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OAK RIDGE NATIONAL LABORATORY
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I. SUMMARY

Under the Atoms-For-Peace Plan, the specification that uranium be limited to 20% enrichment in the U-235 isotope has necessitated development of a highly-concentrated uranium-aluminum alloy as the fuel material in the composite aluminum plates of research reactor fuel elements. Efforts have been directed to determining the suitability of a nominal 48 wt % U-Al alloy in relation to previously established procedures for manufacturing plate-type aluminum fuel elements.

Increasing the uranium concentration from 18 wt % to the 48 wt % resulted in increased segregation, higher strength, and loss of ductility, creating additional fabrication difficulties. Non-uniform deformation of the alloy during roll bonding into composite plates caused localized thinning of the cladding, which may limit the material to specific reactor applications. Substitution of Type 6061 aluminum for Type 1100 aluminum as frame and cladding of the fuel plates improves this condition.

A fuel element, containing the 48 wt % U-Al alloy, was irradiated in the active lattice of the MTR to an estimated burnup of 25% of the U-235 atoms with no observable damage.

II. INTRODUCTION

For the past eight years, plate-type aluminum research reactor fuel elements, containing uranium in the form of an aluminum-uranium alloy of 13 wt % to 18 wt % U, have been readily manufactured and have operated successfully in several reactors. However, under the recent Atoms for Peace Plan, the stipulation that the uranium be limited to a maximum enrichment of 20% in the U-235 isotope has presented a condition in which more than 400% additional uranium must be incorporated in this type of fuel element. Calculations indicate that in the majority of cases, the concentration of uranium in the aluminum-uranium alloy will increase to more than 40 wt % U. Specifically, an 18-plate element, containing 60-mil thick composite fuel plates, requires a 48 wt % U-Al alloy to achieve a fuel-element loading of

190 g of U-235. This report presents the results of investigations conducted to determine the effect of this high concentration of uranium in aluminum on conventional induction melting and casting procedures; cladding techniques for roll bonding into composite fuel plates; methods of joining plates into an assembly by brazing; and the performance of a test element under irradiation in the MTR. The general approach to the problem was to adhere as nearly as possible to methods previously established at ORNL[1] for manufacturing plate-type research reactor fuel elements.

III. CONCLUSIONS

1. A nominal 48 wt % U-Al alloy exhibits random uranium segregation with a spread of approximately 4 wt %. Since the uranium is limited in U-235 enrichment to 20%, the homogeneity of this isotope in the alloy is acceptable.
2. The high percentage of intermetallic compound in the alloy results in a material of high strength but little ductility.
3. The alloy casting cannot be rolled bare without excessive edge cracking and must be framed in aluminum prior to breakdown into plate.
4. During roll-bonding into composite plates, the alloy core exhibits non-uniform deformation at its ends, which causes localized thinning of the plate cladding. This condition is improved by substitution of Al-clad Type 6061 aluminum for Type 1100 aluminum as the plate frame and clad material.
5. Because of the localized thin cladding, the protection offered by the cladding must be evaluated for the specific reactor application.
6. An 18-plate fuel element, containing 190 g of U-235 incorporated in a nominal 48 wt % U-Al alloy was irradiated in the active lattice of the MTR in a flux of 1.9×10^{14} n/cm^2/sec for 4.5×10^{20} nvt, which is estimated to be a burnup of 25% of the U-235 atoms. No significant irradiation damage was observed.

IV. DISCUSSION

A. Fuel Element and Design

An 18-plate element, consisting of 60-mil thick plates, was selected because it represented a design frequently used in research reactors.

However, the volume occupied by the fuel-bearing alloy core was increased from 20 to 28 mils to minimize the uranium concentration required in the fuel alloy, and maximize the number of grams of U-235 in the fuel element. Calculations revealed that a 48 wt % U-Al alloy was required for a fuel element of this design containing 190 g of U-235 with an enrichment of 20%. Critical design parameters of the fuel element are listed in Table I.

Type 6061 aluminum was selected as the frame and clad material for the composite fuel plate instead of the more conventional Type 1100 aluminum. This modification was based upon past experience with other materials, which indicated that whenever a core material with an appreciably higher yield strength than the frame and cladding material is rolled into a composite fuel plate, severe deformation frequently occurs at the ends of the fuel core, resulting in serious thinning of the cladding material in localized areas.[2] As listed in Table II, the yield strength at 540°C of a 43 wt % U-Al alloy is approximately 41% greater than that of the type 1100 aluminum and severe "end effects" may be predicted. Although no aluminum frame and cladding alloys were found which matched the yield strength of the highly concentrated U-Al alloy, the type 6061 aluminum appeared to be the best available. However, the yield strength of the fuel alloy was still 20% greater than this cladding material. It was anticipated that the "end effects" could be minimized but not optimized.

B. Melting and Casting

An important consideration in aluminum fuel element technology is the homogeneity and soundness of the fuel alloy. Although data are available on the homogeneity of aluminum-uranium alloys in the range of 13 to 18 wt % uranium,[3] it was necessary to experimentally determine the effect of higher concentrations of uranium on segregation patterns, and porosity defects in an uranium-aluminum alloy with a nominal 48 wt % U-Al composition. It will be noted in examining the aluminum-uranium phase diagram[4] illustrated in Fig. 1 (Y-20808), that the difference between the liquidus and solidus of the 48 wt % U-Al alloy is approximately 560°C compared to a difference of merely 110°C for an 18 wt % U-Al alloy. Also, during solidification, the composition of the liquid of the 48 wt % alloy decreases to 13 wt % U, a difference of 35 wt %. In the 18 wt % U-Al alloy, the change of the liquid composition during solidification is only 5 wt % U. Based on

TABLE I

DESIGN DATA ON ASSEMBLY CONTAINING 48 WT % ALLOY
FOR IRRADIATION TESTING IN MTR

Number of fuel plates per element	18
Nominal water gap spacing, inches	0.117
Width and length of active portion of plate, inches	2.5 x 23-5/8
Overall width and length of fuel plates, inches (2)	2.8 x 28-5/8
(16)	2.8 x 24-5/8
Total thickness of fuel plates, inches	0.060
Core thickness of fuel plates, inches	0.028
Nominal core composition, wt %	Uranium -48
	Aluminum -52
Nominal U-235 enrichment, %	20.00
U-235 content per plate, grams	10.56
U-235 content per assembly, grams	190
U-235 fuel distribution, grams/cm^2	0.027
Type of MTR assembly	Mark X (Modified)
Side plates - ORNL DWG. D-22055 Overall dimensions, inches	3.169 x 0.188 x 28-5/8

TABLE II

YIELD STRENGTHS OF ALUMINUM ALLOYS AT 540°C

Alloy	Number of Specimens	Yield Strength ** (0.2% offset) PSI
6951*	2	1040
5050*	2	1080
6061*	2	1240
1100*	2	900
42.7 wt % U-Al	1	1500
43.7 wt % U-Al	1	1560

