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STRUCTURES AND PROPERTIES OF URANIUM-FISSIUM ALLOYS

by

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ABSTRACT

A study was made of the phase relations and the properties of uranium-fissium alloys which have compositions bracketing that intended for the first core loading of Experimental Breeder Reactor II. The fissium aggregate in the alloys consisted of the elements Zr, Nb, Mo, Ru, Rh, and Pd. Phase relations are shown to parallel closely those in the dominant U-Mo-Ru ternary system. The uranium gamma phase is stabilized down to 552°C, while the beta phase is entirely suppressed at high fissium contents. Certain crystallographic data are given and the minor phases that occur in the alloys are identified. In cast and gamma-quenched alloys the retention of the high-temperature gamma phase produced low hardness and low density. The thermal expansion behavior of the alloys is shown to be dependent upon composition and prior thermal history. Thermal conductivity data are presented for uranium and the uranium-fissium alloys. The thermal conductivities of the alloys decrease with increasing fissium concentration.

I. INTRODUCTION

Several power reactor systems are now under construction or are planned in which it is intended to reprocess spent fuels by pyrometallurgical methods.^(1,2) In the core-processing method intended for Experimental Breeder Reactor II, spent uranium alloy fuel will be melted in a zirconia crucible and held molten for several hours in the temperature range between 1300°C and 1400°C. The volatile fission products xenon, krypton, and cesium will boil off, while barium, strontium, and the rare earth metals will react with the crucible material and adhere in a reaction layer on the crucible walls. No zirconium will be removed by this process, although some removal can be effected by carbide dressing. The other fission products, refractory metals of the second long period, zirconium, niobium, molybdenum, technetium, ruthenium, rhodium, and palladium will also not be removed. During repeated fuel recycling these will build up, as a complement of residual elements called "fissium" (abbreviation "Fs"), to an equilibrium concentration that depends on the percentage of new fuel

that is added per cycle. Koch⁽³⁾ has estimated that a typical composition (in weight percent) that might result after many reprocessing cycles in which U^{235} is the fissionable base material is as follows:

Zirconium	0.10%	Ruthenium	2.63%
Niobium	0.01%	Rhodium	0.47%
Molybdenum	3.42%	Palladium	0.30%
Technetium	0.99%	Uranium	92.09%

To avoid a continuous change in fuel composition during the early stages of reactor operation, Experimental Breeder Reactor II will, at the start, be fueled with a synthetic fissium alloy, i.e., an alloy made of uranium and stable isotopes of the fissium elements. The first core loading will be an alloy containing 5 w/o fissium. The alloy will be in the form of as-cast rods, 0.144 in. in diameter and 14.22 in. long, made by the injection casting technique previously described by Yaggee et al.⁽⁴⁾

The present investigation, portions of which have been described in two previous papers,^(5,6) deals with the solid-state transformations, structures, and properties of a series of potentially important synthetic uranium-fissium alloys. The properties that were investigated included hardness, density, thermal expansion, and thermal conductivity. In the alloys studied all the fissium elements noted above except technetium were present and, with one exception, the alloys contained the fissium elements in essentially constant ratios with respect to each other. Additional amounts of molybdenum and ruthenium were present in the alloys in substitution for technetium.

II. MATERIALS

The compositions of the alloys and the ratios of the concentrations of each alloying element in weight percent to that of molybdenum, $X\%/Mo\%$, are given in Tables I and II. In the four alloys containing 3, 5, 8 and 10 w/o Fs these ratios were essentially constant. In the fifth alloy, designated U-5 w/o Fs-2.25 w/o Zr, the $Zr\%/Mo\%$ ratio was increased to a value around unity to simulate a composition that might result from a variation in pyrometallurgical refining.

All the alloys were made from uranium of 99.98% purity and alloying elements of 99.85% purity or better. The alloys in Table I were in the form of buttons, 1 in. in diameter by $\frac{1}{4}$ in. in thickness, prepared by arc melting in a furnace previously described.⁽⁷⁾ Melting and casting were done in water-cooled copper molds in an argon-helium atmosphere. Three buttons of each composition were made. Good chemical homogeneity

was attained by melting the buttons a total of six times. Homogeneity was assessed from correlation of chemical analyses, density measurements, and metallographic observations. Chemical analyses were made on two or more samples taken from each of two buttons of the same nominal composition. Table I gives the average compositions of the buttons as determined from the chemical analyses. In all cases, deviations from the averages were less than two times the previously calculated standard deviations, σ , for the analytical method. The 2σ values are included in Table I.

