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UNITED STATES ATOMIC ENERGY COMMISSION

EFFECT OF IRRADIATION UPON INTER DIFFUSION OF STAINLESS STEEL AND URANIUM

Final Report of Program 6.1.4

By
R. Weil
S. H. Paine

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EFFECT OF IRRADIATION UPON INTERDIFFUSION
OF STAINLESS STEEL AND URANIUM

by

R. Weil and S. H. Paine

Irradiation Group

Metallurgy Division by authority of AEC-381 Old 2/13/57

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2. ANL-4364, J. H. Kittel, "Diffusion of Metals Under Irradiation," July-September, 1949, pp. 57-60.
3. ANL-4399, J. H. Kittel and S. H. Paine, "Diffusion of Metals Under Irradiation," Oct. -Dec., 1949; pp. 82-83, 85.
4. ANL-4508, J. H. Kittel, et al., "Diffusion of Metals Under Irradiation," April-June, 1950; pp. 32-33.
5. ANL-4860, R. Weil and S. H. Paine, "Effect of Irradiation Upon Uranium-Stainless Steel Diffusion Couples," April-June, 1952; pp. 112-114.
6. ANL-4966, S. H. Paine, et al., "Effect of Irradiation Upon Uranium-Stainless Steel Diffusion Couples," October-December, 1952; pp. 38, 42-44.
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8. ANL-5097, R. Weil and S. H. Paine, "Interdiffusion in Stainless-Steel-Uranium Couples," April-June, 1953; p. 50.

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4

EFFECT OF IRRADIATION UPON INTERDIFFUSION OF STAINLESS STEEL AND URANIUM

by

R. Weil and S. H. Paine

INTRODUCTION

A study of the interdiffusion between uranium and possible cladding materials is of importance to the design of reactors for several reasons. The cladding material must be thick enough so that fissionable materials do not diffuse to the surface, and the intermetallic compounds which form as a result of diffusion between uranium and most other metals can appreciably affect the mechanical properties and thermal conductivity of fuel assemblies. It is not sufficient to study diffusion by conventional means only; the effect of irradiation must also be appraised.

Stainless steel and uranium were chosen as the components of the diffusion couple because these two materials were used in the fuel elements of the Experimental Breeder Reactor.

EXPERIMENTAL PROCEDURE

A number of diffusion experiments were conducted with couples made of Type 347 stainless steel and uranium (normal and enriched). The tests were performed at temperatures from 400°C to 700°C for 1, 2, 4, 8 and 16 days, unirradiated and irradiated in the CP-3' reactor at Argonne National Laboratory. No attempt was made to isolate the effects of the grain size and orientation of the uranium. These variables were held constant at the beginning of each experiment.

The conventional experimental procedures for diffusion experiments had to be modified in order to adapt them for tests in the reactor. It was necessary to have a small specimen because of the space limitations in the test locations of the reactor and also because of self-shielding. As the whole assembly of the irradiated sample became radioactive, the auxiliary parts had to be expendable. The specimen was designed so as to be heated electrically in order to avoid having an in-pile furnace.

Fabrication of Specimens

The design of all diffusion specimens was essentially the same except that the quantity of uranium varied with enrichment. The diffusion specimen consisted of a Type 347 stainless-steel tube swaged over a

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uranium wire. The tubing was cold drawn to an outside diameter of $3/32$ in. and an inside diameter of 0.044 in. over music wire which was later pulled out in a tensile machine. A piece of tubing $3-1/2$ in. long was used in making the diffusion specimen. The stainless steel tube was cleaned by pulling a string impregnated with lapping compound through the tube and then rinsing with acetone and ethyl alcohol.

The other component of the diffusion couple, the uranium wire, was swaged to 0.044 in. diameter. Between each successive pass through the swaging die the uranium was annealed in the alpha range, except prior to the last pass when it was beta treated at 700°C for 1 min and water quenched. The normal-uranium wire used in making the diffusion specimen was 1 in. long, whereas the highly enriched-uranium wire was only $1/16$ in. long, because an inch-long piece of 93% enriched uranium wire irradiated at 3×10^{12} nv would have brought the temperature of the diffusion couple above the eutectic point, due to fission heating. The uranium was electropolished to a bright finish in a bath composed of 5 parts of ethylene glycol, 8 parts of ethyl alcohol, and 5 parts of phosphoric acid at a current density of 1 amp/cm². After electropolishing, the wire was quickly dried and inserted into the stainless steel tube together with copper or stainless steel end plugs. The stainless steel tube containing the uranium wire was swaged to 0.080 in. diameter to obtain intimate contacts between the components of the diffusion couple. By the swaging operation the uranium wire core was reduced 25% in area.