* Aluminum Association Designation

** Speed of Test - 0.05 in/min

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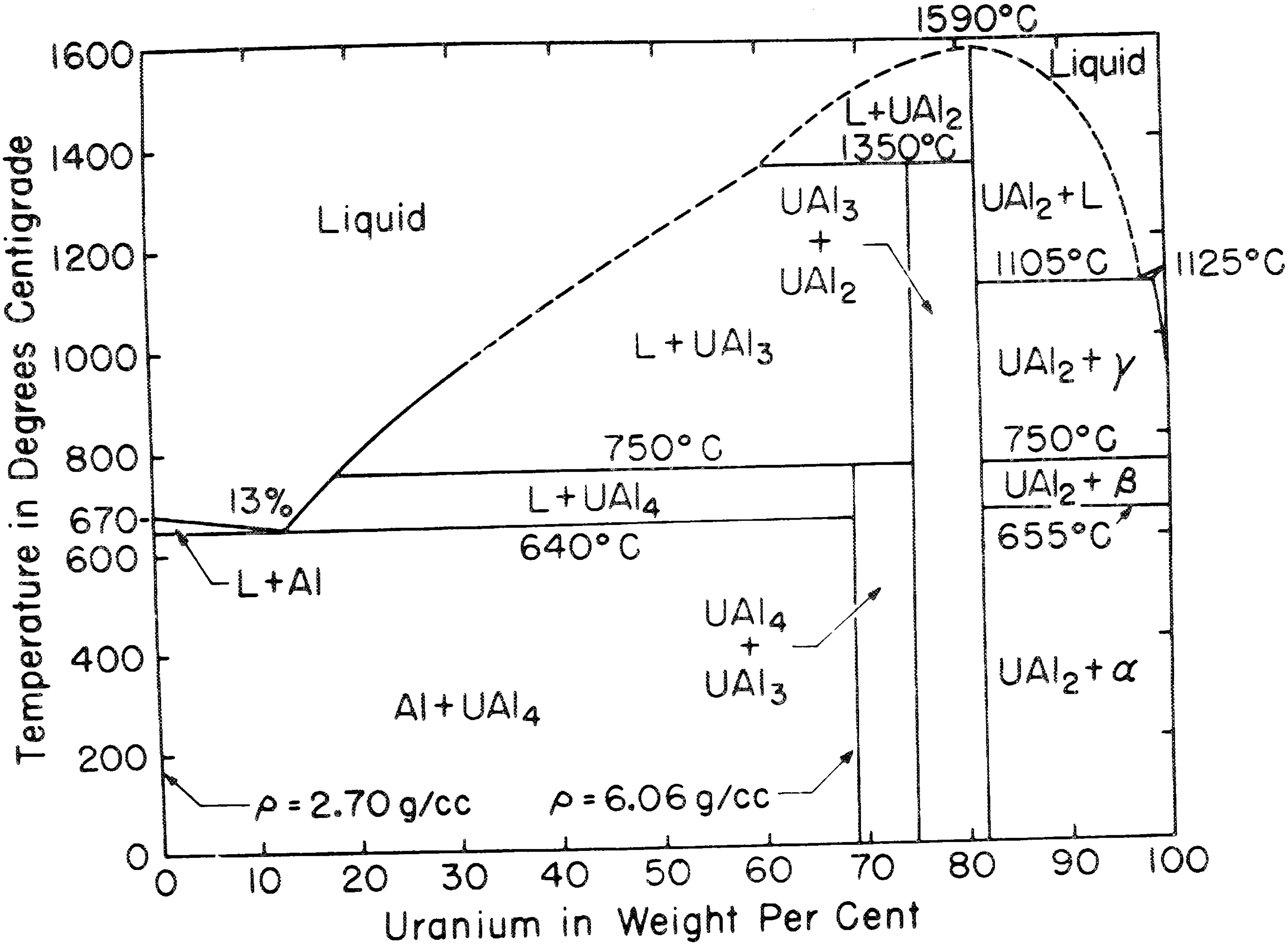

Fig. 1. Aluminum-Uranium Phase Diagram.

these facts, it would be expected that a 48 wt % U-Al alloy would be more prone to segregation than an 18 wt % U-Al alloy under similar melting practices.

The soundness of the casting is closely related to entrapment of gas during solidification under non-equilibrium conditions. Assuming that a major contributor of this gas is the hydrogen in the uranium melting stock, then considerable porosity might be expected in the 48 wt % U-Al alloys because of the large mass of uranium required in the charge. To minimize this problem, the uranium melting stock used in this investigation was vacuum re-melted from biscuit material.

Since the more conventional and widely used 13 to 18 wt % U-Al alloys are air-induction melted in graphite crucibles and poured in graphite molds, it was decided to follow this practice as closely as possible in melting and casting the 48 wt % U-Al alloy. The graphite crucible was large enough to contain a charge of 4500 grams. The cavity of the slab-type graphite mold was 10-in. long x 5 1/4-in. wide x 1-in. thick, with a trapezoidal head for feeding. The mold walls were 1-in. thick. The mold was preheated to 200–350°C.

The procedure followed in melting the alloy is listed below:

1. Charge 2340 g of aluminum pig (99.99% Al).
2. Melt and superheat to 900°C.
3. Add chunk uranium obtained by shearing vacuum cast slabs.
4. Increase melt temperature to 1175°C.
5. Hold melt at 1175°C until uranium has been completely dissolved as determined by graphite probe.
6. Pour in preheated graphite mold.

Location of samples and results of analytical chemistry for a casting prepared using the above procedure are shown in Fig. 2 (ORNL-LR-DWG 24044). It is apparent that up to and slightly above the cropping line, results vary randomly from 44.10 to 49.90 wt % U, a spread of 5.80 wt %. However, further into the head, a sharp increase in uranium concentration is observed. Scalping of the slab revealed considerable subsurface porosity, as illustrated in Fig. 3 (Y-19950). Such castings cracked into pieces during subsequent hot breakdown into plate. A probable explanation for this porosity is that the

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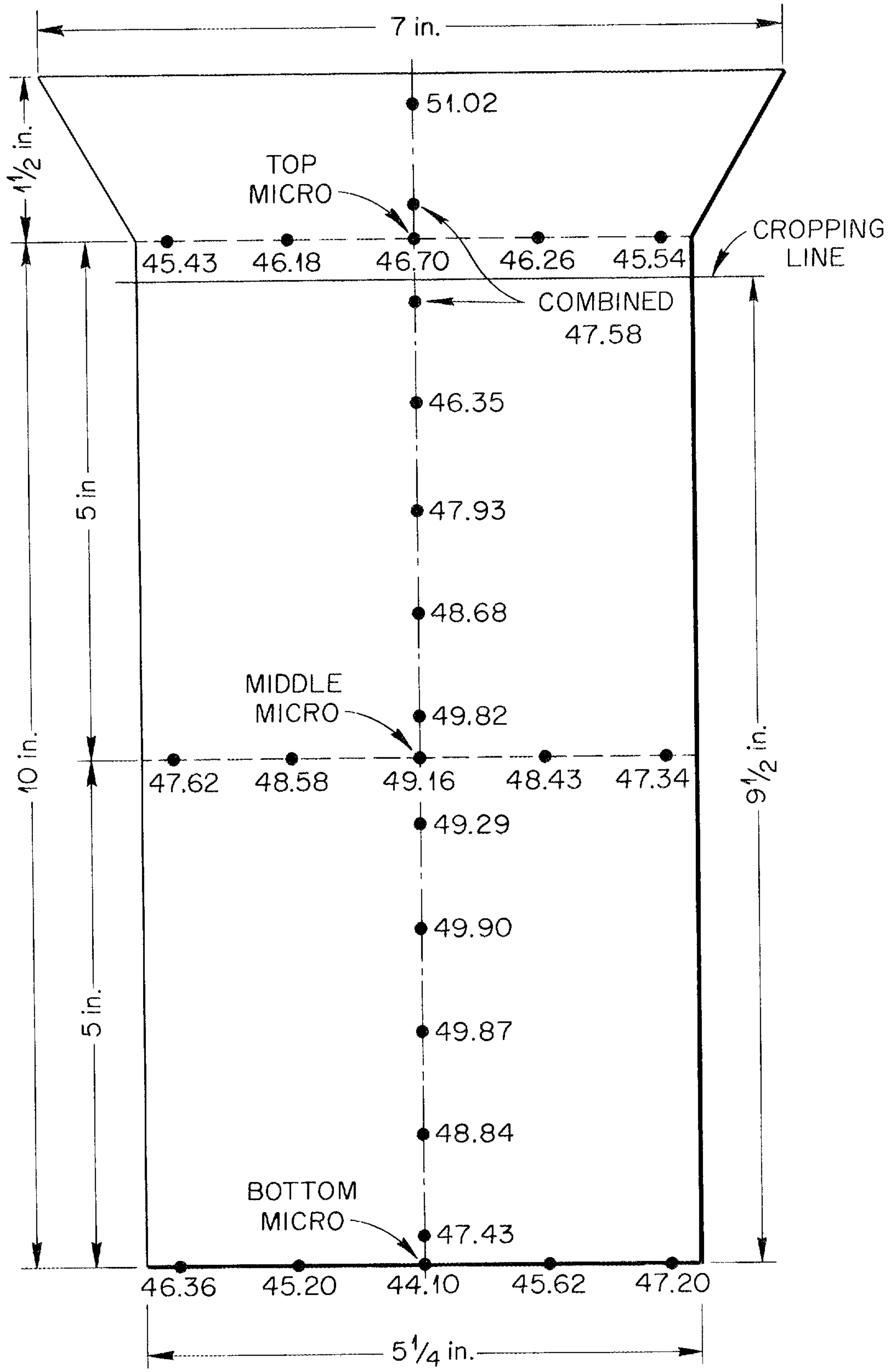

Fig. 2. Uranium Distribution in a 48 wt % U–Al Alloy Billet After One Melting Cycle.