By means of the carbon tetrachloride displacement method the room-temperature density of each whole cast button was measured. Later, the buttons were cut in halves and the density of each piece was determined. Thus three values of the density of each button were obtained, the average of which is given in Table VI. Deviations of individual values from the averages were less than 0.01 g/cc.

The alloys reported in Table II were made by vacuum induction melting and casting and were used solely in studies of thermal conductivity. Melting was done in thoria-coated graphite crucibles. Casting was performed by bottom pouring into a water-cooled copper mold, 1 in. in diameter and 7 in. long. The materials for melting were binary alloys of uranium with the fissile elements in the form of buttons, prepared by arc melting. The prealloying was done to lower melting temperatures. During induction melting, pressures over the melts were of the order of 2×10^{-6} mm Hg, and melts were poured at approximately 1200°C after superheating for times up to one hour in the range from 1300°C to 1400°C. Radiographs by means of radiation from cobalt were made of all ingots, and in all cases no evidence of serious cracks, voids, or fissures was observed. The compositions of the alloys were determined by optical emission spectroscopic analyses of samples taken from the extreme top and bottom portions of the cast ingots. The analytical method, developed at Argonne National Laboratory, is described in detail elsewhere.⁽⁸⁾ Table II gives the top and bottom analyses and the averages. Deviations of top and bottom values from the averages do not exceed the estimated precision of the analytical method.

III. EXPERIMENTAL PROCEDURES

The temperatures of the solid-state transformations occurring in the alloys were first determined approximately by means of thermal analysis. Then the temperatures were determined more accurately and the nature of the transformations established by means of metallographic and X-ray diffraction studies of samples annealed at various temperatures and water quenched after an initial homogenization at 825°C.

The thermal analyses were performed on samples weighing approximately 25 gm as prepared from the arc-cast buttons. The samples were placed within a nickel container, 1 in. in diameter and $1\frac{1}{2}$ in. long with a $\frac{3}{16}$ -in. wall thickness, heated in vacuum to 850°C, held for approximately one hour, and then cooled to room temperature at rates ranging from 0.7 to 7.2°C/min. Cooling rates were controlled by the differential temperature method using two chromel-alumel thermocouples acting in conjunction with a temperature differential controller. One thermocouple was placed within a small hole in the sample, the other in a hole in the container wall. The sample thermocouple was simultaneously used to determine thermal arrest temperatures.

Annealing treatments for metallographic and X-ray diffraction studies were carried out with small specimens wrapped in tantalum foil and sealed in Vycor capsules that had been evacuated at room temperature to a pressure of 2×10^{-6} mm Hg. The treatments were usually conducted at several temperatures within 20°C of the transformation temperatures indicated from thermal analysis data. Times of annealing varied from 24 hr to four weeks, depending on the temperature and the nature of the transformation. Specimens for X-ray diffraction were in the form of needles, about 0.06 cm in diameter, that had been shaped from larger pieces by grinding. After preparation, the needles were annealed in the same way as the metallographic specimens, and after annealing they were electrolytically cleaned in a perchloric-acetic acid bath to remove the microscopic layer of oxidation products that had formed during annealing. Many of the needles were examined metallographically after the X-ray diffraction photograms had been taken; these provided an additional correlation between the metallographic and X-ray studies. Metallographic and X-ray studies were also made with the alloys in the as-cast condition and following thermal analysis.

Diffraction patterns were obtained with a 114.6-mm-diameter Debye-Scherrer camera using filtered CuK-alpha or CrK-alpha radiation. The lattice parameters of the beta phase were determined from back-reflection lines by a modified Cohen least-squares method. A Nelson-Riley graphical extrapolation method was employed to determine the lattice parameter of the gamma phase.

For microexamination, specimens were mounted in Bakelite, ground on water wheels through No. 600 paper, polished on cloth wheels through No. 1 diamond paste, and finally electrolytically polished and etched in a solution of eight parts phosphoric acid, five parts ethylene glycol and five parts ethyl alcohol with cell potentials between 4 and 10 volts. Infrared heat tinting after electrolytic etching successfully enabled differentiation of the retained beta phase and the gamma phase in U-3% Fs alloy specimens.

