	0.56			
1553	17.93	0.29	TOTAL	880.07	15.71
1556	16.47	(1.17)			

TABLE XI. U^{235} Content by Fuel-rod Number for Fuel-element No. 6

Fuel-rod No	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
412	17.86	0.22	571	17.71	0.07
424	17.13	(0.51)	591	18.51	0.87
427	17.94	0.30	673	18.35	0.71
429	17.80	0.16	700	18.54	0.90
441	19.22	1.58	714	17.98	0.34
443	17.88	0.24	1386	18.54	0.90
451	17.95	0.31	1515	18.03	0.39
460	16.23	(1.41)	1544	17.90	0.26
463	18.79	1.15	1546	18.13	0.49
474	18.46	0.82	1570	18.28	0.64
483	17.97	0.33	1576	18.19	0.55
487	19.07	1.43	1579	18.10	0.46
490	17.95	0.31	1610	18.06	0.42
493	17.87	0.23	1620	17.88	0.24
501	18.90	1.26	1637	18.07	0.43
512	19.12	1.48	1640	18.37	0.73
522	19.11	1.47	1643	17.24	(0.40)
523	17.97	0.33	1690	17.86	0.22
525	17.86	0.22	1704	17.77	0.13
533	17.62	(0.02)	1707	18.17	0.53
538	18.20	0.56	1717	17.87	0.23
547	16.36	(1.28)	1718	18.87	1.23
549	18.11	0.47	1720	17.60	(0.04)
554	19.04	1.40			
564	17.77	0.13	TOTAL	886.42	22.06
570	18.22	0.58			

TABLE XII. U^{235} Content by Fuel-rod Number for Fuel-element No. 7

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
434	18.49	0.85	1629	19.01	1.37
462	19.12	1.48	1631	18.20	0.56
472	17.04	(0.60)	1650	17.37	(0.27)
477	16.75	(0.89)	1661	18.28	0.64
531	18.75	1.11	1665	18.07	0.43
551	18.93	1.29	1668	18.21	0.57
574	18.82	1.18	1676	18.42	0.78
606	18.19	0.55	1685	18.54	0.90
661	17.45	(0.19)	1689	17.89	0.25
691	18.47	0.83	1702	18.06	0.42
1514	18.07	0.43	1703	18.23	0.59
1522	18.46	0.82	1705	18.34	0.70
1523	18.52	0.88	1723	18.73	1.09
1536	18.59	0.95	1727	18.29	0.65
1541	17.39	(0.25)	1728	18.53	0.89
1555	18.29	0.65	1750	18.31	0.67
1562	16.99	(0.65)	1784	18.87	1.23
1565	18.13	0.49	1805	18.38	0.74
1571	18.16	0.52	1809	18.96	1.32
1573	18.48	0.84	1812	18.76	1.12
1577	18.35	0.71	1815	18.96	1.32
1581	18.07	0.43	1838	18.37	0.73
1586	18.21	0.57	1924	18.39	0.75
1588	18.25	0.61			
1595	18.19	0.55	TOTAL	895.24	30.88
1604	17.91	0.27			

TABLE XIII. U^{235} Content by Fuel-rod Number for Fuel-element No. 8

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
413	17.65	0.01	1806	17.96	0.32
444	18.86	1.22	1807	18.82	1.18
479	18.54	0.90	1808	18.31	0.67
485	18.98	1.34	1810	18.96	1.32
557	18.22	0.58	1813	18.51	0.87
615	18.88	1.24	1814	17.77	0.13
740	18.99	1.35	1817	18.92	1.28
1605	18.27	0.63	1828	18.36	0.72
1617	18.04	0.40	1832	18.40	0.76
1621	17.47	(0.17)	1836	18.08	0.44
1626	18.15	0.51	1839	18.37	0.73
1644	18.07	0.43	1841	18.50	0.86
1691	18.72	1.08	1842	18.40	0.76
1721	18.34	0.70	1843	18.38	0.74
1724	18.27	0.63	1853	17.26	(0.38)
1725	18.22	0.58	1857	18.96	1.32
1731	18.61	0.97	1858	18.46	0.82
1732	18.25	0.61	1877	18.64	1.00
1734	18.23	0.59	1884	17.13	(0.51)
1746	18.82	1.18	1885	17.32	(0.32)
1782	18.29	0.65	1901	18.37	0.73
1783	18.89	1.25	1910	18.75	1.11
1798	17.32	(0.32)	1939	18.66	1.02
1799	18.29	0.65			
1803	18.90	1.26	TOTAL	898.93	34.57
1804	18.37	0.73			

TABLE XIV. U^{235} Content by Fuel-rod Number for Fuel-element No. 9

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
265	17.95	0.31	1761	18.67	1.03
266	18.31	0.67	1763	17.90	0.26
268	18.65	1.01	1764	18.37	0.73
299	18.20	0.56	1775	18.37	0.73
357	18.18	0.54	1777	18.53	0.89
419	18.21	0.57	1785	18.69	1.05
459	18.31	0.67	1793	18.46	0.82
465	18.29	0.65	1795	18.56	0.92
488	18.64	1.00	1796	17.90	0.26
494	18.31	0.67	1846	18.31	0.67
511	18.34	0.70	1854	18.48	0.84
541	18.54	0.90	1862	18.04	0.40
597	18.04	0.40	1912	18.50	0.86
652	18.55	0.91	1914	18.41	0.77
659	17.65	0.01	1920	18.16	0.52
675	18.28	0.64	1925	18.91	1.27
717	18.37	0.73	1931	18.40	0.76
1639	18.58	0.94	1933	18.70	1.06
1735	17.77	0.13	1935	18.42	0.78
1737	18.62	0.98	1938	18.90	1.26
1739	18.46	0.82	1944	18.40	0.76
1741	18.67	1.03	1954	18.40	0.76
1747	18.52	0.88	1962	18.40	0.76
1755	18.44	0.80			
1758	18.40	0.76			
1759	18.62	0.98	TOTAL	900.78	36.42