Fig. 3. Scalped 48 wt % U-Al Casting After One Melting Cycle.

alloy melt at the time of pouring is supersaturated with hydrogen, and that during solidification the hydrogen is evolved and trapped within the solidifying alloy as gas pockets. It was felt that this condition could be minimized, or possibly eliminated, by approaching equilibrium of hydrogen in the alloy at the solidus temperature. Indications from previous work suggested that remelting might prove helpful. An experiment was conducted in which the melt was permitted to solidify in the crucible, reheated to 1175°C, and again allowed to solidify in the crucible. After each cycle, less effervescence was observed in the top of the melt as it solidified in the crucible. After the fourth cycle no appreciable effervescence could be seen, and the casting was poured at the end of the fifth cycle. Scalping of the slab revealed a marked improvement in soundness as illustrated in Fig. 4 (Y-19974). Additional melts were made, and it was observed that the same melts showed insignificant effervescence after three and on occasion, only two remelts. However, a specification was established to remelt a minimum of four times, with close observation of the degree of effervescence during this treatment, and if necessary, repeat the cycles.

The repeated melt technique did not significantly alter the segregation pattern. As shown in Fig. 5 (ORNL-LR-DWG. 24043), the random segregation varied from 45.61 wt % U to 50.60 wt % U, a spread of 3.99 wt %.

The data shown in Figs. 2 and 5 indicate that the uranium in this alloy exhibited a marked tendency to segregate in the head of the casting. This condition resulted in a decrease in the uranium concentration of the usable material in the body of the casting. Examination of the material in the head revealed considerable porosity. The high-uranium content in this region was caused by depletion of the eutectic constitutents in this region by downward flow of eutectic liquid through the interdendritic network during the final stages of solidification.

Figure 6 (Y-20317, Y-20316, Y-20752) illustrates the microstructures of material removed from the top, middle, and bottom of the remelted casting shown in Fig. 4, at the locations designated in Fig. 5. The structure of the eutectic and the primary UAl_4 intermetallic compound is markedly different in the respective locations. A lamellar eutectic exists at the bottom of the casting, while a more divorced structure occurs at the top. On the basis of x-ray diffraction results, the percentages of inter-

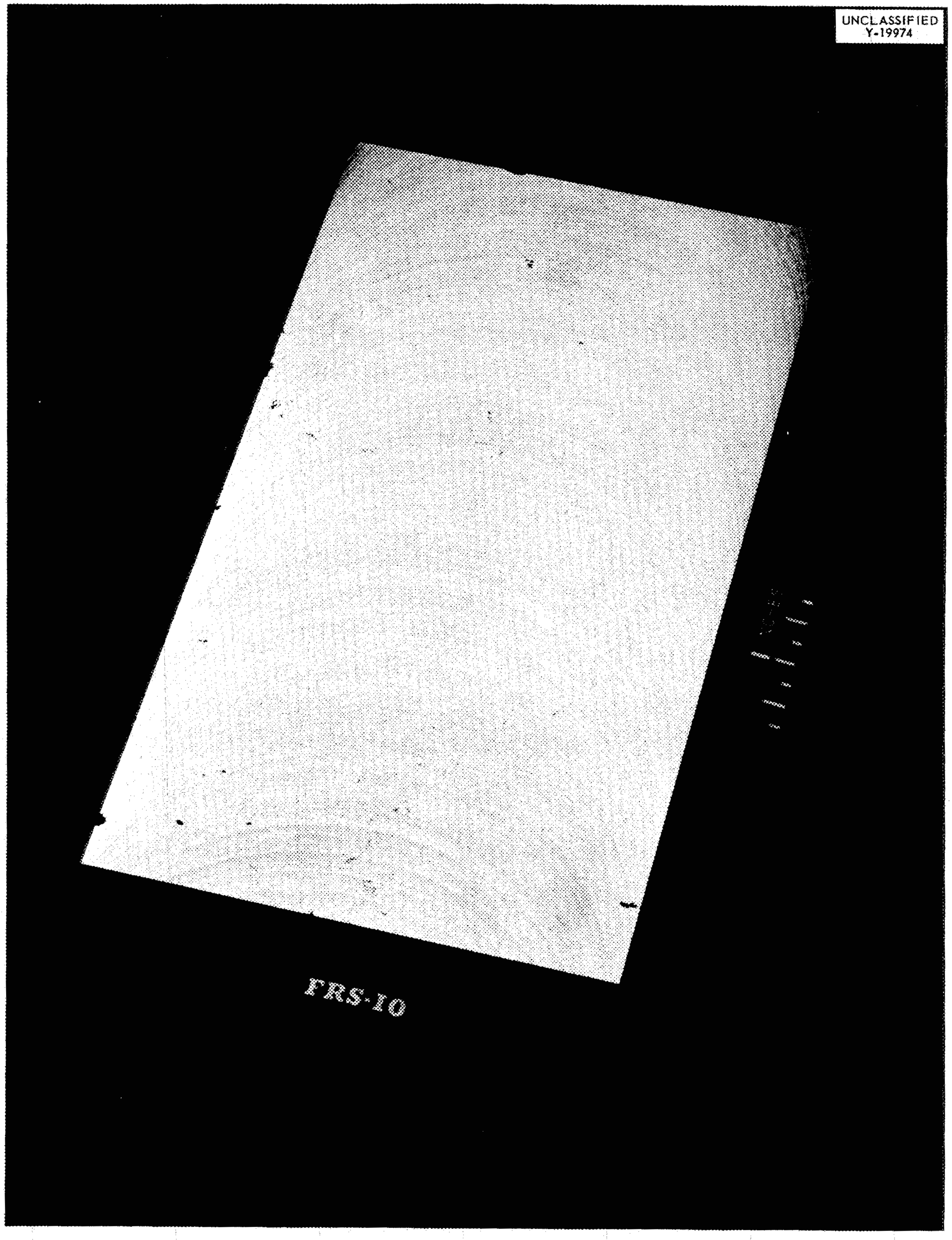

Fig. 4. Scalped 48 wt % U-Al Alloy Casting After Five Repeated Remelts.

