ARGONNE NATIONAL LABORATORY
P. O. Box 299
Lemont, Illinois

IRRADIATION OF PROTOTYPE CP-4 (EBR-I) REACTOR
FUEL SLUGS IN THE CP-3' GOAT HOLE

by

S. H. Paine, P. J. Persiani and W. F. Murphy

Final Report of Metallurgy Division

Program 6.1.1

Partial reports of this work have appeared in sections of the following ANL reports:

- ANL-4596, W. H. Zinn, "Change in Length of Uranium Metal Under Irradiation," Reactor Eng. and Services Div. Quarterly Report, p. 29, (February, 1951).
- ANL-4650, W. H. Zinn, "Change in Length of Uranium Metal Under Irradiation," Reactor Eng. and Services Div. Quarterly Report, p. 18, (May, 1951).
- ANL-4670, S. H. Paine, Jr., "Measurement of Physical Properties of Irradiated Materials in Metallurgy Hot Laboratory," Hot Laboratories and Equipment Information Meeting, p. 113, (May 16-18, 1951).
- ANL-4689, "EBR Project (CP-4)," Monthly Progress Report, pp. 12-13, (September, 1951).
- ANL-4736, W. F. Murphy and S. H. Paine, "Goat Hole Exposures of U^{235} Cylinders," Metallurgy Div. Quarterly Report, p. 77, (September, 1951).

August, 1958

Operated by The University of Chicago
under
Contract W-31-109-eng-38

DISCLAIMER

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

DISCLAIMER

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

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	5
A. INTRODUCTION	5
B. DESCRIPTION OF TESTS	6
C. DISCUSSION OF RESULTS	9
Visual Examination	11
Changes in Dimensions	11
Experimental Variables	12
D. CONCLUSIONS	13
ACKNOWLEDGMENTS	14
REFERENCES	14
APPENDIX I Metallurgical History of Specimens	15
APPENDIX II Irradiation History and Computation of Burnup .	17
APPENDIX III Experimental Data	23

REPORTS ISSUED FOR PROGRAM 6.1.1

- ANL-5537 "Preliminary Studies of Irradiation Damage to Uranium-Zirconium Alloys," S. H. Paine, F. L. Brown and W. F. Murphy (October, 1956).
- ANL-5538 "Pin-Cushion Irradiation Tests of Uranium and Its Zirconium Alloys," S. H. Paine and F. L. Brown (July, 1958).
- ANL-5854 "Pin-Cushion Irradiation Tests of Uranium-Chromium Alloys," S. H. Paine and F. L. Brown (July, 1958).
- ANL-5855 "Irradiation of Prototype CP-4 (EBR-I) Reactor Fuel Slugs in the CP-3' Goat Hole," S. H. Paine, P. J. Persiani and W. F. Murphy (August, 1958).

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1	Wrought Uranium Specimens after 700 Thermal Cycles Between 100°C and 550°C	6
2	Cutaway Diagram of Vertical Dilatometer Capsule	7
3	Radiograph of Horizontal Dilatometer Capsule	8
4	Section Through End of Goat Hole Stringer in which the Horizontal Capsules were Irradiated	8
5	Macrographs Comparing Appearance of Specimens Irradiated Vertically with Those Irradiated Horizontally . . .	9
6	Stereomacrographs of U ²³⁵ Slugs Irradiated in Horizontal Position	22

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I	Summary of Property Changes in U ²³⁵ Specimens	10
II	Irradiation History of Slugs in CP-3' Reactor	17
III	Neutron Flux Measurements Obtained with Cd-In and Dy Foils	18
IV	Determination of Burnup in Vertical Dilatometer Specimens by Cs ¹³⁷ Analysis	20
V	Dilatometer Measurements	23
VI	Pre- and Post-Irradiation Measurements of Specimens	24

IRRADIATION OF PROTOTYPE CP-4 (EBR-I) REACTOR FUEL SLUGS IN THE CP-3' GOAT HOLE

by

S. H. Paine, P. J. Persiani and W. F. Murphy

ABSTRACT

Experiments are described which studied the effect of irradiation upon small U^{235} cylinders simulating in size those designed for the initial CP-4 (EBR-I) fuel loading. Qualitative similarities between thermal cycling and irradiation effects were found, but none of the three types of material tested were entirely dimensionally stable.

