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THE DEVELOPMENT OF B_4C ALUMINUM FOILS
AS CONTROLLABLE NEUTRON ABSORBERS IN
ALUMINUM CLAD NUCLEAR REACTOR FUEL PLATES

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BY

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ABSTRACT

An investigation has been made into the use of aluminum foils containing B_4C installed in or adjacent to the uranium-aluminum alloy cores of aluminum-clad plates for the fuel elements of nuclear test reactors. The effort was directed mainly toward the requirements of the Engineering Test Reactor (ETR). However, the results of the investigation will be applicable to other reactors using the same type fuel system.

The results obtained indicate that the B_4C can be distributed along the center line of fuel plate "meat" in the ETR elements by starting with a 3 to 4 mil-thick aluminum foil containing B_4C . When this technique is used, the control over the B_4C may not be as good as when powder metallurgy procedures are used to make the fuel plate cores. However, it is more easily controlled than in uranium-aluminum alloys. The fuel plates also tend to have higher irradiation-induced swelling rates and lower blister anneal failure temperatures when made by the technique under investigation than when using the powder metallurgy procedures. The failures produced by this technique were found to originate in the B_4C -Al foils. However, this fuel design was found to be adequate for the ETR environment.

SUMMARY

An investigation has been undertaken in the use of B_4C aluminum foils as consumable neutron absorbers in test reactor fuel element plates. This investigation has been stimulated by the possible economic advantage of this method of boron addition to fuel elements.

Two types of foils have been considered. In one, the foil is made by alloying boron and aluminum, and in the other powder metallurgy techniques are used to produce a dispersion of B_4C in aluminum. The technique for production of these foils was similar to that used for fabrication of the fuel plate cores as noted in Appendix D.

The latter method (of fabrication) was found to be more suitable. Since the blister failure temperatures were lower for sample plates containing the B-Al alloy foil when compared with most of the samples taken from plates with B_4C -Al foil. This would be expected since the Al-B phase diagram indicates that the boron would exist in the alloy as a dispersion of intermetallic particles (AlB_2) in the aluminum matrix^[1]. The size, shape, and distribution of these particles would be most difficult to control when preparing the foil by melting techniques. Consequently, a high probability for clumping of the AlB_2 particles would exist. After irradiation, this clumping of boron would tend to produce areas in the fuel plates with high helium concentrations. Those, of course, would tend to produce blisters when the temperatures were increased during the post-irradiation anneal testing.

Two methods of incorporating the boron-containing foils into the plates also have been tried. One approach is to insert the foil between the fuel cores and the claddings of the plates. In this position, the helium agglomeration formed by the boron-neutron reaction would tend to interfere with the heat transfer of the plates. The other approach is to insert the foil in the center line of the plate where it could not interfere with the heat transfer of the plates. This latter technique was employed in almost all of the plates fabricated.

The results obtained indicate that the boron can be distributed along the center line of the fuel plate "meat" in ETR elements by starting with a 3 to 4 mil-thick aluminum foil containing B_4C . Although the control over the boron was not as good as when powder metallurgy techniques were employed, it was

adequate to meet specification requirements. Also, powder metallurgy-fabricated fuel cores generally tend to have lower irradiation-induced swelling rates and higher blister anneal failure temperatures than fuel cores containing B_4C -Al foils. However, the blister temperatures for these types of plates are still sufficiently high to provide an adequate margin or safety in the ETR.

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THE DEVELOPMENT OF B_4C ALUMINUM FOILS AS CONTROLLABLE NEUTRON ABSORBERS IN ALUMINUM CLAD NUCLEAR REACTOR FUEL PLATES

I. INTRODUCTION

A continuing problem in the fabrication of the plates for test reactor fuel elements has been to obtain a uniform dispersion of boron in the fuel plates. One solution to this problem is through the use of powder metallurgy procedures in the fabrication of the fuel plate cores. However, from past contracts with fuel vendors, it has been established that it is more economical for some vendors to fabricate fuel cores by wrought metallurgical procedures. When using this technique, however, considerable trouble is encountered in controlling the amount of boron present in alloy castings and ensuring that it is distributed uniformly throughout the finished fuel plates.

A means of controlling the boron addition while still using wrought metallurgical procedures to fabricate fuel plates would be to make the fuel cores of the plates from wrought uranium-aluminum alloy and use $B_4C + Al$ foil made by powder metallurgy for the boron addition.

The boron-containing aluminum foils are commercially available, or can be readily produced using procedures similar to those used to make aluminum-clad fuel plates. The boron-containing foil layer can be located on the center line of the plates or between the fuel cores and the cladding; however, the former has proved to be more satisfactory.

The scope of this report covers fabrication, destructive and non-destructive testing and irradiation testing of both sample fuel plates and full-sized fuel plates which were made by employing B_4C-Al foils as controllable neutron absorbers. These examinations were conducted over a number of years and will be presented in more or less chronological order.

The development work on B_4C foils was directed toward the ETR (Engineering Test Reactor). Some operating parameters for the ETR are given in Table I. This process of B_4C dispersion may, however, be useful in other plate type fuel elements.

TABLE I

SOME OPERATING PARAMETERS FOR THE ETR

Thermal power density-maximum (kilowatts per gram of ^{235}U)	22.6
Maximum nominal fuel plate surface temperature after 2000 MWd ($^{\circ}\text{C}$)	175
Maximum nominal "meat" (fuel core) temperature after 2000 MWd ($^{\circ}\text{C}$)	240
Nominal ^{235}U content per fuel element (g)	500 ^[a]
Nominal weight of natural boron per fuel element (g)	3.5 to 3.8 ^[a]
Heat transfer surface of fuel element (ft^2)	23.3
^{235}U loading per unit of heat transfer surface (g/ft^2)	21.5
Nominal ^{235}U loading of fuel element cores (g/cc)	0.91
Nominal reactor inlet temperature ($^{\circ}\text{C}$)	44
Nominal reactor outlet temperature ($^{\circ}\text{C}$)	55
Nominal reactor inlet pressure (psig)	200
Nominal reactor outlet pressure (psig)	157
Maximum operating power level (MW, thermal)	175

[a] Prior to Cycle 91 the nominal ^{235}U content per element was 400 grams.
The nominal boron content per element was 2.1 to 2.9 grams.

II. PROTOTYPE ELEMENTS

Preliminary results obtained on sample plates in which $B_4C + Al$ foils were used indicated that this procedure is probably a suitable means for the dispersion of boron in aluminum-clad fuel plates for use in the Engineering Test Reactor (ETR). But, in order to ensure that indeed an improvement in boron control could be obtained and to check the reactor safety, five prototype elements were obtained from a commercial fuel fabricator.

The boron contained in the elements was in the form of -325 mesh B_4C particles, with the naturally occurring percentage of ^{10}B . This B_4C was dispersed in aluminum and rolled into a foil 3 to 4 mils thick containing 7 wt% B_4C . This method of preparation should result in better control of total boron content and homogeneity of the boron distribution since powder metallurgical fabrication techniques are inherently better in this respect than the earlier process of adding boron to the high temperature ($1000^\circ C$) aluminum-uranium melt followed by mold casting. In the alloy process variable quantities of boron are lost from the melt and segregation occurs in the casting resulting in poor control of boron content and distribution.

The foil was positioned between two half-thicknesses of uranium-aluminum alloy cores. After being placed in picture frames and assembled with Type 1100 aluminum alloy cover plates, the fuel plate rolling assemblies were reduced 8 to 1 to produce a finished plate containing a foil thickness of 0.0005 inch at the center line of the fuel plates^[2].

This location of the foil offers two advantages over locating the foil at the core-clad interface:

- (1) The heat transfer from the fuel core to the cladding is not interfered with by the helium voids around the B_4C particles
- (2) The uranium-aluminum alloy core can be made from two batches of fuel material and, thus, improve the control over the uranium content of the plate.

There is, however, one disadvantage, namely, that the helium voids will be located along the neutral axis of the plate where the loss of resistance to the shear forces caused by the bending moments on the plates could be cause for concern.

A detailed structural analysis showed that the location of the B_4C -aluminum foil at fuel center line produces a maximum shear stress of 327 psi. This is a factor of 6.2 less than the shear stress at which the plate would fail^[3].

1. PRE-IRRADIATION INSPECTION

The five experimental elements were inspected using the standard procedures used for all incoming fuel elements for the ETR. These inspections included dimensional inspections, hydraulic flow testing at 140 percent of reactor flow on one element (XE404B), inspections of radiographs of the fuel plates to ensure that the fuel is homogeneously distributed, gamma scanning to determine the fuel loadings in the elements, and reactivity measurements in a critical facility to determine the boron content. In Table II, the fuel and boron contents of the elements are given.

TABLE II

FUEL AND POISON LOADINGS OF EXPERIMENTAL ETR FUEL ELEMENTS

<u>Fuel Element</u>	<u>Boron^[a] (g)</u>	<u>²³⁵U^[b] (g)</u>
XE401B	2.78	400.5
XE402B	3.35	400.6
XE403B	3.14	396.7
XE404B	3.03	400.2
XE405B	2.84	397.4

[a] As determined by reactivity measurement.

[b] As determined by gamma scanning.

From the data in this table, it was concluded that the elements, while slightly high in boron, were of acceptable uniformity in boron content and that excellent control had been maintained over the uranium content. The excellent control over the ²³⁵U content was undoubtedly due to the use of two separate fuel plate cores of slightly different uranium content.

2. IRRADIATION TESTING

The elements were irradiated in the core of the ETR so as to obtain the nominal ETR fuel burnups (30 percent of the original ^{235}U atoms). The first element tested (XE401B) was inserted in-core in an area of relatively low flux. Following the successful irradiation of this element, the other elements were placed in areas of higher flux. Table III shows the irradiation conditions for the elements. No problems were encountered with the elements which could be attributed to the method of loading the fuel and poison.

TABLE III
IRRADIATION CONDITIONS FOR EXPERIMENTAL ETR FUEL ELEMENTS

Fuel Element Number	Tested in ETR Cycle	Percent of Reactor Power	Estimated Fuel Element Average Burnup (percent)	Calculated Average Fuel Element Fission Density fiss/cc x 10^{-20}
XE401B	74 & 75	1.60	30	4.2
XE402B	76	2.34	13	1.8
XE403B	76	2.10	12	1.7
XE404B	80	2.35	33	4.6
XE405B	81	2.27	31	4.4

3. POST-IRRADIATION EXAMINATIONS

A post-irradiation examination was made on element XE401B after an average element burnup of 30 percent in a low-power core position. The examination consisted of channel-spacing measurements, plate-thickness measurements, visual and macro-oblique-light examinations of plate surfaces, and metallographic examinations.

The channels were straight and uniform. There was no channel blockage (Figure 1).

A thickness survey to the nearest 0.5 mil in the core area was made on 14 of the fuel plates from element XE401B. The maximum variation found on

Fig. 1 Back-lighted view of foil element XE401B showing channel uniformity after 30 percent burnup.

any one plate was 1 mil. Considering the accuracy of the micrometer readings, the difference in burnup along the plate of 2.5×10^{20} fiss/cc minimum to 6×10^{20} fiss/cc maximum (representing a theoretical 0.3 to 0.8 mil swelling), the difference in corrosion film buildup (0 to 0.5 mil), and the slight differences which could result from fabrication, the thickness survey could detect nothing that would indicate faulty performance of the fuel. Oblique light examination showed there were no localized flaw or blister areas.