Grooves were filed in the part of the stainless steel tube over the uranium at $3/16$ in. intervals, and thermocouples were spot welded in the grooves. Five thermocouples were attached to the diffusion specimen containing the normal uranium and one thermocouple to the specimen with enriched uranium. The diffusion assembly, consisting of the stainless steel tube containing the uranium and with copper conductor leads attached to the ends of the tube, is shown in Figure 1. A schematic diagram of the assembly with a 1 in. long piece of uranium is shown in Figure 2.

Heating of the Diffusion Assembly

As previously stated, the specimen was heated by passing an electric current through it. This current was controlled to keep the temperature at one thermocouple location constant. The samples with several thermocouples attached to them showed a temperature gradient along the tube. This gradient tended to shift with increasing diffusion time. Holding the temperature constant at the cooler end by controlling the specimen current resulted in the temperature decreasing at the hotter end as time progressed. An auxiliary heater was therefore needed to keep the temperature constant along the tube. The current through the auxiliary heater was controlled by a thermocouple at the high-temperature end. The auxiliary heater was only used on specimens made with normal uranium.

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Temperature Control

The voltage to the specimen and auxiliary heater was held constant by a Sorensen voltage regulator. Figure 3 shows the wiring diagram of the heating circuit of the specimen and auxiliary coil. The currents were manually set by Variable Transformers 1 and 4. The temperatures were kept constant by motor-driven Variable Transformers 3 and 5, which were operated by the temperature controllers. Variable Transformer 2 was operated by limit switches at the ends of the voltage range of Transformer 3. The resetting action was needed because the range of Transformer 3 was only a few volts.

In-Pile Heating Problems

During the irradiations it was not possible to maintain a constant pile power. Occasionally the power was shut off to permit the introduction or removal of other specimens, or it was operated at a lower flux to satisfy the needs of other experimenters. The temperatures in the diffusion specimens were held constant regardless of pile power. It was found inadvisable to stop diffusion while the pile was not operating, as doing so would have resulted in breaking the diffusion bonds because of the differences in the coefficients of thermal expansion of the components of the diffusion couple.

The reason for using a 1/16 in. long piece of enriched uranium of the same diameter as was used in the experiments with normal uranium was that this was the maximum amount for which the temperature drop due to sudden stopping of fission could be controlled. Even with this small quantity of enriched uranium the temperature dropped 10° when the reactor was scrammed. This temperature drop lasted only for a few seconds. The experimental temperatures were chosen so that no phase change occurred in the uranium when the temperature dropped suddenly. It was previously found that passing through the alpha-beta transformation resulted frequently in breaking the contact between the components of the diffusion couple.

No problems were encountered when the reactor was rising to power, as this resulted in a slow temperature change which was easily regulated by the control mechanism.

Measurement of Diffusion Penetration

After diffusion, the specimens were sectioned between each thermocouple and metallographically polished to the plane where the thermocouple wires were attached. Special care was taken to insure that the polished surface was perpendicular to the axis of the specimen. Each thermocouple position yielded one diffusion measurement. It was advantageous to have as many thermocouples as possible on each specimen. Because of the temperature gradient, previously mentioned, each thermocouple indicated a different temperature during the experiment. The width of the diffusion zone was measured on a metallograph.

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Diffusion in a couple consisting of stainless steel and uranium resulted in the formation of several intermetallic compounds as shown in Figure 4. In most specimens two phases were formed by diffusion. Some samples which were diffused at comparatively low temperatures showed only one diffusion phase, the uranium-rich one. The uranium-iron phase diagram⁽¹⁾ shows two intermetallic compounds, UFe_2 and U_6Fe . The two phases formed in most specimens were probably these iron-uranium compounds. As the uranium-iron phase diagram shows practically no solid solubility in the intermetallic compounds or the pure metals, it was held unlikely that any appreciable regions of solid solution resulted from diffusion. The width of the intermetallic compounds could thus be considered as the diffusion zone. The uranium-rich phase was seen as low as $430^\circ C$, whereas the iron-rich phase was not observed below $550^\circ C$ in couples diffused for four days. As seen in Figure 4, the uranium-rich zone was much wider than the iron-rich one and could be measured with greater accuracy. For these reasons, and also as it is mathematically very difficult to calculate diffusion coefficients in multiple-phase systems, it was decided to take the maximum thickness of the uranium-rich phase as a measure of the diffusivity. This was slightly greater, of course, in the cylindrical geometry than it would have been if the diffusion interface had been plane. However, the error so introduced was much smaller than the experimental error.