A. INTRODUCTION

The first fuel loading of Argonne National Laboratory's CP-4 experimental breeder reactor (EBR-I) was initially specified on the basis of thermal cycling tests performed by L. R. Kelman. These showed that specimens of wrought uranium heated briefly in the beta phase temperature range and critically quenched in water maintained their dimensions and surface smoothness much better during subsequent thermal cycling than did specimens prepared in other ways. During the tests it was also shown that the most radical elongation behavior could be expected from uranium rolled in the low alpha temperature range without further treatment above the alpha range, whereas the most radical surface roughening occurred in uranium which had been slow-cooled from the beta range.⁽¹⁾ Figure 1 is a macrophotograph which illustrates these effects.

Very little was known about the irradiation behavior of uranium cylinders sized like the proposed EBR fuel, although foils were known to disintegrate^(2,3) and heavy rods of the Chalk River NRX were known to have a tendency to elongate somewhat. It had been proposed that the reactor fuel loading be operated to accumulate 0.1% total atom burnup, and a test was needed to determine whether beta quenched uranium would have adequate stability at this exposure level. It was also desired to know whether thermal cycling behavior could be correlated with irradiation effects.

It was, therefore, decided to irradiate U^{235} cylinders prepared by the three heat treatments mentioned above and similar in size to the slugs designed for EBR-I. The ANL-CP-3' reactor was available as a test

facility, but massive U^{235} specimens were barred from the vertical thimbles for safety reasons. Therefore, the exposures were performed in the graphite reflector in a biological experimental facility known as the "goat hole." Two experiments were performed under different conditions of encapsulation and at different fission rates. They are described in this report, together with the experimental results.

Figure 1. Wrought uranium specimens after 700 thermal cycles between 100°C and 550°C . Specimens were all originally identical in size and appearance. Left to right, Group 1) Alpha annealed, Group 2) Beta annealed, Group 3) Beta quenched. (L. R. Kelman⁽¹⁾.)

B. DESCRIPTION OF TESTS

Two sets of three cylindrical U^{235} specimens $1/4$ " in diameter and 1" long were prepared, each set containing one specimen of each of the following metallurgical conditions:

- (a) Alpha annealed; fine grained material having a strong rolling texture,
- (b) Beta annealed; coarse grained material, rolling texture removed by the heat treatment,
- (c) Beta quenched; fine grained material, rolling texture removed by the heat treatment.

Fabrication of these specimens is described in Appendix I. Careful measurement of dimensions, surface roughness, density and hardness were made before preparation for irradiation.

One set was encapsulated in individual vertical dilatometers which closely simulated the engineering configuration of the EBR-I fuel rods and were designed to place little, if any, restraint upon the specimens (See Figure 2). A flexible diaphragm-type closure at the top connected to a feeler rod which permitted the length of the specimen to be measured without removing it from its capsule.

Figure 2. Cutaway Diagram of Vertical Dilatometer Capsule.

The other set was encapsulated in individual horizontal dilatometers which were also designed to place minimum restraint on the specimens while permitting length measurements without removal from the capsule. Flexibility in this design was provided by a sylphon bellows around the specimen which was intended to permit periodic radiographic study of gross distortions (See Figure 3). Both the vertical and horizontal dilatometers transferred fission heat from the specimens by means of a small volume of liquid NaK alloy.

Figure 3
Radiograph of Horizontal
Dilatometer Capsule with
Specimen in Place.

The dilatometer assemblies were irradiated in special stringers in the goat hole facility. The vertical capsules occupied three graphite stringers and were cooled by flow of air from a blower which exhausted to the reactor ventilation stack. The horizontal capsules were placed in three channels spaced equilaterally in a fourth stringer (See Figure 4) and cooled by regulated air flow from a compressor which exhausted to the reactor cooling tower. Thermocouples located in wells adjacent to the specimens indicated that temperature within the uranium probably did not exceed 75°C during irradiation.

Irradiation of the vertical dilatometers was interrupted twice for length measurements before the final examination. At the time of the second interruption the beta annealed specimen was removed from its capsule for visual examination, and its irradiation was terminated. The horizontal dilatometers were removed once for measurement before final examination.

