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AN EVALUATION OF THE URANIUM CONTAMINATION ON THE SURFACES OF ALCLAD URANIUM-ALUMINUM ALLOY RESEARCH REACTOR FUEL PLATES

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R. J. Beaver, J. H. Erwin, and R. S. Mateer[1]

ABSTRACT

Reported radioactivity in the Low-Intensity Test Reactor (LITR) water coolant traceable to uranium contamination on the surfaces of the alclad uranium-aluminum plate-type fuel element led to an investigation to determine the sources of uranium contamination on the fuel plate surfaces. Two possible contributors to surface contamination are external sources such as rolling-mill equipment, the most obvious, and diffusion of uranium from the uranium-aluminum alloy fuel into the aluminum cladding. This diffusion is likely because of the 600°C heat treatments used in the conventional fabrication process.[2]

Uranium determinations based on neutron activation analysis of machined layers from fuel plate surfaces showed that rolling-mill equipment, contaminated with highly enriched uranium, was responsible for transferring as much as 180 ppm U^{235} to plate surfaces. By careful practice where cleanliness is emphasized, surface contamination can be reduced to 0.6 ppm U^{235}.

The residue remaining on the plate surface may be accounted for by diffusion of uranium from the fuel alloy into and through the cladding of the fuel plate. Data obtained from preliminary diffusion studies permitted a good estimate to be made of the diffusion coefficient of uranium into aluminum at 600°C: 2.5×10^{-8} cm^2/sec. To minimize diffusion while the plate-type aluminum-base research reactor fuel element is being processed, heat treatments at 600°C should be limited to 2.5 hr. The uranium contamination on the surfaces of the finished fuel plates should then be less than 0.6 ppm U^{235}.

This investigation also revealed that the solubility limit of uranium in aluminum at 600°C is approx 60 ppm.

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[1]Summer Research Participant.

[2]E. J. Boyle and J. E. Cunningham, "MTR-Type Fuel Elements," Proc. Intern. Conf. Peaceful Uses Atomic Energy, Geneva, 1955 9 (1955).

INTRODUCTION

One of the factors, which operators of research reactors, such as the Low-Intensity Test Reactor (LITR) and the Oak Ridge Research Reactor (ORR), must control, is the quantity of radioactive species which contaminate the water coolant. The principal sources of activity are contained either in the water itself or on the surfaces of the aluminum fuel elements. The water can be purified, but activity from sodium-24 at a level ranging from 7.5×10^{-3} to 3.2×10^{-2} μc/ml will still be noticeable. Reactor operators recognize the possibility of additional activity from fuel plate surfaces contaminated with uranium but feel that it should be limited to less than 10^{-4} μc/ml (ref 3). In 1957, Moeller and Ledicotte[4] studied the radioactive nuclides present in the cooling water of the LITR. Prominent nuclides which were identified were neptunium-239 and "certain fission products." They concluded that the source of this nuclide was highly enriched uranium on the surfaces of the fuel plates which was responsible for an iodine-133 activity in the coolant of 6×10^{-5} μc/ml.

There are two possible contributions to surface contamination. The more obvious is the transfer of uranium from rolling-mill equipment to the surfaces of fuel plates. Contamination from this source was examined by scraping or machining 0.001-in.-deep layers from the surfaces of plates which had been heated at 600°C and rolled through highly contaminated rolls as well as through rolls with relatively little uranium contamination. These samples were analyzed for uranium-235 by neutron activation analysis. The other possible source of contamination, although not quite so apparent, is from diffusion of uranium from the uranium-aluminum alloy fuel section into and completely through the cladding of fuel plates during processing. A preliminary examination was made by obtaining samples by machining into the cladding to various depths and then analyzing the machined chips for uranium, again by neutron activation analysis. Because of the preliminary nature of this portion of the investigation, only a limited number of samples were obtained. They were, however,

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[3]Personal communication from F. T. Binford, ORNL Operations Division, ORR Specifications on Radioactivity.

[4]D. W. Moeller and G. W. Ledicotte, Source of Fission Products in LITR Cooling Water, ORNL CF-57-3-120 (March 1957).

sufficient to allow calculations to be made from which the diffusion coefficient and solubility limit of uranium in aluminum at 600°C were estimated.

GENERAL AND THEORETICAL CONSIDERATIONS

Since rolling-mill equipment is obviously a source of contamination in a fabrication facility where uranium or its alloys are rolled, it is necessary to ascertain the quantity of uranium transferred from such equipment to the surfaces of fuel plates during the rolling practices and, subsequently, to determine the percentage of this contaminant which may have been removed during cleaning or brightening treatments of the finished fuel plate. Approach to this problem requires merely a relatively simple sampling of the fuel plate surfaces after the various processing stages and a determination by neutron activation analysis of the uranium concentration in the samples. Then the equipment which transfers contamination on plate surfaces can be isolated.

Since it is possible that at 600°C, given sufficient time, uranium in the aluminum matrix of the uranium-aluminum alloy will diffuse into and completely through the aluminum cladding of the fuel plate, it is desirable to know the amount reaching the surface after a specified time. This, however, requires a knowledge of the diffusion coefficient. The value for this coefficient at 600°C is not known, but from data on other solutes in aluminum[5] is probably on the order of 10^{-8} cm^2/sec. The establishment of the diffusion coefficient requires knowledge of the solid-solubility limit of uranium in aluminum. The uranium-aluminum phase diagram, illustrated in Fig. 1, indicates that no solubility at 600°C exists. Thermodynamically, it cannot be zero. Therefore there will be a driving force for diffusion that will tend to bring the cladding and the matrix of the fuel alloy to the solubility limit of uranium in aluminum.

Support for the diffusion concept of contamination is given by preliminary studies of Kucera[6] on metallographic changes in the vicinity of the core-clad

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[5]Wolfgang Seith, Diffusion in Metals, p. 40, Springer-Verlag, Berlin/Göttingen/Heidelberg, 1955.

[6]Met. Div. Ann. Progr. Rept. Sept. 1, 1959, ORNL-2839, pp. 256–60.