TABLE XV. U^{235} Content by Fuel-rod Number for Fuel-element No. 10

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
435	17.58	(0.06)	1625	18.43	0.79
448	19.08	1.44	1636	18.21	0.57
506	18.35	0.71	1671	18.46	0.82
515	18.25	0.61	1674	18.62	0.98
527	18.68	1.04	1684	18.27	0.63
560	17.93	0.29	1722	18.70	1.06
616	18.28	0.64	1730	17.58	(0.06)
635	17.76	0.12	1742	17.52	(0.12)
670	18.75	1.11	1745	18.23	0.59
678	18.18	0.54	1766	17.56	(0.08)
680	18.72	1.08	1791	18.12	0.48
693	18.22	0.58	1800	18.63	0.99
702	18.24	0.60	1819	17.25	(0.39)
1517	17.47	(0.17)	1820	18.34	0.70
1521	18.47	0.83	1821	18.72	1.08
1527	18.73	1.09	1835	18.41	0.77
1529	18.02	0.38	1845	18.42	0.78
1532	18.43	0.79	1861	18.38	0.74
1533	18.18	0.54	1873	18.40	0.76
1554	17.52	(0.12)	1881	18.77	1.13
1560	18.34	0.70	1883	18.44	0.80
1582	17.36	(0.28)	1886	18.37	0.73
1591	18.22	0.58	1890	18.37	0.73
1592	18.49	0.85			
1593	17.41	(0.23)	TOTAL	893.33	28.97
1624	18.47	0.83			

TABLE XVI. U^{235} Content by Fuel-rod Number for Fuel-element No. 11

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
480	18.30	0.66	1776	17.93	0.29
499	18.48	0.84	1781	17.91	0.27
505	18.51	0.87	1788	17.87	0.23
603	18.81	1.17	1789	17.98	0.34
642	18.09	0.45	1790	17.86	0.22
662	18.01	0.37	1794	18.47	0.83
669	18.18	0.54	1797	18.49	0.85
676	18.01	0.37	1816	18.64	1.00
681	18.61	0.97	1823	18.32	0.68
739	17.74	0.10	1825	18.60	0.96
1545	17.77	0.13	1834	17.72	0.08
1563	18.05	0.41	1847	18.17	0.53
1569	18.07	0.43	1860	17.32	(0.32)
1572	18.17	0.53	1874	18.82	1.18
1574	18.82	1.18	1882	18.61	0.97
1635	17.73	0.09	1913	18.75	1.11
1662	18.17	0.53	1937	18.42	0.78
1736	18.43	0.79	1941	18.40	0.76
1740	18.40	0.76	1945	18.63	0.99
1743	18.52	0.88	1948	18.35	0.71
1744	18.47	0.83	1952	18.66	1.02
1752	18.56	0.92	1953	18.47	0.83
1754	18.40	0.76	1959	18.36	0.72
1760	17.90	0.26			
1765	18.44	0.80	TOTAL	895.91	31.55
1767	18.52	0.88			

TABLE XVII. U^{235} Content by Fuel-rod Number for Fuel-element No. 12

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
314	18.40	0.76	738	18.28	0.64
328	18.49	0.85	1849	18.43	0.79
418	18.31	0.67	1850	18.37	0.73
466	18.30	0.66	1864	17.95	0.31
467	18.30	0.66	1865	17.89	0.25
468	18.41	0.77	1879	18.36	0.72
508	18.84	1.20	1906	18.82	1.18
519	18.30	0.66	1916	17.77	0.13
550	18.55	0.91	1918	18.28	0.64
566	19.10	1.46	1922	18.61	0.97
588	18.49	0.85	1927	18.03	0.39
609	18.70	1.06	1932	18.14	0.50
627	18.32	0.68	1956	18.95	1.31
630	19.00	1.36	1957	18.86	1.22
631	18.51	0.87	1963	18.28	0.64
638	17.99	0.35	1969	18.88	1.24
653	18.93	1.29	1975	18.95	1.31
671	17.90	0.26	1976	18.95	1.31
684	18.18	0.54	1978	19.02	1.38
685	18.56	0.92	1981	19.09	1.45
692	19.05	1.41	1990	18.96	1.32
694	19.17	1.53	2042	19.04	1.40
704	18.89	1.25	2056	18.94	1.30
708	18.14	0.50			
713	18.28	0.64	TOTAL	908.25	43.89
720	18.29	0.65			

TABLE XVIII. U^{235} Content by Fuel-rod Number for Fuel-element No. 13

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
1251	18.05	0.41	1362	18.25	0.61
1254	18.22	0.58	1363	17.61	(0.03)
1261	17.11	(0.53)	1365	17.57	(0.07)
1267	17.94	0.30	1366	17.86	0.22
1271	17.65	0.01	1387	17.19	(0.45)
1275	17.14	(0.50)	1389	17.19	(0.45)
1276	17.06	(0.58)	1393	17.89	0.25
1288	17.82	0.18	1395	17.56	(0.08)
1289	17.82	0.18	1407	17.84	0.20
1293	17.78	0.14	1413	18.11	0.47
1300	18.30	0.66	1415	17.95	0.31
1309	17.82	0.18	1416	17.83	0.19
1310	17.68	0.04	1419	17.89	0.25
1311	17.97	0.33	1421	18.27	0.63
1314	17.68	0.04	1423	17.66	0.02
1335	18.30	0.66	1428	17.20	(0.44)
1336	17.65	0.01	1429	17.91	0.27
1337	18.29	0.65	1433	16.66	(0.98)
1341	17.23	(0.41)	1435	17.44	(0.20)
1342	18.09	0.45	1454	17.28	(0.36)
1347	17.99	0.35	1483	18.00	0.36
1350	18.27	0.63	1496	17.97	0.33
1355	17.80	0.16	1526	18.30	0.66
1357	16.50	(1.14)			
1360	17.56	(0.08)	TOTAL	868.28	3.92
1362	17.13	(0.51)			