During the course of the irradiations special tests were made to determine the average flux in the specimens, from which total atom burnups could be computed. According to these data, all specimens except the beta annealed one mentioned above integrated approximately the same average total atom burnups, which did not exceed 0.02%. Further details of irradiation history and of the burnup determinations appear in Appendix II.

Figure 4. Longitudinal Section Through End of Goat Hole Stringer in which Horizontal Capsules were Irradiated.

C. DISCUSSION OF RESULTS

Pre- and post-irradiation data are given in Appendix III. The visual appearance of all specimens after irradiation is shown in Figure 5, and a summary of property changes is given in Table I.

Figure 5. Macrographs Comparing Appearance of Specimens Irradiated Vertically^(a) with Those Irradiated Horizontally^(b). Magnification 3-X.

Table I

SUMMARY OF PROPERTY CHANGES IN U^{235} SPECIMENS

Heat Treatment and Property Changed	Degree of Change at Indicated Per Cent Average Depletion of U^{235}		
	Vertical Capsule Irradiation		Horizontal Capsule Irradiation
	0.011%	0.019%	0.019%
<u>Alpha Annealed</u>			
Length (% Change)		2.5	4.1
Diameter (% Change)		-0.8	-0.8
Density (% Change)		-0.10	-0.09
Hardness Increase (R_A)		6.0	13.5
% Change in Roughness, Referred to Diameter		-1.04	-0.64
<u>Beta Annealed</u>			
Length (% Change)	0.34		0.4
Diameter (% Change)	0.36		2.4
Density (% Change)	-0.09		-0.10
Hardness Increase (R_A)	6.0		13.0
% Change in Roughness, Referred to Diameter	0.56		1.28
<u>Beta Quenched</u>			
Length (% Change)		0.5	0.5
Diameter (% Change)		0.9	0.7
Density (% Change)		-1.0	-0.10
Hardness Increase (R_A)		1.0	9.0
% Change in Roughness, Referred to Diameter		0	0.08

The total burnup obtained was only 20% of what had been anticipated and all the changes, therefore, are small. It was found, under these circumstances, that the dilatometers gave spurious length indications (see Appendix III) so that progress of elongation could not be detailed with certainty. Radiographs were also deemed useless under near null conditions, so these were not made.

Visual Examination

Comparison of Figure 1 with Figure 5 reveals a striking similarity in the appearance of thermal cycling and irradiation surface effects. The roughening on the irradiated specimens is not as radical as on the examples from thermal cycling, but to the eye it appears very much the same qualitatively. That the irradiation effect is not due to thermal cycling during irradiation has been conclusively proved by single crystal tests performed since completion of this experiment.⁽⁴⁾ Therefore, the similarity is to be attributed to equivalent grain sizes and equivalent textures in this particular experiment.

Differences in the appearance of vertical and horizontal specimens are seen in Figure 5.

(1) The horizontal beta annealed specimen is much rougher than its counterpart. However, it will be recalled that the former was removed from test at a considerably lower burnup level than the latter, and therefore should be expected to be smoother.

(2) In the case of the beta quenched specimens, the vertical specimen appears definitely rougher than the horizontal. This is apparently due to surface oxidation of the former. During irradiation it lost approximately 0.2 grams of weight and was covered with a powdery black oxide when removed from its capsule. Losses on each of the other specimens did not exceed a milligram.

(3) Finally, the vertical alpha annealed specimen is unaccountably somewhat rougher to the eye than its counterpart.

Changes in Dimensions

Roughening of specimens creates an obvious difficulty in interpreting post-irradiation dimensional measurements. For this reason the profile traces before and after irradiation were carefully analyzed for all specimens, and a percent change in roughness, referred to the specimen diameter, has been included in Table I. These numbers may be regarded as corrections to be subtracted from the recorded percent change in diameter. If it be assumed that end roughening is equivalent to side roughening of the specimens, these numbers may also be used (multiplied by the factor 0.25) to correct the recorded percent changes in length.

Analysis of the dimensional data shows a very small positive elongation for the beta quenched, and a similar effect 5 to 8 times as great for the alpha annealed material. The change in the beta annealed condition is probably null or slightly negative, inasmuch as the change in surface roughening is of the same magnitude or greater than the recorded length change, and in the same direction.