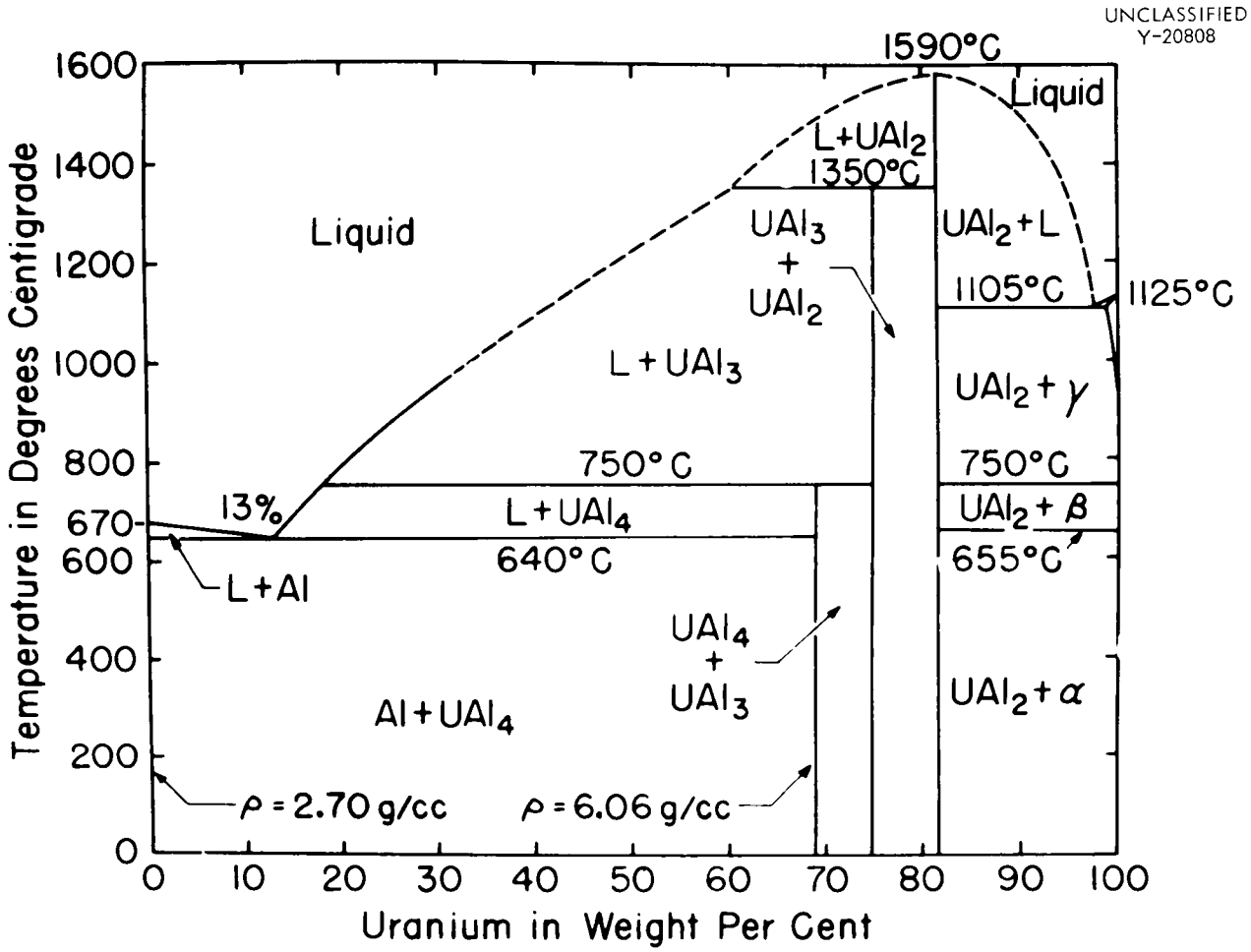


Fig. 1. Uranium-Aluminum Phase Diagram.

interface during prolonged heating at 600°C. The drastic nature of these changes is indicated in Fig. 2. It has not been possible to rationalize this phenomenon completely in terms of simple diffusion of uranium from the matrix of the uranium-aluminum alloy. The full explanation also probably involves the redistribution of minor alloy constituents and impurities (iron and silicon) in the cladding alloy and some interactions of solubility limits. However, there can be no question that diffusion processes between the fuel core and the cladding, and within the cladding itself, can be of significant proportions at this temperature.

To estimate the solid-solubility limit and the diffusion coefficient at 600°C from the limited data anticipated, a series of calculations can be made based on the following solution to Fick's equation:

$$\frac{C}{C_o} = 1 - \psi \left(\frac{x}{2\sqrt{Dt}}\right), \qquad (1)$$

where

C = uranium concentration at a distance x from the bonded interface after a time t,

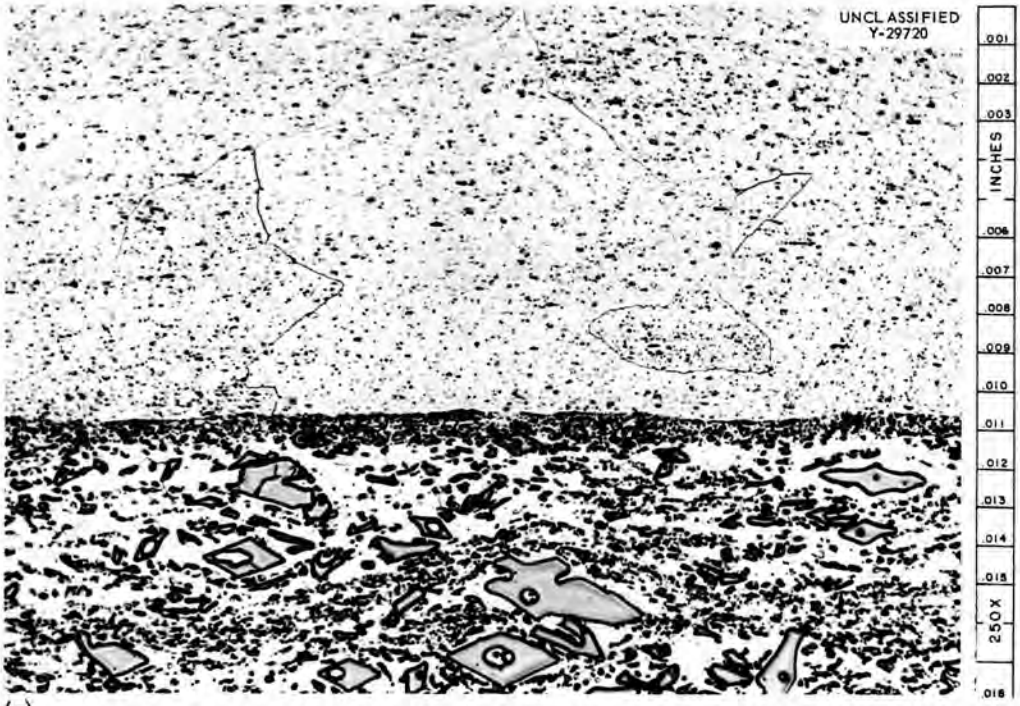
C_o = one-half the solid-solubility limit,

ψ = Gauss error function,

D = diffusion coefficient of uranium in the aluminum cladding.