Metallographic examination of the fuel plates showed there was equal or greater distance between the B_4C particles than between fuel particles and that there was insufficient helium gas pressure buildup in the matrix cavities (containing the B_4C particles) to disturb the mechanical bond between the particle and the matrix or to cause matrix cracking. Figure 2 shows a typical low-power microstructure of the fuel plate. The very dark particles along the center line are B_4C and show the B_4C distribution. Figure 3, which is one of the areas from Figure 2 (at high magnification) still shows the B_4C particles as being very dark, making them appear as voids. However, Figure 4, a different exposure of the same area as Figure 3, reveals the B_4C particles still mechanically bonded to the matrix.

Fig. 2 Microstructure of fuel plate showing B_4C particles (dark particles) along the center line.

Fig. 3 Enlargement of an area from the previous figure (Figure 2). At this exposure, the B_4C particles appear very dark.

Fig. 4 Microstructure of the same area and magnification as previous figure (Figure 3) with a different exposure.

After the completion of irradiation testing, element XE404B also was examined. As noted in Table III, this element had been exposed in a high power ETR core position to a calculated burnup of 33 percent of the original ^{235}U atoms present. The examination of this element was undertaken to confirm the favorable results on element XE401B.

The channel spacing measurements showed that all channel widths were 0.011 inch less than the minimum specified in the as-fabricated elements, indicating that the maximum plate swelling or warping was 0.011 inch as indicated by the decrease in the channel width. Subsequent plate thickness and corrosion measurements of the disassembled element shows that although appreciable swelling has occurred (maximum amount four percent), it was not great enough to account for the change in channel measurements. This led to the conclusion that some plate warpage may have occurred.

Visual inspection revealed a small pinhole in plate 2. Previous examinations of similar surface defects have shown they are associated with impurities which produce a localized galvanic attack. While this is undesirable, it is not a factor in the performance evaluation of B_4C foils.

Metallographic examination of as-irradiated plates showed good bonding at the core-foil interface. Typical microstructures are shown in Figures 5 and 6.

Fig. 5 As-irradiated microstructure of plate 18 from fuel element XE404B.

Fig. 6 As-irradiated microstructure of plate 18 from fuel element XE404B.

Blister anneal tests were made in the hot cell on samples from six plates. The results are compared with burnup values in Table IV. The first definite increase in core volume occurred in most of the plates at 370°C, but no blistering occurred until 430°C in plate 1. Figures 7 and 8 show typical results of blister metallography performed on samples from plates 1 and 18 from XE404B, respectively.

TABLE IV
CORRELATION OF BURNUP AND BLISTER ANNEAL TEMPERATURE FOR XE404B

Sample From Plate Number	Maximum Burnup Sample (fiss/cc x 10 ⁻²⁰)	First Indication of Volume Increase (°C)	Blister Temperature (°C)
1	4.7	400	430
2	5.3	370	510
6	5.7	370	480
14	unknown	370	510
18	6.0	370	480
19	unknown	370	480

The results of these blister anneal tests are compared in Figure 19 with similar tests from all other B₄C foil compositions and the failure-no-failure line for fuel plates containing UAl₃ + B₄C dispersed in aluminum and fabricated by powder metallurgy techniques^[4].

As can be seen, the foil type plates failed at lower temperatures than did the powder metallurgy type plates. However, the failure temperatures are considerably above the ETR fuel element operating conditions and are also above the failure-no-failure line previously determined for U₃O₈ fuel plates (IN-1133, Figure 33)^[5].

Fig. 7 Blister in plate 1 of fuel element XE404B.

Fig. 8 Blister in plate 18 of fuel element XE404B.

III. TESTING OF 500 GRAM ^{235}U PRODUCTION ELEMENTS

In view of the results obtained during the examination of the five prototype ETR B_4C foil fuel elements containing 400 g ^{235}U , it was decided that a limited number of B_4C foil ETR fuel elements loaded with 500 g ^{235}U would be obtained for routine irradiation in the reactor in low power positions (<1.6 percent core power) prior to permitting the routine use of these fuel procedures in the fabrication of ETR fuel elements. The potential margin of safety appeared to be high enough to warrant further tests without offering any apparent failure risk from a properly made element.

Accordingly, 60 ETR elements containing a nominal loading of 500 g of ^{235}U and 3.8 g of boron introduced as B_4C + Al foil were purchased in two shipments of 20 and 40 elements each. The fuel plates used in these elements were fabricated by employing the standard picture frame technique. In this process, the B_4C -aluminum foil was placed between two wrought alloy half cores and covered with the 1100 aluminum cladding and picture frame material. The B_4C -aluminum foils contained 4 to 5 wt% B_4C . The wrought alloy cores contained nominally 30 wt% uranium. The total core roll reduction during fabrication was nominally 8.75 to 1 with the final core thickness of 20 ± 1 mil. A minimum of five hot rolling passes were employed during fabrication with a maximum reduction for any pass being 40 percent. The final cold roll reduction was 20 ± 5 percent.

Because the basis for accepting or rejecting this type of fuel design was not solely based on irradiation performance (although this of course was a major factor), one unirradiated element from each of the two shipments was selected for destructive examination (after having passed receiving inspection) prior to irradiation testing of any production elements. The following tests were performed on these two unirradiated elements (XE19G and XE28G):

- (1) Radiograph and densitometer inspection of all plates
- (2) Immersion density measurements on all plates
- (3) Ultrasonic examination on all plates
- (4) Visual examination on all plates
- (5) Thickness measurements on all plates

- (6) Superficial hardness tests on all plates
- (7) Destructive examination on two plates from each element in accordance with Section 5.2, in ATR Fuel Element Specifications IN-F-3-ATR Rev. 1, Page 13
- (8) Melting point examination of plate core constituents.

These examinations along with the results obtained from the prototype element evaluations indicated that testing of three elements in medium power (<2.0 percent reactor power) reactor positions could proceed. This testing was performed in Cycle 97 of ETR and one medium power element (XE4G) was subsequently examined in the hot cells.

Following the results of the medium power element examination, three elements were irradiated in high power positions (>2.0 percent reactor power) during Cycle 103 of the ETR. One of these high power elements (XE45G) was examined in the hot cell facilities.

The medium power element (XE4G) and the high power element (XE45G) were generally examined in the following manner:

- (1) Visual and channel spacing probe measurements
- (2) Dimensional check
- (3) Photographs of the as-irradiated elements
- (4) Remove side plates
- (5) Oxide thickness survey
- (6) Immersion density measurements
- (7) Plate thickness survey
- (8) Metallography
- (9) Blister test.

The examinations that were carried out on the production elements were designed to evaluate the following factors:

- (1) Uranium and boron control within an element
- (2) Uranium and boron homogeneity within a fuel plate
- (3) Core configuration, internal defects, and bond integrity
- (4) Surface finish and defects
- (5) Clad-core-clad dimensions

- (6) Effect of flux peaking in the element
- (7) Enhanced failure mechanism in the B_4C -aluminum foil due to helium bubble formation
- (8) Vendor control of boron particle size distribution
- (9) Maintenance of channel spacing tolerances in a fuel element following irradiation
- (10) Performance of uranium-aluminum alloy core during a meltdown situation.

All of the production elements tested (both pre-irradiation and post-irradiation) were inspected using the standard procedures for all incoming fuel elements for the ETR.

The results of the unirradiated element examinations (XE19G and XE28G) (except the melting point study) were evaluated to the requirements of Idaho Nuclear Corporation^[a] specification PPCS-250, Rev. 3, and Addendum No. 1 (Subcontract S-292 and -294) to this specification.

1. DESTRUCTIVE EXAMINATION OF UNIRRADIATED ELEMENTS XE19G AND XE28G

These elements were selected at random from the first two incoming shipments of foil elements from the vendor. Plates from these elements were examined primarily to determine the extent of deviation from the purchase specifications in these first shipments of foil elements. Both of these elements had been nondestructively inspected at the vendor's plant and had passed receiving inspection at Idaho Nuclear Corporation. The only areas which were found to deviate from the purchase specifications were:

- (1) The ^{235}U content in plate KRB-35 (XE19G) was determined to be 27.39 ± 0.06 g. The value specified was 26.2 ± 0.8 g
- (2) The length of the fuel core was shorter than specified in several plates

[a] Now Aerojet Nuclear Company.

- (3) The maximum core "dogbone" thickness was excessive in a majority of the plates examined.

None of the above deviations were of sufficient importance to prevent irradiation testing. The remainder of this section gives the details of these examinations.

1.1 Uranium and Boron Homogeneity

Four B_4C foil fuel plates were selected at random (plates KRB-36 and KRA-49 were removed from element XE19G, and KRG-16 and KRA-85 were removed from element XE28G) to be examined for uranium and boron distribution. This was done by means of six punchings each for boron and uranium analysis taken at various locations on the plates. The uranium punchings (labeled U1-U6) were nominally 0.080 inch in diameter and the boron punchings (labeled B1-B6) were 1/2 inch in diameter. Figure 9 shows a diagram of the fuel plate sampling plan. The analysis techniques are described in Appendix A. The actual analytical results obtained are listed in Tables A-I and -II. The distribution of these data indicating degrees of homogeneity is shown graphically and compared with specified values in Figures 10 and 11. It can be seen that all of the data obtained were within specified limits for uranium and boron distribution within a plate. The boron punchings show somewhat wider distribution in concentrations (with respect to tolerance limits) than the uranium punchings; however, it would seem likely that this would be the case because of the manner in which the boron is added. These histograms also indicate that the average boron distribution is slightly to the left of nominal (less boron content) whereas the ^{235}U average is somewhat to the right of nominal (more ^{235}U content). It will be shown from data derived from the post-irradiation examination of six B_4C type foil elements that it is desirable to have the boron concentrations in the foil areas toward the lower limit of the specification because of the blister failure mechanism associated with this type of fuel plate.

Plates KRB-35 (from element XE19G) and KRE-14 (from element XE28G) were totally dissolved for boron and uranium analysis. Table V shows the results of these analyses. The total uranium obtained in plate KRB-35 was 29.45 ± 0.06 g. The total ^{235}U in this plate was 27.39 ± 0.06 g. The specification

Fig. 9 Fuel plate sampling plan used for the destructive tests. The "L" and "T" samples were prepared for metallographic examination. The "U" samples were 0.080-inch diameter punchings used for uranium analysis. The "B" samples were 1/2-inch diameter punchings used for boron analysis.

Fig. 10 Boron distribution within four B_4C foil plates.

Fig. 11 ²³⁵U distribution within four B₄C foil plates.

