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EFFECTS OF HIGH BURNUP ON NATURAL URANIUM

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ABSTRACT

Results are given from experiments in which unrestrained specimens of unalloyed natural uranium were irradiated to total atom burnups ranging up to 1.82 percent (15,500 MWD/T) at temperatures from 50° to 220°C. A few specimens were also thermally cycled. The specimens represented material with four different fabrication histories: (1) rolled at 300°C; (2) rolled at 300°C and quenched from the beta phase, (3) rolled at 300°C, quenched from the beta phase, and recrystallized in the alpha phase, and (4) rolled at 600°C. It was found that the 300°C rolled specimens in the as-rolled condition grew in length at a rapid rate when subjected to irradiation, although they maintained relatively smooth surfaces. The growth rate of this material appeared to decrease with increasing irradiation temperature. The beta quenched specimens were much more stable dimensionally but developed roughened surfaces. The 600°C rolled material showed intermediate behavior. It was concluded that 300°C rolled and beta quenched uranium can withstand at least 2 a/o burnup without disintegration due to irradiation damage. A qualitative similarity was found between the irradiation growth rates of the four materials and their growth rates under thermal cycling.

INTRODUCTION

Economic studies of solid-fuel reactors have shown the desirability of achieving maximum burnup of fuel atoms before replacing the fuel elements. For power reactors the amount of burnup, or fuel lifetime, is normally limited by either of the following two factors: (1) the reactivity of the fuel has decreased excessively because of progressive changes in its isotopic composition, and (2) the fuel has become physically damaged by irradiation and fission products to such an extent that the reactor cannot operate efficiently and safely. The evaluation of item (1) has been covered in detailed theoretical investigations.^(1,2) It is the purpose of this report to present experimental data to aid in the evaluation of item (2).

In 1952, when the present irradiations were started, it was known qualitatively that uranium was damaged by irradiation and that the amount of damage was related to its prior metallurgical history. Relatively little

information was available on the rates at which the damage occurred and on the effects of burnups exceeding a few tenths percent of all atoms. Although a few experiments⁽³⁻⁵⁾ had been reported where 1 a/o burnup was attained, the specimens in each case were quite small so that the effect of surface damage was inordinately large.

It was decided, therefore, to make an investigation of the progressive physical changes occurring in uranium with increasing burnup, using specimens of sufficient size so that data on such changes as density and hardness could be obtained. In particular, the purposes of the investigation were (1) to compare the behavior under moderate irradiation of uranium specimens having widely dissimilar textures, (2) to study the ultimate modes of failure, under irradiation, of uranium with the above textures, and (3) to compare irradiation growth rates with thermal cycling growth rates also obtained on the above materials.

Results obtained on a number of the above specimens with 0.1 a/o burnup or less have been previously reported.⁽⁶⁾ Other studies, to be separately reported, were also made on the effect of irradiation cycling⁽⁷⁾ and irradiation of single crystals.⁽⁸⁾

EXPERIMENTAL MATERIALS AND PROCEDURE

The availability of the MTR, with its high thermal flux, enabled the irradiations to be made on natural uranium. This was considered desirable from the experimental point of view, for the macroscopic absorption cross section of natural uranium is low enough that specimens of appreciable diameter (e g., 0.2 in.) can be irradiated with negligible self-shielding and flux depression factors. In addition, the general availability of natural uranium made its behavior under irradiation a subject of widespread interest.

The selection of metallurgical treatments for the irradiation specimens was determined primarily from results obtained from earlier investigations of the behavior of uranium under thermal cycling.⁽⁹⁾ Based on those results, uranium was prepared with the following four histories.

- (1) Rolled at 300°C.
- (2) Rolled at 300°C, heated to 735°C (in the beta phase) for 30 minutes, and water quenched.
- (3) Rolled at 300°C, heated to 735°C for 30 minutes, water quenched, and held at 575°C (in the alpha phase) for 2 hours.
- (4) Rolled at 600°C.

Uranium rolled at 300°C (history 1), which is below the recrystallization temperature, contains a large component of (010) poles parallel to the rolling direction, whereas uranium rolled at 600°C (history 4), which is above the recrystallization temperature, contains much less of the (010) component.⁽¹⁰⁾ Uranium quenched from the beta phase (histories 2 and 3) retains relatively little of the preferred orientation resulting from prior rolling. The anneal at 575°C (history 3) was used to permit the alpha phase to recrystallize into an equiaxed structure. Photomicrographs of both longitudinal and transverse sections of the above materials are shown in Figures 1 through 4.

In order for the irradiations to provide a maximum of useful data it was considered essential that the fuel specimens be irradiated in such a manner as to be initially, at least, free of all physical restraint. Thus, any dimensional instability which the specimens might develop under irradiation would be able to proceed at its natural rate. Accordingly, capsules were designed with interior dimensions such that the specimens contained in them could freely move about,⁽¹¹⁾ as shown in Figure 5.

To make use of the high thermal flux and inherent water cooling in the MTR it was also necessary to provide in the capsule an efficient means of transferring heat from the specimen to the capsule wall, which was in direct contact with process water flowing at about 25 linear feet per second. This was accomplished by including within each capsule, before final closure, sufficient eutectic NaK alloy to fully cover the specimen. The basic design of the original capsules remained essentially unaltered throughout the irradiations, although improvements were made from time to time in methods of filling and assembling the capsules. Materials used for the capsules included zirconium and aluminum. So that some range of irradiation temperatures at a given thermal flux could be obtained, the zirconium capsules were made with uniform internal diameters but with wall thicknesses of 0.092, 0.22, and 0.34 inch. The specimen size selected was a diameter of 3/16 in. by 1.00 in. long. With the above variations in zirconium capsule wall thickness, plus occasional use of aluminum capsules with a 0.092 in. thick wall, it was possible in the irradiation facilities made available to obtain calculated central temperatures in the specimens ranging from 50° to 220°C. The assembled capsule shown in Figure 5 has a wall thickness of 0.092 in.