This relationship is expressed graphically in Fig. 3, where C_2 is the solid-solubility limit and $C_2/2$, one-half the solid solubility limit, is C_o in the above expression.[5] To determine the diffusion coefficient, it is necessary to know the solid-solubility value, as well as the uranium concentration, at various distances from the alloy interface. If a number of values for C can be determined, it is possible, by assuming various diffusion coefficients, to analytically estimate C_o and, of course, the solid-solubility limit.

This representation is obviously an ideal condition, and although there is no doubt that the interface does not remain at $x = 0$, the scope of this investigation did not include studies to determine the direction of distortion. The assumption was made that uranium diffuses from the alloy much faster than it can be replenished by dissolution of the UAl_4 intermetallic compound and that the uranium in the aluminum matrix decreases as though it were in simple



(a)

(b)

Fig. 2. Comparison of Bonded Interface in Uranium-Aluminum Alclad Fuel Plate (a) after Cladding by Roll Bonding at 600°C and (b) after 14-Day Heat Treatment at 600°C. Electropolish: 15 parts ethyl alcohol; 1 part perchloric. Etch: 5% NaOH. 250X.

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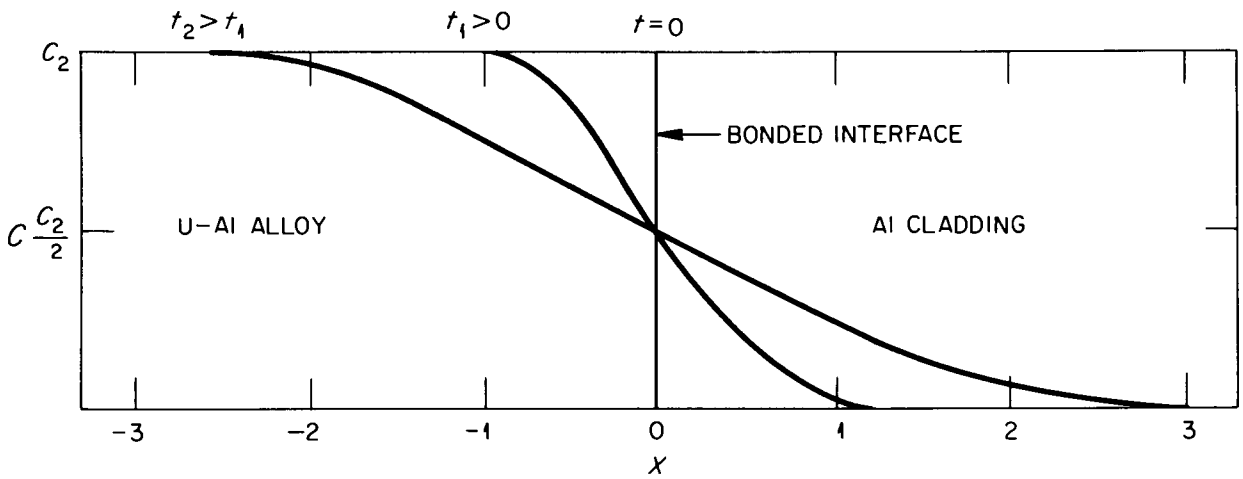

X = DISTANCE
t = TIME
C_2 = SOLID SOLUBILITY LIMIT
$\frac{C_2}{2}$ = 1/2 SOLID SOLUBILITY LIMIT = C_0

Fig. 3. Ideal Representation of Diffusion from Uranium-Aluminum Alloy into Aluminum Cladding of Alclad Fuel Plates.

solid solution. In fact, analysis of the data is by "curve fitting" on a simple model of a complex diffusion process. However, the parameters obtained represent an over-all measure of the extent of diffusion and should permit analytical extrapolation under conditions of practical interest.

EXPERIMENTAL PROCEDURE

The experimental procedure for evaluating surface contamination was to utilize plates produced with equipment in the Metal Forming and Casting Laboratory of the Metallurgy Division at the Oak Ridge National Laboratory (ORNL). Samples were obtained by scraping surfaces of the plates to a depth of approx 0.0005 in. and the uranium concentration was determined by neutron activation analysis.

Contamination From Rolling Mill

Samples were obtained from plates after the following sequences in the fuel plate processing:

1. hot rolling at 600°C through rolls contaminated with uranium;
2. flux annealing for 40 min at 600°C, cleaning in 2% HF-15% HNO_3 aqueous solution, and rinsing in water;
3. cold rolling through noncontaminated rolls;
4. annealing for 60 min at 600°C, cleaning in 2% HF-15% HNO_3 aqueous solution, and rinsing in water.

A comparative series of samples was prepared in accordance with this procedure with the exception that the hot rolling was conducted through rolls only partially contaminated with uranium. The results of the neutron activation analyses for uranium in the surface layers then permit an evaluation of the contamination as affected by the equipment and fabrication processes.

Contamination From Diffusion

To arrive at an estimate of values for the solid-solubility limit and diffusion coefficient at 600°C, plates were roll-bonded at 600°C and subsequently heat treated for 3, 6, and 9 hr at this temperature. After each heat treatment, the plates were fixed in a vacuum chuck, and a strip, 1/2 in. wide x 10 in. long, was machined from the center portion of the plate surface. The depth of the cut was varied from 0 to 0.003 in., 0.003 to 0.006 in., and 0.006 to 0.009 in. The sample obtained was completely dissolved and then analyzed by neutron activation analysis for uranium.