This behavior correlates inversely with expansion coefficient measurements made on three of the specimens before irradiation. The beta annealed material had an elongation rate of $13.6 \times 10^{-6}/^{\circ}\text{C}$, the beta quenched rate was 12.1×10^{-6} and the alpha annealed rate was 6.4×10^{-6} . The 13.6 value approaches the condition of complete randomness of orientation, and the other numbers show varying degrees of preferential orientation of the [010] along the specimen axis. The correlation seems sensitive enough to provide a basis of prediction concerning irradiation growth of specimens.

The elongation behavior also tends to correlate with effects produced by thermal cycling. However, Figure 1 does not show any difference in the behavior of thermally cycled beta quenched and beta annealed specimens, whereas there is a slight difference under irradiation. This may be due to some variation in heat treatment, or it may mean that correspondence between the two effects is limited to materials having pronounced textures. In either case this experiment yields no information which would permit more than the qualitative correlation just mentioned.

A further caution concerning the elongation data is in order. Most of the damage in U^{235} specimens of massive size when irradiated in a thermal flux is concentrated at and near the surface. In these cylinders the depth required to completely absorb the neutron flux must be small indeed, for the assumption that flux current into the specimens is equal to the surface flux yields the right burnup value (see Appendix II). Therefore, the interior volume must be regarded as remaining essentially undamaged while the surface layer is subject to high damage. The growth behavior of specimens under such conditions should be expected to differ from the behavior of specimens irradiated to the same average burnup levels but having a more uniform damage distribution. Operation of the EBR-I has shown that fast fission elongation rates are larger than those predicted by this experiment.

Experimental Variables

The reactor was shut down periodically to permit normal servicing and changing of experiments. These events may be regarded as mild thermal cycles. However, studies of the effect of cycling variables upon thermal cycling growth⁽⁵⁾ seem to indicate that temperature spans as low as 50°C and ambient cooling rates such as would be found in the graphite reflector could produce no appreciable growth by the thermal cycling mechanism.

Comparison of data in Table I indicates that the two experimental methods produced the following differences in behavior of the test specimens: (1) Hardnesses of the horizontal capsule specimens increased most, (2) the alpha annealed specimen from the horizontal test elongated

60% more than its counterpart in the vertical experiment, and (3) the beta quenched specimen from the vertical test decreased in apparent density an order of magnitude more than its counterpart in the horizontal capsule.

The first two differences may have a common basis. They may indicate that the single foil experiment, on which the recorded atom burnup in the horizontal specimens is based, is in error and that these specimens achieved appreciably higher burnup. The possibility cannot be entirely ruled out, on the other hand, that the observed effects are due to differences in irradiation temperature. In view of the low temperature of the irradiations the first alternative seems more probable than the second.

The third item listed above, upon consideration of all the data, may be explained as an overheating event involving only the vertical beta quenched specimen. The post-irradiation appearance of this specimen (Figure 5a) suggests that some surface scale may be present. The negligible hardness change also indicates that the specimen has been overheated. It is conceivable that the dilatometer leaked air and permitted an oxide heat transfer barrier to form on the specimen surface, or that the air cooling was interrupted late in the irradiation long enough to permit annealing of the hardness damage and scavenging of oxygen from NaK in the dilatometer. The first explanation is perhaps more plausible than the second. A leakage of some 50 mg of oxygen would be required by a U_3O_8 reaction to produce the observed weight loss and excessive density change. More than 0.3 g of oxide would be produced, of which only about 85 mg would have to remain attached to the specimen. These hypothetical data agree quite well with the qualitative evidence found when the specimen was removed from its dilatometer, and provide a reasonable explanation of the anomalous density and hardness changes.

D. CONCLUSIONS

The findings may be summarized as follows:

(1) Irradiation in a thermal flux caused alpha annealed U^{235} cylinders to elongate markedly; beta annealed specimens showed little or no dimensional change; and beta quenched specimens slightly more. Surface roughening correlated with grain size and preferred orientation in the specimens.

(2) The irradiation changes are qualitatively similar to those seen in comparable specimens which have been thermally cycled, but no basis for a quantitative correlation is seen.

(3) The irradiation elongation behavior correlates with pre-irradiation thermal expansion coefficient measurements made on the specimens. Sensitivity of this correlation appears good, and it should be investigated more carefully.

(4) Use of the experimental data quantitatively to predict the behavior of U^{235} in a fast neutron flux is not warranted, because of radical differences in distribution of radiation effects within the specimens.