The space in the MTR reflector made available included the positions A-4, A-6, and A-7. In view of the fact that the diameters of the above capsules did not conform to the existing holes in the reflector, and since many more capsules were to be irradiated than could be accommodated in the three holes made available, special aluminum A-pieces, one of which is shown in Figure 6, were made and inserted into the three locations. Each special A-piece contained four holes with three different diameters that provided a 1/16 in. thick annulus of cooling water around the 13 capsules which could be stacked in each hole.

The irradiated capsules were returned at intervals to Argonne National Laboratory, where they were opened with a remotely operated lathe. The specimens were cleaned of adhering NaK by dipping them successively in normal butyl alcohol, water, and acetone, after which they were photographed at twice magnification. They were then measured for changes in dimensions, and, generally, weight, density, and hardness. Densities were measured by weight difference in CCl_4 . Specimens which were to be measured for density changes were cleaned in 10 molar nitric acid prior to density determinations. Nitric acid of similar concentration was also used to remove samples for burnup analyses.

It was desired to report the exposure of the specimens in terms of the fraction of all the atoms in the material which had undergone fission or, as expressed more briefly, "a/o burnup." Each capsule therefore contained a thermal flux monitor in the form of an encapsulated wire weighing about 2 milligrams with the nominal composition 99 w/o Al, 0.5 w/o Mn, and 0.5 w/o Co. This alloy was originally recommended by the late R. Fiore, who was using it for monitoring irradiations at Hanford. As used in the present investigation, the Co^{60} gamma activity induced in the monitors was counted in solution with a sodium iodide crystal spectrometer. Absolute disintegration rates were obtained by comparison with a solution with a known disintegration rate supplied by the National Bureau of Standards.

It was realized, however, that in the case of natural uranium total atom burnups calculated simply from integrated neutron flux and resulting U^{235} fission would be usable only for relatively short irradiations, since the specimens were in a relatively high resonant flux. Under these conditions, it was evident that considerable conversion of U^{238} to plutonium would occur, which would in turn contribute fissions at an increasing rate to the over-all burnup. Therefore, burnup in almost all of the specimens was determined by analyzing the irradiated material for fission product Cs^{137} . The advantage of this method is that total fissions are obtained, regardless of whether they originated from uranium or plutonium. A few irradiated specimens were also analyzed for plutonium.

Thermal cycling tests were performed in a vertical tube cycling apparatus⁽⁹⁾ in which the specimen could be transferred rapidly between two tanks of NaK at different temperatures. The thermal cycle used consisted of holding the specimen for two minutes in NaK at 50°C and for five minutes in NaK at 550°C . Transfer time between the two temperatures was five seconds.

EXPERIMENTAL RESULTS

Tables I through IV show the irradiation histories of the various specimens. The volume fission rates, calculated irradiation temperatures, atom burnups, and observed changes in the specimens are tabulated in

Tables V through VIII. The latter tables also show the average lengthwise growth rate, G_i , which was calculated from the relation

$$G_i = \frac{1}{L} \frac{dL}{dN} = \frac{\ln L/L_0}{\text{fraction of total atoms fissioned}} = \frac{\text{microin./in.}}{\text{fissions}/10^6 \text{ total atoms}}$$

where L_0 = initial length
 L = final length
 N = unit of atom burnup

The above expression thus takes into account the fact that the amount of growth at any given level of burnup is dependent upon the instantaneous length of the specimen at that time. It has been found both convenient and accurate to express the growth rate in microunits of length change per unit length for one fission per million total atoms. For small length changes the following approximation may be used:

$$G_i = \frac{\% \text{ length change}}{\text{a/o burnup}}$$

Burnups analyzed in the specimens ranged from 0.0056 to 1.82 a/o, and volume fission rates varied from 2.8×10^{12} to 32.3×10^{12} fissions/cm³-sec. As mentioned earlier, temperatures existing at the centers of the specimens during irradiation were calculated to range from 50° to 220°C.

Uranium Rolled at 300°C

As shown in Table V, the specimens made from 300°C-rolled material elongated at a relatively rapid rate when subjected to irradiation. The ten specimens which had not elongated sufficiently so as to be partially restrained by their irradiation capsules showed an average growth rate of $G_i = 693$. The additional four specimens, which were irradiated to higher burnups, were found to have coiled about in their irradiation capsules as a result of being partially restrained, as shown in Figure 7. For want of a more exact method, the lengthwise growth of these latter specimens was computed from observations of the amounts by which their diameters had decreased. However, in spite of the large experimental error involved, it appeared evident that the lengthwise growth rates of the partially restrained specimens were diminished by a factor of two or three. Growth of the unrestrained specimens has been shown as a function of burnup in Figure 8. The growth coefficient, G_i , of the unrestrained specimens has been shown as a function of calculated irradiation temperature in Figure 9. Although the experimental scatter is large, there appears to be a decrease in growth rate with increasing irradiation temperature. As may be noted from Figure 7, the surfaces of the 300°C-rolled specimens developed a longitudinally striated or woody appearance when subjected to irradiation, although they remained relatively smooth otherwise.