TABLE V

ANALYSIS OF B₄C FOIL PLATES KRB-35 AND KRE-14

Plate Number	Plate Weight (g)	Total Boron (mg)	B-10 (wt%)	B-11 (wt%)	Total Uranium (g)	Total ²³⁵ U (g)
KRB-35	254.2	210 ± 2	18.34	81.66	29.45 ± 0.06	27.39 ± 0.06
KRE-14	---	205.9 ± 0.4	19.82	80.18	29.23 ± 0.07	27.23 ± 0.08

on ²³⁵U for this plate is (1/19 of 498.11)^[a] ± 0.8 g. This is equal to 26.2 ± 0.8 g per plate. Plate KRB-35 was, therefore, high in ²³⁵U content by 0.39 ± 0.06 g. The boron content in KRB-35 was 210 ± 2 mg. The specified value is (1/19 of 3.54)^[b] ± 0.04 or 190 ± 40 mg.

[a] This was the total ²³⁵U content in the element determined by the vendor.

[b] This was the total boron content in the element as determined by the vendor.

The total uranium obtained in plate KRE-14 was 29.32 ± 0.07 g. The total ^{235}U in this plate was determined to be between 27.15 g and 27.31 g. The specification on ^{235}U in this plate is $(1/19 \text{ of } 503.27) \pm 0.8$ g. This is equal to 26.5 ± 0.8 g per plate. The ^{235}U content in plate KRE-14 was, therefore, determined to be within specifications. The boron content in KRE-14 was 205.9 ± 0.4 mg. The specification is $(1/19 \text{ of } 3.49) \pm 0.04$ g or 184 ± 40 mg. The boron was, therefore, seen to be within specifications.

1.2 Conformance with Specified Clad-Core-Clad Dimensions, Core Configuration, and Surface Defect Tolerances

1.21 Clad-Core Dimensions. The clad-core-clad dimensions (listed in Tables A-III and -IV) were determined by thickness measurements taken from "L" and "T" sections seen in Figure 9. The "L" and "T" sections were cut from the fuel plate, mounted, polished, and etched. The measurements were then made on a Kentron Microhardness Tester by movement of the stage with a micrometer and location of the respective interfaces with a crosshair in the microscope. All measurements obtained were then spot checked and measurements not within specifications were verified by another operator. The specified thickness for the core is $20 \pm \frac{0}{2}$ mils except in the core "dogbone"^[a] area. Here the thickness over the first one inch from each end must not exceed 26 mils and such high area shall not exceed 1/4 inch in the plate longitudinal direction. The specification for total plate thickness is 50 ± 1 mils. A typically shaped "dogbone" area is seen in Figure 12. A typical core cross section is seen in Figure 13.

All of the core thickness readings taken from the transverse sections ("non-dogbone" areas) were found to be essentially within specifications. Many of the readings that were taken at the maximum thickness of the core "dogbone" were, however, found to be greater than 26 mils. The actual range of the data is seen in Figure 14. In this figure, the maximum thickness readings obtained in the "dogbone" areas of 36 plates examined are plotted against relative frequency of occurrence. It can be seen that nearly 25 percent of the data were greater than specification.

[a] The "dogbone" area refers to a thicker core area near the end of the fuel core runout. The maximum thickness in the "dogbone" area is listed in Tables A-III and -IV. These data were derived from measuring the maximum core thickness in the "L" sections of Figure 9.

Fig. 12 A typically shaped "dogbone" area. The dark spot in the foil is a B_4C particle. Note that no clumping of the B_4C has occurred.

Fig. 13 A typical transverse cross section showing good B_4C distribution and grain growth along the clad-core interface.

Fig. 14 Graph showing the relative frequency of occurrence of maximum core thickness readings obtained in the "dogbone" areas of 36 B₄C fuel plates examined. Four readings in the "dogbone" area were taken for each plate. The actual data are seen in Tables A-III and -IV.

1.22 Core Configuration Control and Internal Defects. All of the fuel plates were radiographed and inspected for fuel core dimensions and such internal defects as particle flaking. A visual check of radiograph homogeneity was made. All of the plates were within specifications except KRA-51, KPU-43, and KPU-47. The cores of these plates were determined to be short and did not fill the minimum rectangle for this specification. None of the plates were noticeably inhomogeneous, contained flaked fuel particles in the picture frame area, or showed core smearing. A positive print from a radiograph of a typically shaped core (in the "dogbone" region) is seen in Figure A-1.

1.23 Surface Defects. All of the plates were visually examined, after the side plates had been removed at the machine shop. All of the plates were found to be acceptable.

1.3 Bond Integrity

All of the plates examined were evaluated for the relative soundness of the bonds between core, cladding, and foil areas. This evaluation was conducted by three different methods as described below.

1.31 Metallography. All sections mounted for clad-core-clad dimensions were polished and etched to reveal grain growth across the clad-core-clad interface and these values of percent grain growth were averaged for each plate.

The bonding examination (determination of percent grain growth) was performed under polarized light at about 50 magnifications after etching with NaOH for two minutes. The plates were then scanned in the length direction and an estimate of percent of grain growth was arrived at for each plate. The majority of the weight was given to the picture frame interface areas because grain growth is much easier to evaluate in these areas.

All values were between 75 and 95 percent grain growth and well above the 50 percent minimum specified. A typical microstructure is seen in Figure A-2.

1.32 Bend Tests. A core specimen from every plate except KRB-35 was bent through a 180 degree angle. The specimens that did not break were then bent in the opposite direction through a 270 degree angle. The radius of the bend in each case was 25 mils. This procedure always causes a fracture of the core and cladding. The bend-tested specimen is then mounted, polished, and viewed at a magnification of 50 diameters or greater to reveal any parting of the cladding material from the core at the break. In all cases, the bend test showed no breaking away of the clad from the core. A typical bend test is seen in Figure A-3.

1.33 Ultrasonic Examination. All of the plates were examined by water immersion ultrasonic techniques for macroscopic nonbonds and boron "clumping". A nonbonded area of larger than 1/16 inch nominal diameter is detectable by this process. None of the scans indicated unbonded areas in the fuel plates examined or areas of gross segregation of B_4C particles in the foil area of the fuel plates.

1.4 Immersion Density

All of the plates examined were measured for density by employing the immersion technique using the Archimedes Principle. The actual values obtained for each plate are given in Table A-V.

1.5 Melting Point Examination of ETR Boron Foil Plate Core Constituents

Samples from ETR boron foil fuel plate KRE-92 (element XE28G) were examined on a hot stage metallograph to compare the melting temperatures of the core constituents. This was done to evaluate the possibility of the UAl alloy core "clumping" away from the B_4C poison foil layer during a fuel plate meltdown situation. Figure 15 shows an as-received section from plate KRE-92.

The two black areas in the center of the photomicrograph represent B_4C particles in the center line foil layer. The fuel particles are a nominal 30 wt% U, UAl alloy. The clad, matrix, and foil layers are composed of 1100 aluminum.

Fig. 15 As-received core cross section from plate KRE-92, element XE28G.

This section was then heated slowly in a hot stage metallograph until some melting of the core was initially detected at 635°C. Heating was continued and at 640°C some intergranular penetration of the B_4C foil layer (Figure 16) was noted. Figure 17 shows this same area at 645°C. Here the UAl₄ particles are in a molten eutectic and the B_4C foil layer is partially melted and is alloyed with the fuel matrix. Penetration of the cladding is also noted in the grain boundaries near the core. Still further heating indicated that melting of both clad and core was complete at 660°C.

It would appear that if the heat source was the fuel core and the clad was partially cooled (the case occurring during fuel plate meltdown), the overheating would cause subsequent melting of the core fuel material which would penetrate the 1100 aluminum B_4C impregnated foil layer. It is, therefore,

Fig. 16 Same section as shown in Figure 15 at about 640°C. Melting of the core matrix is well along in the bottom section of the fuel.

Fig. 17 Same area as shown in Figure 15 at about 645°C. UAl₄ particles are in molten eutectic. Cladding has been penetrated in the grain boundaries near core.

very likely that a foil element would have the B_4C flowing with the molten fuel, a desirable situation in a meltdown accident.

2. MEDIUM POWER IRRADIATION TESTING AND EXAMINATION OF ETR B_4C FOIL FUEL ELEMENTS XE2G, XE3G, AND XE4G

The hot cell examination of ETR B_4C foil elements XE2G, XE3G, and XE4G, which were operated in medium power positions in the ETR, was completed in February 1969. Pre-irradiation and post-irradiation channel spacing measurements of these elements were made prior to insertion in the reactor and shortly after removal from Cycle 97, respectively. Table VI gives the core position, fuel loading, and burnup data for these elements. After evaluation of the data obtained from the hot cell examination of these elements, it was concluded that the performance of the elements was satisfactory, that this type of fuel element can safely be used in medium power positions (<2.0 percent reactor power) of the ETR, and that tests should proceed with elements in high power positions (>2.0 percent reactor power).

Plate numbers 1 and 2 from elements XE2G and XE3G were examined because these were determined by gamma scanning to be the hottest plate positions. All of the fuel plates from XE4G were examined. The examination consisted of tests for channel blockage, oxide thickness, swelling, relative gamma activity, density, blister formation temperature, blister metallography, and fuel burnup.

2.1 Channel Spacing Measurements

Figures B-1 and -2 show plots giving a comparison of pre-irradiation to post-irradiation channel spacing measurements between selected plates undergoing the highest differential heat flux from end to end (see Table VI for fuel element reactor conditions). The specification for channel spacing between these plates is 0.119 ± 0.007 inch for channel numbers 1, 2, 17, and 18; 0.115 ± 0.007 inch for channel numbers 3 and 16; and 0.105 ± 0.007 inch for all other channels. Generally, all the channel spacing dimensions (both before and after irradiation) were within specifications, except channel 3 from elements XE2G and XE3G and channel 14 from element XE4G. Both number 3 channels were uniformly narrow both prior to and after irradiation. Channel 14 had one narrow spot of 0.092 inch which was observed. However, it would not appear

TABLE VI

IRRADIATION CONDITIONS FOR MEDIUM POWER TEST ELEMENTS

Serial Number	XE2G	XE3G	XE4G
Core Position	F12	G14	H14
Initial Fuel Content (g)	507.5	507.2	507.7
Percent of Total Core Power	2.02	2.03	2.05
Total Core MWd	5310	5310	5310
Total Fuel Burnup in Element (g)	134.1	134.7	136.1
Ratio of Peak Axial Flux to Avg. Axial Flux	1.31	1.31	1.31
Ratio of Peak Midplane Flux to Avg. Midplane Flux	1.86	1.56	1.50
<u>Fractional Fuel Burnup</u>			
Overall Average	0.26	0.27	0.27
Average in Hotspot Plane	0.33	0.33	0.34
Hotspot in Element	0.53	0.47	0.46

that this irregularity caused significant decreases in coolant flow through this channel as evidenced by the fact that excessive oxide buildup was not seen on the surface of the plates in this area.

Details of the channel spacing measurement technique are given in Appendix B.

2.2 Visual Examination in Hot Cell

After the elements had been received in the hot cell, the end boxes were removed and a visual examination was made for any type of channel blockage. This examination of the three elements revealed three small foreign particles of the type seen in Figure 18 lodged in the flow channels of element XE2G. A close examination of the surface of each plate after it was milled free of the side plates showed that these particles caused no visible change in the oxide buildup on any plate adjacent to where the foreign particles were lodged. This would imply that if these particles were present during irradiation,

they did not cause any significant change in the water flow or the cooling rate for this element.