ACKNOWLEDGMENTS

Specimens were fabricated by A. B. Shuck, Metallurgy Division. The vertical dilatometer experiment was designed and expedited by W. H. Zinn and H. V. Lichtenberger, Reactor Engineering Division. J. L. Armstrong, Central Shops, designed the horizontal capsule apparatus. Technical assistance during the course of the irradiations was given by F. R. Taraba, J. H. Kittel, P. Tedeschi, G. J. Deily and F. Pausche, of the Metallurgy Division, and by O. Hillig and H. Johnson, Reactor Engineering Division. F. L. Brown and S. T. Zegler, Metallurgy Division, performed the photography and measured expansion coefficients, respectively.

REFERENCES

1. Kelman, L. R., "Dimensional Changes in Uranium Under Thermal Cycling," J. Met. and Ceramics, TID-68, 4, 7-40 (September 1949).
2. Weber, C. B., "Beta Experiment Observations," (1948-1949) Nuclear Eng. Course, KAPL-545 (May 1949).
3. Lambert, J. B., "Special Request KAPL-79; The 'Beta' Experiment," HW-25330, (August 1952).
4. Paine, S. H. and Kittel, J. H., "Analysis of Irradiation Growth in Single Crystals of Uranium," ANL-5676 (1958).
5. Mayfield, R. M., "The Effect of Cycling Variables Upon the Growth Rate of 300°C Rolled Uranium," ANL-4905 (June 1952).

APPENDIX I

Metallurgical History of Specimens

The specimens were 0.25" x 1" cylinders of highly enriched uranium, fabricated as follows:

Original Bar received as 5/8" round, 4.490" long, weight 460 grams. Chemical Analysis at Y-12 showed (ppm) C - 105, Al - 5, B - 0.8, Be - 0.02, Ca - 10, Fe - 45, Li - 0.2, Mg - 4, Na - 1, Si - 65. (Spectrographic)

Rolling was done at 300°C in nine passes; .624" -- .610" -- .564" -- .520" -- .480" -- .443" -- .409" -- .390" -- .380". (Diameter)

Annealed 600°C 1 hour, slow cooled.

Swaging was done at 300°C in eight passes; .380" -- .363" -- .341" -- .322" -- .300" -- .283" -- .265" -- .249". (Diameter)

Cutoff of 1" pieces was accomplished by girdling with a V-notch, chilling in liquid N₂, and fracturing.

Heat Treatment was varied to produce three types of structure which have been of interest in thermal cycling studies.

(1) Fine grain, preferred orientation; secured by annealing the as-swaged material one hour at 575°C in vacuum, followed by furnace cool. The vacuum furnace work was done at about 3×10^{-5} mm.

(2) Coarse grain, random orientation; secured by annealing two hours at 725°C, followed by furnace cool. Specimens were re-annealed one hour at 575°C in vacuum and slow cool.

(3) Fine grain, random orientation; secured by heating rapidly into the beta range and water quenching. Heating was by induction, in an argon atmosphere. A Tocco machine using a 20-turn coil 1.5" I.D. x 7" long, balanced with 180 kva capacitance, was operated at 110 volts, 7.5 amps, 8.5 kw, with a -14% to -16% kilovar power factor, for 22.5 seconds, followed immediately by the quench. Specimens were stress-relieved one hour at 575°C in vacuum and slow cooled.

Finishing was performed by cleaning up the fractured end surfaces in a lathe and bright electropolishing all over.

Identification of specimens was accomplished by marking with Rockwell A hardness indentations, as follows:

Heat Treatment	Lot No.	MET-No.	Marks of Rockwell A
Alpha anneal	(3-44-1a6e	V-11	(....)
	(3-44-1a6f	H-12	(... ..)
Slow beta anneal	(3-44-1a6c	V-17	(...)
	(3-44-1a6d	H-18	(... ..)
Fast beta quench	(3-44-1a6a	V-5	(..)
	(3-44-1a6b	H-6	(... ..)

APPENDIX II

Irradiation History and Computation of BurnupReactor Log Data

The CP-3' reactor normally operated at a level of 275 KW during the course of the experiment. Dates of insertion and removal, and KWH of reactor power integrated during the exposures are listed in Table II, together with equivalent time of exposure, based on a constant 275 KW operating level. Nominal unperturbed flux reported for the goat hole graphite was 3.5×10^{11} nv, at an average temperature of 40° C.