Subsequent Experiments on Nucleation of Diffusion Phases

Some experiments were performed to determine whether irradiation altered the temperature at which the uranium-rich phase was first observed. In order to choose the experimental conditions which would give a maximum number of fissions at the diffusion interface without exceeding the nucleation temperature range, two initial tests were made to evaluate the variation of specimen temperature with pile power for various uranium enrichments. The results of the tests are appended. On the basis of these tests a $1/2$ in. long piece of uranium wire containing 30% U^{235} was used in subsequent experiments to determine the irradiation effect on the nucleation temperature of the uranium-rich phase. As the location where the diffusion zone was first observed did not generally coincide with the location of a thermocouple it was necessary to interpolate. In order to make the interpolation more accurate the first and second thermocouples at the cooler end were placed $3/32$ in. apart. At the location of these two thermocouples the temperature gradient was steepest. Two other thermocouples were placed at intervals of $3/16$ in. The tests were conducted in VT-II of the CP-3' reactor at a flux of about 1.4×10^{12} nv. The nucleation of the diffusion phase was arbitrarily defined as a reaction product 0.1 mm in width when viewed at 1000X. The temperature at which the diffusion phase first occurred was then determined from a graph of temperature vs. distance along the specimen.

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DISCUSSION OF EXPERIMENTAL RESULTS

The data obtained by measuring the thickness of the intermetallic layers resulting from diffusion at various temperatures were treated in a way similar to the procedure suggested by Lustman and Mehl.⁽²⁾ It was assumed that the logarithm of the thickness of the uranium-rich zone (L_u) was proportional to the inverse of the absolute temperature (T). All data were plotted according to this relationship.

Results of Control Experiments

The first series of experiments were performed to determine the variation of the thickness of the uranium-rich zone with temperature in unirradiated couples. Figures 5 to 8 show this variation for diffusion times of 1, 2, 4 and 8 days. The data from which the graphs were plotted can be found in Tables I and IV. The solid lines in the figures were obtained by least squares analyses of the data, and the equations resulting from these analyses are shown in the tables. From the graphs of compound thickness versus temperature it is apparent that no noticeable discontinuity or change in slope occurred at the alpha-beta transformation temperature of uranium (933°K , $1/T = 1.07 \cdot 10^{-3}$). It will be seen later that diffusion through the compound zone was the controlling mechanism, and it therefore seems clear that no phase changes occurred in the compounds within the temperature range observed. In this respect the uranium-stainless steel system is found to be quite analogous to the uranium-iron system.⁽¹⁾

The thicknesses of the diffusion zone at 500°C , 550°C , 600°C , 650°C and 700°C were calculated from the least squares equations and plotted as a function of time, assuming the same relation which Lustman and Mehl⁽²⁾ used, namely,

$$(L_u)^n = kt \quad (1)$$

where t is the time and k is the rate constant. The curves are shown in Figure 9. The solid lines again are the results of least-squares analyses of the data points. In the equations for the variation of the thickness of the uranium-rich diffusion zone with time at various temperatures, the following constants were obtained:

Temperature ($^\circ \text{C}$)	Exponent n	Rate constant k (microns ^{n} /day)
500	1.952	9.8276
550	2.033	50.771
600	2.108	243.23
650	2.178	1075.5
700	2.242	4432.5

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The exponent n defined in Equation (1) is approximately equal to 2. According to Fick's Law this value of the exponent indicates that diffusion is the controlling factor in the formation of the intermetallic compound zones. It can further be noted from the tabulated values that the exponent is increasing with temperature. According to Lustman and Mehl there is no way to explain an exponent larger than 2 by the rate theory. They suggest that values of n greater than 2 might be caused by changes occurring in the products of the reaction. It may be significant that the value of n becomes greater than 2 at approximately the same temperature at which the iron-rich phase is first observed.