Uranium Rolled at 300°C and Quenched from the Beta Phase

Quenching the 300°C rolled material from the beta phase effected a striking change in its behavior under irradiation, as shown in Table VI and Figure 10. The most obvious effect of the beta phase heat treatment was a marked reduction in G_i , the irradiation growth rate, which equalled an average value of 25 for the 19 specimens containing up to 0.5 a/o burnup. With increasing burnup the growth rate began to diminish and, as shown in Figure 11, there is some indication that reversal may have occurred, i.e., the specimens may have begun to contract at burnups above about 1.5 a/o. Surface roughening was much more evident in the case of the beta quenched material than in the as-rolled specimens. The amount of roughening was generally proportional to the amount of burnup received.

Uranium Rolled at 300°C, Quenched from the Beta Phase, and Recrystallized in the Alpha Phase

Annealing beta quenched material, as shown in Figures 2 and 3, produced a more equiaxed grain structure and enlarged the over-all grain size to some extent. These modifications in microstructure did not appear to have affected significantly the growth rate of unrecrystallized beta quenched material, as shown in Table VII and Figure 11. Typical specimens are shown after irradiation in Figure 12, and it may be noted that surface roughening again was clearly evident.

Uranium Rolled at 600°C

Growth rates of the specimens fabricated by rolling at 600°C are shown in Table VIII. It can be noted that the behavior of this material was intermediate between the 300°C rolled specimens and those which were quenched from the beta phase. As shown in Figure 13, there was no tendency for growth rate to diminish with increasing burnup. The growth rate of the 32 specimens not restrained by their irradiation capsules averaged $G_i = 77$. The appearance of typical specimens is shown in Figure 14, where it can be noted that surface roughening was also intermediate between that shown by 300°C rolled and by beta quenched material.

General Observations

Of the 57 specimens measured for density changes resulting from irradiation, 53 were found to have decreased in density. Figure 15 shows, for the four types of material, density decreases as a function of burnup. The four specimen materials all appeared to decrease in density at similar rates. Since weight changes in the specimens were slight, the decreases in density can be attributed to volume increases in the irradiated materials.

Hardness generally increased as a result of irradiation, as shown in Figure 16. Measurement of hardness was not reliable on specimens with more than a few tenths percent burnup because of warping and surface roughening.

Surface roughening was also largely responsible for the apparent diameter increases observed, particularly on the beta quenched groups.

As the irradiations proceeded, it became evident that the fission rate was not diminishing with increasing depletion of the U^{235} initially present in the specimens. Conversion of U^{238} to plutonium was therefore proceeding at a rate at least adequate to compensate for burnup of the U^{235} atoms. For example, specimens with indicated burnups near 0.6 a/o, based on their original U^{235} contents and on the thermal flux to which they were exposed, were found by chemical analysis to contain approximately 0.8 a/o burnup. In the extreme case, specimen B-15 with an analyzed burnup of 1.82 a/o contained only approximately 0.65 a/o burnup resulting from fission of U^{235} . Eleven irradiated specimens were analyzed for residual plutonium, and the plutonium found is shown vs. analyzed atom burnup in Figure 17. It can be noted that the weight percent residual plutonium in the specimens is approximately equal to the total atom percent burnup

Thermal Cycling Results

Several specimens from each of the four types of material were thermally cycled, and the growth rate observed for each material is shown in Table IX. The thermal cycling growth rate, G_t , is analogous to the irradiation growth rate, G_i , and is calculated from the relation

$$G_t = \frac{1}{L} \frac{dL}{dN} = \frac{\ln L/L_0}{N} = \text{microin./in. per thermal cycle}$$

where L_0 = original length
 L = final length
 N = number of thermal cycles.

As in the case of irradiation growth, the above expression takes into account the changing length of the specimen. G_t values were measured after 100, 125, 200, and 250 cycles. It was found that the material which had been 300°C rolled, beta quenched, and recrystallized was the most stable dimensionally, followed in order of increasing instability by 300°C rolled and beta quenched, 600°C rolled, and 300°C rolled material.

DISCUSSION

Figure 18 shows a comparison of irradiation growth of the specimens, and the figure shows that dimensional instability of uranium under irradiation clearly depends upon prior fabrication history. For example,

in the case of the as-rolled specimens the irradiation growth rate dropped considerably when the rolling temperature was raised from 300° to 600°C. Preferred orientation studies on these materials have shown that, as the rolling temperature of uranium is increased, the amount of (010) component in the fiber axis decreases.⁽¹⁰⁾ The above indication that lengthwise growth of rolled uranium rods under irradiation depends primarily upon the amount of (010) poles aligned in the rolling direction was further confirmed when single crystals of uranium were irradiated.^(6,8) In these irradiations both true and pseudo single crystals of uranium were found to grow under irradiation in the [010] direction with a G_i value of about 420.

However, the above G_i value for single crystals is only about 60% of that observed for the 300°C rolled material. It appears, therefore, that growth in polycrystalline uranium results not only from the basic instability of the individual grains but also from an additional mechanism that depends upon the presence of grain boundaries. Until definitive experiments have been made to resolve the conflicting hypotheses that have been advanced to account for irradiation growth of single crystals of uranium,⁽¹²⁾ it is unlikely that a completely adequate theory can be developed for the dimensional behavior of polycrystalline uranium when subjected to irradiation. The apparent decrease in growth rate with increasing irradiation temperature shown in Figure 9 has also been observed by British investigators.⁽¹²⁾

The dimensional changes observed in the beta quenched specimens were much less than those in the as-rolled specimens, presumably because of the reduction in preferred orientation which results from beta heat treatment.⁽¹⁰⁾ Quenching uranium from the beta phase, therefore, provides a method of effectively reducing the growth tendency under irradiation of uranium previously rolled at 300°C

The amount of surface roughening which developed in the irradiated specimens was in direct proportion to their grain size prior to irradiation. (Post-irradiation grain size was not determined.) Thus, the 300°C rolled specimens maintained a relatively smooth surface during irradiation, the 600°C rolled specimens were somewhat more roughened, while the beta quenched specimens showed serious surface damage. The direct relation which was demonstrated to exist between grain size and surface roughening presumably results from the fact that the individual grains at the surface of a given specimen are only partially restrained by adjacent grains. Since each grain is inherently unstable under irradiation, and since restraint of surface grains is not complete, some deformation can occur, the relative amount of which will depend upon the orientation of each surface grain. Where grain size is large, absolute grain deformations will also be large, i.e., surface roughening will develop.