TABLE XIX. U^{235} Content by Fuel-rod Number for Fuel-element No. 14

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
302	19.14	1.50	1869	18.27	0.63
309	19.14	1.50	1929	18.60	0.96
317	17.98	0.34	1934	18.16	0.52
428	18.28	0.64	1955	18.25	0.61
478	18.28	0.64	1958	18.35	0.71
529	19.02	1.38	1961	19.04	1.40
534	18.31	0.67	1968	19.07	1.43
576	18.31	0.67	1972	18.38	0.74
618	18.23	0.59	1984	18.50	0.86
620	18.70	1.06	1985	19.00	1.36
622	18.96	1.32	1987	17.69	0.05
637	19.11	1.47	1994	19.08	1.44
645	18.01	0.37	1995	17.60	(0.04)
647	19.09	1.45	1996	19.09	1.45
656	18.91	1.27	1998	18.98	1.34
664	17.72	0.08	2022	19.05	1.41
682	17.67	0.03	2025	19.11	1.47
705	18.89	1.25	2027	18.66	1.02
710	19.05	1.41	2050	18.10	0.46
712	17.61	(0.03)	2053	18.93	1.29
725	19.03	1.39	2155	19.08	1.44
726	18.25	0.61	2167	19.25	1.61
729	19.14	1.50	2175	19.14	1.50
1837	18.46	0.82			
1848	18.35	0.71	TOTAL	911.99	47.63
1851	18.97	1.33			

TABLE XX. U^{235} Content by Fuel-rod Number for Fuel-element No. 15

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
528	17.71	0.07	1870	18.00	0.36
644	17.93	0.29	1895	18.12	0.48
686	17.63	(0.01)	1898	18.28	0.64
696	17.88	0.24	1909	18.73	1.09
703	18.02	0.38	1921	19.61	0.97
727	19.03	1.39	1967	19.02	1.38
1253	17.24	(0.40)	1970	18.96	1.32
1280	17.16	(0.48)	1988	19.05	1.41
1281	17.91	0.27	1993	18.35	0.71
1283	17.22	(0.42)	2036	18.37	0.73
1359	17.15	(0.49)	2039	18.69	1.05
1364	17.17	(0.47)	2041	19.01	1.37
1373	17.28	(0.36)	2046	17.53	(0.11)
1390	17.66	0.02	2049	19.09	1.45
1443	18.00	0.36	2051	19.23	1.59
1448	17.70	0.06	2057	18.34	0.70
1461	17.90	0.26	2058	17.66	0.02
1462	17.58	(0.06)	2134	18.74	1.10
1474	17.56	(0.08)	2149	19.26	1.62
1498	18.19	0.55	2159	19.13	1.49
1516	17.89	0.25	2163	18.77	1.13
1519	17.94	0.30	2179	18.69	1.05
1524	18.24	0.60	2220	19.19	1.55
1713	17.62	(0.02)			
1714	17.64	-	TOTAL	891.03	26.67
1779	18.96	1.32			

TABLE XXI. U^{235} Content by Fuel-rod Number for Fuel-element No. 16

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
663	19.27	1.63	2055	18.31	0.67
665	18.60	0.96	2060	18.95	1.31
667	18.31	0.67	2065	18.83	1.19
793	19.26	1.62	2129	18.84	1.20
829	17.80	0.16	2130	19.11	1.47
833	17.89	0.25	2132	18.85	1.21
1844	18.70	1.06	2142	19.14	1.50
1892	18.88	1.24	2147	18.81	1.17
1894	18.87	1.23	2148	19.02	1.38
1897	18.13	0.49	2151	19.33	1.69
1902	18.99	1.35	2154	18.76	1.12
1903	18.52	0.88	2156	19.15	1.51
1908	18.55	0.91	2164	18.82	1.18
1974	19.03	1.39	2176	19.08	1.44
1977	19.08	1.44	2181	18.69	1.05
1983	19.07	1.43	2185	19.23	1.59
1991	18.99	1.35	2186	19.11	1.47
2001	18.70	1.06	2191	19.27	1.63
2004	18.97	1.33	2193	19.22	1.58
2006	18.76	1.12	2195	19.14	1.50
2010	19.11	1.47	2203	19.17	1.53
2013	18.75	1.11	2208	19.08	1.44
2014	19.02	1.38	2237	18.87	1.23
2021	19.11	1.47			
2037	19.06	1.42	TOTAL	924.61	60.25
2044	18.41	0.77			

TABLE XXII. U^{235} Content by Fuel-rod Number for Fuel-element No. 17

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
414	17.05	(0.59)	1481	17.76	0.12
423	17.53	(0.11)	1485	18.04	0.40
440	17.57	(0.07)	1488	18.42	0.78
481	17.43	(0.21)	1490	18.12	0.48
1358	17.94	0.30	1493	18.24	0.60
1378	18.50	0.86	1494	17.96	0.32
1381	17.85	0.21	1502	17.83	0.19
1382	17.76	0.12	1506	17.94	0.30
1436	18.19	0.55	1549	18.55	0.91
1439	18.50	0.86	1567	18.53	0.89
1440	18.60	0.96	1597	18.15	0.51
1442	17.97	0.33	1599	18.49	0.85
1444	17.97	0.33	1611	18.60	0.96
1445	18.53	0.89	1612	18.13	0.49
1446	18.42	0.78	1614	17.75	0.11
1447	17.78	0.14	1630	17.92	0.28
1455	17.75	0.11	1649	18.54	0.90
1456	17.76	0.12	1666	18.03	0.39
1463	18.57	0.93	1678	18.01	0.37
1466	17.89	0.25	1681	18.07	0.43
1467	17.94	0.30	1692	17.75	0.11
1470	17.98	0.34	562	18.00	0.36
1471	17.70	0.06	1105	17.98	0.34
1472	18.41	0.77			
1478	17.76	0.12			
1480	17.67	0.03	TOTAL	883.83	19.47