DISCUSSION OF RESULTS

Contamination From Rolling Mill

Average values of uranium-235 on the surfaces of fuel plates after various sequences in the fabrication process are listed in Table 1. Detailed results are given in Table 1 of Appendix A. As expected, because of uranium contamination on the hot-rolling mill, uranium concentration on the plate surfaces

Table 1. Uranium-235 Concentration in Scrapings from the Surfaces of Alclad Uranium-Aluminum Alloy Fuel Plates after Pertinent Sequences in Plate Processing

Fabrication Sequence	Average U^{235} Concentration (ppm)	
	Hot-Rolling Mill Contaminated with U^{235}	Hot-Rolling Mill Partially Contaminated
After hot rolling at 600°C on Mesta 2-High Mill	180.0	8.9
After flux annealing at 600°C for 40 min, etching in 2% HF-15% HNO_3 aqueous solution, and water rinsing	4.2	1.6
After cold rolling through "clean" rolls on United 2-High Mill	4.2	
After annealing for 60 min at 600°C, cleaning in 2% HF-15% HNO_3 aqueous solution, and rinsing in water	No data obtained	0.6

after hot rolling was 180 ppm U^{235}, which is considered extremely high. The contamination was significantly reduced after the flux-annealing treatment, acid cleaning, and water rinsing. Partial cleaning of the rolls by rolling aluminum stock combined with kerosene washing reduced the surface contamination of hot-rolled product to 8.9 ppm U^{235}. Again, the acid cleaning and water rinsing were observed to reduce the contamination significantly. Additional cleaning after blister annealing, acid pickling, and water rinsing resulted in further reduction to 0.6 ppm U^{235}. Analyses of the acid cleaning and water rinse solutions verified the presence of uranium, apparently removed from the plate surfaces.

Neutron activation analyses of type 1100 aluminum cladding stock revealed an average uranium concentration of 0.80 ± 0.02 ppm. Detailed results are given in Table A.5. Contribution of the uranium-235 isotope from this material is therefore a negligible 0.008 ppm.

Contamination From Diffusion

Uranium values (based on the data in Table A.4) obtained in the preliminary diffusion studies are plotted in Fig. 4, with the average values from this plot listed in Table 2. The following assumptions were necessary for analytical

Table 2. Average Uranium Concentrations Obtained from Fig. 4 for Various Distances from the Bonded Interfaces after Diffusion from Uranium-Aluminum Alloy into Type 1100 Aluminum Cladding at 600°C

Distance from Bonded Interface (cm)	Uranium Concentration (ppm) after Heat Treatments of		
	3 hr	6 hr	9 hr
0.02	3.5	16.0	33.0
0.03	0.2	7.0	19.0
0.04	0	3.0	10.0
0.05	0	0	4.0

treatment of the data for estimation of diffusion coefficient of uranium in this system and the solubility limit of uranium in aluminum:

1. The diffusion coefficient is independent of concentration.
2. The solubility limit in the aluminum matrix of the uranium-aluminum alloy is the same as in the aluminum cladding.
3. Uranium is the only solute that is diffusing.

The restrictions which these assumptions impose can lead only to first approximations for C_o and D when applied to data from the complex diffusion process under consideration.

If the data of Table 2 were to conform to the ideal case of Eq. (1), C_o and D would be true constants. In particular, if D were known, substitution of each C value from Table 2 would lead to the same value of C_o. If the D value were incorrect, a series of different values would be obtained for the constant C_o. The constancy of C_o under trial substitutions of various D