The final mode of failure of the specimens under irradiation, as manifested by actual physical disintegration, depended primarily upon the type of dimensional instability which was displayed. Thus, the 300°C rolled

specimens irradiated above 0.7 a/o burnup showed a large number of transverse fractures, which probably resulted from stresses that developed because of the extensive elongation which occurred in the material. However, the ultimate type of failure exhibited by this material could best be determined by irradiating specimens under conditions where they could elongate indefinitely with no physical restraint, a condition which was only partially realized in the present experiments.

The beta quenched specimens deteriorated chiefly as a result of continuing surface damage. Although no fracturing was observed, the appearance of several of the high-burnup specimens was such that some disintegration could be expected at burnups above 2 a/o. The importance of this type of damage, however, is largely a function of specimen size. Thus, small specimens might be expected to fail because of surface damage eventually reaching the center of the specimens, whereas large specimens would develop high residual stresses that would probably cause fracturing after the uranium was embrittled from irradiation.

The density decreases which were observed were found to be essentially independent of prior fabrication history and irradiation temperature. As is evident in Figure 15, the density decreased initially at a rate of about 4.8% per atom percent burnup. After about 0.5 a/o burnup, however, the rate of density decrease began to diminish, so that specimens irradiated to about 1.8 a/o burnup had decreased in density by only 3.9%. The rate of decrease in density was such as to indicate that the observed changes were due primarily to the creation of additional atoms, rather than from the phenomenon known as "swelling." The latter mechanism, which produces a relatively large decrease in density, is believed to be due to the nucleation and growth of fission gas bubbles and has not been observed to operate at temperatures below 300° to 400°C.⁽¹²⁻¹⁵⁾

In order to determine microstructural changes resulting from irradiation, a specimen of 300°C rolled and beta quenched material with 0.25 a/o burnup (specimen C-15) was sectioned transversely and metallographically polished. The microstructure observed is shown in Figure 19, along with similar unirradiated material. It is evident that the normal grain structure of this material was drastically altered by the irradiation it received. It has been calculated by Seitz that after 10% burnup of the U^{235} in a natural uranium sample each atom has been displaced about 17 times.⁽¹⁴⁾ In the specimen shown in Figure 19, about 35% of the U^{235} has fissioned, so that on the basis of the above calculation each atom would have been displaced, on the average, some 60 times. If the individual atoms in the specimen were shifted about to this extent during irradiation, it is not surprising that external indications of such features as grain boundaries and slip lines have been largely obliterated. No evidence of porosity was found in the specimen although it had decreased in density over two percent. This is a further indication that the observed density decrease in this specimen, at least, was not due to swelling.

The hardness increases which were generally observed have been found to be characteristic in irradiated fuels. They are probably due more to fission product impurity atoms than to interstitials and vacancies, as it has been shown that annealing irradiated uranium does not restore pre-irradiation ductility.⁽⁶⁾

A comparison of irradiation growth rates with thermal cycling growth rates for the four materials investigated is shown in Table X. The results show a qualitative similarity, i.e., the relative order of dimensional stability of the materials was the same under both irradiation and thermal cycling. Other investigations at this Laboratory on unalloyed uranium have shown similar results. It appears, therefore, that thermal cycling may frequently provide a qualitative indication of the dimensional behavior of unalloyed uranium with various fabrication histories when subjected to irradiation, and that the use of thermal cycling for this purpose in the past has been largely justifiable. It should be mentioned, however, that no such similarity in behavior has been noted at this Laboratory in the case of uranium-base alloys. For example, a uranium-zirconium alloy was found to elongate rapidly under thermal cycling but to shorten under irradiation. The use of thermal cycling as an indication of irradiation behavior should always be used with reservations and at the present time the possibility of application to uranium alloys is very doubtful.

CONCLUSIONS

1. Uranium growth under irradiation is a function of the fabrication history of the material and the irradiation temperature. In general, the degree of instability under irradiation is directly proportional to the amount of preferred orientation and in particular to the amount of (010) poles parallel to the rolling direction.
2. Surface roughening of uranium under irradiation is directly related to the pre-irradiation grain size.
3. Fine grained, highly oriented uranium disintegrates under irradiation by a process of transverse fracturing, whereas coarse grained, randomly oriented material fails by progressively deeper surface damage. Uranium which has been rolled at 300°C and beta quenched should withstand 2 a/o burnup without disintegrating, particularly if used with diameters comparable to the experimental specimens reported herein.
4. Uranium decreases in density under irradiation at a rate largely independent of prior fabrication history.
5. Uranium increases in hardness when subjected to irradiation.

6 For the materials used in this investigation, a qualitative similarity existed between irradiation growth rates and thermal cycling growth rates.