Fig. 18 Photograph taken in the hot cell looking down the flow channels of XE2G (after the end box had been removed). It is seen that particles (carried by reactor coolant flow) are visible between plates 3 and 4 and plates 8 and 9. A metal ship is visible between plates 6 and 7.

2.3 Maximum Oxide Thickness and Plate Thickness Survey

Dermatron (eddy current device) measurements were taken on each plate to determine the maximum oxide coating thickness. Test readings were taken on each plate to locate the maximum buildup areas and then six readings from these areas were tabulated. In general, the maximum buildup on the plates varied from 0.53 to 0.92 mil with these readings occurring in the high burnup areas. These readings indicated acceptable corrosion resistance and were similar to other oxide buildup data reported for 1100 clad ETR fuel elements^[6].

Several plots of total plate thickness versus plate length both prior to and after removal of the oxide coating on the surface of the plate are seen in Figures B-3 and -4. The total thickness of the plates after chemical stripping varied to a maximum of 1 mil over manufacturing specifications (50 ± 1 mil). Both the oxide buildup and the increase in thickness of the plates were within acceptable limits.

2.4 Immersion Density

The immersion density values for each plate examined are given in Table B-I. These densities vary from 2.96 to 2.99 g/cc. No density measurements were made on these plates prior to irradiation; therefore, exact values of core swelling and density changes during irradiation could not be determined. However, Table A-V gives the whole plate densities determined for the two unirradiated B₄C foil elements (XE19G and XE28G) destructively examined. These plate densities varied from 2.98 to 3.02 g/cc. Using these values as typical for the unirradiated densities, no significant swelling was seen.

2.5 Blister Tendency

Blistering of irradiated fuel plates is due to the accumulation of gaseous fission products, mainly Xe and Kr, in the fuel particle voids. As the gases accumulate, the internal pressure of the gas inside the voids increases. When the internal gas pressure exceeds the strength of the material, the void expands. The plates under examination also contain ¹⁰B (in the form of B₄C in the foil). Therefore, helium gas is also produced by the ¹⁰B + n → ⁷Li + ⁴He reaction. Helium may diffuse through the matrix, collect in the voids, and increase the internal pressure in the void. Even though the gas pressure forces are restrained in the fuel plate during irradiation, it is known that at some elevated temperature the restraining forces will break down and blistering will occur. Therefore, blistering of selected samples was intentionally induced by post-irradiation incremental heat treatments to indicate the maximum operating temperature at various fission densities.

Two 12-inch long samples (the width was that of the fuel plate after it was removed from the side plates) were removed from the end and middle of each plate examined. Identifying numbers were then stamped on these specimens. A total of 46 specimens were cut and subjected to 100°F (40°C) incremental annealing beginning at 600°F (315°C). The first blisters were seen after the 900°F (482°C) anneal, although some plate warpage of about 1/4 inch in a 12 inch section was observed at 700°F (372°C) on plate 4-7 and 800°F (427°C) on plates 4-15 and 4-18.

Following blister testing, 10 samples removed from known locations in several plates were submitted for radiochemical isotopic burnup determination. The burnup results obtained from these samples are given in Table B-II. These results were used to calibrate "gamma scans" taken at the center line

of each fuel plate removed from XE4G. These scans indicated the gross gamma activity obtained by a detector head employing a 0.5 inch by 10 mil aperture. The full plate length was traversed under this detector to obtain a plate longitudinal gamma scan. Figures B-5 and -6 show the relationship between plate position in fuel element XE4G and estimated burnup derived from the calibrated scans. The blister failure temperatures are also shown for the middle sections and the end sections of each plate. The end sections are the bottom 12 inches of each plate and the middle sections are the next 12 inches from the bottom. The blister anneal failure temperatures of the burnup samples shown in Table B-II and the blister data from all other B_4C foil compositions are compared in Figure 19 with the failure-no-failure line for fuel plates containing $UAl_3 + B_4C$ dispersed in aluminum and fabricated by powder metallurgy techniques. It can be seen that blister temperatures obtained from the above samples are generally below the failure-no-failure line for powder metallurgy UAl_x fuel plates; however, they still provide an adequate safety margin in the ETR environment.

2.6 Blister Metallography

Figures B-7 through -10 show typical results of blister metallography. In each case, a macroscopic photograph of the blistered sample is seen with a microscopic cross section of the blister (indicated by an arrow in the top photo) showing its origin. In general, the metallography of the blister samples revealed that the blisters originated within the B_4C foil and in some cases (the larger blisters) extended from there into the fuel core areas or the fuel core to cladding interface. All of the blisters observed were associated with the particles of B_4C within the foils. It can be seen from a blister resistance standpoint that the B_4C impregnated aluminum foil is the weak point in the fuel plate; however, the plates still show a high blister threshold (as seen in Figure 19). Dispersion type fuel plates normally show blister formation at the core-cladding interface.

Fig. 19 Blister data from all B_4C foil compositions superimposed on established failure-no-failure line for sample fuel plates with $UAl_3 + B_4C$ dispersed in aluminum and fabricated by powder metallurgy techniques.

3. HIGH POWER IRRADIATION TESTING AND EXAMINATION OF ETR B₄C FOIL FUEL ELEMENTS XE23G, XE24G, AND XE45G

The examination of B₄C foil elements XE23G, XE24G, and XE45G, which were operated at high power during Cycle 103, was completed in February 1970. Channel spacing measurements of these elements were made prior to insertion in the reactor and shortly after removal from Cycle 103. Table VII gives the core position, fuel loading, and calculated burnup data for these three elements. After evaluation of the data obtained during the hot cell examination of these elements, it was concluded that the performance of the elements was satisfactory; that B₄C foil fuel elements loaded with 500 g of ²³⁵U and 3.8 ± 0.1 g of boron can safely be used in some high power positions of the ETR (those that would produce no more than 1.1×10^{21} fiss/cc maximum core burnup of ²³⁵U) providing adequate controls preventing "clumping" of B₄C particles are maintained; and that the maximum cycle power production does not exceed 6000 MWd.

The examination carried out in the hot cells consisted of tests for channel blockage, oxide thickness, swelling, relative gamma activity, density, blister formation temperature, blister metallography, and fuel burnup. The two hottest (highest burnup as determined by gamma scanning) plates from elements XE23G and XE24G (plates 1 and 2), and all of the plates from XE45G, generally underwent the above examination. All of the fuel plates from the three elements were visually examined.

3.1 Channel Spacing Measurements

Figures C-1 and -2 present plots giving a comparison of pre-irradiation to post-irradiation channel spacing measurements between selected plates from element XE45G. The specifications for channel spacing are given in Section 2.1. Generally, all of the readings from the elements examined were within the pre-irradiation specifications except channel 18 (XE24G) and channel 16 (XE45G). It would appear that either plate 16, plate 17, or both of these plates swelled during irradiation and thus caused the overall narrowing of the channel by approximately 4 mils as noted in trace 16 (XE45G). All of the plates swelled slightly in the thickness direction during irradiation; however, this channel and channel 18 (XE24G) were sufficiently close to the tolerance

TABLE VII

IRRADIATION CONDITIONS FOR HIGH POWER TEST ELEMENTS

Serial Number	XE23G	XE24G	XE45G
Core Position	K10	H11	I10
Initial Fuel Content (g) ^[a]	501.0	500.9	512.9
Boron Content (g) ^[b]	3.93	3.88	3.84
Percent of Total Core Power	2.19	2.40	2.46
Cycle 103 MWd	5785	5785	5785
Total Fuel Burnup in Elements (g)	158.4	173.5	177.9
Ratio of Peak Axial Flux to Average Axial Flux	1.37	1.29	1.47
Ratio of Peak Midplane Flux to Average Midplane Flux	1.49	1.51	1.39
<u>Fractional Fuel Burnup</u>			
Overall Average	0.32	0.35	0.35
Average in Midplane	0.41	0.42	0.47
Hotspot in Element	0.54	0.56	0.58

[a] Shippers values.

[b] Calculated from ETRC measurements.

limits before irradiation so that a small amount of swelling produced a narrow position in the channels after irradiation.

3.2 Visual Examination in Hot Cell

After the elements had been received by the TRA Hot Cells, the end boxes were removed and a visual examination was made for any type of channel blockage. This examination of the three elements revealed no abnormalities such as lodged particles, indication of blistering, or warping of the fuel plates. A close examination of the surface of each plate after it was milled free of the side plates showed the plates to be free of large scratches and abnormal discoloration. Figure 20 shows the surface of some typical fuel plates after removal from XE23G.

Fig. 20 Visual appearance of typical fuel plates after removal from element XE23G. The areas of changing shades of gray indicate different oxide thicknesses.

3.3 Estimated Core Swelling

The immersion density values obtained for each plate (after stripping) are given in Table VIII. These densities vary from 2.96 to 3.01 g/cc. No density measurements were made on these plates prior to irradiation and exact figures for initial core weight or volume were not available from the vendor; therefore, core swelling calculations from experimental data on these plates could not be made in the normal manner. However, several simplifying assumptions listed below were made which permitted the probable swelling range to be calculated.

- (1) The total ^{235}U and natural boron content of each plate, as furnished by the vendor, is correct
- (2) The fuel alloy used in the plates averaged 30.2 wt% uranium and did not vary significantly from this figure
- (3) The B_4C -Al foil has an average volume of 1.38 cc for each plate
- (4) The weight of the fuel core remains constant during irradiation.

TABLE VIII

WHOLE PLATE DENSITIES OF XE24G AND XE45G

Plate No.	Weight (g)	Density (g/cm ³)	Plate No.	Weight (g)	Density (g/cm ³)
24-1	236.33	2.96	45-9	234.51	2.97
24-2	230.14	2.96	45-10	234.89	2.97
45-1	236.19	2.96	45-11	231.29	2.98
45-2	236.47	2.96	45-12	230.36	2.98
45-3	236.56	2.97	45-13	232.17	2.98
45-4	239.21	2.97	45-14	231.48	2.98
45-5	237.84	2.96	45-15	230.28	2.98
45-6	237.28	2.97	45-16	226.00	3.01
45-7	237.78	2.97	45-17	226.30	2.99
45-8	237.91	2.96			

The average fuel plate swelling data are shown in Table IX. These values were calculated for plates 1 through 17 from element XE45G. Figure 21 shows the calculated percent $\frac{\Delta V}{V}$ values for each plate core plotted versus average fuel plate core fission density and compares these points with the theoretical swelling curve for uranium aluminum alloy cores, the experimental range of curves for MTR and ETR alloy cores, and the experimental curve for typical ETR UAl_x powder metallurgy type elements. The points plotted for the plates from XE45G (as seen in Figure 21) show close correlation with the previously established curves for alloy fuel plates. All of the points plotted are above the swelling curve for typical UAl_x powder metallurgy fuel plates. Also, if one extrapolates from these data points to the level of 11×10^{20} fiss/cc (maximum burnup in XE45G) it can be seen that the swelling in the higher burnup areas of the core would be in the range of 5 to 7 percent.

3.4 Total Plate and Oxide Thickness Survey

A thickness survey of the plates was made prior to removal of the oxide coating on the surface. These thicknesses varied from 0.0490 to 0.0540 inch.