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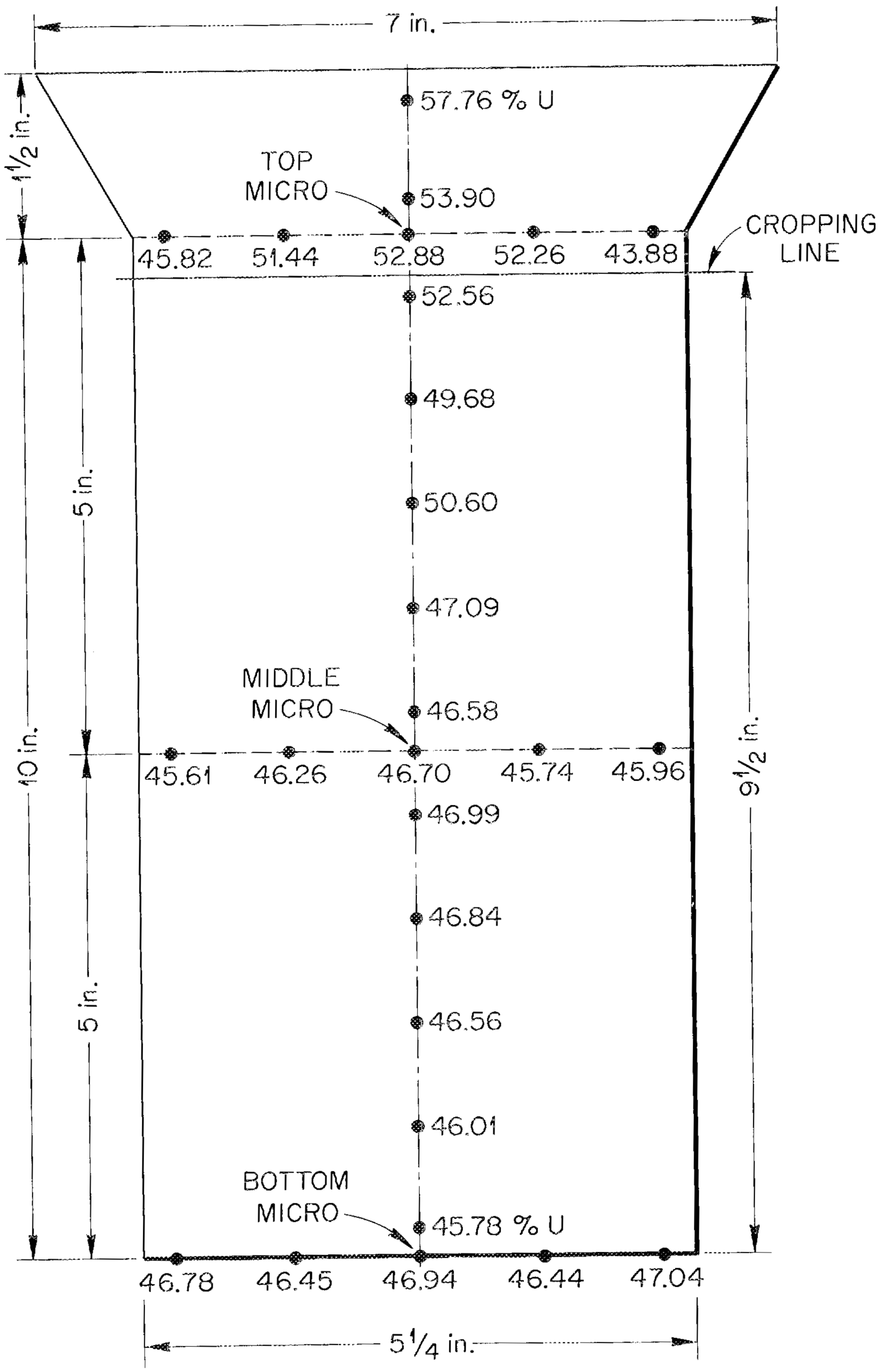

Fig. 5. Uranium Distribution in a Cast 48 wt % U–Al Alloy Billet After Five Repeated Remelts.

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Fig. 6. Microstructure of Samples Removed from Top, Middle, and Bottom of Cast 48 wt % U-Al Alloy Billet. Electrolytic polish - etch ($HClO_4$ + C_2H_5OH). 500 X.

metallic compounds and aluminum present in the samples are estimated below:

	Top	Middle	Bottom
UAl_4	55%	50%	60%
UAl_3	none	none	none
Al	45%	50%	40%

Twelve slabs of nominal 48 wt % U-Al alloy were prepared for the test elements, using the remelt technique described, and rolled into plate approximately 40-in. in length. Generally, 10 cores were punched from each plate and samples for uranium analyses sheared from the alloy skeleton at locations adjacent to two successive fuel cores. The analytical data are listed in Table III.

The results are quite scattered. Several castings exhibited homogeneity of the uranium which was nearly equivalent to 17 wt % U-Al alloys; other castings showed considerable segregation. In the majority of cases, the degree of segregation of the uranium would not materially effect accurate prediction of the mass of U-235 in the fuel element, since the uranium contains only 20% of the U-235 isotope. It is important that the U-235 content in any one fuel core does not exceed the limit established by heat-transfer considerations. Therefore, the portion of the casting (generally the extreme top), which is so highly concentrated in uranium that the U-235 content is in excess of the established tolerance, must be rejected and recycled.

The effect of segregation in predicting the U-235 content in a fuel element was analyzed and the results presented in Table IV. Two cases were considered for comparative purposes. In the first case, a highly segregated casting was selected; in the second case, a very homogeneous casting was chosen. In each case the U-235 content was predicted using two methods of calculation. In the first method, six analytical results were used to calculate the U-235 content of each core, and the total weight of U-235 in the ten cores obtained. In the second method, the average analysis, based on only three samples, was used to calculate the U-235 content of each core, and the total weight of U-235 in the ten cores obtained. It will be observed that in Case No. 1, in which the alloy was quite badly segregated, the simple sampling procedure yielded results which were within one per cent

TABLE III

ANALYTICAL URANIUM ANALYSES OF HOT ROLLED ALLOY PLATES

Sample Location	Casting Number											
	1 Wt % U	2 Wt % U	3 Wt % U	4 Wt % U	5 Wt % U	6 Wt % U	7 Wt % U	8 Wt % U	9 Wt % U	10 Wt % U	11 Wt % U	12 Wt % U
A	46.95	47.46	43.78	46.98	46.73	44.10	45.11	45.52	46.44	44.49	43.07	45.02
B	47.46	47.22	46.48	46.16	47.05	46.84	46.69	45.56	46.19	44.56	44.84	45.67
C	47.10	47.64	45.74	46.04	47.07	48.20	47.40	45.68	46.26	45.11	48.75	46.80
D	46.54	47.28	47.90	45.84	47.36	49.87	47.19	45.69	46.00	45.37	49.46	47.78
E	46.44	46.39	46.54	45.64	47.20	50.80	46.98	45.65	45.63	45.01	50.29	48.80
F	-------	-------	43.74	-------	45.88	50.10	46.90	45.11	45.42	45.03	50.86	49.80
Average Analysis Based on 100% Casting-to-Slab Yield*	-------	-------	45.70	-------	46.88	48.32	46.71	45.53	45.99	44.93	47.88	47.31
Deviation from Mean (+)	-------	-------	+2.20	-------	+0.48	+2.58	+0.69	+0.16	+0.45	+0.44	+2.98	+2.49
Deviation from Mean (–)	-------	-------	–1.96	-------	–1.00	–4.22	–1.60	–0.42	–0.57	–0.44	–4.81	–2.29
Average Analysis Based on 85% Casting-to-Slab Yield*	46.90	47.20	46.09	46.13	47.08	47.96	46.67	45.62	46.10	44.91	47.28	46.81
Deviation (+)	+0.56	+0.44	+1.81	+0.85	+0.28	+2.84	+0.73	+0.07	+0.34	+0.46	+3.58	+1.99
Deviation (–)	–0.46	–0.81	–2.31	–0.49	–0.35	–3.86	–1.56	–0.10	–0.47	–0.42	–4.21	–1.79

*This yield is for the cropped casting which is 77% of the charged metal.

TABLE IV

EFFECT OF SEGREGATION IN PREDICTING U-235 CONTENT OF PLATE-TYPE ALUMINUM FUEL ELEMENTS
CONTAINING U-AL ALLOYS IN THE 44 TO 48 WT % U RANGE

Uranium Analysis	Actual A	Calculated Core No. 1	Calculated (A + B)/2	Calculated Core No. 2	Actual B	Calculated Core No. 3	Calculated (B + C)/2	Calculated Core No. 4	Actual C	Calculated Core No. 5	Calculated (C + D)/2	Calculated Core No. 6	Actual D	Calculated Core No. 7	Calculated (D + E)/2	Calculated Core No. 8	Actual E	Calculated Core No. 9	Calculated (E + F)/2	Calculated Core No. 10	Actual F	Ave.	Total gms U-235
Case No. 1-A																							
Wt % U(1)	43.07	43.51	43.95	44.39	44.84	45.82	46.80	47.78	48.75	48.93	49.11	49.29	49.46	49.66	49.87	50.08	50.29	50.43	50.57	50.71	50.86	47.88	-------
gms U-235	-------	9.44	-------	9.63	-------	9.94	-------	10.37	-------	10.62	-------	10.70	-------	10.76	-------	10.87	-------	10.94	-------	11.00	-------	-------	104.27
Case No. 1-B																							
Wt % U	43.07	-------	-------	-------	-------	-------	-------	-------	48.75	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	50.86	47.56	-------
gms U-235	-------	10.32	-------	10.32	-------	10.32	-------	10.32	-------	10.32	-------	10.32	-------	10.32	-------	10.32	-------	10.32	-------	10.32	-------	-------	103.20
Case No. 2-A																							
Wt % U(2)	46.44	46.38	46.32	46.25	46.19	46.21	46.23	46.24	46.26	46.20	46.13	46.06	46.00	45.92	45.84	45.76	45.67	45.61	45.54	45.49	45.42	45.99	-------
gms U-235	-------	10.06	-------	10.04	-------	10.03	-------	10.03	-------	10.03	-------	10.00	-------	9.96	-------	9.93	-------	9.90	-------	9.87	-------	-------	99.85
Case No. 2-B																							
Wt % U	46.44	-------	-------	-------	-------	-------	-------	-------	46.26	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	45.42	46.00	-------
gms U-235	-------	9.98	-------	9.98	-------	9.98	-------	9.98	-------	9.98	-------	9.98	-------	9.98	-------	9.98	-------	9.98	-------	9.98	-------	-------	99.80