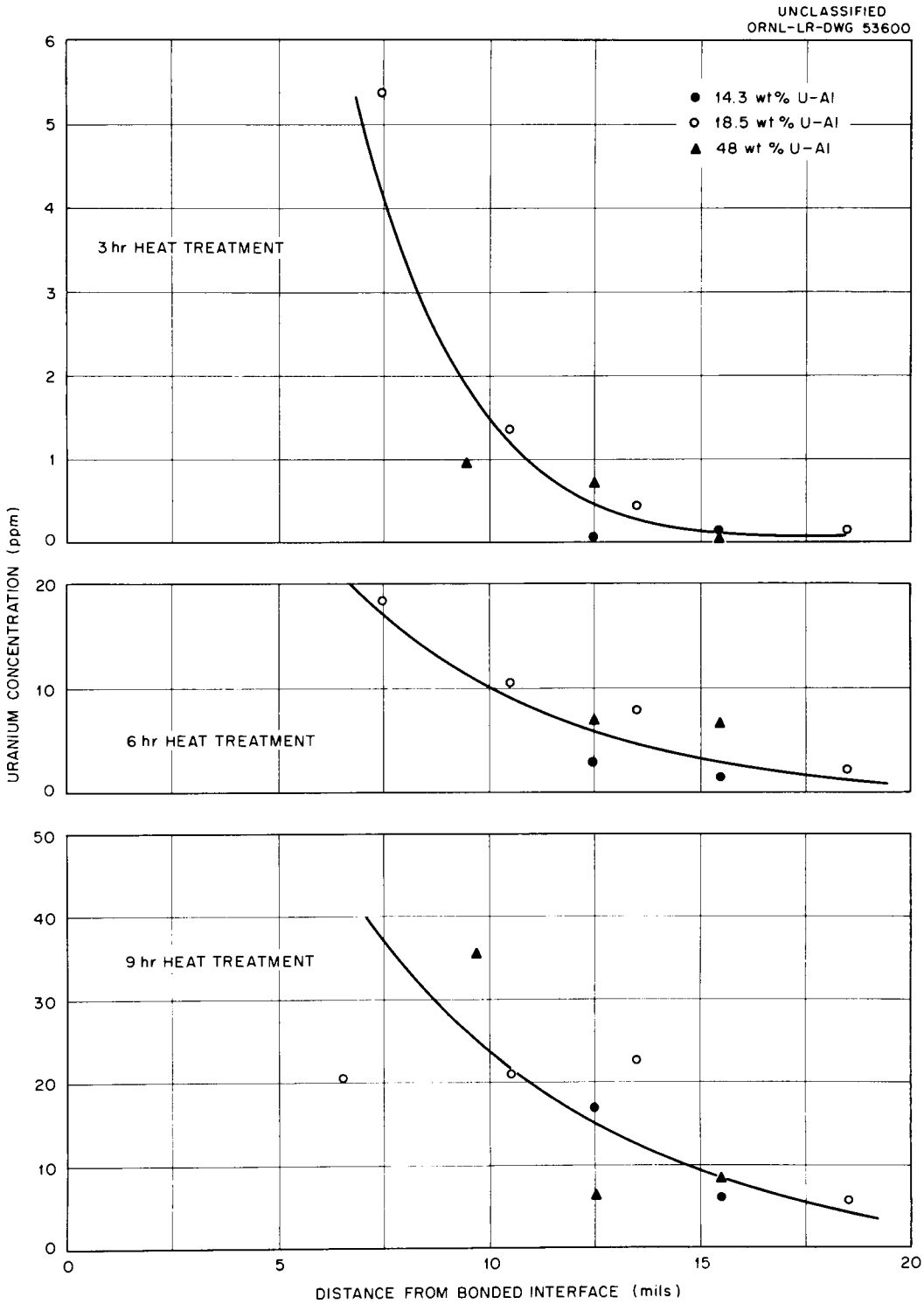

Fig. 4. Relationship Between Uranium Concentration and Distance from Bonded Interface of Uranium-Aluminum Alloy Plates Clad with Type 1100 Aluminum and Heat Treated at 600°C for 3, 6, and 9 Hr. Plotted from averages listed in Table A.4.

values for the data of Table 2 is therefore a test for the best-fit value of D. Results of a series of such calculations are given in Table 3 for assumed

Table 3. Calculated C_o Values Versus Assumed Diffusion Coefficients from 10^{-9} to 10^{-7} cm^2/sec for Diffusion of Uranium from Uranium-Aluminum Alloy into Type 1100 Aluminum Cladding at 600°C after Various Heat-Treatment Periods*

Distance from Bonded Interface (cm)	Uranium Concentration (ppm) For Diffusion Coefficient (cm^2/sec) of				
	1×10^{-9}	5×10^{-8}	2×10^{-8}	1×10^{-8}	1×10^{-7}
			Heat Treated for 3 hr		
0.02	116	5	6	7	4
0.03	3	3	50	∞	10
0.04	0	0	0	0	0
0.05	0	0	0	0	0
			Heat Treated for 6 hr		
0.02	∞	24	32	46	21
0.03	∞	13	23	41	11
0.04	∞	8	17	54	6
0.05	0	0	0	0	0
			Heat Treated for 9 hr		
0.02	1100	46	57	77	42
0.03	∞	32	48	79	27
0.04	∞	21	39	91	16
0.05	∞	10	25	80	8

*Based on results listed in Tables 1 and 2 of Appendix B.

values of D. From these data an estimate of C_o = 30 ppm was made. In no case was C_o found to be a true constant; however, the most consistent values were found for a diffusion coefficient of 2×10^{-8} cm^2/sec.

Accepting these values as a first approximation, it is possible to predict the extent of diffusion through aluminum cladding of various thicknesses and for heat treatments at 600°C other than these specifically tested. These results are listed in Table 4 and are based on the calculations listed in Table B.2 and the estimated value of 30 ppm U for C_o.

Table 4. Data Relating Diffusion of Uranium at 600°C as a Function of Distance and Time from Bonded Uranium-Aluminum Alloy into Type 1100 Aluminum Cladding*

Distance from Bonded Interface (cm)	Uranium Concentration (ppm) Heat-Treatment Time (hr)								
	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	10.0
0.01	7.05	12.24	14.91	16.59	18.00	18.93	20.16	21.30	23.4
0.02	0.525	2.85	5.22	7.05	8.82	10.08	11.91	13.50	17.79
0.03	0.01	0.54	1.20	2.28	3.39	4.47	6.30	7.74	12.84
0.04		0.03	0.18	0.54	1.02	1.62	2.85	4.02	8.70
0.05			0.02	0.09	0.24	0.48	1.08	1.86	5.55
0.06				0.01	0.06	0.09	0.33	0.72	3.39
0.07							0.09	0.24	1.89

*Diffusion coefficient = 2×10^{-8} cm^2/sec.

Since the formula used in these analyses is based on an infinite solid and the case at hand is a finite solid, it is necessary to make corrections. This can be estimated by taking into account a "reflection" curve from the plot generated for the infinite solid.[7] These curves are compared in Fig. 5 in which the "reflection" curve is shown. Corrected values are tabulated in Table 5. Based on the data listed in Table 5, the uranium concentration at various distances from the bonded interface into the cladding as a function of time at 600°C is graphically illustrated in Fig. 6. The data show that to limit the uranium-235 contamination on the surfaces of finished alclad uranium-aluminum alloy fuel plates to 0.5 ppm, heat treatment of the plates at 600°C should be confined to a period of less than 2.5 hr. After 3 hr, the uranium contamination is 1 ppm; after 5 hr, 4 ppm; and after 10 hr, may reach a value as high as 10 ppm. The importance of limiting the heat treatment is obvious.

[7]Wolfgang Seith, Diffusion in Metals, p. 17, Springer-Verlag, Berlin/Göttingen/Heidelberg, 1955.