TABLE XXIII. U^{235} Content by Fuel-rod Number for Fuel-element No. 18

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
416	17.73	0.09	1489	18.38	0.74
417	18.05	0.41	1491	18.69	1.05
421	17.94	0.30	1492	18.15	0.51
464	16.93	(0.71)	1495	18.23	0.59
555	17.93	0.29	1497	17.70	0.06
687	18.42	0.78	1500	18.40	0.76
1332	18.13	0.49	1503	18.23	0.59
1351	17.52	(0.12)	1507	17.37	(0.27)
1377	17.39	(0.25)	1509	18.13	0.49
1379	17.91	0.27	1510	17.26	(0.38)
1380	18.21	0.57	1525	17.95	0.31
1384	18.03	0.39	1559	17.54	(0.10)
1388	17.27	(0.37)	1564	18.54	0.90
1430	17.16	(0.48)	1603	17.97	0.33
1434	17.24	(0.40)	1613	18.48	0.84
1441	17.91	0.27	1616	17.77	0.13
1449	17.79	0.15	1641	17.85	0.21
1450	18.65	1.01	1645	17.95	0.31
1453	18.32	0.68	1664	18.06	0.42
1458	18.47	0.83	1669	18.01	0.37
1464	17.39	(0.25)	1686	18.08	0.44
1468	16.37	(1.27)	1696	17.61	(0.03)
1469	17.75	0.11	1699	17.88	0.24
1476	17.97	0.33			
1477	18.51	0.87	TOTAL	877.42	13.06
1482	18.20	0.56			

TABLE XXIV. U^{235} Content by Fuel-rod Number for Fuel-element No. 19

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
639	18.94	1.30	2080	18.34	0.70
753	17.71	0.07	2082	19.20	1.56
770	18.24	0.60	2086	18.93	1.29
783	18.96	1.32	2090	18.40	0.76
805	19.17	1.53	2091	18.34	0.70
818	18.22	0.58	2096	18.88	1.24
831	18.93	1.29	2097	18.87	1.23
866	19.20	1.56	2098	18.76	1.12
909	17.93	0.29	2100	18.84	1.20
1710	17.43	(0.21)	2101	18.85	1.21
1891	17.11	(0.53)	2103	18.39	0.75
1965	18.84	1.20	2107	18.37	0.73
1980	18.12	0.48	2109	18.48	0.84
2002	18.80	1.16	2123	18.80	1.16
2009	18.99	1.35	2128	18.73	1.09
2017	18.78	1.14	2136	18.72	1.08
2018	19.29	1.65	2153	19.26	1.62
2045	18.95	1.31	2157	18.72	1.08
2052	19.09	1.45	1262	18.73	1.09
2059	18.97	1.33	2165	18.73	1.09
2063	18.99	1.35	2173	19.12	1.48
2071	18.94	1.30	2189	18.68	1.04
2073	19.23	1.59	2222	18.78	1.14
2074	18.98	1.34			
2075	19.23	1.59	TOTAL	917.21	52.85
2077	19.25	1.61			

TABLE XXV. U^{235} Content by Fuel-rod Number for Fuel-element No. 20

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
347	18.20	0.56	2174	17.05	(0.59)
579	17.04	(0.60)	2200	18.83	1.19
589	18.77	1.13	2202	18.36	0.72
605	17.28	(0.36)	2205	18.34	0.70
634	17.12	(0.52)	2207	17.09	(0.55)
640	17.12	(0.52)	2210	18.29	0.65
641	18.64	1.00	2221	18.28	0.64
654	18.56	0.92	2225	18.87	1.23
683	17.98	0.34	2241	18.39	0.75
728	17.98	0.34	2244	18.34	0.70
777	17.34	(0.30)	2247	18.34	0.70
828	19.25	1.61	2248	18.05	0.41
884	19.11	1.47	2251	17.06	(0.58)
2024	18.08	0.44	2252	18.70	1.06
2047	19.25	1.61	2253	18.08	0.44
2062	19.17	1.53	2255	17.25	(0.39)
2099	18.84	1.20	2257	17.24	(0.40)
2104	17.25	(0.39)	2262	18.75	1.11
2105	17.27	(0.37)	2263	17.26	(0.38)
2115	18.79	1.15	2270	17.14	(0.50)
2121	18.90	1.26	2275	16.99	(0.65)
2126	18.40	0.76	2282	15.94	(1.70)
2127	17.33	(0.31)	2321	19.06	1.42
2143	18.84	1.20			
2152	18.38	0.74	TOTAL	883.99	19.63
2161	17.40	(0.24)			

TABLE XXVI. U^{235} Content by Fuel-rod Number for Fuel-element No. 21

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
601	17.01	(0.63)	2070	19.02	1.38
607	17.41	(0.23)	2093	18.00	0.36
633	18.27	0.63	2102	18.87	1.23
765	19.11	1.47	2112	18.27	0.63
787	17.98	0.34	2118	18.93	1.29
803	19.23	1.59	2131	18.90	1.26
840	18.55	0.91	2133	17.11	(0.53)
844	18.58	0.94	2137	18.78	1.14
902	19.26	1.62	2139	17.35	(0.29)
910	19.25	1.61	2144	18.81	1.17
914	19.17	1.53	2170	17.11	(0.53)
917	18.28	0.64	2199	18.59	0.95
925	18.25	0.61	2201	18.25	0.61
937	18.08	0.44	2236	17.24	(0.40)
1037	18.21	0.57	2240	19.05	1.41
1973	17.94	0.30	2246	18.19	0.55
2011	19.02	1.38	2249	17.73	0.09
2012	19.03	1.39	2269	17.60	(0.04)
2019	18.93	1.29	2284	18.69	1.05
2040	18.14	0.50	2292	17.77	0.13
2043	19.21	1.57	2325	17.83	0.19
2054	19.19	1.55	878	18.73	1.09
2064	18.96	1.32	1964	18.10	0.46
2066	17.74	0.10			
2067	18.95	1.31			
2069	19.11	1.47	TOTAL	901.78	37.42