(1) Data of Casting No. 11, Table III.
(2) Data of Casting No. 9, Table III.

of the value obtained by the more precise method. In Case No. 2, simple sampling of a homogeneous alloy permitted a prediction within 0.05% of the established value, obtained by extensive sampling.

C. Breakdown of Alloy Casting Into Plate

All castings were preheated for three hours at 600°C and rolled to plate on a 20-in. x 30-in. two-high mill with a ten-minute reheat between passes. Rolling of the first few castings was unsuccessful because of severe edge cracking. This condition was greatly minimized by inserting the cropped and scalped casting in an aluminum frame and enclosing by tack welding 0.024-in. thick sheets of Type 1100 aluminum to both sides of the frame. Type 1100 aluminum was initially selected as the frame material. Because of its lower yield strength, the type 1100 aluminum separated from the U-Al alloy during rolling. Substitution of 6061 aluminum appeared to cause too much constraint, as evidenced by transverse cracking of the U-Al alloy during the final stages of rolling. This condition was minimized by removing the core from the frame prior to the last mill pass. The inconvenience of removing the frame during rolling may be eliminated with the selection of an aluminum alloy with a 600°C yield strength intermediate between Types 1100 and 6061 aluminum.

Framing of the cast slab did not eliminate edge cracking. In an effort to improve this condition, several hot-rolling reduction schedules were investigated, and the one listed below was ultimately selected.

Pass No.	Mill Setting % Reduction Per Pass
1	10
2	10
3	10
4	20
5	30
6	30
7	15

Edge cracks, penetrating as much as one inch into the alloy, were common with this practice. As a result of this condition, the casting-to-fuel core yield was only 32% compared to a casting-to-fuel core yield of

72% for alloys in the 13 to 18 wt % U range. Further work is required to improve this yield.

The total reduction in reducing the thickness from 1.048-in. to 0.255-in. was 76%. The ten fuel cores punched from the composite alloy plate were calculated to have a clad-core-clad thickness of 0.006 - 0.243 - 0.006-in. and a uranium content based on the average analyses of the alloy.

D. Fabrication of Composite Fuel Plates

Three factors must be considered in roll bonding composite aluminum fuel plates containing uranium-aluminum alloys:

1. Complete metallurgical bonding between mating surfaces
2. Satisfactory fit between core and frame during rolling.
3. Uniform deformation of the fuel alloy and the aluminum cladding.

Conditions for obtaining metallurgical bonding have been well established in the past for roll bonding 13 to 18 wt % U-Al alloys into composite Type 1100 aluminum clad plates;[1] i. e., preheat temperature of 595°C, total reduction in thickness of 84%, and reduction per pass of 35%.

The second factor is related to matching the yield strengths, at the hot-rolling temperature, of the materials selected for the core and frame of the composite billet. It is an important consideration because the billets are rolled in air, and if the fit is not proper, air becomes entrapped in the composite, resulting in blisters during subsequent heat treating.

The third factor also appears to be a function of the yield strengths, at the hot-rolling temperature, of the core, frame, and clad materials. In the event of a wide spread in yield strengths between these components, serious "end effects" are likely to occur. In the case of a rather brittle and high-strength alloy, such as the 48 wt % U-Al alloy, and a ductile low-strength Type 1100 aluminum, it may be predicted that severe deformation will occur at the ends of the fuel cores which often appears as a "dog bone" shape. This condition causes localized thinning of the clad and may result in actual rupture of the clad. Of the aluminum alloys tested during this work, the one which had a yield strength at 540°C that most nearly matched the yield strength of the highly concentrated U-Al alloy was Type 6061 aluminum. As shown previously in Table II, the 1240 psi yield strength was still 20% less than the apparent 1560 psi yield strength of the fuel alloy. Roll-bonding investigations were conducted using this material as the aluminum cladding and, although it was not felt that its use would completely eliminate the "end effects", it was considered superior to Type 1100 aluminum in this respect.

The results of the roll-bonding investigations are listed in Table V. Analyses of the "end effect" was based on metallographic measurements of two samples from each of five plates, and the average, maximum, and minimum cladding thickness determined. Since the "dog bone" shape varies from one plate to another under identical fabrication conditions, probabilities must be considered. Although the minimum value is considered extremely important, the average value shows significant trends.

The first experiment indicated that the 48 wt % U-Al alloy and Type 1100 aluminum combination was not satisfactory. As illustrated in Fig. 7 (Y-19090), fracture of cladding was observed, and the average value of 2.5 mils indicated a high probability of clad failures. Although the data are limited, they provide support to the theory proposed previously. The remainder of the investigation was confined to the application of Type 6061 material as the frame and cladding material.

As shown in Fig. 8 (Y-21068), experiment No. 2 resulted in a marked improvement, and in fact, the 8.4-mil average and 3-mil minimum represent the best results obtained in the investigation. However, during brazing, 25% of the plates blistered, and it was felt that bonding was not satisfactory because of the decrease in total reduction.

Type 1100 aluminum was added to the surfaces of the Type 6061 on the assumption that bonding would be improved if it was confined to Type 1100 aluminum mating surfaces. Both sides of the Type 6061 frame material were clad with Type 1100, and one side of the Type 6061 cover-plate material with Type 1100 by roll bonding prior to assembling into composite fuel billets. The 6061 material in experiments Nos. 3 through 5 were clad with 8% Type 1100. Little improvement of the "end effect" occurred, and the 22% blister rejections during brazing indicated that the total reduction ratio of 80% was not sufficient to achieve satisfactory bonding. The thickness of 1100 on 6061 was reduced to two per cent to gain more of the higher strength material. The results shown in experiment No. 6 reveal a noticeable

TABLE V

SUMMARY OF FABRICATION DATA USING 6061 AND ALCLAD 6061 CLADDING AND FRAME MATERIAL IN MANUFACTURING COMPOSITE FUEL PLATES CONTAINING 48 WT % U-AL ALLOY WITH A NOMINAL CLAD-CORE-CLAD THICKNESS OF 17-26-17 MILS

Experiment	No. of Plates	Type Aluminum Cladding Material	Type Aluminum Frame Material	% Total Hot Reduction	% Reduction Per Pass	Hot Rolling Temp. °C	Localized Cladding Thickness (mils) Above Core End			Blister Rejections	
							Min[a]	Max[b]	Ave[c]	Prior to Brazing	After Brazing
1*	5	1100	1100	84	50	600	0	6	2.5	------	------
2	8	6061	6061	76	50	575	3	13	8.4	none	25%
3	18	Alclad 6061 8% Alclad	Alclad 6061 8% Alclad	84	45	575	0	8	4.4	------	none
4	8	Alclad 6061 8% Alclad	Alclad 6061 8% Alclad	80	40	535	0	9	4.5	------	------
5	12	Alclad 6061 8% Alclad	Alclad 6061 8% Alclad	80	40	600	0	7	3.8	------	22%
6	30	Alclad 6061 2% Alclad	Alclad 6061 2% Alclad	80	35	535	3	9	6.9	21%	33%
7	36	Alclad 6061 2% Alclad	Alclad 6061 2% Alclad	84	35	535	-	---	----	25%	33%
8	50	Alclad 6061 4% Alclad	Alclad 6061 4% Alclad	84	35	535	0 3	8 8	5.7 6.0[d]	none	none