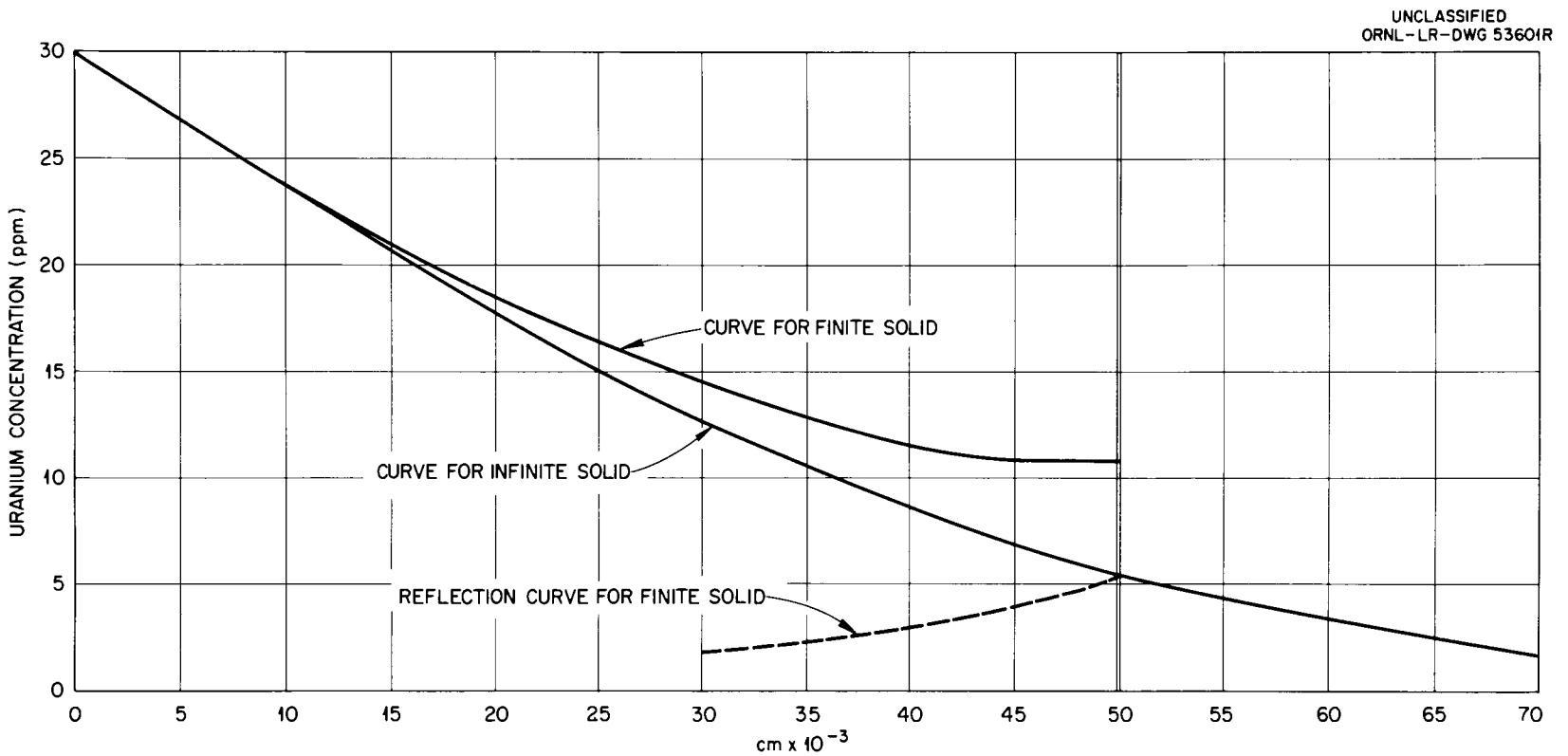

Fig. 5. Comparison of Curves Generated for Infinite and Finite Diffusion of Uranium from Uranium-Aluminum Alloy into Aluminum Cladding of Alclad Fuel Plates after 10-Hr Heat Treatment at 600°C.

Table 5. Modification of Data of Table 4 Relating Diffusion of Uranium at 600°C as a Function of Distance and Time from Bonded Uranium-Aluminum Alloy into Type 1100 Aluminum Cladding*

Distance from Bonded Interface (cm)	Uranium Concentration (ppm) Heat-Treatment Time (hr)								
	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	10.0
0.01	7.05	12.24	14.91	16.59	18.00	18.93	20.16	21.30	23.4
0.02	0.53	2.85	5.22	7.05	8.32	10.08	11.91	13.50	17.79
0.03	0.01	0.54	1.20	2.28	3.39	4.47	6.39	7.98	14.73
0.04		0.03	0.18	0.55	1.08	1.69	3.18	4.74	12.60
0.05			0.04	0.18	0.48	0.96	2.16	3.72	11.10
0.06									
0.07									

*Based on 0.058-cm-thick cladding.

CONCLUSIONS

1. Uranium on rolling-mill equipment can be transferred to the surface of rolled-aluminum fuel plates and cause significant increases in activity levels in the water coolant of research reactors.

2. In processing alclad uranium-aluminum alloy fuel plates containing highly enriched uranium, it is conceivable that surface contamination can be limited to a maximum of 0.5 ppm U^{235} if the rolling-mill equipment is free of this contaminant and if heat treatment of fuel plates at 600°C is limited to 2.5 hr.

3. Uranium concentration in type 1100 aluminum cladding stock is 0.80 ± 0.02 ppm.

4. Diffusion of uranium from the uranium-aluminum alloy fuel core into the type 1100 aluminum cladding may contribute significantly to uranium contamination on the surfaces of fuel plates processed at 600°C. The estimated diffusion coefficient of uranium from the uranium-aluminum alloy core into the type 1100 aluminum cladding at 600°C is 2×10^{-8} cm^2/sec. (The estimated solid-solubility limit of uranium in aluminum at 600°C is 60 ppm.)