TABLE IX
CALCULATED AVERAGE CORE SWELLING FOR
PLATES 1 THROUGH 17 FROM ELEMENT XE45G

Plate No.	Average Plate Fission Density Estimated from Gross Gamma Activity $\times 10^{-20}$ fiss/cc	Calculated % $\Delta V/V$
XE45G-1	7.1	3.6
2	6.2	3.5
3	6.4	2.5
4	6.0	2.7
5	5.6	2.3
6	6.0	2.7
7	5.8	2.4
8	5.4	3.2
9	5.3	2.6
10	5.0	2.6
11	5.4	2.8
12	5.3	3.4
13	5.3	3.1
14	5.4	3.3
15	5.6	3.1
16	5.0	0.8 ^[a]
17	5.4	3.1

[a] This value was determined to be an outlier from the group of calculated values obtained.

Fig. 21 Calculated percent $\Delta V/V$ values for plates 1 to 17 from element XE45G plotted versus average fuel plate core fission density. These data are compared with the theoretical swelling curve for UAl alloy cores, the experimental range of curves for MTR and ETR alloy cores, and the experimental curve for typical ETR UAl_x powder metallurgy type elements.

The thickness survey for each plate does seem to show a trend of generally greater thickness in the middle of the plates (higher burnup areas) than at the ends. On the average, the oxide coating on both sides of the fuel plates in the high burnup areas varied between 0.8 to 1.5 mils in thickness. Total plate thickness measurements for five selected plates in relation to plate length and gamma amplitude are given in Figures C-3 through -6.

3.5 Blister Tendency

Three eight-inch long samples (the width was that of the fuel plate after it was removed from the side plate) were removed from a number of plates for blister testing. These blister sections were labeled A, B, and C (as shown in Figures C-3 through -6 for several typical plates) and comprise the lower 24 inches of each plate tested (the grooved end is the top of the plate). Identifying numbers were then stamped on these specimens. A total of 69 specimens were cut and subjected to incremental [100°F (40°C) increments] annealing beginning at 400°F (205°C). The first blisters were seen after the 800°F (430°C) anneal for most of the plates examined.

It has previously been shown that blisters in B₄C foil type fuel plates (at high burnup levels) of the type under consideration tend to form preferentially

in the foil area. This tendency can be seen for plate 2 of XE45G in Figures 22 and 23. The cracks in the plates examined, which ultimately caused blistering of the plates, seem to originate in every case from the B_4C particles in the foil. The blisters also formed quite rapidly when a critical temperature was reached.

Isotopic burnup values (radiochemical analysis -- Table X) at positions of known gamma activity were used to calibrate the gamma scans. Figure 19 shows the blister anneal failure points for plates 1, 2, and 7 from XE45G, plate 1 from XE23G, and plate 1 from XE24G. These failure points are also compared with those for the medium power position elements XE2G, XE3G, and XE4G, and the failure-no-failure line determined for fuel plates containing powder metallurgy UAl_x cores (such as standard ETR fuel plates). It can be seen from this figure that all of these B_4C samples are somewhat below the failure-no-failure line for powder metallurgy samples. However, a blister resistance of better than 400°C is maintained at these burnup levels. This provides an adequate margin of safety for the ETR.

3.6 Blister Metallography

Figures C-7 through -10 show typical results of metallography performed on several plates (Table X and Figures C-3 through -6). In each case, a macroscopic photograph of the blistered sample is seen with a microscopic cross section of the blister (indicated by the arrow in the top photo) showing its origin. Figure C-11 shows an as-irradiated (before blister testing) photomicrograph from the "D" section of plate 2 from XE45G.

Fig. 22 Cross section cut through blister produced by post-irradiation anneal in plate 2 of element XE45G.

Fig. 23 High magnification view of core of plate 2 of element XE45G, after blister anneal.

TABLE X
RADIOCHEMICAL ANALYSIS DATA FOR
XE-23, 24, AND 45-G

<u>Section</u>	<u>Plate No.</u>	<u>Blister Initiation Temperature (°C)</u>	<u>Fission Density x 10⁻²⁰ fiss/cc</u>	<u>²³⁵U Depletion Percent</u>
C	23-1	430	7.9	36.6
C	23-1	"	9.4	43.2
B	45-1	"	10.8	49.7
B	45-1	"	11.1	51.0
A	45-2	480	7.6	35.1
B	45-7	430	7.7	35.5
B	24-1	"	9.8	45.0
B	24-1	"	9.6	44.3

IV. SAMPLE FUEL PLATES IRRADIATED TO EXTENDED BURNUP

1. INTRODUCTION

Following the examination performed on the three boron foil fuel elements irradiated in high power positions of the ETR during Cycle 103, the results were submitted to the Atomic Energy Commission in February of 1970. After reviewing these results, the AEC proposed the following two studies: (a) sample fuel plate irradiations to determine the effect of helium generation in boron foil elements relative to blister performance at high levels of burnup and with increased boron contents, and (b) examination of the seven percent limit on swelling to determine whether or not it should be retained as an operational limit. Meanwhile approval for general utilization of boron foil fuel elements in the ETR was granted, provided that a fission density of 1.1×10^{21} fiss/cc of core was not exceeded for a given fuel plate. The fabrication procedure and the results obtained from the examination of the sample fuel plates irradiated to extended burnup are contained in the remainder of this section.

2. FABRICATION

The standard fabrication procedure used to produce these sample fuel plates is given in Appendix D. A drawing showing dimensions of the INC-16 irradiation plate is given in Figure 24.

Composition 155 sample fuel plates were fabricated to represent full sized B_4C foil fuel plates. These plates were of sandwich construction with cladding and picture frame of 1100 aluminum alloy and two core layers containing 29 wt% alloy separated by a 1-1/2 mil thick foil layer containing 4.5 wt% B_4C . The composition 156 plates were similar except that the foil layer contained 5.4 wt% B_4C (20 percent increase in B_4C). These were fabricated to test the effects of greater amounts of helium formation along the plate center line.

Fig. 24 Drawing showing dimensions and cross-sectional view of INC-16 sample fuel plate.

3. IRRADIATION TESTING

The B_4C sample fuel plates (compositions 155 and 156) were irradiated in tiers 5, 6, and 7 in the G-12 position of the ETR during Cycles 109, 110, and 111. During this exposure, a peak calculated burnup of 1.8×10^{21} fission/cc of core was obtained after 18,670 MWd of operation.

Figure 25 shows the type of facility used to hold the samples during irradiation. The outside configuration was the same as a fuel element but tiers of sample holders contained the fuel plates inside a filler piece. A removable end box provided the proper flow distribution. There was a total of nine tiers and positions for 12 sample fuel plates in each tier. Although there were nine compositions of fuel plates irradiated, only the two types of B_4C foil plates (compositions 155 and 156) will be discussed in this report since the remaining compositions were ATR types.

Fig. 25 Sample train irradiation facility with the outside configuration of a fuel element.

4. VISUAL EXAMINATION

All of the INC-16-1 sample fuel plates were examined visually in the ETR canal after removal of the sample train from the reactor. Selected plates were again examined in the TRA Hot Cells. No blistering, excessive swelling, warping, or other abnormalities were observed in these examinations.

5. OXIDE AND GROSS THICKNESS MEASUREMENTS

Total plate thickness (both before and after irradiation) and eddy current oxide thickness data obtained on both sides of each plate examined are given in Table XI. The calculated percent change in core thickness is also given for each plate. All of the data in this table are as predicted and the calculated change in thickness of the core agreed well in every case with the swelling calculated from density measurements (Table XII).

TABLE XI

TOTAL PLATE THICKNESS AND OXIDE MEASUREMENTS

Plate No.	Total Average Plate Thickness As Fabricated -Mils	Total Average Plate Thickness After Irradiation ^[a] -Mils	Calculated % Change in Thickness of Core ^[b]	Oxide Thickness	
				Mils A Side	Mils B Side
155-11	49.7	51.9	11.0	0.65	0.70
155-23	49.7	51.5	9.0	0.70	0.73
155-10	49.5	51.5	10.0	0.66	0.65
155-13	49.4	51.5	10.5	0.72	0.70
156-45	49.4	51.5	10.5	0.58	0.66
156-64	48.5	50.7	11.0	0.73	0.60
156-58	49.6	51.5	9.5	0.69	0.61
156-49	49.7	51.4	8.5	0.59	0.57

[a] These numbers do not include the oxide film.

[b] These numbers are based on an assumed core thickness of 20 mils. Because of assumptions involved in calculating these numbers, they are not as accurate as measured swelling data (based on density measurements) given in Table XII.

TABLE XII
SWELLING AND BLISTER TEST RESULTS

<u>Composition</u>	<u>Plate No.</u>	<u>Calculated Fiss/cc[b]</u>	<u>Blister Temperature (°C)</u>	<u>Core Swelling, % $\Delta V/V$</u>	
				<u>Measured</u>	<u>Expected^[a]</u>
ETR B ₄ C Foil 4.5 wt% B ₄ C	155-11	1.78	430	9.1	11.4
	155-23	1.60	430	8.6	10.2
	155-16	1.62	455	[c]	10.3
	155-09	1.62	455	[c]	10.3
	155-14	1.62	455	[c]	10.3
	155-24	1.59	480	[c]	10.1
ETR B ₄ C Foil 5.4 wt% B ₄ C	156-45	1.79	430	9.2	11.5
	156-64	1.63	430	8.7	10.4
	156-65	1.60	455	[c]	10.2

[a] Net volume increase due to the formation of solid fission products.

[b] These numbers are multiplied by 10^{21} .

[c] Density measurements were not made on these samples; therefore, measured core swelling data could not be calculated.

6. SWELLING AND BLISTER RESULTS

In Table XII, core swelling is presented in terms of the percent increase in core volume as a function of irradiation. These data were calculated from immersion density measurements made both before and after irradiation. The expected core swelling is derived from the net volume increase due to the formation of solid fission products. The latter quantity has been calculated as a function of fission density. The results show that measured core swelling generally is in reasonable agreement with (slightly less than) the expected curve for alloy cores. These swelling data are plotted in Figure 26 as a function of irradiation exposure. Swelling data from composition 154 plates (standard ETR type) are also shown for comparison. It can be seen that the measured swelling in standard ETR UAl_x powder metallurgy cores is less than that of the alloy cores in B_4C foil type plates. This is due primarily to the fact that these plates have core voids which accommodate a portion of the fission products. Alloy cores have no voids to accommodate fission products.

Fig. 26 Measured core swelling for B_4C foil fuel plates compared with swelling measured for ETR UAl_x powder metallurgy sample fuel plates.

Blister testing was carried out in 100°F increments from 400°F (205°C) to 600°F (315°C) and 50°F increments from 600°F to failure. The blister temperature data given in Table XII indicate the temperature at which blisters first appeared on the plates. These results plus other data from previous B₄C foil examinations are plotted in Figure 19. It is notable that the slope of this line decreases at high burnups and appears to approach linearity.