*Listed for Comparative Purposes

(a) Represents the minimum value observed of approximately 20 measurements from 5 plates
(b) Represents the maximum value observed of approximately 20 measurements from 5 plates
(c) Represents the average value observed of approximately 20 measurements from 5 plates
(d) Represents the average value observed of approximately 6 measurements from 1 plate

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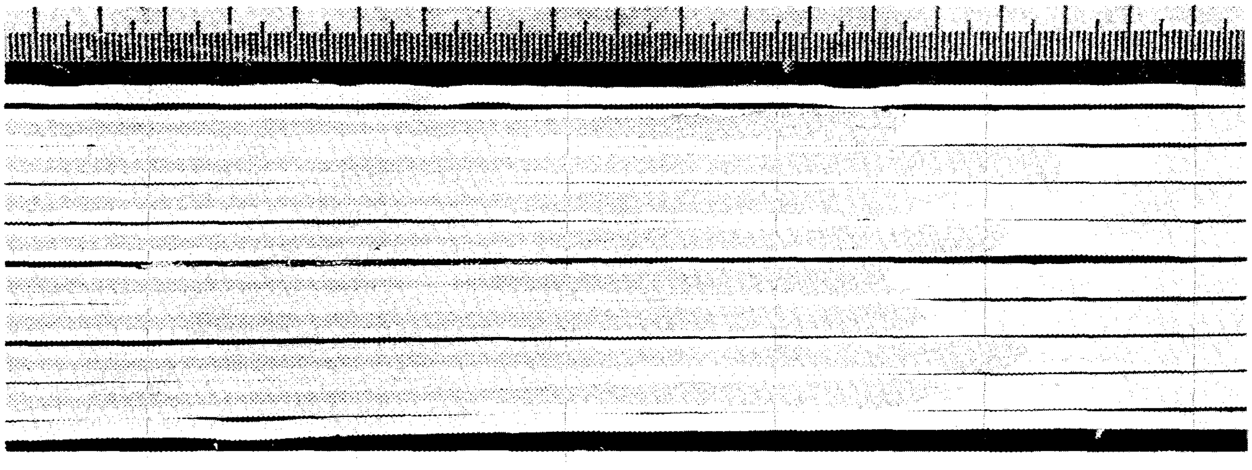

Fig. 7. Specimen 12588. As Polished. Longitudinal Sections of Composite Plates Containing 48 wt % U-Al Alloy Framed and Clad with Type 1100 Aluminum. Note the clad failure in top plate and the severe deformation of the alloy resulting in pronounced variations in the fuel core thickness. 3 X.

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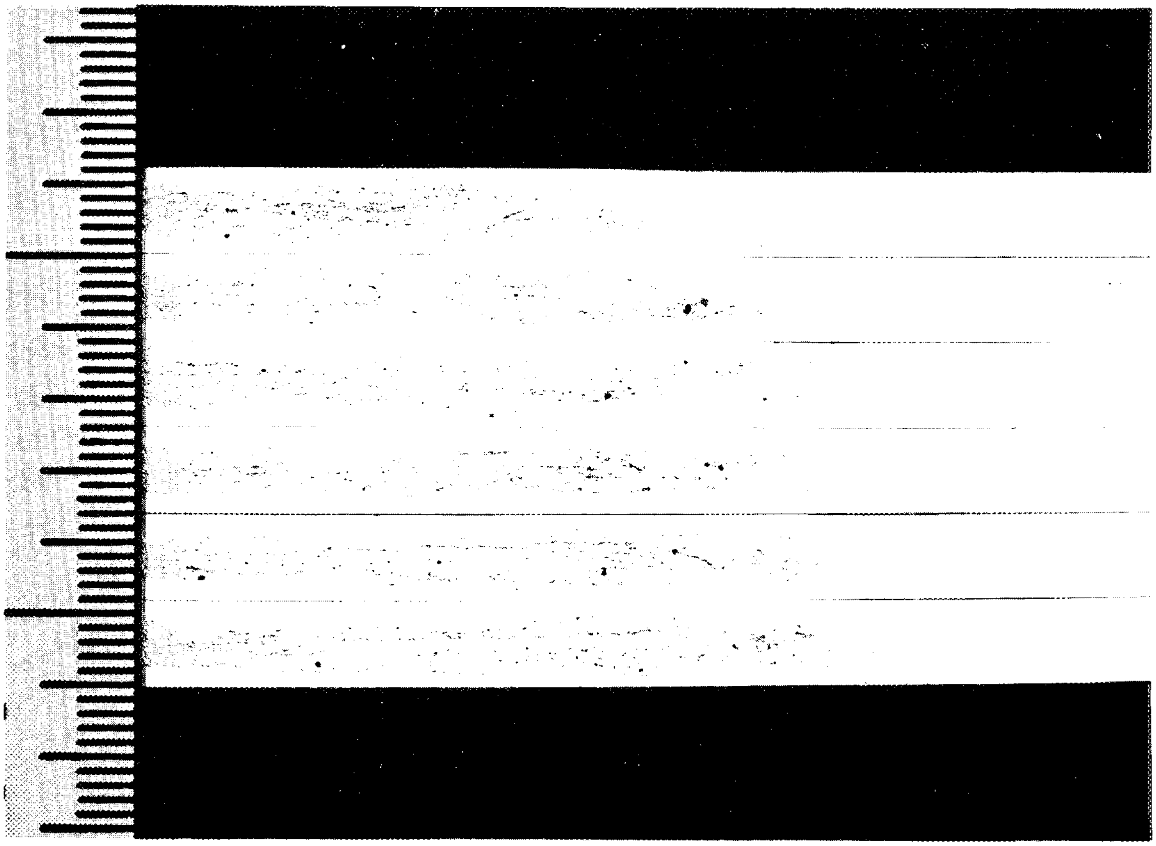

Fig. 8. Specimen 14584. As Polished. Longitudinal Sections of Composite Plates Containing 46 wt % U-Al Alloy Framed and Clad with Type 6061 Aluminum. Note improvement of localized cladding above "dogbone" effect. Reductions in thickness ratio was 76%. 7 X.

improvement in the "end effect", and it can be observed that the average localized clad thickness is between 6 and 7 mils with no clad failures. However, experiment No. 7 revealed that even with a 84% total reduction in thickness, 25% blister rejection occurred during flux annealing, and 33% additional blister rejections occurred during brazing. These rejections were attributed to poor bonding resulting from a lack of sufficient Type 1100 on the composite frames and covers. Increasing the type 1100 on the frame and covers to four per cent resulted in satisfactory bonding of the composite plate, as shown in experiment No. 8. However, the "end effects" became worse, indicating that the thickness of the layer of the high-strength Type 6061 on the bi-metallic cover plate of the billet is related to the degree of "end effect" in the final product. The 5.7-mil average localized cladding thickness was accepted for manufacturing the enriched plates for the test elements because of the limited time the elements would be in the reactor. It is of interest to note in experiment No. 8 that in the examination of one specimen from each of five separate plates, a cladding failure during fabrication was observed; however, measurements of six specimens from one plate revealed a minimum of 3 mils and an average of 6 mils. These results emphasize the fact that the probability of a cladding failure during fabrication does exist with this material combination, but is not as great as that with the type 1100 frame and clad combination. The effects of Al-clad 6061 on "dogboning" is shown in Figs. 9 (Y-20310), 10 (Y-20313), and 11 (Y-20314). Subsequent to this work, an eddy-current procedure has been established for nondestructive evaluation of the localized cladding thickness variations at the core ends of the fabricated composite plate.[5]

E. Forming and Assembling

Design specifications for MTR-type fuel elements stipulate a plate curvature with a 5-1/2 in. radius.[6] Because of the high strength of the 48 wt % U-Al alloy, it was not possible to press the composite plates at room temperature to the proper curvature. Preheating of the plate to 540°C and pressing immediately resulted in plates with acceptable curvature, which could be properly assembled into a fuel element.