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TABLE I

Irradiation History of 300°C Rolled Specimens

Spec. No.	Date Placed in Reactor	Date Removed from Reactor	Exposure, MWD	Location in Reactor
A-17	9-9-52	1-31-53	3455	A-4 SW
A-18	9-9-52	12-8-52	2077	A-4 SW
AB-4-1	4-23-54	4-27-54	120	VH-2
AB-4-2	4-23-54	4-27-54	120	VH-2
AB-4-3	4-23-54	4-27-54	120	VH-2
AB-18-1	5-6-54	5-7-54	30	VH-2
AB-19-1	4-21-54	4-23-54	60	VH-2
AB-20-1	5-2-54	5-6-54	120	VH-2
AB-21-1	5-7-54	5-15-54	240	VH-2
B-18	9-3-52	5-21-53	6318	A-6 SW
C-11	9-3-52	12-8-52	2163	A-7 SW
C-12	9-3-52	3-19-56	31075	A-7 SW
C-13	9-3-52	1-31-53	3541	A-7 SW
C-14	9-3-52	10-17-52	785	A-7 SW

TABLE II

Irradiation History of 300°C Rolled and Beta Quenched Specimens

Spec. No.	Date Placed in Reactor	Date Removed from Reactor	Exposure, MWD	Location in Reactor
A-2	12-8-52	7-27-53	5850	A-4 SW
A-4	12-8-52	1-31-53	1378	A-4 SW
A-5	9-9-52	10-17-52	699	A-4 SW
A-6	9-9-52	1-31-53	3455	A-4 SW
A-7	9-9-52	11-3-53	10585	A-4 SW, A-7 SE
A-8	9-9-52	11-3-53	10585	A-4 SW, A-7 SE
A-10	9-9-52	5-21-53	6232	A-4 SW
A-11	9-9-52	12-8-52	2077	A-4 SW
AB-18-2	5-6-54	5-7-54	30	VH-2
AB-19-2	4-21-54	4-23-54	60	VH-2
AB-20-2	5-2-54	5-6-54	120	VH-2
AB-21-2	5-7-54	5-15-54	240	VH-2
B-1	9-3-52	12-8-52	2163	A-6 SW
B-2	9-3-52	5-21-53	6318	A-6 SW
B-3	9-8-52	3-6-55	21587	A-6 SW, A-7 NE
B-4	9-3-52	10-16-54	18809	A-6 SW, A-7 NE
B-5	9-3-52	1-31-53	3541	A-6 SW
B-6	9-3-52	10-17-52	785	A-6 SW
B-7	10-17-52	7-27-53	7228	A-6 SW
C-8	9-3-52	5-19-54	15507	A-7 SW, A-7 NW
C-9	9-3-52	12-8-52	2163	A-7 SW
C-10	9-3-52	5-21-53	6318	A-7 SW
C-15	9-3-52	1-31-53	3541	A-7 SW
C-16	9-3-52	10-17-52	785	A-7 SW
C-17	10-17-52	7-27-53	7228	A-7 SW
C-19	12-8-52	7-27-53	5850	A-7 SW

TABLE III

Irradiation History of 300°C Rolled, Beta Quenched,
and Recrystallized Specimens

Spec. No.	Date Placed in Reactor	Date Removed from Reactor	Exposure, MWD	Location in Reactor
A-13	9-9-52	10-17-52	699	A-4 SW
A-14	9-9-52	11-3-53	10585	A-4 SW, A-7 SE
A-15	9-9-52	11-3-53	10585	A-4 SW, A-7 SE
A-16	9-9-52	5-21-53	6232	A-4 SW
A-19	9-9-52	12-8-52	2077	A-4 SW
B-13	9-3-52	12-8-52	2163	A-6 SW
B-14	9-3-52	5-21-53	6318	A-6 SW
B-15	9-3-52	3-6-55	21587	A-6 SW, A-7 NE
B-16	9-3-52	10-16-54	18809	A-6 SW, A-7 NE
B-19	9-3-52	1-31-53	3541	A-6 SW
B-20	9-3-52	10-17-52	785	A-6 SW
C-1	9-3-52	12-8-52	2163	A-7 SW
C-2	9-3-52	5-21-53	6318	A-7 SW
C-3	9-3-52	1-31-53	3541	A-7 SW
C-4	9-3-52	10-17-52	785	A-7 SW
C-7	12-8-52	7-27-53	5850	A-7 SW

TABLE IV

Irradiation History of 600°C Rolled Specimens

Spec. No.	Date Placed in Reactor	Date Removed from Reactor	Exposure, MWD	Location in Reactor
A-21	12-8-52	1-31-53	1378	A-6 NW
A-22	12-8-52	1-31-53	1378	A-6 NW
A-23	12-8-52	5-21-53	4155	A-6 NW
A-24	12-8-52	5-21-53	4155	A-6 NW
A-25	12-8-52	5-21-53	4155	A-6 NW
A-32	12-8-52	7-27-53	5850	A-6 NW
A-33	12-8-52	7-27-53	5850	A-6 NW
AB-18-3	5-6-54	5-7-54	30	VH-2
AB-19-3	4-21-54	4-23-54	60	VH-2
AB-20-3	5-2-54	5-6-54	120	VH-2
AB-21-3	5-7-54	5-15-54	240	VH-2
B-21	12-8-52	1-31-53	1378	A-7 NW
B-22	12-8-52	1-31-53	1378	A-7 NW
B-23	12-8-52	5-21-53	4155	A-7 NW
B-24	12-8-52	5-21-53	4155	A-7 NW
B-25	12-8-52	5-21-53	4155	A-7 NW
B-34	12-8-52	7-27-53	5850	A-7 NW
B-37	12-8-52	7-27-53	5850	A-7 NW
B-41	5-21-53	7-27-53	1695	A-6 SW
B-42	5-21-53	7-27-53	1695	A-6 SW
C-21	12-8-52	1-31-53	1378	A-4 NW
C-22	12-8-52	1-31-53	1378	A-4 NW
C-23	12-8-52	1-31-53	1378	A-4 NW
C-24	12-8-52	5-21-53	4155	A-4 NW
C-25	12-8-52	5-21-53	4155	A-4 NW
C-26	12-8-52	5-21-53	4155	A-4 NW
C-27	12-8-52	5-21-53	4155	A-4 NW
C-28	12-8-52	5-21-53	4155	A-4 NW
C-29	12-8-52	5-21-53	4155	A-4 NW
C-30	12-8-52	5-21-53	4155	A-4 NW
C-31	12-8-52	5-21-53	4155	A-4 NW
C-32	12-8-52	5-21-53	4155	A-4 NW
C-33	12-8-52	5-21-53	4155	A-4 NW
C-35	1-31-53	7-27-53	4472	A-7 SW
C-36	1-31-53	5-21-53	2777	A-4 NW
C-37	1-31-53	5-21-53	2777	A-4 NW
C-38	1-31-53	5-21-53	2777	A-4 NW
C-39	5-21-53	7-27-53	1695	A-7 SW
C-40	5-21-53	7-27-53	1695	A-7 SW