The rate constant k of Equation (1) has approximately the same dimension as the diffusion coefficient, namely, (length)²/time. The activation energy of this rate constant was calculated by plotting the logarithm of the k values against the inverse absolute temperature. The equation thus obtained is:

$$\ln(k) = 31.90 - \frac{45,620}{RT} \quad (2)$$

where R is the gas constant in calories/degree/mole. Figure 10 shows a graph of Equation 2.

Some preliminary diffusion data in the uranium stainless steel system which were obtained by J. H. Kittel⁽³⁾ agree quite well with the results discussed above.

Results of Experiments with Normal Uranium under Irradiation

On the basis of the results obtained from the unirradiated specimens it was decided to diffuse the irradiated ones for two and four days. To facilitate comparisons between irradiated and unirradiated diffusion couples, an error band was constructed from the data of the unirradiated normal uranium-stainless steel diffusion specimens. The two dotted lines in Figures 6 and 7 represent a distance of one standard deviation from the least-squares mean. A standard deviation is defined by the equation

$$\sigma = \sqrt{\frac{\sum x^2}{m}} \quad (3)$$

where σ is the standard deviation, x the deviation of the individual values from the least-squares average, and m is the number of data points.

A number of samples made with normal uranium were irradiated in two test locations of the CP-3' heavy-water reactor at Argonne National Laboratory. Some of the specimens were placed in the goat hole in a flux of about 4.5×10^{11} nv and the others were in the Central Thimble VT-1 in

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a flux of about 3.2×10^{12} nv. Figures 11 and 12 show the experimental points in relationship to the error band of the unirradiated specimens. The data from which the figures were drawn and also the time each sample was at the various power levels in the reactor can be found in Tables V and VI.

The data from the goat hole specimens lie on the high side of the error band in the 2-day run (Figure 11), but data from the goat hole 4-day run and both 2- and 4-day runs at the higher flux level in VT-1 are distributed quite symmetrically within the error band.

Results from Experiments with Enriched Uranium under Irradiation

Another series of experiments was conducted with specimens made with 93% enriched uranium. A few control tests were made without irradiation to ascertain that the data from the enriched samples coincided with those from unirradiated normal uranium. Figure 13 and 14 show the data from the enriched specimens plotted with the normal uranium control error band. All points from the irradiated, enriched samples fell slightly below the error band for unirradiated normal uranium, whereas the points from the unirradiated enriched specimen fell, with one exception, within the error band. It thus appears that there is a slight decrease in diffusion due to irradiation. However, in Figures 6 and 7 it is noted that some experimental points from unirradiated, normal uranium also fell below the error band. The data from the enriched-uranium experiments are tabulated in Tables VII and VIII.

Determination of Temperature of Nucleation of Diffusion Phases

The results of the experiments to determine the minimum temperature at which the diffusion phase could be observed are tabulated in Table IX and plotted in Figure 15. The solid line in Figure 15 is an extrapolation obtained from the curves in Figure 9. It is seen that the majority of the points from the enriched uranium-stainless steel couples fit the extrapolated curve rather well. However, the points from the samples made with unirradiated normal uranium seem to fall on a curve somewhat lower than the extrapolated curve, but parallel to it. The decrease in diffusion may possibly have been caused by specimen preparation. A deviation from the straight line relationship is also quite evident at lower temperatures. The lowest temperature at which a diffusion phase was observed was 380°C , both in unirradiated normal uranium and in one specimen of the irradiated enriched uranium. In general, however, the diffusion phase was formed in the irradiated specimens at a higher temperature than in those unirradiated. There appears, therefore, to be no over-all irradiation effect on the temperature at which the phase becomes visible.

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The Iron-Rich Phase

It was previously pointed out that the width of iron-rich phase could not be measured as accurately as the uranium-rich one. However, from a practical viewpoint the diffusion of uranium in stainless steel is of considerable interest; therefore some measurements were made. The most consistent data for the formation of iron-rich zones was obtained in four-day experiments. Figure 16 shows a graph of the thickness-temperature relationship. The data for the graph is tabulated in Table X. A comparison between the least-squares equations for the formation of iron-rich compounds with those for uranium-rich compounds shows that the so-called activation energy of the former is about twice as great as that of the latter.

CONCLUSIONS

The experimental findings may be briefly summarized as follows:

- 1) The solid state reaction between uranium and stainless steel is essentially a diffusion reaction. In the range from 500°C to 700°C the activation energy of the rate constant is 42.6 kcal per mole. The general behavior in the stainless steel uranium system is analogous to that in the U-Fe system. Nucleation of the reaction product in 16 days time was first observed at 380°C.
- 2) At neutron fluxes up to 3×10^{12} nv, pile irradiation does not accelerate the diffusion rate noticeably in runs up to 16 days, nor induce the initial nucleation of diffusion reaction products to occur at temperatures lower than found in unirradiated control experiments.