TABLE XXVII. U^{235} Content by Fuel-rod Number for Fuel-element No. 22

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
561	18.20	0.56	2198	18.22	0.58
782	18.80	1.16	2213	18.53	0.89
807	18.72	1.08	2214	18.28	0.64
815	19.26	1.62	2226	17.85	0.21
819	18.63	0.99	2232	18.16	0.52
841	18.72	1.08	2233	17.11	(0.53)
863	18.37	0.73	2239	18.36	0.72
864	19.25	1.61	2243	18.06	0.42
890	17.55	(0.09)	2245	18.27	0.63
913	17.51	(0.13)	2254	18.23	0.59
916	18.36	0.72	2259	18.43	0.79
976	18.33	0.69	2264	18.35	0.71
1056	18.16	0.52	2265	17.67	0.03
1086	18.22	0.58	2267	17.86	0.22
1632	17.89	0.25	2272	18.24	0.60
1709	18.22	0.58	2273	18.25	0.61
1778	18.55	0.91	2278	18.31	0.67
1801	18.80	1.16	2288	17.79	0.15
1979	17.98	0.34	2296	17.80	0.16
2000	18.13	0.49	2317	18.40	0.76
2048	17.95	0.31	2320	17.83	0.19
2068	17.41	(0.23)	2375	18.14	0.50
2106	18.37	0.73	2377	17.75	0.11
2120	18.78	1.14			
2169	18.59	0.95	TOTAL	893.16	28.80
2182	18.52	0.88			

TABLE XXVIII. U^{235} Content by Fuel-rod Number for Fuel-element No. 23

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
755	18.25	0.61	2020	18.22	0.58
756	18.23	0.59	2089	18.18	0.54
780	18.57	0.93	2094	18.19	0.55
790	17.80	0.16	2095	18.00	0.36
800	18.15	0.51	2150	18.20	0.56
802	17.72	0.08	2160	18.28	0.64
824	17.92	0.28	2168	17.68	0.04
848	18.00	0.36	2171	18.54	0.90
849	17.69	0.05	2178	18.55	0.91
893	18.64	1.00	2215	18.43	0.79
903	18.30	0.66	2217	18.55	0.91
905	18.26	0.62	2227	18.25	0.61
911	18.16	0.52	2234	18.23	0.59
940	18.00	0.36	2250	18.26	0.62
944	17.76	0.12	2261	17.93	0.29
977	17.86	0.22	2274	18.19	0.55
978	17.83	0.19	2277	18.21	0.57
979	17.48	(0.16)	2290	18.45	0.81
986	17.86	0.22	2299	17.72	0.08
1026	17.83	0.19	2322	17.73	0.09
1034	19.06	1.42	2324	18.07	0.43
1041	17.77	0.13	2376	19.02	1.38
1048	18.34	0.70	2381	17.78	0.14
1058	17.45	(0.19)			
1087	17.65	0.01	TOTAL	887.20	22.84
2003	17.96	0.32			

TABLE XXIX. U^{235} Content by Fuel-rod Number for Fuel-element No. 24

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
751	18.75	1.11	1064	17.98	0.34
779	17.87	0.23	1065	18.49	0.85
789	17.66	0.02	2283	17.79	0.15
791	18.46	0.82	2286	19.13	1.49
796	17.60	(0.04)	2294	18.07	0.43
809	18.25	0.61	2295	19.08	1.44
810	18.58	0.94	2307	18.60	0.96
816	17.80	0.16	2312	17.50	(0.14)
826	18.07	0.43	2313	17.69	0.05
827	17.92	0.28	2319	17.16	(0.48)
832	17.80	0.16	2326	18.31	0.67
851	17.87	0.23	2327	18.32	0.68
856	17.98	0.34	2333	18.19	0.55
883	17.89	0.25	2335	17.56	(0.08)
888	18.09	0.45	2340	18.32	0.68
895	18.07	0.43	2342	17.98	0.34
897	17.80	0.16	2346	18.57	0.93
898	17.70	0.06	2350	17.94	0.30
906	17.72	0.08	2361	18.12	0.48
955	17.81	0.17	2374	18.19	0.55
997	18.14	0.50	2383	19.13	1.49
1006	17.84	0.20	2386	18.15	0.51
1015	17.88	0.24	2393	18.06	0.42
1033	17.90	0.26			
1050	18.28	0.64	TOTAL	886.22	21.86
1057	18.16	0.52			

TABLE XXX. U^{235} Content by Fuel-rod Number for Fuel-element No. 25

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
112	17.95	0.31	1014	18.41	0.77
190	17.84	0.20	1023	16.97	(0.67)
211	17.86	0.22	1036	17.28	(0.36)
222	18.04	0.40	1053	18.39	0.75
234	17.89	0.25	1063	18.01	0.37
383	17.77	0.13	1070	16.72	(0.92)
920	16.44	(1.20)	1075	17.27	(0.37)
928	16.97	(0.67)	1085	17.27	(0.37)
934	16.97	(0.67)	1088	18.25	0.61
936	16.54	(1.10)	2306	18.10	0.46
941	17.98	0.34	2308	17.95	0.31
951	17.25	(0.39)	2318	19.25	1.61
954	18.18	0.54	2330	17.63	(0.01)
964	17.30	(0.34)	2359	18.07	0.43
966	18.48	0.84	2362	18.10	0.46
972	18.15	0.51	2366	18.19	0.55
975	18.07	0.43	2388	18.21	0.57
982	18.30	0.66	2399	16.67	(0.97)
983	17.96	0.32	2401	16.70	(0.94)
985	18.18	0.54	2404	17.03	(0.61)
990	17.87	0.23	2406	16.96	(0.68)
994	18.25	0.61	2407	16.91	(0.73)
998	18.03	0.39	2410	16.23	(1.41)
999	17.93	0.29			
1009	16.53	(1.11)	TOTAL	864.27	(0.09)
1010	16.97	(0.67)			