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Y-20310

Fig. 9. Specimen 14323. As Polished. Longitudinal Sections of Composite Plates Containing 48 wt % U-Al Alloy Framed and Clad with Type 6061 Aluminum. Type 6061 aluminum clad with 8% type 1100 aluminum. Localized clad thinning not acceptable. 6 X.

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Y-20313

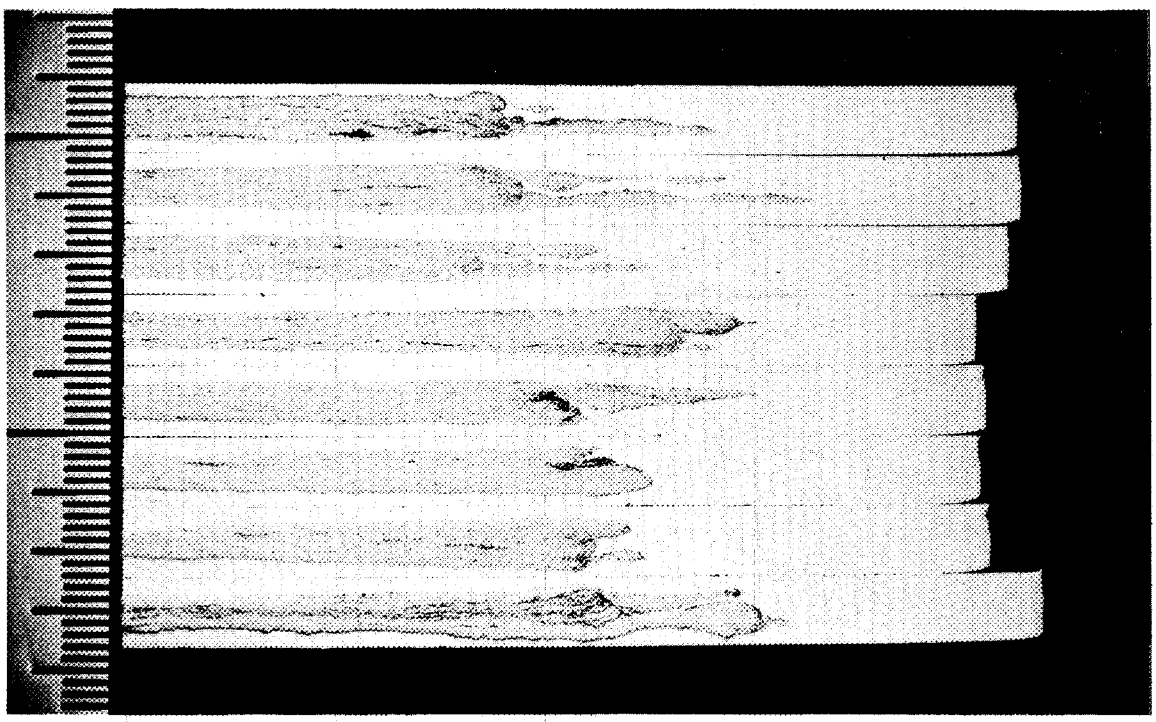

Fig. 10. Specimen 14369. As Polished. Longitudinal Sections of Composite Plates Containing 48 wt % U-Al Alloy Framed and Clad with Type 6061 Aluminum. Type 6061 aluminum clad with 2 % type 1100 aluminum. Bonding not satisfactory. Clad thinning more severe than in Fig. 8. 6 X.

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Y-20314

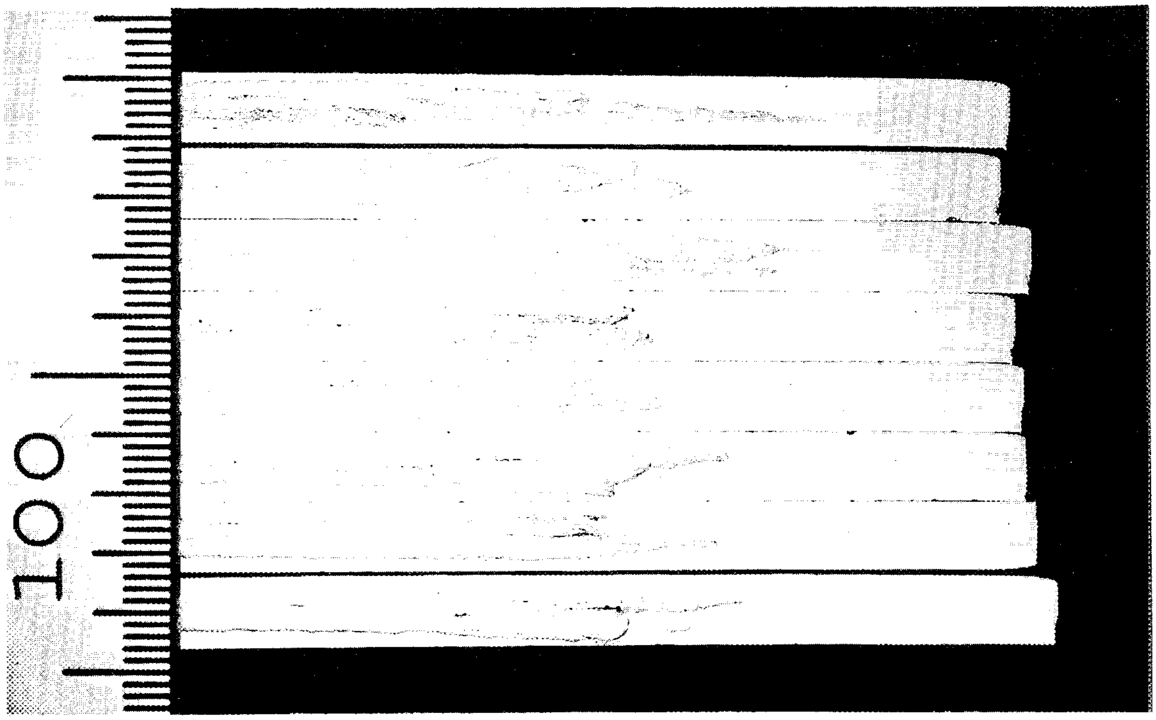

Fig. 11. Specimen 14370. As Polished. Longitudinal Sections of Composite Plates Containing 48 wt % U-Al Alloy Framed and Clad with Type 6061 Aluminum. Type 6061 aluminum clad with 4 % type 1100 aluminum. Localized clad thinning effect is pronounced because total hot reduction increased to 84%. Composite plates in test fuel elements fabricated under these conditions. 6 X.

F. Brazing

Conventional techniques were used for the fuel element brazing. The brazing cycle selected for joining MTR-type fuel units specifies a brazing temperature of 607°C.[1] Type 6061 aluminum has a solidus temperature of 582°C;[7] therefore, during brazing the material is in the liquid plus solid region for approximately 30 minutes. To determine whether or not Type 6061 would become severly damaged at the brazing temperature, this material was heated for 8 and 24 hr at 607°C.

Metallographic examination failed to reveal any serious effects from these treatments. The microstructures are illustrated in Figs. 12 (Y-23106) and 13 (Y-23107). Visual examination of the surfaces of the fuel plates clad with Type 6061 aluminum after brazing into the fuel array also failed to show any deleterious effects.

G. Irradiation Testing

One fuel element was inserted in the MTR for two cycles, Nos. 78 and 79, at a flux of 1.9×10^{14} n/cm^2/sec and a total nvt of 4.5×10^{20}. Calculations indicate that the burnup of U-235 atoms was approximately 25%.

After irradiation, the fuel element was examined in the hot cell at the MTR. Measurements were made of the fuel-element width, using a micrometer, and of the plate spacings, using a calibrated elliptical probe. The results which are tabulated in Table VI indicate that no significant changes in external measurements or water gaps occurred during irradiation.

Six plate surfaces were examined for flaws which may have been attributed to irradiation damage. This examination failed to reveal any defects.