7. BLISTER AND AS-IRRADIATED METALLOGRAPHY

Figure 27 is a cross section through an as-irradiated composition 155 B₄C foil sample fuel plate. Because the boron has been essentially all transformed to helium during irradiation, many small voids have been left along the fuel plate center line. From Figure 28 it is apparent that blistering takes place when the internal pressure inside the voids increases sufficiently to propagate cracking within the foil layer. This same tendency is observed in composition 156 (high boron) sample fuel plates (Figures 29 and 30). The external appearance of the B₄C foil blister failures is shown in Figure 31. It can be seen in this figure that blistering was extensive. For comparison, the external appearance of a composition 154 sample fuel plate is shown in Figure 32 after blistering at 850°F.

Fig. 27 Cross section of as-irradiated composition 155 (standard B_4C foil) sample fuel plate. Note the large number of helium voids along the foil center line.

Fig. 28 Composition 155 sample fuel plate following blister failure at 800°F (430°C). Note the crack propagation along the foil center line.

Fig. 29 Cross section of as-irradiated composition 156 (high boron) sample fuel plate. Note the relatively greater number of helium voids along the foil center line than in Figure 27.

Fig. 30 Composition 156 sample fuel plate following blister failure at 800°F (430°C).

Fig. 31 Typical external appearance of compositions 155 and 156 blister failures at 430°C. Note the very large amount of swelling that took place. No blisters were seen until this temperature. The area enclosed by the dotted line is the blistered portion of the sample.

Fig. 32 External appearance of the first sign of blistering for a composition 154 (standard ETR) sample fuel plate. Note that only one small blister has formed in the corner of the plate marked by the arrow.

V. CONCLUSIONS

As a result of the work done on this project, the following conclusions have been reached:

- (1) It has been shown that B_4C can be successfully distributed along the center line of a wrought uranium-aluminum alloy core by starting with a 0.004 to 0.010 inch aluminum foil containing B_4C . This foil is then inserted between two UAl alloy half cores at the time of fuel plate fabrication by the roll-bond picture-frame technique (described in Appendix D).
- (2) Several hundred B_4C -foil type fuel elements have been produced by a commercial vendor to date. The control of uranium and boron within these elements and the homogeneity within the fuel plates compare favorably with UAl_x powder metallurgy type elements in this respect. Specified fabrication controls on core configuration, flaking, bond integrity, and clad-core-clad dimensions have not produced a high reject rate in B_4C foil type plates, and these types of defects in general have not been a problem.
- (3) Numerous B_4C foil fuel elements have been irradiated to date in low and medium power positions in the ETR. Three of these elements have been irradiated in high power reactor positions. All of these elements have been visually examined in the ETR canal, after removal from the reactor. No warping or blistering has been detected on any of the fuel plates within these elements.
- (4) Sample fuel plates containing B_4C foils did not warp or show signs of blistering after irradiation to 18,670 MWd in the ETR and a peak fission density of 18×10^{20} fission/cc. This is approximately 20 percent higher than the current peak fission density attained in the hot position of the ETR during a 6,000 MWd cycle.

- (5) The swelling for the B_4C foil sample fuel plate compositions is approximately 9 to 10 percent at the highest burnup levels (1.5 to 1.8×10^{21} fiss/cc). This exceeds the 7 percent swelling limit which has been used in the past as the recommended guideline. However, since the samples in this test were unrestrained, the 7 percent growth limit must be examined from a thermal stress and buckling standpoint before unrestricted release can be given beyond the 7 percent limit for full sized fuel elements for nominal maximum operation in the ETR (ie, up to 1.5×10^{21} fiss/cc and 9.5 percent core swelling expected from fission atomic volume increase for this burnup).
- (6) The minimum blister failure temperature obtained at a maximum burnup of 1.8×10^{21} fiss/cc is still 430°C . Other samples with lower fission densities either blistered at this temperature or higher temperatures. In general, the blister failure temperatures for B_4C foil samples are below the failure-no-failure curve for UAl_3 and B_4C dispersed in aluminum and fabricated by powder metallurgy (Figure 19). However, the B_4C foil plates still provide an adequate temperature safety margin for the ETR (Table I).
- (7) Metallography indicated that the foil area of the core is the weak point in relation to blister resistance. However, this was expected because of the helium produced from the boron during irradiation. It would appear that slightly higher than normal B_4C concentration in the foil is not detrimental to the blister resistance because the composition 156 INC-16 sample fuel plates (20 percent more boron in the foil than standard plates) did not show an appreciably lower blister resistance.

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APPENDIX A

DETAILS OF THE DESTRUCTIVE EXAMINATIONS OF
UNIRRADIATED B₄C FOIL ELEMENTS XE19G AND XE28G

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APPENDIX A

DETAILS OF THE DESTRUCTIVE EXAMINATIONS OF
UNIRRADIATED B₄C FOIL ELEMENTS XE19G AND XE28G

1. URANIUM + BORON DISTRIBUTION

The analytical chemistry data on punchings removed from ETR fuel plates KRB-36, KRH-49, KRG-16, and KRH-85 are reported in Tables A-I and -II. The uranium and boron whole plate analyses performed on plates KRB-35 and KRE-14 are reported in Table V.

The uranium in both the punchings and the whole plate analysis was determined by a isotopic dilution mass spectrometric procedure with a precision of 0.3 percent relative standard deviation for a single analysis. Boron was determined for the punchings by a recently developed colorimetric procedure with a precision of 1.1 percent relative standard deviation for a single analysis.

The whole plate boron analyses were determined by a combination of titrimetry and emission spectrography. The fuel plates were dissolved in nitric acid with mercury (11) catalysis and then filtered to yield two phases, a boron rich residue phase, and a boron lean filtrate phase. The boron in the residue was determined by a titrimetric procedure after dissolution. Emission spectrography was used to determine boron in the filtrate. The combined precision for the total boron content in a plate by this method is 1 percent relative standard deviation for a single analysis^[a].

The relative standard deviation of the results obtained, as seen in Table A-I (²³⁵U in plates KRB-36, KRA-14, KRG-16, and KRH-85) is 329 ± 15.8 mg/in.² (4.80 percent), 307 ± 7.39 mg/in.² (2.41 percent), 319 ± 19.3 mg/in.² (6.04 percent), and 315 ± 5.60 mg/in.² (1.78 percent), respectively. The range of ²³⁵U content in these punchings (from all four plates) was 55 mg/in.² (294 to 349). As seen in Table A-I, the range of specified ²³⁵U per punching is 50 mg/in.² (227 to 377). The distribution of ²³⁵U was, therefore, within specification for these plates.

[a] The analyses for whole plate uranium and boron were generally performed in replicate with a resulting precision of 0.2 percent → 0.4 percent relative standard deviation for the average.

TABLE A-I
URANIUM DISTRIBUTION IN PUNCHINGS FROM FOUR
ETR B₄C PLATES

Sample Code		Sample Wt, mg	Uranium ^[b] mg/Sample	²³⁵ U wt%	²³⁵ U mg/g Sample	²³⁵ U[a,c,d] mg/in. ² of Plate
KRB-36	U1	12.85	1.699	93.15	123.2	317
	U2	12.85	1.866	93.16	135.3	348
	U3	12.88	1.731	93.13	125.2	322
	U4	12.86	1.858	93.13	134.5	346
	U5	12.64	1.657	93.13	122.1	309
	U6	12.83	1.778	93.12	129.1	331
KRA-49	U1	12.53	1.589	93.14	118.1	296
	U2	12.54	1.629	93.12	121.0	303
	U3	12.68	1.656	93.13	121.6	308
	U4	12.72	1.649	93.13	120.8	307
	U5	12.78	1.703	93.09	124.0	317
	U6	12.76	1.679	93.11	122.5	313
KRG-16	U1	12.89	1.744	39.14	135.3	349
	U2	12.74	1.543	93.16	121.1	309
	U3	12.80	1.588	93.15	124.1	318
	U4	12.81	1.566	93.14	122.2	313
	U5	12.80	1.665	93.16	130.1	333
	U6	12.60	1.472	93.19	116.8	294
KRA-85	U1	12.68	1.533	93.12	120.9	307
	U2	12.67	1.620	93.15	127.9	324
	U3	12.67	1.564	93.15	123.4	313
	U4	12.65	1.587	93.15	125.5	317
	U5	12.58	1.575	93.14	125.2	315
	U6	12.68	1.563	93.16	123.3	313

[a] These values were calculated by assuming a constant punching area of 0.005 in.².

[b] Uranium was determined in the punchings with a precision of 0.3% relative standard deviation for a single analysis.

[c] The specification for range of ²³⁵U homogeneity within a fuel plate is 302 ± 75 (25%) mg ²³⁵U/in.² plate.

[d] The relative standard deviation of the results obtained for plates KRB-36, KRA-49, KRG-16, and KRA-85 is 329 ± 15.8 mg/in.² (4.80%), 307 ± 7.39 mg/in.² (2.41%), 319 ± 19.3 mg/in.² (6.04%), and 315 ± 5.60 mg/in.² (1.78%), respectively.

TABLE A-II

BORON AND SILICON DISTRIBUTION IN PUNCHINGS FROM
FOUR ETR B₄C FOIL PLATES

Sample Code		Boron ^[b] μg/Sample	Sample Wt, g	Boron μg/g Sample	Boron ^[a,d,e] μg/in. ² of Plate	Silicon ^[c] wt%
KRB-36	B1	412	0.4980	827	2100	0.75
	B2	389	0.5037	772	1980	
	B3	378	0.3970	760	1930	
	B4	355	0.5015	707	1810	0.75
	B5	438	0.4963	882	2230	
	B6	391	0.5026	777	1990	
KRA-49	B1	376	0.4951	759	1920	0.77
	B2	402	0.4960	810	2050	
	B3	452	0.4949	913	2310	
	B4	430	0.4959	867	2190	0.76
	B5	422	0.4942	853	2150	
	B6	430	0.4955	867	2190	
KRG-16	B1	435	0.4990	871	2220	
	B2	490	0.4959	989	2500	
	B3	480	0.4986	963	2450	
	B4	469	0.4940	949	2390	
	B5	497	0.4966	1000	2540	
	B6	506	0.4944	1023	2580	
KRA-85	B1	454	0.4964	915	2320	
	B2	460	0.4960	927	2350	
	B3	438	0.4969	881	2230	
	B4	428	0.4980	860	2180	
	B5	413	0.4939	836	2110	
	B6	346	0.4932	701	1770	

[a] These values were calculated by assuming a constant punching area of 0.196 in.².

[b] Boron was determined in the punchings with a precision of 1.1% relative standard deviation for a single analysis.

[c] Silicon analysis was performed on three punchings combined. Precision data were not obtained for these analyses.

[d] The specification for range of boron homogeneity within a fuel plate is 2290 ± 690 (30%) μg boron/in.² of plate.

[e] The relative standard deviation of the results obtained for plates KRB-35, KRA-49, KRG-16, and KRA-85 is 2010 ± 144 μg/in.² (7.19%), 2130 ± 134 μg/in.² (6.30%), 2450 ± 130 μg/in.² (5.30%), and 2110 ± 211 μg/in.² (9.75%), respectively.