Hardness measurements were made with the button alloys in the following three conditions: (a) as cast, (b) as homogenized for 66 hr at 825°C and water quenched, and (c) as reannealed, after homogenization, for varying times up to four weeks at 375, 500, 600, and 700°C, followed by water quenching. The heat treatments to produce condition (b) were performed on half-sections of the as-cast buttons, and specimens for the condition (c) treatment were cut from these pieces.

Measurements of room-temperature density were made with the same alloys in the as-cast condition and as annealed for eleven days at 500°C and water quenched. The densities of the 3 w/o Fs and 5 w/o Fs alloys were also determined following homogenization for 66 hr at 825°C and water quenching. The measurements were made, by the carbon tetrachloride displacement method, with brightly electropolished specimens weighing from 8 to 50 gm.

Other portions of the arc-cast buttons were used for measurements of thermal expansion. Three conditions were studied: (a) as-cast, (b) as annealed for 48 hr at 850°C, and (c) as annealed for 11 days at 500°C with both (b) and (c) treatments followed by water quenching. The measurements were made with a precision quartz differential dilatometer that has been previously described.⁽⁹⁾ Specimens were 0.20 in. in diameter and 0.90 in. long, and had been machined from the centers of cast buttons. Data on length dilation were obtained on heating and cooling the specimens twice between room temperature and elevated temperatures at rates of approximately 1°C/min. The data, corrected for the expansion of quartz, are presented in Tables VII through XI.

Measurements of thermal conductivity as a function of temperature were made with the alloys of compositions given in Table II in the as-cast condition and also with as-cast high-purity uranium. The uranium was cast in the same manner as that described for the alloys. The concentrations of impurity elements present in the uranium as determined from chemical and spectrographic analysis are given in Table III. Thermal conductivity measurements were made in vacuum by the comparative method, with Armco iron as a standard. The details of the method and the apparatus used have been previously described.⁽¹⁰⁾ The specimens used were 2 cm in diameter and 15 cm long, and were machined from the cast ingots.

IV. RESULTS AND DISCUSSION

A. Transformation Temperatures and Structures

The phase relations in the alloys were found to parallel closely those in the dominant U-Mo-Ru ternary system, which has been the subject of a concurrent study in this Laboratory by Dwight.^(11,12) Figure 1 shows a

portion of the vertical section in this ternary system in which the weight ratio of molybdenum to ruthenium is 1.0:0.80, approximating the ratio of the two elements in the uranium-fissium alloys. Because of the similarity between the transformations in U-Mo-Ru alloys and those in the uranium-fissium alloys, this vertical section will be found useful during subsequent portions of this report.

Fig. 1. Vertical Section through the Uranium-rich Corner of the U-Mo-Ru Ternary System at the Mo:Ru Ratio of 1.0:0.8 (from unpublished work by Dwight). Micro No. 30162.

Although pure gamma uranium is not stable below 769°C,⁽¹²⁾ the alloyed gamma phase of all the uranium-fissium alloys persists as a stable phase down to 552°C, at which it apparently decomposes eutectoidally. The formation of the beta phase from the gamma phase is lowered from 759°C to 682°C by 3 w/o Fs. Higher fissium contents entirely suppress the beta phase, and the alpha phase forms directly from the gamma phase. Only three other phases are found: (a) A phase whose X-ray diffraction pattern indicates that it is isomorphous with the compound U_2Ru found by Dwight^(11,12) and by Park.⁽¹²⁾ The crystal structure of U_2Ru has been determined by Berndt⁽¹³⁾ to be monoclinic (space group either $P2_1/n$ or $P2_1/n$) with $a_0 = 13.110 \pm 0.004 \text{ \AA}$, $b_0 = 3.345 \pm 0.002 \text{ \AA}$, $c_0 = 5.206 \pm 0.002 \text{ \AA}$, $\beta = 96^\circ 9.24' \pm 0.2'$. (b) A low-temperature phase which is isostructural with the delta phase in the uranium-molybdenum system. The crystal structure of the delta has been reported to be tetragonal, of the $MoSi_2$ -type.⁽¹⁴⁾ (c) A CsCl-type phase, $ZrRu$, which has been studied by Dwight,⁽¹⁵⁾ that only occurs in an identifiable concentration in the high zirconium alloy. Hereafter these three phases will be referred to respectively as U_2Ru , delta, and $ZrRu$, although it is acknowledged that they may exhibit solubility for the other components of the alloys and thus deviate from their binary compositions.