Table II

IRRADIATION HISTORY OF SLUGS IN CP-3' REACTOR

Irradiation Periods		KWH of Reactor Operation		275 KW Equivalent Irradiation Time (10 ⁶ sec)
In	Out	Period Totals	Cumulative Totals	
<u>Vertical Experiments</u>				
11-21-50	2-19-51	326,562	326,562	4.275
2-26-51	6-22-51	477,345	803,907	10.524
7- 9-51	10-22-51	437,347	1,241,254	16.249
<u>Horizontal Experiments</u>				
1- 8-51	3-12-52	1,748,430	1,748,430	22.889
3-24-52	12-24-53	2,416,975	4,165,405	54.529

Flux Measurements

Unknown flux perturbation factors caused by absorption of the specimens made initial computations of anticipated burnup very uncertain. Therefore, after the beta annealed specimen was removed from its vertical dilatometer it was replaced with a Cd-In alloy sample (14.1% Cd, 85.9% In by weight) having identical dimensions and a macroscopic cross section approximating enriched uranium. After irradiating for 0.22 kw hr, the sample was melted at 135° C and stirred continuously to insure homogeneity of the active atoms throughout the melt. The molten alloy was solidified by dropping it into a beaker of acetone. This was then rolled to a thickness of 1 mil. Foils were made having an area of 1 cm² and the activities were

compared with foils of similar composition and dimensions which had been irradiated in the standard pile. In order to avoid introducing a correction for the Cd^{117} (2.8h) and Cd^{115} (2.3d) activities the time interval from end of irradiation to completion of counting all foils was kept low and did not exceed six hours. This procedure limited the Cd activity error to the order of 0.1%.

A similar experiment was performed to determine the flux perturbation in the horizontal dilatometers. One of them was removed from the graphite stringer and replaced by a dummy capsule having a Cd-In cylinder in the specimen position.

In both the experiments the flux in the specimen foil is related to the average flux in the standard foil by the ratio of the activities after making cadmium ratio corrections. The cadmium ratios in the standard pile and in the reactor position were 5.8 and 17 respectively. A 5% correction was made on the unperturbed flux in the standard pile for the depression of the flux and self shielding factor. Results obtained from these measurements indicated total average flux perturbations of 95.3% in the vertical, and of 98.6% in the horizontal dilatometer positions. The residual fluxes in both positions turned out to be half an order of magnitude smaller than had been anticipated. They are listed in Table III.

Table III

NEUTRON FLUX MEASUREMENTS OBTAINED WITH DYSPROSIUM
AND CADMIUM-INDIUM FOILS

Position in Goat Hole	Surface Flux ⁽¹⁾		Volume Flux ⁽²⁾ Average 10^{10} nv	% Flux Attenuation ⁽³⁾	
	Range 10^{10} nv	Average 10^{10} nv		Average Surface	Average Volume
Vertical Dilatometer					
Top of Specimen	9.0 to 23.0	7.8			
Middle of Specimen	6.8 to 12.0	8.0			
Bottom of Specimen	13.0 to 23.0	9.2			
Average for entire Specimen		8.0	1.64	77.1	95.3
Horizontal Dilatometer					
Average for entire Specimen			.49		98.6

(1) By dysprosium foils

(2) By cadmium-indium foils

(3) Based on a reported unperturbed flux of 3.5×10^{11} nv.

Inasmuch as the Cd-In experiments monitored only the average volume flux in the specimen, another experiment was performed in a vertical dilatometer to investigate the flux distribution on the cylindrical surface. Dysprosium foils were wrapped around a Cd-In cylinder and activated in the graphite stringer. One of the foils was calibrated against a standard dysprosium foil to obtain an absolute measurement. The results of this test appear in Table III. It will be seen that the range of measurements at top, middle and bottom circumference is large. This is quite probably due to heavy "shading" on the side farthest from reactor core. A strong Wilkins effect makes the flux at the extreme edges of the ends unduly large, and it will be seen that the graphically determined averages are not greatly influenced by it.