TABLE V

Effects of Irradiation on 300°C Rolled Specimens

Spec. No.	Burnup, a/o	Average Burnup Rate, fissions/cm ³ -sec (x 10 ¹²)	Irrad. Temp., °C		Length Change, %	Average Lengthwise Growth Rate, G _l ^(a)	Diameter Change, %	Weight Change, mg	Density Change, %	Hardness Change, RA
			Surface	Center						
AB-18-1	0.0057	32.3	140	160	3.68	630	- 2.3	-	-	0.9
AB-19-1	.0076	21.6	100	110	5.6	720	- 2.1	-	-	.9
AB-20-1	.0190	27.2	130	150	13.3	660	- 6.5	-	-	4.3
AB-4-3	.022 ^(b)	31.2	130	150	11.9	510	-	-	-	-
AB-4-1	.022 ^(b)	31.2	130	150	13.1	560	-	-	-	-
AB-4-2	.022 ^(b)	31.2	130	150	13.8	590	-	-	-	-
C-14	.032	7.0	60	70	27.4	760	-11.1	0.2	-0.284	-
AB-21-1	.035	24.9	110	130	29.0	720	-13.1	-	-	4.6
A-18	.053	4.4	75	80	58.5	870	-18.3	.2	- .58	-
C-11	.11	8.5	60	75	173	910	-38.9	1.0	-1.35	-4.8
C-13	.26	12.5	75	90	320 ^(c)	550	-51.0	- 7.4	-2.60	-
A-17	.38	19.8	180	210	220 to 730 ^(c)	310 to 560	-44 to -65	-32.4	-1.60	-
B-18	.73	19.8	150	180	480 to 940 ^(c)	230 to 320	-58 to -69	- 7.7	-3.27	-
C-12	1.55 ^(d)	8.5	60	75	800 ^(c)	140	-66	(e)	-	-

^aG_l = microin./in. per fission/10⁶ total atoms.^bCalculated from thermal flux measurements.^cGrowth was partially restrained by irradiation capsule.^dEstimated from adjacent analyzed specimens.^eWeight could not be obtained because most of the specimen could not be removed from irradiation capsule.

TABLE VI

Effects of Irradiation on 300°C Rolled and Beta Quenched Specimens

Spec. No.	Burnup, a/o	Average Burnup Rate, fissions/cm ³ -sec (x 10 ¹²)	Irrad. Temp., °C		Length Change, %	Average Lengthwise Growth Rate, G _L (a)	Diameter Change, %	Weight Change, mg	Density Change, %	Hardness Change, R _A
			Surface	Center						
AB-18-2	0.0056	31.8	140	160	0.018	3.2	-1.22	-	-	4.6
AB-19-2	.0079	22.4	100	110	.32	43	-3.19	-	-	6.2
A-5	.018	4.4	75	80	.39	22	- .21	0.1	-	-
AB-20-2	.019	27.0	130	150	.55	29	- .80	-	-	6.9
C-16	.020	4.3	50	60	.39	20	.27	-.5	0.00	-4.0
B-6	.024	5.2	70	75	.50	21	.11	-.9	-	-
AB-21-2	.033	23.4	110	130	.92	28	-1.28	-	-	9.6
B-1	.061	4.8	70	75	3.79	61	.70	-.4	-.35	-
A-4	.089	10.8	120	130	3.2	35	3.19	.6	1.43	-
A-11	.100	7.9	100	110	6.2	31	3.04	.8	.52	-
C-17	.12	2.8	45	50	2.7	22	4.3	.2	- .40	12.9
C-9	.16	12.5	75	90	6.4	39	3.6	.5	- .79	-5.5
B-7	.18	4.3	65	75	3.8	21	4.8	.1	-	-
A-2	.19	5.5	80	85	4.0	21	9.6	.5	-	-
A-6	.22	11.3	120	140	3.3	15	1.6	.3	-	-
B-5	.23	10.8	100	120	8.0	33	10.1	.1	-	-
C-15	.25	11.9	70	85	4.1	16	7.5	.7	-2.14	5.0
C-19	.39	11.3	70	85	4.5	11	5.9	2.2	-1.93	-.1
B-2	.40	10.8	100	120	5.2	7.5	5.9	2.1	-	-
C-8	.52(b)	5.7	55	60	3.0	5.7	3.7	-	-	-
C-10	.60	15.9	80	100	11.0	17	2.7	.4	-2.41	-
A-10	.63	17.0	160	190	4.8	7.4	8.0	2.9	-	-
A-7	1.00	15.9	160	180	17.1	16	21.3	-3.2	-3.30	-
A-8	1.33	21.5	200	220	16.5	10	18.1	-4.8	-2.70	-
B-3	1.73	13.6	120	140	5.0	2.8	8.0	-11.2	-3.93	-
B-4	1.75	15.9	130	150	7.3	3.0	10.7	-330.4	-4.05	-

^aG_L = microin./in. per fission/10⁶ total atoms.^bEstimated from adjacent analyzed specimens.