The equilibrium phase transformations and resulting structures are summarized in Table IV and discussed for each of the alloys below

U-3 w/o Fs

This alloy was found to retain a single-phase gamma structure down to $682 \pm 2^\circ\text{C}$, at which a precipitation of the beta phase begins. Figure 2a illustrates the supersaturated martensitic alpha structure to which the gamma transforms upon quenching from the single-phase region. The beta-plus-gamma region extends down to $660 \pm 3^\circ\text{C}$. On water quenching, the beta is retained in a metastable condition, but the gamma still transforms to martensitic alpha. Figure 2b shows the appearance of retained beta (light) plus martensitic alpha in a specimen annealed 1 week at 680°C and water quenched. Coprecipitation of beta and U_2Ru is initiated at $660 \pm 3^\circ\text{C}$ and continues down to $636 \pm 2^\circ\text{C}$. On quenching from the three-phase region, both beta and gamma are retained. Figure 2c shows the three-phase structure, gamma (gray) plus beta (light) plus U_2Ru (black), that results after annealing for 1 week at 657°C and water quenching. The beta phase decomposes eutectoidally at $636 \pm 2^\circ\text{C}$ to alpha plus gamma plus U_2Ru , and the three-phase region extends down to $552 \pm 3^\circ\text{C}$. The distribution of alpha (gray), gamma (light), and U_2Ru particles in a specimen annealed just below the beta eutectoid temperature can be seen in Figure 2d. The retention of the gamma phase upon quenching from the beta-plus-gamma-plus- U_2Ru field (660 - 636°C), and from the alpha-plus-gamma-plus- U_2Ru field (636 - 552°C) is attributed to the increased concentration of fissionium in the gamma in these temperature ranges. It will be seen later in discussing the higher fissionium alloys that the retainability of metastable gamma increases with increasing fissionium concentration. The delta phase was found from X-ray analysis to form at $552 \pm 3^\circ\text{C}$, apparently as the result of the eutectoidal decomposition of gamma to alpha plus delta plus U_2Ru . Dwight's work⁽¹¹⁾ supports this. Coalescence of the delta and U_2Ru phases on annealing at temperatures below 552°C proceeds very slowly. Figure 2e shows that the two minor phases are still in finely disseminated form even after 4 weeks at 500°C .

U-5 w/o Fs

Single-phase gamma is stable in this alloy down to $725 \pm 3^\circ\text{C}$, at which the precipitation of U_2Ru begins. Beta does not occur in the alloy, although Figure 1 shows that it does occur in the ternary alloy having 5 w/o (Mo + Ru) in the fissionium ratio. Precipitation of U_2Ru continues down to $642 \pm 2^\circ\text{C}$, at which gamma begins to reject alpha. The formation of delta occurs at $552 \pm 3^\circ\text{C}$ as in the U-3 w/o Fs alloy.

Fig. 2. Microstructures of Annealed and Quenched U-3 w/o Fs Alloy. (All specimens were initially homogenized 66 hr at 825°C and water quenched. All photomicrographs were taken at 500X, with bright field illumination except where otherwise noted. Etchant: Phosphoric Acid.)

Figure 3 illustrates microstructures that result when the alloy is isothermally annealed in the several above-defined phase regions and water quenched. Some small amounts of unidentified inclusions were present in the microstructures, as may be seen in Figures 3a through 3c. In the microstructures of the specimens quenched from above the gamma eutectoid temperature, 552°C, gamma is present in a metastable condition (Figures 3a through 3e). The relative proportions of gamma and U₂Ru in the alloy at 720°C and 645°C can be seen from Figures 3b and 3c, respectively. Figure 3d illustrates the coarse alpha grains (light) that are formed on annealing at 640°C. Figure 3e shows the contrasting fine alpha-grain Widmanstätten structure that is rejected from gamma on annealing at a lower temperature, 600°C, within the same phase region. Coalescence of the alpha, delta, and U₂Ru phases at 500°C appears to occur even more slowly than in the U-3 w/o Fs alloy, as evidenced by the very fine unresolved structure shown in Figure 3f.