The foil measurements give the following relationship between average flux within the specimen and the average flux at its surface:

$$\bar{\phi} = 0.205 \phi_s \quad (1)$$

This relationship may also be computed according to diffusion theory, $\Sigma_a = 595b$ and a U^{235} content of 93.5% in the Bessel function

$$\frac{\bar{\phi}}{\phi_s} = \frac{2}{Kr_0} \frac{I_1(Kr_0)}{I_0(Kr_0)} \quad (2)$$

Here K is the sum of the macro cross section for absorption and the cross section for scattering. It happens that this computation gives exactly the same coefficient seen in equation (1). The contributions made by the end surfaces are ignored, however, so the agreement is not quite as good as indicated.

Burnup Determinations.

Burnups may be computed from the data in Tables II and III. Using a cross section of $\Sigma_f = 495$ barns for fission at 40°C, the Cd-In foil data yield total atom burnup values of 0.0132% for both the vertical and horizontal experiments. If the average surface flux, ϕ_s , in the Dy foil experiment is assumed to be equal to the current, J , into the cylinders, the burnup turns out to be 0.0192%. If the Fermi relationship, $\phi_s = \sqrt{3} \cdot J$, is used, the result is 0.0111%. Inasmuch as the Fermi distribution is based on an infinite plane black body, this number would certainly be a lower limit and one would expect a small finite cylinder to have an appreciably greater factor than $\sqrt{3}$.

It should be pointed out that all the foil measurements were taken in one specimen position. The assumption that they apply equally to all specimens is, therefore, only a first approximation. Since the time when burnup estimates were of importance in the engineering of CP-5 the three specimens

irradiated in vertical dilatometers have been processed by the Chemical Engineering Division and burnups have been determined by Cs^{137} radiochemistry. The final analyses are as follows:

Table IV

DETERMINATION OF BURNUP IN VERTICAL DILATOMETER
SPECIMENS BY Cs^{137} ANALYSIS

Metallurgical Condition	Length of Irradiation, 10^6 sec	Total Atom Burnup, %
Alpha annealed	16.2	0.0185
Beta annealed	10.5	0.0110
Beta quenched	16.2	0.0190

Extrapolation of the beta annealed burnup result to the irradiation time of the other two specimens gives a value of 0.0170%, which is approximately 10% lower than the other two analyses. Relative accuracy of the radiochemical method is usually considerably better than this, so it is probable that this difference is real. No burnup analyses were made of the horizontal dilatometer specimens. The similarity between the Cd-In foil results in the two experiments however, indicates that the burnup was probably slightly less than 0.02%.

Temperature of Irradiation

As has been mentioned, it was hoped that the burnup integrated in the specimens would be in the order of 0.1% of total atoms. Air cooling was provided to keep metal temperatures below 150°C maximum at heat outputs of 100 watts per specimen. If a final total atom burnup of 0.02% is accepted as maximum, this would correspond to heat outputs of 14.2 and 4.2 watts for the vertical and horizontal experiments, respectively. Under such conditions of heating and cooling it is very doubtful that actual metal temperatures would normally exceed 75°C. The recorded temperatures differed very little from ambient in the goat hole.

APPENDIX III

Experimental Data

Appearance of Specimens

The machined surfaces on the specimens were roughened somewhat by a subsequent etching and electrolytic polish. No photographic record was made before irradiation, but careful surface profiling was done, and a verbal description of the appearance of the surfaces as seen under a low power binocular microscope was recorded. Profiling was repeated after irradiation, and stereobinocular photographs were made of 3 specimens (see Figure 6).

(1) Alpha Annealed Specimens

Surface texture on the alpha annealed specimens seemed slightly coarser than the other specimens before irradiation. The chemical treatment had developed a faint general trace of longitudinal fibrous structure with a few more pronounced markings. Deformations at the hardness indentations were very regular. Profiling showed a duplex pattern in which a fine structure, 0.0001" to 0.0004" deep and approximately 0.001" wide, was superposed on a grosser structure 0.0008" to 0.0015" deep and 0.010" wide. This caused a variance in radius of ± 0.0017 " for V-11 and of ± 0.0013 " for H-12.

Post-irradiation measurements showed that the fine structure was gone and that the surface contours had smoothed out so that radial variance was only ± 0.0004 " for V-11 and ± 0.0005 " for H-12. Visual appearance is shown in Figure 5 and Figure 6.