TABLE VII

Effects of Irradiation on 300°C Rolled, Beta Quenched, and Recrystallized Specimens

Spec. No.	Burnup, a/o	Average Burnup Rate, fissions/cm ³ -sec ($\times 10^{12}$)	Irrad. Temp., °C		Length Change, %	Average Lengthwise Growth Rate, G _l (a)	Diameter Change, %	Weight Change, mg	Density Change, %	Hardness Change, RA
			Surface	Center						
B-20	0.016	3.5	60	65	0.29	18	0.16	0.1	-0.19	- 0.8
A-13	.027	6.8	90	100	.69	25	.42	.1	- .21	.4
C-4	.048	10.2	65	80	.82	17	.64	.3	- .14	- 1.7
B-13	.084	6.8	80	90	.70	8.3	3.90	.5	- .43	- 4.1
C-1	.092	7.4	60	70	4.1	44	1.50	.5	- .37	- 4.1
A-19	.14	11.3	120	140	6.5	45	7.4	.8	- .69	-10.7
B-19	.17	7.9	85	95	3.0	17	3.5	.8	-1.47	-
C-7	.27	7.9	65	75	7.1	25	5.3	-8.5	- .62	6.0
C-3	.30	14.2	80	95	6.1	21	4.3	1.1	-1.48	-
C-2	.52	14.2	80	95	7.2	12	2.7	8.7	-4.25	-
B-14	.55	14.7	120	140	5.8	7.5	3.2	2.8	-4.07	-
A-16	.75	20.4	190	220	10.2	13	1.1	3.5	-2.80	-
A-14	1.14	18.1	170	190	13.5	11	4.2	2.3	-2.75	17.8
A-15	1.25	20.4	190	220	11.5	8.7	8.9	.6	-2.55	8.2
B-16	1.70	15.3	130	150	10.1	5.7	5.2	-382.4	-4.65	-
B-15	1.82	14.2	120	140	9.5	5.0	-10 to +21	- 52.4	-3.80	-

^aG_l = microin./in. per fission/10⁶ total atoms.

TABLE VIII
Effects of Irradiation on 600°C Rolled Specimens

Spec. No.	Burnup, a/o	Average Burnup Rate, fissions/cm ³ -sec (x 10 ¹²)	Irrad. Temp., °C		Length Change, %	Average Lengthwise Growth Rate, G _i ^(a)	Diameter Change, %	Weight Change, mg	Density Change, %	Hardness Change, R _A
			Surface	Center						
AB-18-3	0.0056	32.3	140	160	0.63	110	- 0.64	-	-	-
AB-19-3	0.0076	21.6	100	110	.87	110	- 0.37	-	-	-
AB-20-3	0.019	27.2	130	150	1.29	70	- 1.4	-	-	-
A-21	0.028	3.5	65	70	2.2	78	- 1.9	0.4	-0.88	7.0
B-21	0.029	3.6	60	65	1.9	65	1.8	1.9	-0.22	7.9
AB-21-3	0.032	24.9	110	130	2.07	65	- 1.7	-	-	9.8
C-21	0.032	4.0	50	55	3.0	92	- 0.8	-27.2	-0.75	1.4
B-22	0.041	5.1	70	75	2.3	55	0.0	2.6	-0.52	7.5
A-22	0.047	5.7	80	90	2.7	57	0.5	2.3	-0.90	8.6
C-22	0.052	6.2	55	65	3.2	61	1.3	6.3	-0.37	4.9
B-41	0.054	5.4	70	80	4.7	85	- 2.1	0.9	0.084	12.2
C-36	0.063	3.9	50	55	4.0	62	1.1	2.4	-0.41	-
B-42	0.070	6.8	80	90	5.8	81	- 4.8	2.1	-0.20	12.6
C-23	0.072	9.1	65	75	5.0	68	- 1.6	7.3	-0.23	9.0
C-40	0.097	9.6	65	80	9.6	95	- 6.4	1.6	-0.29	7.3
C-37	0.10(b)	6.2	55	65	4.8	47	- 2.7	1.5	-	-
C-39	0.10	10.2	65	80	9.6	92	- 5.9	0.8	-0.32	11.7
A-33	0.12	3.4	65	70	9.9	79	- 7.7	1.4	-0.51	25.2
B-37	0.13	3.8	65	70	8.5	63	- 7.5	1.7	-0.39	8.0
B-23(c)	0.13	5.3	70	80	25	170	33	13.9	-	-
C-38	0.15(b)	9.1	65	75	11	70	- 3.2	2.0	-	-
C-33	0.15	6.2	55	65	8.2	53	- 1.1	1.7	-0.67	-
B-24	0.15(b)	6.2	75	85	15.5	96	- 6.9	1.6	-	-
B-34	0.19	5.4	70	80	18.0	87	- 8.5	0.4	-0.58	8.2
C-35	0.19	7.4	60	70	14.8	73	- 7.7	0.6	-0.44	12.7
A-23	0.21	8.5	100	110	17.2	76	- 5.3	- 1.4	-1.04	-
A-32	0.21	6.2	85	95	20.2	88	- 9.5	0.1	-0.77	18.7
C-32	0.25(b)	10.2	65	80	17	63	- 6.8	1.5	-	13.3
B-25	0.25(b)	10.2	80	90	27	96	- 9.6	1.9	-	-
A-24	0.29	11.9	130	150	27	82	- 8.3	0.9	-1.35	-
C-31	0.35(b)	14.2	80	95	29	73	-10.7	4.0	-	-
A-25	0.35	14.2	140	160	35.8	87	-14.9	2.1	-	-
C-24	0.36	14.7	80	100	35.3	84	-14.6	1.8	-1.31	-
C-30	0.43	17.6	85	110	> 36(d)	> 72	-17.1	2.4	-1.76	-
C-25	0.44(b)	18.1	85	110	> 36(d)	> 70	-10.1	-69.3(e)	-	-
C-29	0.49(b)	19.8	95	120	> 36(d)	> 63	-	- 1.1	-	-
C-26	0.51(b)	21.0	95	120	> 36(d)	> 40	-17	9.9	-	-
C-27	0.52	21.5	95	120	> 36(d)	> 59	-16	2.4	-	-
C-28	0.53(b)	21.5	95	120	> 36(d)	> 58	-16	-55.1(e)	-	-