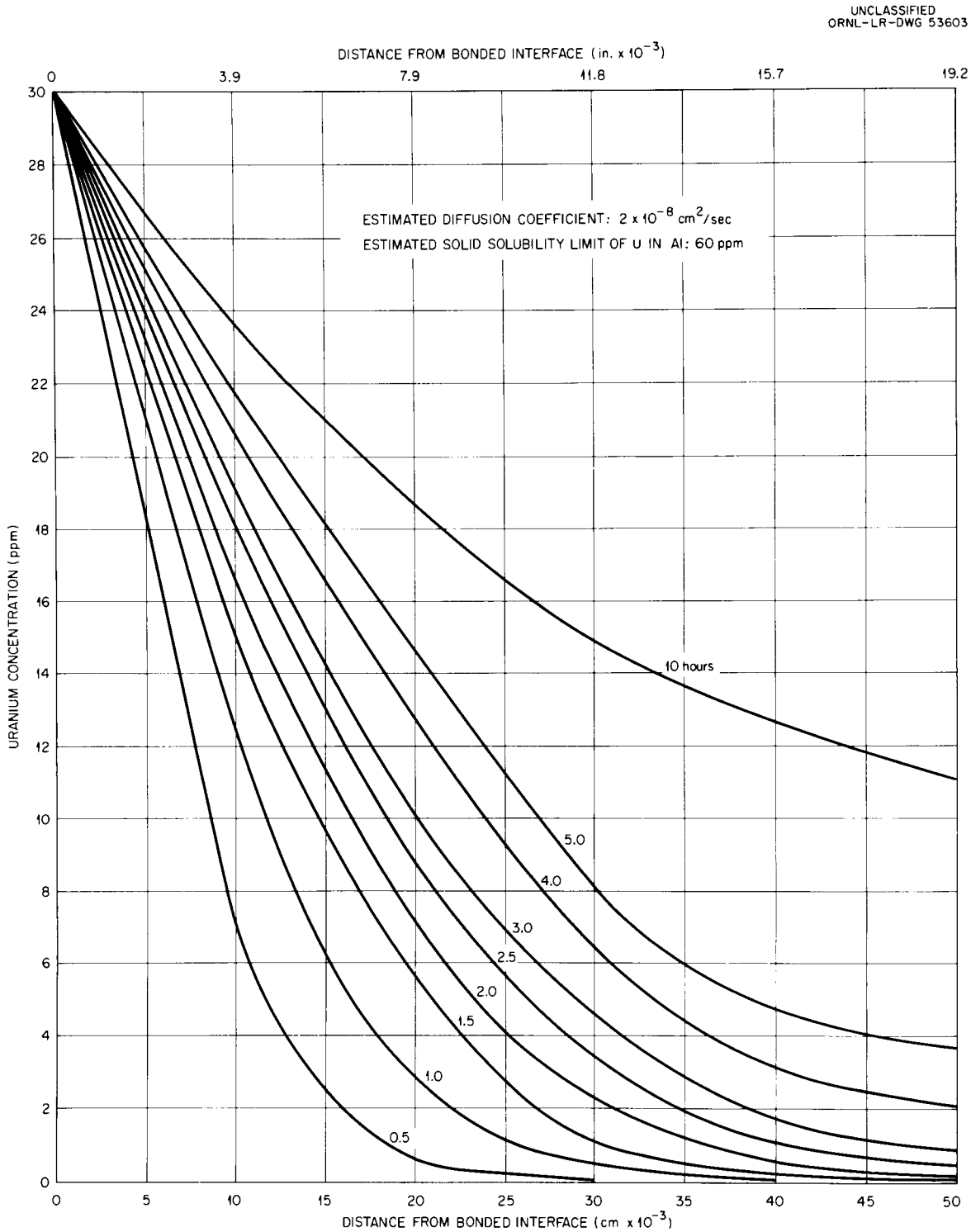

Fig. 6. The Effect of Heat Treatment at 600°C on Diffusion of Uranium from Uranium-Aluminum Alloy into the Aluminum Cladding of Alclad Fuel Plates.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of H. J. Wallace of the Metal Forming and Casting Group, who prepared the composite plate specimens used in this investigation. R. J. Gray and his co-workers in the Metallographic Group are also recognized for their efforts in illustrating the effect of diffusion at the bonded interface of alclad uranium-aluminum alloy fuel plates. The assistance of G. W. Ledicotte of the Nuclear Analysis Group in conducting the neutron activation analyses is fully appreciated.

APPENDIX A

DATA ON NEUTRON ACTIVATION ANALYSES FOR URANIUM IN THE CLADDING OF ALCLAD URANIUM-ALUMINUM ALLOY FUEL PLATES

Table A.1. Data on Uranium-235 Contamination on Surfaces of Aluminum Fuel Plates Based on Scrapings from the Surfaces after Important Sequences in Fuel Plate Processing

Fabrication Sequence	Specimen Number	Uranium-235 Concentration (ppm) Contaminated Rolls	Uranium-235 Concentration (ppm) Partially Contaminated Rolls
After hot rolling at 600°C on Mesta 2-High Mill	HA	138–158	
	HB	91–108	
	HC	291–295	
	D582-1		9.2–11.4
	D582-2		8.9–9.5
	D582-3		7.3–9.6
	D582-4		7.8–7.8
After flux annealing plate for 40 min at 607°C, cleaning in 2% HF–15% HNO_3 aqueous solution, and rinsing in water	FH	5.3–5.9	
	FI	3.2–3.6	
	FJ	3.7–3.7	
	1X		0.6–1.4
	2X		1.8–5.3
	3X		0.5–1.1
	4X		0.7–1.1
After cold rolling on United 2-High Mill	CK	4.1–4.4	
	CL	5.1–5.4	
After annealing 60 min at 607°C, cleaning in 2% HF–15% HNO_3 aqueous solution, and rinsing in water	1B		0.4–0.6
	2B		0.4–1.0
	3B		0.4–1.2
	4B		0.5–0.7
	5B		0.3–0.5
2% HF–15% HNO_3 aqueous solution	ACD		0.12–0.12 (mg/ml)
	ACE		0.12–0.12 (mg/ml)
Water rinse	HOG		0.003–0.003 (mg/ml)
	HOF		0.08–0.08 (mg/ml)

Table A.2. Uranium-235 Contamination on the Surfaces of Finished Alclad Uranium-Aluminum Alloy Fuel Plates Based on the Outer 0.003-in. Thickness of the Aluminum Cladding

Type of Plate	Specimen No.	Uranium-235 Concentration (ppm)
ORR	B-56-0	0.09–0.11
ORR	B-672-12	0.39–0.54
ORR	D-669-A	0.37–0.40
BSR	D-682-0	0.15
TSF	B-61	0.20–0.28
TSF	B-45	0.38–0.46
TSF	B-63	0.18–0.19
	Average	0.28

Table A.3. Neutron Activation Analyses of Uranium Content in Machining Shavings of Type 1100 Cladding of Uranium-Aluminum Alloy Fuel Plates after Machining into the Surface of the Composite Plate to Various Depths Subsequent to Designated Heat Treatment at 600°C