(2) Beta Annealed Specimens

Surface texture of these specimens seemed finer than the other specimens before irradiation, and the profile interpreted this visual appearance as an absence of the gross pattern observed in the alpha annealed specimens. A few pronounced longitudinal striations were seen. Hardness marks were irregular and there was a tendency for the metal to pile up at one side of the depressions. Radial variance of ± 0.0017 " for V-17 and ± 0.0012 " for H-18 was found by measurement of the profile envelope.

Post-irradiation radial variance was ± 0.0024 " for V-17 and ± 0.0028 " for H-18. The fine profile structure and the longitudinal markings were replaced by a gross pattern in which individual burnups averaged approximately 0.025" in diameter. These may be seen in the figures (Figures 5 and 6). The horizontal dilatometer specimen (H-18) is visibly rougher than the vertical specimen (V-17) because of the shortened neutron exposure of the latter.

Figure 6. Stereo-Macrographs of U-235 Slugs Irradiated in Horizontal Position to 0.02% Total Atom Burnup.

17003, 17001, 17002

2X

Heat Treatments: a) Alpha anneal; b) Beta anneal; c) Beta quench.

(3) Beta Quenched Specimens

Surface texture was fine, and no longitudinal markings appeared. The hardness marks were regular in shape. Profile pattern was duplex and very similar to that produced by the alpha annealed specimens. Radial variance for V-5 was ± 0.0017 , and for H-6 ± 0.0016 .

Post-irradiation radial variance was essentially unchanged in both specimens, but the fine profile pattern was erased and only the rougher contour having bumps which averaged approximately 0.010" in diameter remained.

Property Measurements

The dilatometer length changes after each exposure are given in Table V. No rational basis for normalizing these data to the observed lengths of specimens after final exposure can be found.

Table V

DILATOMETER MEASUREMENTS

Specimen Number	Increase in Dilatometer Length (in.)		
	After First Exposure	After Second Exposure	After Third Exposure
<u>Beta Quenched</u>			
V-5	0.0004	0.0005	0.0118
H-6	0.0040	0.0059	
<u>Alpha Annealed</u>			
V-11	0.0056	0.0152	0.0335
H-12	0.0123	0.0444	
<u>Beta Annealed</u>			
V-17	0.0000	0.0056	
H-18	0.0019	0.0059	

Pre- and post-irradiation dimensional measurements are given in Table VI. The lengths are an average of four observations, with an average variance of ± 0.0002 " before and ± 0.0015 " after irradiation. Diameters are the average of approximately ten readings, with the average variance of ± 0.0005 " for alpha annealed and ± 0.0010 " for beta annealed and beta quenched specimens before irradiation. These numbers became ± 0.0018 " and ± 0.0013 ", respectively, after irradiation.

Densities were obtained by immersion in CCl_4 . The data in Table VI are the average of at least two, and usually 4 determinations.

Table VI

PRE- AND POST-IRRADIATION MEASUREMENTS OF SPECIMENS

Heat Treatment	Specimen No. (1)	Length (in.)		Diameter (in.)		Density (g cm^{-3})		Hardness (R_A)	
		Before	After	Before	After	Before	After	Before	After
Alpha anneal	V-11	1.0003	1.0256	0.2470	0.2451	18.776	18.758	56.0	62.0
	H-12	1.0000	1.0405	0.2470	0.2450	18.776	18.759	56.0	73.5
Beta anneal	V-17 ⁽²⁾	1.0001	1.0035	0.2506	0.2515	18.779	18.762	48.0	54.0
	H-18	0.9998	1.0037	0.2504	0.2564	18.779	18.759	49.0	62.0
Beta quench	V-5	0.9999	1.0051	0.2471	0.2494	18.777	18.592	52.0	53.0
	H-6	0.9999	1.0050	0.2473	0.2491	18.777	18.759	53.5	62.5

(1) V and H indicate vertical and horizontal dilatometer experiments.

(2) Burnup of 0.011%, all others 0.019%.

The pre-irradiation hardnesses are averaged from the readings made in identifying the specimens. At least five post-irradiation readings were made on each specimen.

Thermal expansion coefficients of the H specimens were measured before irradiation only. They turned out to be 6.4, 13.6 and $12.1 \times 10^{-6}/^\circ\text{C}$ for the alpha annealed, beta annealed and beta quenched specimens, respectively.