^aG_i = microin./in. per fission/10⁶ total atoms.

^bEstimated from adjacent analyzed specimens.

^cSpecimen was swelled, apparently due to internal defect.

^dGrowth was partially restrained by irradiation capsule.

^eWeight loss due primarily to specimen damage incurred during opening of irradiation capsule.

TABLE IX

Growth Rates Under Thermal Cycling of Materials Used for Irradiation Specimens

Spec. No.	Fabrication History	Ave. $G_t^{(a)}$ after stated no. of thermal cycles			
		0-100	0-125	0-200	0-250
1S	300°C Rolled		410	390	
2S	300°C Rolled		440	400	
21S	300°C Rolled	510			430
10S	300°C Rolled and Beta Quenched		40	44	
12S	300°C Rolled and Beta Quenched	-20			2
1S	300°C Rolled, Beta Quenched, and Recrystallized	34		33	
2S	300°C Rolled, Beta Quenched, and Recrystallized	52		44	
3S	300°C Rolled, Beta Quenched, and Recrystallized	36		29	
4S	300°C Rolled, Beta Quenched, and Recrystallized	36		34	
5S	600°C Rolled		400	360	
6S	600°C Rolled		400	350	
22S	600°C Rolled	430			340

^a G_t = microin./in. per thermal cycle. Each thermal cycle consisted of 2 minutes in NaK at 50°C and 5 minutes in NaK at 550°C. Transfer time between the two temperatures was 5 seconds.

TABLE X

Comparison of Irradiation and Thermal Cycling Growth Rates

Specimen Material	$G_i^{(a)}$	$G_t^{(b)}$
300°C Rolled	693	395
300°C Rolled and Beta Quenched	25	44
300°C Rolled, Beta Quenched, and Recrystallized	24	35
600°C Rolled	77	355

^a G_i = microin./in. per fission/ 10^6 total atoms. For the as-rolled materials, the G_i values tabulated are the average of all specimens not restrained by their irradiation capsules. For the beta-quenched materials, the G_i values tabulated are for specimens with burnups up to 0.50 a/o.

^b G_t = microin./in. per thermal cycle. The G_t values tabulated are the average growth rates obtained after 200 cycles.

Figure 1. Microstructure of 300°C rolled specimens before irradiation.

a. Transverse Section

20816

250X

b. Longitudinal Section

20817

250X

Figure 2. Microstructure of 300°C rolled and beta quenched specimens before irradiation.

a. Transverse Section

20818

250X

b. Longitudinal Section

20819

250X

Figure 3. Microstructure of 300°C rolled, beta quenched, and recrystallized specimens before irradiation.

a. Transverse Section

b. Longitudinal Section

Figure 4. Microstructure of 600°C rolled specimens before irradiation.

a. Transverse Section

20822

250X

b. Longitudinal Section

20823

250X

106-1760

Figure 5. Assembled irradiation capsule.

(twice scale)

106-3014

Figure 6. Typical special aluminum A-piece made for insertion in the MTR reflector to accommodate four columns of irradiation capsules with three different diameters. The length of the piece is $46\frac{5}{8}$ inches.

106-2890

Figure 7. Effect of irradiation on uranium specimens rolled at 300°C.

Figure 8. Length changes in unrestrained irradiated uranium specimens rolled at 300°C.

106-3179

Figure 9. Effect of irradiation temperature on the growth rate of 300°C rolled uranium.

106-2892

Figure 10. Effect of irradiation on typical uranium specimens rolled at 300°C and quenched from the beta phase.

Figure 11. Length changes in irradiated uranium specimens rolled at 300°C and quenched from the beta phase.

106-2891

Figure 12. Effect of irradiation on typical uranium specimens rolled at 300°C, quenched from the beta phase, and recrystallized in the alpha phase.

Figure 13. Length changes in irradiated uranium specimens rolled at 600°C.

106-2889

Figure 14. Effect of irradiation on typical uranium specimens rolled at 600°C.

Figure 15. Effect of irradiation on the density of uranium with four different fabrication histories.

Figure 16. Effect of irradiation on the hardness of uranium with three different fabrication histories.

Figure 17. Residual plutonium as a function of analyzed burnup in irradiated natural uranium.

Figure 18. Effect of fabrication history on the lengthwise growth of uranium under irradiation.

Beta Quenched Uranium Before Irradiation

Beta Quenched Uranium After Irradiation

(100 diameters, polarized light)

106-2129

Figure 19. Effect of 0.25 a/o burnup on the microstructure of 300°C rolled and beta quenched uranium.