U-8 w/o Fs and U-10 w/o Fs

The transformations and resulting structures in these two alloys parallel those in the U-5 w/o Fs alloy. For 8 and 10 w/o Fs the rejection of U₂Ru from gamma is initiated at $812 \pm 10^\circ\text{C}$ and $832 \pm 3^\circ\text{C}$, respectively. Both alloys have larger equilibrium concentrations of U₂Ru than does the 5 w/o Fs alloy. Initial alpha rejection begins at $607 \pm 7^\circ\text{C}$ for the U-8 w/o Fs alloy and at about 580°C for the U-10 w/o Fs alloy. The temperature of formation of the delta phase was again found to be $552 \pm 3^\circ\text{C}$ for both alloys. The fact that the delta-formation temperature is the same at all fissium concentrations suggests that delta forms by a common isothermal transformation and supports the belief that it is the eutectoidal decomposition of the gamma phase.

Photomicrographs of the U-8 w/o Fs and the U-10 w/o Fs alloys illustrating the appearance and distribution of the phases in annealed and quenched specimens are shown in Figures 4 and 5, respectively. X-ray diffraction results showed the retention of gamma in both alloys on quenching from above 552°C. Microstructures of both alloys as quenched from the single-phase gamma region (see Figures 4a and 5a) did not differ significantly from that shown in Figure 3a for the U-5 w/o Fs alloy. Figures 4b through 4d and 5b through 5d show the microstructures that result when the alloys are isothermally annealed within the two-phase gamma-plus-U₂Ru region and water quenched. The U₂Ru phase occurs both as thin platelets precipitated along preferred crystallographic planes of the gamma matrix and as spherical particles forming an almost continuous intergranular network. Figure 4e shows the Widmanstätten structure of alpha precipitated from gamma on annealing the 8 w/o Fs alloy in the alpha-plus-gamma-plus-U₂Ru region. Figures 4f and 5e show the unresolved structures obtained after annealing both alloys for 4 weeks at 500°C.

1 week at 730°C; w. q.

a. Gamma plus inclusions. Micro No. 24374

1 week at 720°C; w. q.

b. Gamma plus U_2Ru plus inclusions (dark).
Micro No. 24518.

1 week at 645°C; w. q.

c. Gamma plus U_2Ru . Micro No. 24429.

1 week at 640°C; w. q.

d. Gamma plus alpha (light) plus U_2Ru (dark gray). Micro No. 24428.

4 weeks at 600°C; w. q.

e. Gamma plus alpha (Widmanstatten) plus
 U_2Ru (gray). Micro No. 23975.

4 weeks at 500°C; w. q.

f. Alpha plus delta plus U_2Ru .
Micro No. 24286.

Fig. 3. Microstructures of Annealed and Quenched U-5 w/o Fs Alloy. (All specimens were initially homogenized 66 hr at 825°C and water quenched. All photomicrographs were taken at 500X with bright field illumination. Etchant: Phosphoric Acid.)

66 hours at 825°C; w. q.

a. Gamma plus inclusions. Micro No. 23980.

66 hours at 800°C; w. q.

b. Gamma plus U₂Ru. Micro No. 24521.

1 week at 760°C; w. q.

c. Gamma plus U₂Ru. Micro No. 24433.

1 week at 615°C; w. q.

d. Gamma plus U₂Ru. Micro No. 24430.

4 weeks at 600°C; w. q.

e. Gamma plus alpha Widmanstatten plus U₂Ru (dark). Micro No. 23977.

4 weeks at 500°C; w. q.

f. Alpha plus delta plus U₂Ru. Micro No. 24288.

Fig 4 Microstructures of Annealed and Quenched U-8 w/o Fs Alloy (All specimens homogenized 66 hr at 825°C and water quenched prior to annealing. Figure 4a illustrates the microstructure of the alloy following the homogenization heat treatment. All photomicrographs were taken at 500X with bright field illumination. Etchant: Phosphoric Acid.)

1 week at 835°C, w. q.

1 week at 830°C, w. q.

4 weeks at 700°C, w. q.

a. Gamma plus inclusions. Micro No. 24440.

b. Gamma plus U₂Ru. Micro No. 24439.

c. Gamma plus U₂Ru. Micro No. 24074

4 weeks at 600°C, w. q.

4 weeks at 500°C; w. q.

d. Gamma plus U₂Ru.
Micro No. 23978.

e. Alpha plus delta plus U₂Ru.
Micro No. 24289.