Thus, the results of work on an intermetallic compound forming system are similar to several other investigations which also have found irradiation not to affect interdiffusion rates. Duwez and Johnson⁽⁴⁾ found no irradiation effects on diffusion in copper-nickel and copper-gold powder compacts. Johnson and Martin⁽⁵⁾ also were unable to ascertain an increase in diffusion rate in copper-gold samples after irradiation in a Hanford reactor. Cyclotron irradiation was found to produce no significant change in the self-diffusion in silver, according to Johnson and Martin.⁽⁶⁾

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REFERENCES

- (1) R. W. Buzzard and H. E. Cleaves: The Binary Alloys of Uranium. J. Metallurgy and Ceramics 1, 20 (1948).
- (2) B. Lustman R. F. Mehl: Rate of Growth of Intermediate Alloy Layers in Structurally Analogous Systems. Trans. AIME, IMD. 147, 369 (1941).
- (3) J. H. Kittel: Layer Formation by Interdiffusion Between Some Reactor Construction Metals, ANL-4937.
- (4) P. Duwez and R. D. Johnson: The Effect of Irradiation on Diffusion in Copper-Gold and Copper-Nickel Powder Compacts. NAA-SR-168.
- (5) R. D. Johnson and A. B. Martin: The Effect of Hanford Irradiation on the Diffusion of Gold Into Copper. NAA-SR-173.
- (6) R. D. Johnson and A. B. Martin: The Effect of Cyclotron Bombardment on Self-Diffusion in Silver. J. Appl. Phys. 23, 1245 (1952).

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APPENDIX

Some experiments were conducted to determine the relationship between the temperature of specimens, due to fission heating only, and the power level of the CP-3' reactor. Various enrichments of uranium were used in this study.

All experiments were conducted in the vertical thimbles. The diffusion specimens after swaging consisted of a uranium wire 0.038 in. in diameter in a stainless steel tube, the wall thickness of which was 0.020 in.

The diffusion specimens made with the 1 in. long wire of normal uranium showed a temperature rise of only a few degrees at a flux of 3.2×10^{12} nv. The specimens made with pieces of 93% enriched uranium wire, which were 5/64 in. long after swaging in the tube, reached a temperature of 130°C in the same flux.

Two special tests were conducted to determine the temperature at the various thermocouple positions as a function of pile power. One specimen made with an inch-long piece of 14% enriched uranium was so tested. The results are given in Table XI. The other specimen consisted of a 1/2 in. long, 14% enriched-uranium wire in a stainless-steel tube with three thermocouples attached. It was placed in Vertical Thimble II. The flux in this thimble is about 1.4×10^{12} nv at 275 KW. The results of this experiment are tabulated in Table XII. The temperatures attained in a sample made with a 1/2 in. long, 31% enriched uranium wire which was used in the experiment to determine the temperature at which the diffusion phase first becomes visible are also shown in Table XII.

Figures 17 and 18 show graphically the relationship between pile power and specimen temperature.

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Table I

THICKNESS OF URANIUM-RICH PHASE AT VARIOUS TEMPERATURES

Normal Uranium - Unirradiated - 24 Hour Experiments		
Specimen No.	Thickness of Uranium-Rich Phase (L_u) (Microns)	Temperature (T) ($^{\circ}$ K)
17	30.4	957
	24.6	932
	20.4	909
23	20.8	904
	11.6	870
	7.8	840
25	16.2	880
	13.2	865
	10.2	846
40	48.0	985
	40.4	970
	17.4	882
	30.8	941
43	50.8	992
	44.8	972
	30.4	938
	20.0	890

Least Squares Analysis Equation

$$\ln (L_u) = 13.835 - \frac{9794}{T}$$

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Table II

THICKNESS OF URANIUM-RICH PHASE AT VARIOUS TEMPERATURES

Normal Uranium - Unirradiated - 48 Hour Experiments		
Specimen No.	Thickness of Uranium-Rich Phase (L_u) (Microns)	Temperature (T) ($^{\circ}$ K)
13	17.0	867
	12.8	845
	8.6	823
15	47.8	957
	35.0	932
21	16.0	867
	12.2	845
	8.0	818
22	31.2	910
	20.2	874
	13.4	836
	5.6	791
30	24.0	901
	20.0	884
	14.4	851
32	24.2	894
	16.0	867
33	30.0	907
	20.2	882
	15.4	855
	8.2	816
38	31.2	905
	22.8	885
	17.2	855
	9.8	818
41	67.0	996
	57.2	980
	47.4	951
	20.2	886
73	2.5	731
	4.7	773
	5.3	780
	4.6	767