TABLE XXXI. U^{235} Content by Fuel-rod Number for Fuel-element No. 26

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
160	17.17	(0.47)	1066	18.25	0.61
655	18.90	1.26	1067	18.21	0.57
760	14.86	(2.78)	1076	18.26	0.62
794	18.49	0.85	1079	18.14	0.50
820	18.26	0.62	1082	18.29	0.65
837	17.92	0.28	1083	18.19	0.55
852	15.45	(2.19)	2302	17.91	0.27
857	17.68	0.04	2304	17.57	(0.07)
859	17.84	0.20	2305	18.14	0.50
922	18.06	0.42	2310	18.57	0.93
932	18.17	0.53	2323	18.47	0.83
933	18.08	0.44	2328	17.86	0.22
938	17.99	0.35	2329	17.89	0.25
942	18.05	0.41	2334	17.94	0.30
948	17.98	0.34	2336	17.79	0.15
984	17.94	0.30	2338	17.57	(0.07)
1000	17.86	0.22	2339	17.93	0.29
1001	18.09	0.45	2347	18.40	0.76
1013	18.01	0.37	2355	18.19	0.55
1016	18.18	0.54	2357	17.89	0.25
1019	18.26	0.62	2367	18.37	0.73
1046	18.38	0.74	2370	18.05	0.41
1047	18.10	0.46	2371	17.98	0.34
1055	18.13	0.49			
1059	18.36	0.72	TOTAL	879.99	15.63
1061	17.92	0.28			

TABLE XXXII. U^{235} Content by Fuel-rod Number for Fuel-element No. 27

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
39	17.66	0.02	1003	18.34	0.70
88	17.51	(0.13)	1007	17.86	0.22
172	17.64	-	1017	17.81	0.17
176	18.03	0.39	1018	17.84	0.20
199	17.57	(0.07)	1021	18.12	0.48
358	17.83	0.19	1025	18.17	0.53
649	18.72	1.08	1029	18.42	0.78
716	18.96	1.32	1040	18.01	0.37
744	18.09	0.45	1044	17.27	(0.37)
799	17.98	0.34	1060	18.27	0.63
806	17.54	(0.10)	1081	18.05	0.41
918	18.25	0.61	2316	19.02	1.38
923	18.12	0.48	2360	17.92	0.28
929	17.66	0.02	2364	18.07	0.43
931	18.10	0.46	2391	18.40	0.76
935	17.86	0.22	2409	17.62	(0.02)
939	18.05	0.41	2411	17.25	(0.39)
952	18.75	1.11	2431	17.53	(0.11)
960	18.12	0.48	2432	17.43	(0.21)
961	18.73	1.09	2451	17.74	0.10
962	18.33	0.69	2455	17.33	(0.31)
963	18.36	0.72	2466	17.22	(0.42)
981	17.83	0.19	1051	18.13	0.49
987	17.21	(0.43)			
993	18.10	0.46	TOTAL	879.81	15.45
1002	16.99	(0.65)			

TABLE XXXIII. U^{235} Content by Fuel-rod Number for Fuel-element No. 28

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
144	18.04	0.40	2408	16.98	(0.66)
329	17.45	(0.19)	2412	16.99	(0.65)
380	17.45	(0.19)	2413	17.70	0.06
411	17.44	(0.20)	2415	17.42	(0.22)
458	17.77	0.13	2417	17.38	(0.26)
604	19.02	1.38	2420	17.44	(0.20)
748	18.79	1.15	2428	17.45	(0.19)
870	18.33	0.69	2435	17.49	(0.15)
943	18.33	0.69	2442	17.72	0.08
946	18.08	0.44	2452	17.76	0.12
947	18.28	0.64	2456	17.42	(0.22)
957	17.94	0.30	2457	17.53	(0.11)
967	17.21	(0.43)	2460	17.54	(0.10)
988	18.18	0.54	2461	17.35	(0.29)
1008	18.07	0.43	2462	17.47	(0.17)
1035	18.16	0.52	2464	17.21	(0.43)
1045	17.05	(0.59)	2465	17.65	0.01
1049	18.14	0.50	2467	17.58	(0.06)
1069	17.18	(0.46)	2468	17.50	(0.14)
1078	18.36	0.72	2469	17.51	(0.13)
1552	17.97	0.33	2477	17.37	(0.27)
1872	18.73	1.09	2495	17.45	(0.19)
1943	17.95	0.31	2506	17.56	(0.08)
2015	18.79	1.15			
2297	19.29	1.65	TOTAL	871.78	7.42
2384	18.31	0.67			

TABLE XXXIV. U^{235} Content by Fuel-rod Number for Fuel-element No. 29

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal Over (Under), g
356	17.70	0.06	2647	17.88	0.24
437	17.43	(0.21)	2648	18.25	0.61
2414	17.45	(0.19)	2650	17.92	0.28
2416	17.36	(0.28)	2652	17.06	(0.58)
2425	17.45	(0.19)	2653	17.31	(0.33)
2427	17.36	(0.28)	2655	17.88	0.24
2430	16.84	(0.80)	2656	17.92	0.28
2433	17.58	(0.06)	2657	18.04	0.40
2470	17.45	(0.19)	2658	17.29	(0.35)
2471	17.45	(0.19)	2659	17.30	(0.34)
2472	17.98	0.34	2660	18.00	0.36
2474	17.46	(0.18)	2663	17.99	0.35
2478	17.41	(0.23)	2664	17.89	0.25
2481	18.00	0.36	2665	17.26	(0.38)
2484	17.42	(0.22)	2667	17.23	(0.41)
2485	16.94	(0.70)	2668	17.29	(0.35)
2486	17.51	(0.13)	2671	17.28	(0.36)
2490	17.90	0.26	2672	17.06	(0.58)
2493	16.94	(0.70)	2673	17.33	(0.31)
2494	16.84	(0.80)	2674	18.25	0.61
2500	17.44	(0.20)	2676	17.85	0.21
2502	17.48	(0.16)	2677	17.48	(0.16)
2515	16.80	(0.84)	2678	17.88	0.24
2526	16.94	(0.70)			
2537	16.53	(1.11)			
2646	17.99	0.35	TOTAL	857.29	(7.07)