Fig 5 Microstructures of Annealed and Quenched U-10 w/o Fs Alloy (All specimens were initially homogenized 66 hr at 825°C and water quenched. All photomicrographs were taken at 500X with bright field illumination. Etchant: Phosphoric Acid.)

U-5 w/o Fs-2.25 w/o Zr

The addition of 2.25 w/o Zr to the U-5 w/o Fs alloy results in the suppression of the U_2Ru phase. Instead, the CsCl-type compound ZrRu occurs from temperatures as high as 975°C down to room temperature. Gamma coexists with ZrRu down to $662 \pm 3^\circ\text{C}$. Figures 6a and 6b show ZrRu preferentially occurring in parent gamma grain boundaries in specimens quenched from 975°C and 700°C, respectively. X-ray diffraction results show that the gamma is not retained upon quenching, but instead transforms to martensitic alpha. At 662°C rejection of alpha from gamma begins and continues down to $552 \pm 3^\circ\text{C}$. Figure 6c shows the structure of gamma plus alpha plus ZrRu that is observed when the alloy is quenched from 650°C. The ZrRu is in the form of a discontinuous network with alpha precipitated around it. The delta phase forms at 552°C, but the nature of its formation in the alloy is not certain. Figure 6d shows the very fine structure obtained in the alloy after 4 weeks at 500°C.

B. Thermal Arrest Data

Although the thermal analysis work was performed prior to the metallographic and X-ray diffraction studies described in the previous section, its discussion has been deferred until this point so that the thermal arrests that were observed can be associated with the various equilibrium transformations. As will be evident, all the transformations are sluggish, and therefore the cooling curves are not characterized by sharp, easily identifiable arrests. Even when slow cooling rates were employed, the transformations were either depressed to lower temperatures or entirely suppressed. Figure 7 shows cooling curves obtained when the alloys were cooled from 850°C at rates varying from 0.4°C/min to 3.0°C/min.

Two thermal arrests are noted for the U-3 w/o Fs alloy. The first, at 670°C, is associated with the formation of beta from gamma; the second, at 627°C, with the decomposition of beta. The region of the curve below 627°C is probably characterized by the formation of alpha by a sequence of irreversible transformations whose details were not explored. The microstructure of the alloy after cooling, shown in Figure 8a, was found from X-ray diffraction to consist of only alpha and metastable gamma, showing that the formation of the U_2Ru and delta phases was suppressed.

The weak arrest at 710°C noted in Figure 7 for the U-5 w/o Fs alloy is associated with the precipitation of U_2Ru from gamma. Figure 8b shows the needle-like appearance of U_2Ru in the final microstructure. Although the microstructure of the U-8 w/o Fs alloy shown in Figure 8c clearly shows the precipitation of U_2Ru , no thermal arrest associated with the reaction was observed. The absence of this arrest for the 8 w/o Fs alloy is anomalous, since the arrest was again detected when the 10 w/o Fs alloy was studied (760°C inflection shown in Figure 7).

Fig. 6. Microstructures of Annealed and Quenched U-5 w/o Fs-2.25 w/o Zr Alloy. (All specimens were initially homogenized 66 hr at 825°C and water quenched. All photomicrographs were taken at 500X with bright field illumination. Etchant: Phosphoric Acid.)

Fig. 7. Cooling Curves for U-Fs Alloys. Micro No. 30538

U-3 w/o Fs

a. Alpha plus gamma. Micro No. 22418.

U-5 w/o Fs

b. Gamma plus alpha plus U_2Ru needles. Micro No. 22752.

U-8 w/o Fs

c. Gamma plus U_2Ru needles. Micro No. 23982.

U-10 w/o Fs

d. Gamma plus U_2Ru . Micro No. 24276.

U-5 w/o Fs-2.25 w/o Zr

e. Alpha plus gamma plus $ZrRu$. Micro No. 23972.

Fig. 8. Microstructures of U-Fs Alloys Slow Cooled from 850°C at Rates of from 0.4 to 3.0°C per min. (All photomicrographs were taken at 500X with bright field illumination. Etchant: Phosphoric Acid.)

The arrests at 608°C, 484°C, and 530°C for the 5, 8 and 10 w/o Fs alloys, respectively, are all associated with the partial decomposition of gamma to alpha, as is the 638°C arrest observed for the U-5 w/o Fs-2.25 w/o Zr alloy. The amounts of alpha formed in the U-8 w/o Fs and U-10 w/o Fs alloys were small, since alpha lines could not be identified in the X-ray diffraction patterns of the alloys after cooling. The formation of delta was suppressed in all the higher fissium alloys.