Least Squares Analysis Equation

$$\ln(L_u) = 13.569 - \frac{9293}{T}$$

Standard Deviation Equations

$$\ln(L_u) = 13.569 \frac{9228}{T}$$

$$\ln(L_u) = 13.569 \frac{9358}{T}$$

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Table III

THICKNESS OF URANIUM-RICH PHASE AT VARIOUS TEMPERATURES

Normal Uranium - Unirradiated - 96 Hour Experiments		
Specimen No.	Thickness of Uranium-Rich Phase (L_u) (Microns)	Temperature (T) ($^{\circ}$ K)
24	36.0	896
	27.2	872
	17.4	840
	9.2	803
27	38.2	903
	24.4	868
37	41.4	908
	28.0	879
	15.2	835
39	78.0	979
	73.6	968
	63.8	954
	46.0	923
42	80.0	976
	58.0	949
	36.6	902

Least Squares Analysis Equation

$$\ln (L_u) = 14.006 - \frac{9387}{T}$$

Standard Deviation Equation

$$\ln (L_u) = 14.006 - \frac{9427}{T}$$

$$\ln (L_u) = 14.006 - \frac{9348}{T}$$

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Table IV

THICKNESS OF URANIUM-RICH PHASE AT VARIOUS TEMPERATURES

Normal Uranium - Unirradiated - 192 Hour Experiments		
Specimen No.	Thickness of Uranium-Rich Phase (L_u) (Microns)	Temperature (T) ($^{\circ}$ K)
55	28.0	859
	57.8	896
	64.8	910
	19.6	842
75	44.0	883
	81.2	937
	100.0	966
	101.2	970
77	3.0	724
	8.0	775
	15.2	800
	14.2	798

Least Squares Analysis Equation

$$\ln(L_u) = 14.112 - \frac{9175}{T}$$

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Table V

THICKNESS OF URANIUM-RICH PHASE AT VARIOUS TEMPERATURES

Normal Uranium - Irradiated - 48 Hour Experiments			
Specimen No.	Integrated Flux (nvt)	Thickness of Uranium-Rich Phase (L_u) (Microns)	Temperature (T) ($^{\circ}$ K)
45	$\sim 5 \times 10^{16}$	19.6	867
	*	44.4	949
46	$\sim 5 \times 10^{16}$	52.6	963
	*	38.4	939
47	$\sim 5 \times 10^{16}$	59.0	971
	*	24.4	881
		42.2	945
49	4.8×10^{17}	35.8	928
	**	55.2	970
		62.0	983
		14.0	850
		2.0	717
50	4.7×10^{17}	26.2	917
	**	42.2	950
		48.8	964
		50.0	965
51	4.6×10^{17}	48.0	970
	**	40.4	956
		24.2	920

*Flux at full power = 4.5×10^{11} nv. Variations not recorded.

**Flux at full power = 3.2×10^{12} nv.

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Table VI

THICKNESS OF URANIUM-RICH PHASE AT VARIOUS TEMPERATURES

Normal Uranium - Irradiated - 96 Hour Experiments			
Specimen No.	Integrated Flux (nvt)	Thickness of Uranium-Rich Phase (L_U) (Microns)	Temperature (T) ($^{\circ}K$)
44	$\sim 1 \times 10^{17}$ *	34.2	885
		52.4	943
		70.0	962
		77.2	979
48	$\sim 1 \times 10^{17}$ *	13.6	830
		56.4	945
		39.8	905
		59.2	961
52	7.7×10^{17} **	4.2	756
		21.0	861
		37.8	912
		65.4	953
53	1.00×10^{18} **	7.4	778
		26.2	877
		46.4	919
		60.0	951
		65.8	956
54	1.03×10^{18} **	34.2	894
		51.2	938
		66.0	952

*Flux at full power = 4.5×10^{11} nv. Variations not recorded.