Sample No.	Uranium-Aluminum Alloy Concentration (wt %)	Cladding Thickness (mils)	Uranium Concentration (ppm) at Machining Depth of		
			0–3 mils	3–6 mils	6–9 mils
		Heat-Treated for 3 hr			
D669B	18.5	15	0.37–0.40		
D669C	18.5	15		1.28–1.32	
D669D	18.5	15			5.22–5.34
D669A	14.3	20	0.14–0.17		
D669B	14.3	20		0.19–0.25	
D669C	14.3	20			0.12–0.14
Si-30-11A	48.0	17	0.04–0.10		
Si-30-11B	48.0	17		0.53–0.82	
Si-30-11C	48.0	17			0.85–0.89
		Heat-Treated for 6 hr			
D669E	18.5	15	8.0–8.5		
D669F	18.5	15		10.3–10.6	
D669G	18.5	15			17.5–19.6
D682F	14.3	20	2.3–2.3		
D682G	14.3	20		1.4–1.4	
D682H	14.3	20			2.8–3.0
Si-30-11F	48.0	17	5.4–7.8		
Si-30-11H	48.0	17			37.7–50.5
D669I	18.5	15	23.1–23.6		
D669J	18.5	15		20.0–23.0	
D669K	18.5	15			21.0–20.8
D682I	14.3	20	6.0–6.1		
D682J	14.3	20		6.7–6.7	
D682K	14.3	20			16.5–17.4
Si-30-13I	48.0	17	8.3–8.9		
Si-30-13J	48.0	17		15.3–18.0	
Si-30-13K	48.0	17			46.1–53.4

Table A.4. Summary of Average Uranium Concentration* in Various Layers of Aluminum Cladding of Uranium-Aluminum Alloy Plates after Heat Treatment at 600°C

Weight Per Cent of Uranium in Alloy	Cladding Thickness (mils)	Depth Machined into Surface (mils)	Uranium Concentration (ppm) Heat-Treatment Period (hr)		
			3	6	9
14.3	20	0–3	0.2	2.3	6.1
		3–6	0.2	1.4	6.7
		6–9	0.1	2.9	17.0
18.5	15	0–3	0.4	8.3	23.4
		3–6	1.3	10.5	21.2
		6–9	5.3	18.6	20.9
48.0**	17	0–3	0.1	6.6	8.6
		3–6	0.7		16.7
		6–9	0.9	44.0	49.8

*From Table A.3.
**Alloy contained 3% Si.

Table A.5. Uranium Analyses of Type 1100 Aluminum Stock Utilized as Cladding Material in Fabrication of Alclad Uranium-Aluminum Alloy Fuel Plates

Sample No.	Uranium Concentration (ppm)
1	0.8–0.9
2	0.6–0.8
3	0.8–0.9
4	0.8–0.8
Average	0.8
Standard deviation	0.02

APPENDIX B

DATA RELATING TO ESTIMATE OF DIFFUSION OF URANIUM FROM URANIUM-ALUMINUM ALLOY FUEL CORE INTO TYPE 1100 ALUMINUM CLADDING OF COMPOSITE FUEL PLATES

Table B.1. Calculation of C/C_o Values Based on Specific Diffusion Coefficients (D)

Distance from Bonded Interface (cm)	$\frac{X}{2\sqrt{Dt}}$ for D Values (cm^2/sec) of					C/C_o for D Values (cm^2/sec) of				
	1×10^{-7}	5×10^{-8}	2×10^{-8}	1×10^{-8}	1×10^{-9}	1×10^{-7}	5×10^{-8}	2×10^{-8}	1×10^{-8}	1×10^{-9}
					3-hr Heat Treatment					
0.02	0.15	0.21	0.34	0.48	3.04	0.83	0.75	0.630	0.50	0.03
0.03	0.91	1.26	2.04	2.88	9.12	0.20	0.07	0.004	0	0
0.04	0.61	0.856	1.36	1.92	6.08	0.400	0.230	0.054	0	0
0.05	0.76	1.07	1.70	2.41	7.60	0.300	0.140	0.016	0	0
					6-hr Heat Treatment					
0.02	0.22	0.30	0.48	0.68	2.16	0.760	0.680	0.497	0.350	0
0.03	0.32	0.46	0.72	1.02	3.24	0.660	0.540	0.309	0.170	0
0.04	0.43	0.61	0.96	1.36	4.32	0.550	0.390	0.175	0.055	0
0.05	0.54	0.75	1.20	1.70	5.38	0.460	0.300	0.090	0.015	0
					9-hr Heat Treatment					
0.02	0.18	0.25	0.40	0.55	1.76	0.800	0.720	0.580	0.430	0.013
0.03	0.26	0.37	0.59	0.83	2.64	0.713	0.600	0.400	0.240	0
0.04	0.35	0.50	0.79	1.11	3.51	0.620	0.480	0.260	0.110	0
0.05	0.44	0.62	0.99	1.39	4.40	0.534	0.380	0.160	0.050	0

Table B.2. Calculated Values for C/C_o Based on Diffusion Coefficient (D) of 2×10^{-8} cm^2/sec

Distance from Bonded Interface (cm)	$\frac{X}{2\sqrt{Dt}}$ Heat-Treatment Period (hr)									C/C_o Heat-Treatment Period (hr)								
	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	10.0	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	10.0
0.01	0.84	0.59	0.48	0.42	0.37	0.34	0.30	0.27	0.19	0.235	0.408	0.497	0.553	0.600	0.631	0.672	0.710	0.780
0.02	1.68	1.18	0.97	0.84	0.75	0.68	0.59	0.53	0.37	0.175	0.095	0.174	0.235	0.294	0.336	0.397	0.450	0.593
0.03	2.51	1.67	1.45	1.25	1.12	1.02	0.89	0.80	0.56	0.0004	0.018	0.040	0.076	0.113	0.149	0.210	0.258	0.428
0.04	3.34	2.36	1.94	1.67	1.49	1.37	1.18	1.06	0.75	0	0.001	0.006	0.018	0.034	0.054	0.095	0.134	0.290
0.05		2.96	2.41	2.09	1.86	1.71	1.48	1.32	0.93	0	0	0.0006	0.003	0.008	0.016	0.036	0.062	0.185
0.06				2.50	2.74	2.05	1.77	1.59	1.12	0	0	0	0.0004	0.002	0.003	0.011	0.024	0.113
0.07				2.92	2.61	2.39	2.07	1.86	1.31	0	0	0	0	0	0	0.003	0.008	0.063

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