A second set of cooling curves, which are not shown in this report, were obtained for slightly higher cooling rates, from 4.0°C to 7.2°C per min. In general, only one thermal arrest, that associated with the partial rejection of alpha, was observed for all the alloys. A single exception was the U-10 w/o Fs alloy, which also showed an arrest associated with the precipitation of U_2Ru from gamma. As to be expected, the temperatures of the arrests were significantly lower than those corresponding to the same reactions on the previous slower cooling. The effect of the higher cooling rates upon reaction temperatures can be seen from Figure 9, wherein arrest temperatures are plotted versus the cooling rates on the approach to the arrests.

Fig. 9

Effect of Cooling Rate upon
Reaction Temperatures.
Micro No. 30539.

The points at zero cooling rate are the transformation temperatures determined from the equilibrium studies. In the U-3 w/o Fs alloy the temperature of the gamma-to-alpha reaction decreases linearly with increasing cooling rate. In the remaining alloys, reaction temperatures follow curves of the form

$$T = a + be^{-Cr} \quad ,$$

where T is the reaction temperature in degrees Centigrade, r is the cooling rate in degrees Centigrade per minute, and a , b , and c are constants. The empirical equations derived for the various transformations and their graphical representations are shown in Figure 9. The agreement with the experimental points is generally good.

In Figure 10 are the microstructures that were obtained when the alloys were cooled from 850°C to room temperature at rates of from 4.0°C to 7.2°C per min. Figure 10a and Figure 10b show the fine alpha-plus-gamma mixtures of the 3 and 5 w/o Fs alloys. In Figure 10c, U_2Ru is seen as a very fine precipitate in the U-8 w/o Fs alloy, although no thermal arrest related to the precipitation reaction was observed. In the microstructure of the U-10 w/o Fs alloy (see Figure 10d), the light-appearing intergranular phase is U_2Ru , and its massiveness is attributed to incomplete dissolution of the phase on treating the cast alloy for 1 hr at 850°C prior to cooling.

C. As-cast Microstructures

In the arc-melted and cast condition, the 3, 5, 8 and 10 w/o Fs alloys were found by X-ray diffraction to consist of metastable gamma and martensitic alpha in varying proportions. The intensities of diffraction line indicated that, with increasing fissium concentration, the proportion of metastable gamma increased. The U-10 w/o Fs alloy also contained a small amount of U_2Ru . The U-5 w/o Fs-2.25 w/o Zr alloy consisted of martensitic alpha plus small amounts of the delta and ZrRu phases. Some typical microstructures of the alloys in the as-cast condition are shown in Figure 11. A small amount of unidentified angular-appearing particles are present in the alpha-plus-gamma matrix of the U-3 w/o Fs alloy shown in Figure 11a. The 5, 8 and 10 w/o Fs alloys all show evidence of coring, indicating a large difference between liquidus and solidus temperatures. In the U-5 w/o Fs-2.25 w/o Zr alloy (see Figure 11e), ZrRu is again seen to occur in the form of a discontinuous network.

U-3 w/o Fs

a. Alpha plus gamma. Micro No. 22376.

U-5 w/o Fs

b. Alpha plus gamma. Micro No. 22751.

U-8 w/o Fs

c. Gamma plus U_2Ru .
Micro No. 23981.

U-10 w/o Fs

d. Gamma plus U_2Ru .
Micro No. 23989.

U-5 w/o Fs-2.25 w/o Zr

e. Alpha plus gamma plus $ZrRu$.
Micro No. 23137.

Fig. 10 Microstructures of U-Fs Alloys Slow Cooled from 850°C at Rates of from 4.0°C to 7.2°C per min. (All photomicrographs were taken at 500X with bright field illumination. Etchant: Phosphoric Acid.)

U-3 w/o Fs

U-5 w/o Fs

U-8 w/o Fs

a. Unidentified phase in matrix of gamma plus martensitic alpha. Micro No. 22353.

b. Gamma plus alpha. Micro No. 22623.

c. Gamma plus alpha. Micro No. 22358.