The relative standard deviation of the results obtained in the boron punchings, as seen in Table A-II (total boron in plates KRB-36, KRA-49, KRG-16, and KRA-85), is $2010 \pm 144 \text{ } \mu\text{g/in.}^2$ (7.19 percent), $2130 \pm 134 \text{ } \mu\text{g/in.}^2$ (6.30 percent), $2450 \pm 130 \text{ } \mu\text{g/in.}^2$ (5.30 percent), and $2160 \pm 211 \text{ } \mu\text{g/in.}^2$ (9.75 percent), respectively. The range of total boron content in these punchings (from all four plates) was $810 \text{ } \mu\text{g/in.}^2$ (1770 to 2580). As seen in Table A-II, the range of permissible boron distribution is $1380 \text{ } \mu\text{g/in.}^2$ (1600 to 2980). The distribution of total boron was, therefore, within specification for these plates.

2. CLAD-CORE-CLAD DIMENSIONS

The actual clad-core-clad dimensions determined by measurement of metallographic mounts are seen in Table A-III (fuel element XE19G) and Table A-IV (fuel element XE28G). The "dogbone" sections (L_1 , L_2 , L_3 , and L_4) represent maximum core thicknesses determined for each respective section. The core thickness readings, taken from the transverse sections removed from each plate (T_1 , T_2 , T_3 , and T_4) represent the average of several readings made on each mount in a random manner across the fuel plate.

TABLE A-III

CLAD-CORE-CLAD DIMENSIONS IN MILS FOR PLATES FROM XE19G

Plate Number		L ₁ "Dogbone" Sections	L ₂ Sections	T ₁ Transverse Sections	T ₂ Sections	T ₃ Transverse Sections	T ₄ Sections	L ₃ "Dogbone" Sections	L ₄ Sections
1	KRB-40	12,27,11	11,28,11	15,20,15	15,20,15	15,20,15	15,20,15	11,27,11.5	13,25,11.5
2	KRB-35	Not Determined							
3	KRB-36	12.5, 26,12	13,26,11	15,20,15	15,20,15	15,20,15	15,20,15	13,25,11.5	13,26,11
4	KRA-31	13,26,12	11,28,12	15.5,20,15	15,20,15	15,20,15	15.5,19.5,15	12,24,14	13,25,12
5	KRJ-30	12,27,12	11.5,25.5,13	15,19,16	15,20,15	14,20,15.5	15,20,15	12,26,12	10,26,13
6	KRA-44	11,25,13.5	11,26,12	15,20,15	15,20,15	15,20,15	15,20,15	11,26,12.5	12,26,12
7	KRA-47	13,25,12.5	13,26,12	15,20,15	15,20,15	15,20,15	15,20,15	12,26,13	12.5,25,13
8	KRA-49	13,25,12	12.5,25,13	15,20,15	15,20,15	15,20,15	15,20,15	12.5,20,12.5	12.5,25,12.5
9	KRA-51	12,26,11.5	13,25,13	15,20,15	15,21,15	15,20,15	15,20,15	12,25,13	13,26,11.5
10	KPU-38	13,26,12	11,26,13	14.5,20,16	15,20.5,15	14.5,21,14.5	15,20,15	14,23,13	13.5,25,12
11	KPU-40	15,21,14	15,22,14	15,20,15	15,20,15	15,20,15	15,20,15	Missing	
12	KPU-41	14,26,11	12,24,14	15,20,15	15,20,15	15,20,15	15,20,15	12,26.5,13	13,26,12
13	KPU-43	14,21,14.5	11.5,25,13.5	15,20,15	15,20,15	15,20,15	15,20,15	13,27,10	12,25,13
14	KPU-44	12,25,13	12,26,13	15.5,20,14.5	15.5,20,15.5	15,20,15	15.5,20,15.5	12,25,12	13,25,12
15	KPU-47	12.5,25,13	13,24,13.5	15,20,15	15,20,15	15,20,14.5	15,20,15	13.5,24,12.5	13,25,12.5
16	KPU-49	11,26,12.5	13,26.5,11	15,19,15	15,20,15	15,19.5,16	15,20,15	12,27,12.5	12.5,26,13
17	KPU-50	Missing	11.5,25,15	15,20,15	15,21,14	14.5,20,15	15,21,15	14,23,14	13,26,13
18	KPU-53	10,27,13	10,27,14	15,20,15	15,20,15	15,21,14	15,20,15	12,26,13	12,26,13
19	KRE-28	Missing	12.5,25,13	14.5,20,15	15,20,15	15,20,15	15,20,15	13,25,12	12.5,25,13

TABLE A-IV

CLAD-CORE-CLAD DIMENSIONS IN MILS FOR PLATES FROM XE28G

Plate Number		L ₁ "Dogbone" Sections	L ₂ Sections	T ₁ Transverse Sections	T ₂ Sections	T ₃ Transverse Sections	T ₄ Sections	L ₃ "Dogbone" Sections	L ₄ Sections
1	KRA-84	11,28,10	12,72,10	15,21,14	14,22,14	15,20,15	15,20,15	13,28,9	13,25,12
2	KRA-85	10,30,10	12,72,10	16,19,15	15,19,16	15,20,15	15,20,15	13,27,9	13,28,9
3	KRA-86	12,25,13	11,27,12	14,22,12	15,19,16	15,20,14	15,20,15	11,29,10	10,29,11
4	KRE-14	Not Determined							
5	KRE-78	13,25,12	11,28,11	14,21,15	14,22,14	15,20,15	15,20,15	12,24,14	12,25,12
6	KRE-79	12,25,13	11,28,11	14,21,15	14,22,14	15,20,15	14,21,15	10,29,11	10,28,12
7	KRE-81	12,26,12	11,26,13	14,22,13	14,22,14	13,22,15	12,22,16	12,26,13	11,25,14
8	KRE-85	14,24,12	14,21,14	15,20,13	14,20,15	16,20,14	15,21,13	12,26,11	10,27,11
9	KRE-89	11,26,13	14,25,10	14,20,15	14,21,15	13,22,15	13,20,16	9,26,15	9,27,11
10	KRE-91	11,26,12	12,28,9	13,19,16	12,23,14	13,19,16	17,19,14	13,23,11	10,27,12
11	KRE-92	13,26,10	13,24,13	15,21,13	14,20,16	14,19,16	14,21,14	9,22,18	12,26,12
12	KRE-93	9,28,10	11,25,13	14,21,15	13,20,15	13,19,15	13,21,15	10,26,12	12,27,11
13	KRF-22	9,30,9	10,28,10	13,20,15	14,21,5	15,20,15	13,21,14	13,25,12	13,24,13
14	KRF-43	12,26,11	11,26,12	16,19,14	14,21,15	15,20,15	15,19,15	13,25,11	12,25,11
15	KRG-01	13,24,12	13,24,12	13,21,16	14,22,14	13,20,15	15,21,14	21,27,11	11,25,13
16	KRG-08	11,25,14	13,25,12	15,21,14	13,22,15	13,21,15	15,20,15	12,24,13	15,23,12
17	KRG-11	12,24,12	12,24,14	11,21,16	14,21,14	13,21,15	15,20,15	12,25,13	11,28,11
18	KRG-12	13,24,13	15,23,12	15,20,15	14,22,14	14,22,14	15,21,14	13,23,14	12,26,12
19	KRG-16	11,24,14	14,24,11	15,20,15	16,19,15	13,22,14	14,20,15	9,28,13	13,23,15

TABLE A-V

PLATE DENSITY MEASUREMENTS

Element XE19G	Plate Number	Dry ^[a] Weight	Density ^[b]
1	KRB-40	255.225	3.012
2	KRB-35	254.290	3.019
3	KRB-36	256.250	3.000
4	KRA-31	256.460	3.000
5	KRJ-30	256.465	3.007
6	KRA-44	256.600	2.998
7	KRA-47	254.165	3.004
8	KRA-49	254.140	3.000
9	KRA-51	255.680	2.998
10	KPU-38	254.755	3.014
11	KPU-40	259.750	3.009
12	KPU-41	260.035	3.012
13	KPU-43	260.300	3.001
14	KPU-44	259.040	3.004
15	KPU-47	259.200	3.003
16	KPU-49	259.430	3.009
17	KPU-50	258.845	3.005
18	KPU-53	258.660	3.001
19	KRE-28	252.735	3.013
XE28G			
1	KRA-84	253.529	2.992
2	KRA-85	254.323	2.990
3	KRA-86	254.740	2.985
4	KRE-14	251.760	2.993
5	KRE-78	255.195	2.986
6	KRE-79	254.345	2.986
7	KRE-81	255.240	2.983
8	KRE-85	---	2.984
9	KRE-89	---	2.984
10	KRE-91	---	2.982
11	KRE-92	---	2.980
12	KRE-93	---	2.986
13	KRE-22	---	2.989
14	KRE-43	---	2.976
15	KRG-01	---	2.979
16	KRG-08	---	2.978
17	KRG-11	252.002	2.989
18	KRG-12	249.189	2.987
19	KRG-16	254.620	2.985

[a] All weights are in grams.

[b] All densities are in grams/cc.

Fig. A-1 A positive print of a radiograph of a typical fuel plate showing both ends of the fuel core runout. The top of each print indicates the end of the core runout.

Fig. A-2 A typical cross section showing good grain growth across the clad-picture frame-clad interface.

Fig. A-3 This shows a typical bend test specimen. Note the good adherence of clad and core.

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APPENDIX B
DETAILS CONCERNING THE TESTING AND EXAMINATION OF
ELEMENTS XE2G, XE3G, AND XE4G

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APPENDIX B

DETAILS CONCERNING THE TESTING AND EXAMINATION OF
ELEMENTS XE2G, XE3G, AND XE4G

1. CHANNEL SPACING MEASUREMENT TECHNIQUE

All channel spacing measurements which were taken prior to irradiation were made by employing a probe inserted to known distances from the top of the fuel plate within the channel. An improved method was developed for the post-irradiation channel spacing measurements and was subsequently used for all latter measurements. This system which involved ultrasonic sensing devices is described in detail in Reference 7.

Basically, this system measures channel width by measuring the transmission time of an 8-MHz sound burst across the flow channel. A time-to-analog converter is used to obtain an analog signal directly proportional to channel thickness. The system also has a channel longitudinal distance-to-analog converter. The thickness signal is connected to the "Y" axis of a recorder, and the longitudinal distance signal is connected to the "X" axis to make a channel thickness profile as the detector is pulled through the channel. This system has a ± 0.5 mil accuracy and 0.1 mil resolution over a 50 to 175 mil range of channel widths. This instrument is also affected by temperature gradients.

The dashed lines in Figures B-1 and -2 represent the measurements taken prior to irradiation not employing the improved ultrasonic system.