**Flux at full power = 3.2×10^{12} nv.

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Table VII

THICKNESS OF URANIUM-RICH PHASE AT VARIOUS TEMPERATURES

93% Enriched Uranium - 48 Hour Experiments			
Specimen No.	Integrated Flux (nvt)	Thickness of Uranium-Rich Phase (L_u) (Microns)	Temperature (T) ($^{\circ}$ K)
74	*	30.4	916
72	*	41.8	948
		28.2	907
		41.2	942
		48.6	961
79	*	44.0	954
61	$5.2 \times 10^{17} **$	37.0	954
63	$5.5 \times 10^{17} **$	17.0	877
64	$4.8 \times 10^{17} **$	25.0	916

*Unirradiated.

**Flux at full power = 3.2×10^{12} nv.

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Table VIII

THICKNESS OF URANIUM-RICH PHASE AT VARIOUS TEMPERATURES

93% Enriched Uranium - 96 Hour Experiments			
Specimen No.	Integrated Flux (nvt)	Thickness of Uranium-Rich Phase (L_U) (Microns)	Temperature (T) ($^{\circ}K$)
71	*	18.0	844
		45.0	920
		66.0	960
		64.6	962
		42.2	932
66	$1.06 \times 10^{18}^{**}$	24.2	883
62	$9.8 \times 10^{17}^{**}$	65.6	963

*Unirradiated.

**Flux at full power = 3.2×10^{12} nv.

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Table IX

THICKNESS OF URANIUM-RICH PHASE AT VARIOUS TEMPERATURES

16 Day Experiments			
Specimen No.	Integrated Flux (nvt)	Thickness of Uranium-Rich Phase (L_U) (Microns)	Temperature (T) ($^{\circ}K$)
82	**	1.0	653
		1.6	673
		3.8	722
		5.0	737
87	**	1.4	693
		8.0	733
89	**	1.0	669
		3.0	691
		6.0	723
		4.2	700
88	$\sim 1 \times 10^{18}$	1.0	674
	***	3.6	693
		1.0	655
86	$\sim 1 \times 10^{18}$	62.8	885
	***	7.6	775

*Normal uranium. All other specimens in table are 31% enriched.

**Unirradiated.

***Flux at full power = 1.4×10^{12} nv. Variations not recorded.

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Table X

THICKNESS OF IRON-RICH PHASE AT VARIOUS TEMPERATURES

Normal Uranium - Unirradiated - 96 Hour Experiments	
Thickness of Iron-Rich Phase (L_{Fe}) (Microns)	Temperature (T) (°K)
1.0	845
1.8	865
1.3	839
2.2	872
4.0	896
3.0	879
5.2	906
2.1	879
14.8	955
15.0	970
17.8	982
4.6	901
12.3	950
20.0	977
3.0	867
5.0	904

Least Squares Analysis Equation

$$\ln (L_{Fe}) = 20.183 - \frac{16,844}{T}$$

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Table XI

TEMPERATURE AS A FUNCTION OF PILE POWER AT DIFFERENT
THERMOCOUPLE POSITIONS FOR 14% ENRICHED URANIUM
IN VERTICAL THIMBLE I

Pile Power (KW)	Temperature (°C)				
	T.C. Position 1	T.C. Position 2	T.C. Position 3	T.C. Position 4	T.C. Position 5
50	78	92	102	102	92
100	120	146	160	160	146
150	168	208	222	224	210
175	192	237	253	258	241
200	213	262	284	289	272
225	235	289	313	317	297
250	258	317	340	346	322
275	280	348	370	375	252

Table XII

TEMPERATURE AS A FUNCTION OF PILE POWER AT DIFFERENT
THERMOCOUPLE POSITIONS FOR 14% AND 31% ENRICHED
URANIUM IN VERTICAL THIMBLE II

Pile Power (KW)	Temperature (°C)				
	T.C. Position 1	T.C. Position 2	T.C. Position 3	T.C. Position 4	Uranium Enrichment
75	47	54	49		14%
175	73	86	77		14%
275	91	120	100		14%
275	95	104	140	184	31%

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Figure 3.

Diagram of Power Wiring for Diffusion
Specimen and Auxiliary Heater

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Figure 4. Cross section of uranium-stainless steel diffusion specimen after annealing.

Micro 14222

(Polarized Light)

100X

1. Uranium core.
2. Uranium-rich phase.
3. Iron-rich phase.
4. Stainless-steel jacket.

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Figure 9.

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