TABLE XXXV. U^{235} Content by Fuel-rod Number for Fuel-element No. 30

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
171	18.06	0.42	2533	17.96	0.32
246	18.41	0.77	2534	16.96	(0.68)
273	17.42	(0.22)	2536	17.45	(0.19)
282	18.43	0.79	2550	17.88	0.24
359	17.95	0.31	2544	17.98	0.34
379	17.45	(0.19)	2547	17.86	0.22
707	17.42	(0.22)	2548	17.84	0.20
1038	17.21	(0.43)	2561	17.80	0.16
2418	17.92	0.28	2568	17.75	0.11
2419	17.43	(0.21)	2569	16.68	(0.96)
2423	17.38	(0.26)	2571	17.86	0.22
2436	17.97	0.33	2577	17.97	0.33
2453	18.22	0.58	2578	16.75	(0.89)
2473	18.25	0.61	2580	18.04	0.40
2479	17.92	0.28	2581	17.80	0.16
2480	17.42	(0.22)	2584	17.88	0.24
2482	18.16	0.52	2589	16.74	(0.90)
2483	17.41	(0.23)	2593	17.65	0.01
2487	17.43	(0.21)	2594	17.83	0.19
2489	17.86	0.22	2597	18.11	0.47
2499	18.18	0.54	2612	17.66	0.02
2504	17.45	(0.19)	2675	17.15	(0.49)
2510	17.94	0.30	2541	18.35	0.71
2511	17.42	(0.22)			
2523	17.37	(0.27)	TOTAL	868.22	3.86
2527	18.19	0.55			

TABLE XXXVI. U^{235} Content by Fuel-rod Number for Fuel-element No. 31

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
252	17.94	0.30	2599	17.00	(0.64)
307	17.88	0.24	2601	17.67	0.03
360	18.00	0.36	2605	17.75	0.11
378	18.42	0.78	2606	17.87	0.23
388	18.19	0.55	2607	17.72	0.08
2543	17.92	0.28	2609	16.55	(1.09)
2545	17.94	0.30	2611	16.67	(0.97)
2554	17.85	0.21	2614	17.02	(0.62)
2556	17.81	0.17	2617	16.91	(0.73)
2558	17.36	(0.28)	2618	16.59	(1.05)
2560	17.05	(0.59)	2621	17.43	(0.21)
2563	17.77	0.13	2622	17.67	0.03
2564	18.41	0.77	2623	16.91	(0.73)
2567	17.80	0.16	2624	17.57	(0.07)
2570	17.92	0.28	2626	17.66	0.02
2572	18.01	0.37	2628	16.75	(0.89)
2575	16.91	(0.73)	2629	18.16	0.52
2579	18.04	0.40	2631	17.19	(0.45)
2582	16.64	(1.00)	2636	18.01	0.37
2583	17.48	(0.16)	2637	18.37	0.73
2586	17.15	(0.49)	2638	17.15	(0.49)
2587	17.83	0.19	2640	17.19	(0.45)
2588	16.68	(0.96)	2641	18.37	0.73
2590	17.52	(0.12)			
2596	16.94	(0.70)	TOTAL	858.80	(5.56)
2598	17.16	(0.48)			

TABLE XXXVII. U^{235} Content by Fuel-rod Number for Fuel-element No. 32

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
318	18.15	0.51	2368	18.33	0.69
470	17.83	0.19	2387	18.40	0.76
473	18.35	0.71	2389	17.72	0.08
510	17.97	0.33	2505	17.71	0.07
558	18.01	0.37	2521	17.50	(0.14)
559	17.97	0.33	2559	17.24	(0.40)
592	18.36	0.72	2565	17.75	0.11
722	18.13	0.49	2566	16.74	(0.90)
724	18.04	0.40	2574	17.98	0.34
814	18.28	0.64	2576	17.70	0.06
921	18.34	0.70	2585	18.38	0.74
924	17.80	0.16	2591	17.96	0.32
927	17.03	(0.61)	2592	17.48	(0.16)
930	18.05	0.41	2603	16.53	(1.11)
949	17.65	0.01	2608	17.42	(0.22)
1042	17.91	0.27	2615	17.06	(0.58)
1438	18.02	0.38	2616	16.98	(0.66)
1475	17.75	0.11	2627	17.90	0.26
1566	18.59	0.95	2630	17.39	(0.25)
1634	18.54	0.90	2634	16.76	(0.88)
1697	16.62	(1.02)	2639	17.86	0.22
1999	19.00	1.36	2642	17.02	(0.62)
2079	18.78	1.14	2643	18.04	0.40
2271	17.88	0.24			
2291	18.33	0.69	TOTAL	873.36	9.00
2363	18.13	0.49			

TABLE XXXVIII U^{235} Content by Fuel-rod Number for Fuel-element No 33-A Zircaloy-2 Jacket,
Al- U_3O_8 Core with 0 005-0 008-cm Annulus

Fuel-rod No	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under) g
27	16 88	(0 76)	337	16 90	(0 74)
64	16 76	(0 88)	339	16 43	(1 21)
71	16 64	(1 00)	345	16 48	(1 16)
84	16 25	(1 39)	348	16 88	(0 76)
116	16 76	(0 88)	350	16 87	(0 77)
128	16 72	(0 92)	354	16 24	(1 40)
147	16 75	(0 89)	368	16 89	(0 75)
149	16 76	(0 88)	369	14 57	(3 07)
173	16 86	(0 78)	375	16 46	(1 18)
197	14 59	(3 05)	392	16 88	(0 76)
218	17 04	(0 60)	396	16 22	(1 42)
238	16 27	(1 37)	399	17 05	(0 59)
239	16 27	(1 37)	400	17 05	(0 59)
255	16 76	(0 88)	404	16 87	(0 77)
261	16 45	(1 19)	408	16 27	(1 37)
269	16 45	(1 19)	750	16 83	(0 81)
277	16 38	(1 26)	759	16 65	(0 99)
278	17 01	(0 63)	812	16 65	(0 99)
279	16 77	(0 87)	817	16 84	(0 80)
286	17 04	(0 60)	830	16 84	(0 80)
290	16 37	(1 27)	839	16 60	(1 04)
292	16 86	(0 78)	854	16 62	(1 02)
305	16 43	(1 21)	877	16 64	(1 00)
310	14 60	(3 04)			
319	16 45	(1 19)	TOTAL	810 48	(53 88)
326	16 63	(1 01)			