TABLE B-I

WHOLE PLATE DENSITIES OF XE2G, XE3G, AND XE4G (g/cm³)

Plate No.	Density	Plate No.	Density	Plate No.	Density
2G-1	2.97	4G-5	2.98	4G-13	2.98
2G-2	2.97	4G-6	2.97	4G-14	2.98
3G-1	2.98	4G-7	2.98	4G-15	2.99
3G-2	2.98	4G-8	2.96	4G-16	2.98
4G-1	2.97	4G-9	2.98	4G-17	2.97
4G-2	2.97	4G-10	2.99	4G-18	2.98
4G-3	2.97	4G-11	2.98	4G-19	2.97
4G-4	2.97	4G-12	2.98		

TABLE B-II

RADIOCHEMICAL ANALYSIS DATA FOR
XE2G AND XE4G

Section	Plate No.	Blister Initiation Temperature (°C)	Average Fission Density x 10 ⁻²⁰ fiss/cc	²³⁵ U Depletion Percent	Core Volume-cc (Less Foil Volume)
Mid	2-2	480	7.1	32.6	25.9
End	4-6	540	2.3	10.5	26.0
End	4-6	540	2.7	12.4	26.0
Mid	4-6	480	5.6	26.0	26.0
Mid	4-6	480	5.7	26.4	26.0
End	4-6	480	5.6	26.6	26.0
End	4-9	540	5.1	26.3	26.2
End	4-11	540	5.0	23.2	26.3
Mid	4-18	480	7.3	33.6	26.0
Mid	4-19	480	6.5	30.0	26.0

Fig. B-1 Pre-irradiation and post-irradiation end-to-end channel spacing measurements of channels 1, 2, and 3 from element XE4G. The horizontal lines on each side of the channel spacing plots indicate the tolerance bands.

Fig. B-2 Pre-irradiation and post-irradiation end-to-end channel spacing measurements of channels 16, 17, and 18 from element XE4G. The horizontal lines on each side of the channel spacing plots indicate the tolerance bands.

Fig. B-3 Comparison of total plate thickness before and after removal of the oxide coating and the maximum oxide coating on the "A" side of plates 1, 2, 3, and 4 from XE4G.

Fig. B-4 Comparison of total plate thickness before and after removal of the oxide coating and the maximum oxide coating on the "A" side of plates 16, 17, 18, and 19 from XE4G.

Fig. B-5 Temperature at which initial blistering occurred on samples removed from the middle sections of element XE4G compared with estimated maximum fission density.

Fig. B-6 Temperature at which first blistering occurred on samples removed from the end sections of element XE4G compared with estimated maximum fission density.

A. The arrow indicates area used for metallography sample. Blisters taper off toward lowest activity end of section.

50X

As-Polished

B. Cross section of blister above showing origin in foil area with blisters extending into the core-cladding interface.

Fig. B-7 Blister anneal results on the midsection of plate 19 (XE4G) following initial blistering at 480°C.

A. Arrow indicates blister area used for metallography. The blisters again taper off toward the low activity end of the section.

Fig. B-8 Blister anneal results on the midsection of plate 18 (XE4G) following initial blistering at 480°C.

A. The blisters are formed along the "picture frame" of the fuel plate due to flux peaking in this area.

50X

As-Polished

B. Cross section of the above blister showing that it is limited to the foil area.

Fig. B-9 Blister anneal results on the end section from plate 6 (XE4G) following initial blistering at 540°C.

A. Large blisters were seen in this section following annealing. Almost all of the blisters were formed in a 100°F (40°C) increment.

B. The cross section of the blister indicated above showed that the separation extended into the core-cladding interface from the foil area.

Fig. B-10 Blister anneal results on the end section of plate 11 (XE4G) at 590°C. The first blistering along the picture frame was seen after the 480°C anneal.

APPENDIX C
FIGURES DETAILING THE TESTING AND EXAMINATION
OF ELEMENTS XE23G, XE24G, AND XE45G

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Fig. C-1 Pre-irradiation and post-irradiation end-to-end channel spacing measurements of channels 1, 2, and 3 from element XE45G. The horizontal lines on each side of the channel spacing plots indicate the tolerance bands.

Fig. C-2 Pre-irradiation and post-irradiation end-to-end channel spacing measurements of channels 16, 17, and 18 from element XE45G. The horizontal lines on each side of the channel spacing plots indicate the tolerance bands.

ANC-B-172

Fig. C-3 Center line gamma activity and total plate thickness at the center line versus plate length for plate 1 from XE45G. The locations of metallographic samples, burnup punchings, and blister sections are also given.

ANC - B-175

Fig. C-4 Center line gamma activity and total plate thickness at the center line versus plate length for plate 7 from XE45G. The locations of metallographic samples, burnup punchings, and blister sections are also given.

ANC-B-176

Fig. C-5 Center line gamma activity and total plate thickness at the center line versus plate length for plate 1 from XE23G. The locations of metallographic samples, burnup punchings, and blister sections are also given.

Fig. C-6 Center line gamma activity and total plate thickness at the center line versus plate length for plate 1 from XE24G. The locations of metallographic samples, burnup punchings, and blister sections are also given.

ANC-B-173

A. Overall view of test section "B". The arrow indicates area used for metallography sample.

200X As-Polished
B. Photomicrograph showing cracks produced in B_4C -Al foil by blister testing.

Fig. C-7 Blister anneal results on plate 1 from element XE45G at 800°F.

A. Overall view of test section "B". The arrow indicates area used for metallography sample.

200X

As-Polished

B. Photomicrograph showing cracks produced in B_4C -Al foil by blister testing.

Fig. C-8 Blister anneal results on plate 7 from element XE45G at 800°F.

A. Overall view of test section "B". The arrow indicates area used for metallography sample.

200X

As-polished

B. Photomicrograph showing cracks propagated in B_4C -Al foil and extending in U-Al alloy core.

Fig. C-9 Blister anneal results on plate 1 from element XE24G at 800°F.

A. Overall view of test section "C". The arrow indicates area used for metallography sample.

200X

As-Polished

B. Photomicrograph of B₄C particle and cracks in foil produced by blister anneal.

Fig. C-10 Blister anneal results on plate 1 of element XE23G at 800°F.

Fig. C-11 Microstructure of foil in the as-irradiated condition. The sample was prepared from plate 7 of element XE45G at 800°F.

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APPENDIX D

STANDARD FABRICATION PROCEDURE FOR INC-16 B₄C-AL

FOIL ALLOY FUEL PLATES

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APPENDIX D

STANDARD FABRICATION PROCEDURE FOR INC-16 B₄C-AL FOIL ALLOY FUEL PLATES

1. FUEL CORE FABRICATION

1.1 UAl Alloy Cores

- (1) Gather together uranium, aluminum, and silicon core materials.
- (2) Melt aluminum and stir in silicon. Then add uranium. Freeze in crucible to allow outgassing to occur. Reheat and pour into mold.
- (3) Take density determination on a sample of UAl alloy to determine weight percent uranium.
- (4) Cut a 5 to 7 gram sample for chemical analysis.
- (5) Hot roll at 500°C to required thickness of 0.44 ± 0.001 inch.
- (6) Radiograph to determine homogeneity.
- (7) Punch cores from ingot. Each plate will have two fuel cores and one B₄C -- aluminum foil. The two fuel cores are to be punched from the ingot with the rolling direction of one running longitudinal and the other running transverse. Use the 0.500 x 1.875 inch size punch.
- (8) Weigh cores to the fourth significant figure and record weights.

1.2 B₄C and Aluminum Foils (for UAl Alloy Cores)

- (1) Gather together material
 - a. Aluminum powder
 - b. B₄C powder
- (2) Weigh precise quantities of each powder for a batch to make a compact 2 x 3 x 0.160 inch. Thickness tolerance is ± 0.025 inch.

NOTE: This will give enough foil for approximately 50 plates.
- (3) Blend powders for four hours.
- (4) Wipe compacting die and punches clean and apply a light coating of a saturated stearic acid and methanol solution (used as lubricant). Pour powders into compacting die and level powder.

- (5) Compact powder using a pressure of 150 tons on the rams. (This is equal to 25 tsi on the compact.) Hold pressure for five seconds. The compact size is 2.0 x 3.0 inch.
- (6) Gather together material for picture frame and cladding (1100 aluminum).
- (7) Roll to proper thickness and cut to size measuring 4 x 5 inch. Thickness of picture frame is to be 0.003 to 0.005 inch less than compact. Cladding thickness is to be 5 percent of compact thickness.
- (8) Clean picture frames and cladding by immersion in Oakite 160 solution, rinsing in water, pickling in 50 percent HNO_3 solution, rinsing in water, rinsing in methanol, and drying with hot air.
- (9) Assemble the compact into the picture frame and install cladding plates which are to be held in place by means of two rivets (occasionally electron beam welding).
- (10) Preheat the assembly for 3/4 hour at 500°C. Hot roll using two 10 percent reduction passes at the beginning and 20 percent reduction on successive passes and a five minute reheating time between each pass until the proper thickness of 0.010 inch is reached.
- (11) Blister anneal plates for one hour at 525°C. Halfway through the anneal, the plates are to be rotated end for end in the furnace. Allow to cool. Inspect plates for blisters.
- (12) Cut picture frame from the rolled out compact (foil).
- (13) Ultrasonically scan the foil.
- (14) Have foil neutron radiographed, if possible.
- (15) Punch foils from compact. This foil is to be placed between the two UAl alloy cores when assembled for rolling. Use the 0.500 x 1.875 inch size punch.
- (16) Weigh foils to the fourth significant figure and record weights.

2. SAMPLE FUEL PLATE FABRICATION

- (1) Gather together material for picture frame and cladding.
- (2) Roll to proper thickness and cut to size measuring 5 x 6 inch.
- (3) Clean picture frames and cladding by immersion in Oakite 160 solution, rinsing in water, pickling in 50 percent HNO_3 solution, rinsing in water, rinsing in methanol, and drying with hot air.
- (4) Assemble the core compacts into the picture frames by inserting a B_4C foil between two UAl alloy cores. The UAl alloy cores are to be assembled so that the rolling directions of the ingots are 90 degrees of each other (perpendicular to each other). Place cladding material on each side of picture frame and cores. Plates are to be held in place by means of two rivets (occasionally electron beam welding).
- (5) Preheat the assembly for 3/4 hour at 500°C. Hot roll using two 10 percent reduction passes at the beginning and 20 percent reduction on successive passes and a five minute reheating time between each pass until a thickness of 0.059 ± 0.002 inch is reached. During rolling, the plates are to be rotated end for end and turned over from side to side as to allow the plates to be rolled from every conceivable direction.
- (6) Blister anneal plates for one hour at 500°C. Halfway through the anneal, the plates are to be rotated end for end in the furnace. Allow to cool. Inspect plates for blisters.
- (7) Cover both sides of plates with masking tape and roll level. Radiograph plates to determine core length. Mark plates to indicate ends of cores.
- (8) Section the plates by shearing between four plates. Mark the four pieces thus produced so as to maintain the identity of the cores.
- (9) Cold roll plates until cores are 2.44 ± 0.03 inch long.
- (10) Cover both sides of plates with masking tape and roll level.
- (11) Radiograph plates to locate cores.

- (12) Shear plates to final dimensions of $2.312 \pm 0.005 \times 2.875 \pm 0.005$ inch. Save the scraps for tensile specimens and hardness tests.
- (13) Remove masking tape and place identifying numbers on plates.
- (14) Clean fuel plates using procedures given in item 3 above.
- (15) Determine Rockwell superficial hardness on the 15-T scale on the scraps from the plates.
- (16) Weigh plates, determine density, and give to metallographic laboratory personnel for pre-irradiation inspection.