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Y-23106

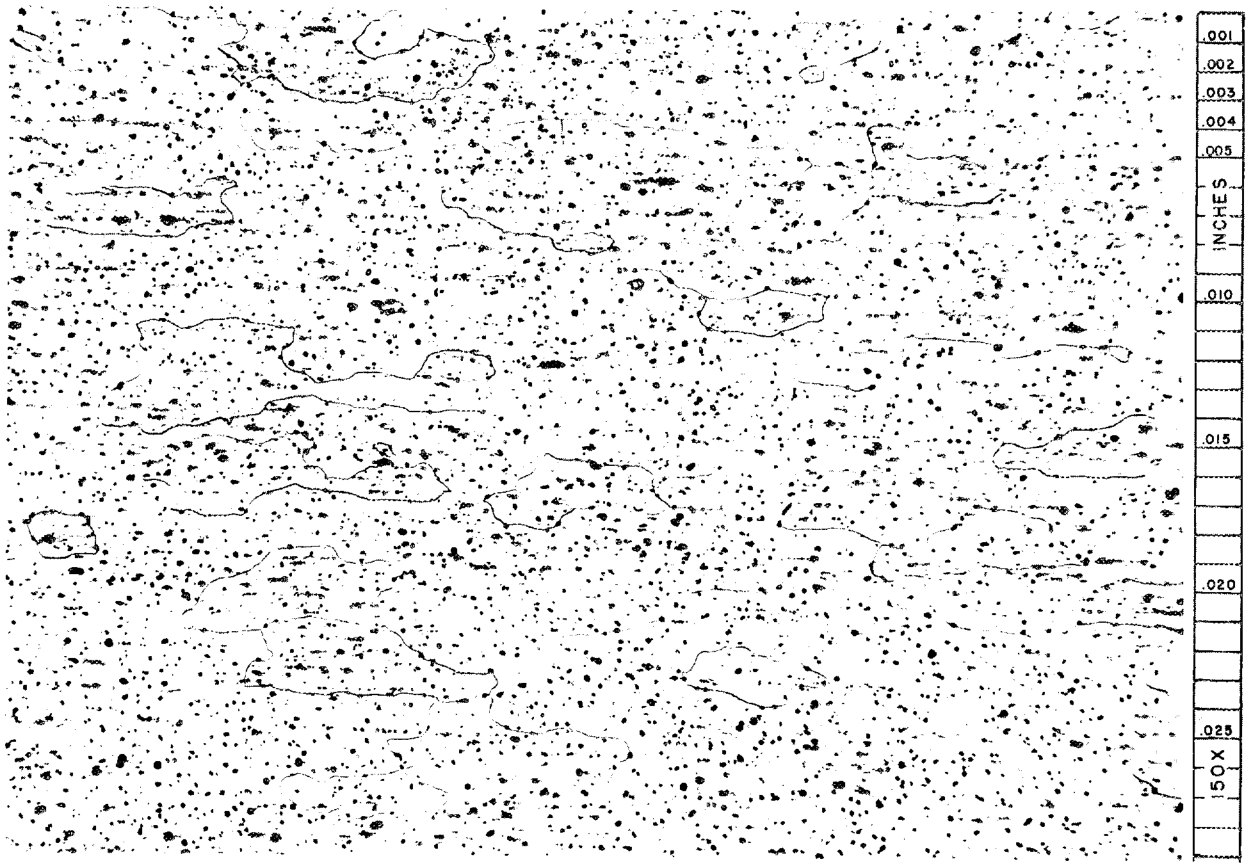

Fig. 12. Microstructure of Type 6061 Aluminum After 8 hr Heat Treatment at 607°C and Air Quench. Etch - 2% HF. 150 X.

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Y-23107

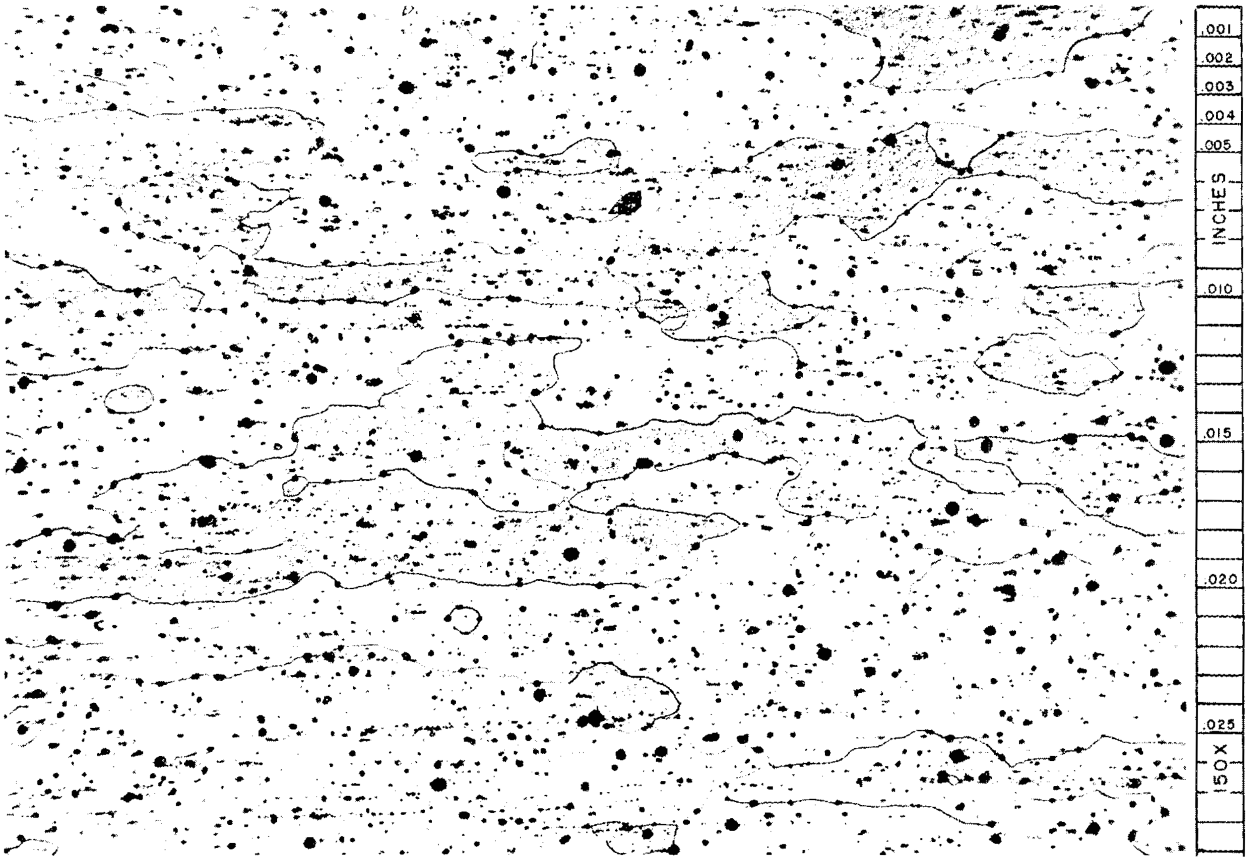

Fig. 13. Microstructure of Type 6061 Aluminum After 24 hr Heat Treatment at 607°C and Air Quench. Etch - 2% HF. 150 X.

TABLE VI

COMPARATIVE MEASUREMENTS OF FUEL ELEMENT OR-30-1 CONTAINING COMPOSITE ALUMINUM FUEL PLATES COMPOSED OF A CORE OF NOMINAL 48 WT % U-AL ALLOY AND TYPE 6061 ALUMINUM CLADDING

I.

Spacing Number	Pre-Irradiation Plate Spacing, Location Along Fuel Element: 2½ in.	Pre-Irradiation Plate Spacing, Location Along Fuel Element: 12 in.	Post-Irradiation Plate Spacing, Location Along Fuel Element: 2½ in.	Post-Irradiation Plate Spacing, Location Along Fuel Element: 12 in.
2	117	115	116	116
6	123	116	124	119
7	114	117	117	115
9	108	----	117	----
10	124	124	122	125
12	119	122	121	123
13	119	115	119	117
15	112	110	115	108

II.

Pre-Irradiation Width: Location Along Element (in.)	Width (in.)	Post-Irradiation Width: Location Along Element (in.)	Width (in.)
2½	2.994	2½	3.011
12	2.997	12	3.018
18	2.998	18	3.016
24	2.993	24	3.007

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