TABLE XXXIX U^{235} Content by Fuel-rod Number for Fuel-element No 34-A Al (A288) Jacket
Al (X-8001)- U_3O_8 Core with No Annulus

Fuel-rod No	Calculated Net U^{235} g	Deviation from Nominal, Over (Under), g	Fuel-rod No	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under) g
1	16 91	(0 73)	49	16 72	(0 92)
2	16 88	(0 76)	50	16 73	(0 91)
4	16 37	(1 27)	51	16 76	(0 88)
5	16 36	(1 28)	52	16 46	(1 18)
6	16 32	(1 32)	53	16 45	(1 19)
7	18 25	0 61	54	16 78	(0 86)
9	18 25	0 61	55	16 43	(1 21)
11	18 30	0 66	56	16 44	(1 20)
12	18 28	0 64	57	16 38	(1 26)
13	16 65	(0 99)	59	16 40	(1 24)
14	16 64	(1 00)	60	16 76	(0 88)
15	16 32	(1 32)	61	16 89	(0 75)
16	16 64	(1 00)	62	16 91	(0 73)
17	16 64	(1 00)	63	16 92	(0 72)
19	16 61	(1 03)	65	16 91	(0 73)
20	16 24	(1 40)	66	16 89	(0 75)
21	16 65	(0 99)	68	16 94	(0 70)
22	16 65	(0 99)	69	16 94	(0 70)
27	16 25	(1 39)	70	16 43	(1 21)
28	16 25	(1 39)	72	16 42	(1 22)
30	16 26	(1 38)	73	16 41	(1 23)
39	16 21	(1 43)	76	16 38	(1 26)
40	16 22	(1 42)	78	16 33	(1 31)
41	16 72	(0 92)			
46	16 75	(0 89)	TOTAL	819 06	(45 30)
47	16 76	(0 88)			

TABLE XL. U^{235} Content by Fuel-rod Number for Fuel-element No. 35-A: Zircaloy-2 Clad Bonded to $Al-U_3O_8$ Core

Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g	Fuel-rod No.	Calculated Net U^{235} , g	Deviation from Nominal, Over (Under), g
30	15.70	(1.94)	230	16.01	(1.63)
41	15.72	(1.92)	232	16.03	(1.61)
45	16.04	(1.60)	233	16.04	(1.60)
53	15.75	(1.89)	237	12.54	(5.10)
61	12.54	(5.10)	249	15.75	(1.89)
67	15.46	(2.18)	253	15.52	(2.12)
74	16.04	(1.60)	258	15.73	(1.91)
78	16.04	(1.60)	276	15.96	(1.68)
81	15.74	(1.90)	284	15.44	(2.20)
86	15.96	(1.68)	308	15.71	(1.93)
114	16.06	(1.58)	315	16.04	(1.60)
126	15.52	(2.12)	323	15.73	(1.91)
129	16.04	(1.60)	330	16.06	(1.58)
135	15.74	(1.90)	342	15.52	(2.12)
137	12.51	(5.13)	361	15.96	(1.68)
151	15.45	(2.19)	362	15.73	(1.91)
156	15.95	(1.69)	365	15.95	(1.69)
170	16.01	(1.63)	390	15.52	(2.12)
188	15.75	(1.89)	402	15.79	(1.85)
194	16.01	(1.63)	403	15.52	(2.12)
196	15.96	(1.68)	761	15.78	(1.86)
200	15.45	(2.19)	885	15.77	(1.87)
201	15.99	(1.65)	901	15.76	(1.88)
207	15.53	(2.11)			
220	15.99	(1.65)	TOTAL	764.53	(99.83)
224	15.72	(1.92)			

ACKNOWLEDGMENTS

The authors extend their appreciation to the following individuals who aided in the fabrication of the EBWR spiked-core fuel elements:

F. G. Foote and R. E. Macherey for their guidance;

W. R. Burt, Jr., and R. L. Salley for supervision of evaluation and assembly operations;

C. J. Renken and R. H. Selner for inspection of jacket tubing and end-plug stock;

The technicians of the Foundry and Fabrication Group for the many operations required to assemble fuel-element components;

Central Shops personnel for fabrication of fuel- and frame-assembly components.

REFERENCES

1. R. E. Macherey, C. H. Bean, N. J. Carson, Jr., and J. R. Lindgren, Manufacture of Fuel Plates for the Experimental Boiling Water Reactor, ANL-5629 (June 1957).
2. R. C. Lied, E. D. Lynch, and J. H. Handwerk, The ZrO_2 -CaO- UO_2 Ceramic Fuel Fabrication for the EBWR Spiked Core Elements, ANL-6168 (May 1961).
3. E. A. Wimunc and J. M. Harrer, Hazards Evaluation Report Associated with the Operation of EBWR at 100 MW, ANL-5781, Addendum (Revision 1) (October 1960).
4. C. J. Renken, Progress Report on Nondestructive Testing by Electromagnetic Methods, ANL-6414 (July 1962).
5. R. L. Salley and C. H. Bean, Assembly, Sodium Bonding, and Inspection of EBR-II Blanket Rods, ANL-6418, to be published.
6. EBWR Project Group, EBWR Test Report (100-MWt Operation), ANL-6703 (January 1964).