U-10 w/o Fs

U-5 w/o Fs-2.25 w/o Zr

d. Gamma plus alpha plus U_2Ru . Micro No. 22359.

e. Alpha plus delta plus $ZrRu$. Micro No. 22632.

Fig 11 Microstructures of As-Cast U-Fs Alloys (All photomicrographs were taken at 500X with bright field illumination Etchant. Phosphoric Acid)

D. Crystallographic Data

Figure 12 shows the relation between the lattice parameters of the gamma phase of uranium-fissium alloys and the fissium concentration for the alloys in which a retained gamma structure can be produced. The compositions for which points are shown are those of the 5, 8 and 10 w/o Fs alloys, converted to atomic percent using a weighted mean atomic weight of 98.3 for fissium. Each alloy was quenched from a temperature at which it consisted entirely of the gamma phase. The lattice parameter is seen to be linear with solute concentration in the range studied. Extrapolation to zero fissium concentration yields a value for a_0 of 3.479 Å, which lies between two values derived by similar extrapolations with uranium-molybdenum alloys: 3.474 Å [Wilson and Rundle⁽¹⁶⁾] and 3.4808 Å [Dwight⁽¹⁷⁾].

Fig. 12

Room-temperature Gamma-phase
Lattice Parameters of Uranium-
Fissium Alloys.
Macro No. 106-4363.

Lattice parameters determined for the beta phase in the U-3 w/o Fs alloy quenched from 650°C were as follows: $a_0 = 10.611 \pm 0.001$ Å; $c_0 = 5.590 \pm 0.001$ Å; $c/a = 0.527$. The limiting solubility of fissium in the beta phase was not determined in this investigation. However, the work of Dwight⁽¹¹⁾ indicates that the solubility at 650°C is probably around 0.5 w/o. No data were obtained for the solubility of fissium in alpha uranium or for the effect of dissolved fissium on the lattice parameter.

None of the diffraction patterns yielded delta phase or U_2Ru phase patterns having sufficient line intensity and quality for measurements of the lattice parameters. A value for a_0 of 3.27 Å was determined for the ZrRu phase in the U-5 w/o Fs-2.25 w/o Zr alloy. This value is in fair agreement with the value of 3.253 Å determined by Dwight⁽¹⁵⁾ with the pure compound.

E. Hardness

The hardness data obtained for the alloys are given in Table V. In Figure 13 the hardnesses of the 3, 5, 8 and 10 w/o Fs alloys, as cast and as homogenized for 66 hr at 825°C and water quenched, are plotted versus composition. Both plots show a decrease in hardness on passing from 3 w/o to 5 w/o Fs. This results from the disappearance of martensitic alpha in favor of retained gamma. The rise in hardness that accompanies further increases in fissium concentration is attributed to increasing concentrations of U_2Ru . The fact that the quenched hardnesses are lower than the as-cast values is indicative of the greater degree of gamma retention that is brought about by a higher cooling rate. The 5 w/o Fs alloy is particularly sensitive to cooling rate, and the quenched hardness shown in Figure 13 is somewhat misleading, since it was obtained on a rather large specimen. When smaller specimens were quenched from gamma-phase temperatures, VHN values in the vicinity of 150 were obtained. The hardness of the U-5 w/o Fs-2.25 w/o Zr alloy, not shown in Figure 13, was VHN = 375 for the as-cast condition and VHN = 261 for the homogenized and quenched condition.

Fig. 13. Effect of Composition upon Hardness of Uranium-Fission Alloys.
Macro No. 24809.

In Figures 14 through 17 the hardness values obtained for the alloys as annealed at 700°C, 600°C, 500°C, and 375°C and water quenched are plotted versus the times of annealing. In all cases the alloys were initially homogenized for 66 hr at 825°C and water quenched. The hardness values for the alloys in the homogenized and quenched condition are plotted on the ordinates in Figures 14 through 17. Figure 14 demonstrates that annealing at 700°C produced hardnesses not significantly different from the as-quenched values. This is reasonable since, as seen from Figure 1, the alloys at 700°C are still essentially single-phase gamma. In Figure 15 it is seen that annealing at 600°C for one hour increases the hardness of each alloy significantly. The increases are related in all cases to the precipitation of low-temperature phases. In all except the U-8 w/o Fs alloy overaging occurs at times greater than one hour. In the U-8 w/o Fs alloy hardening continues for times up to 672 hr (4 weeks), reflecting the sluggishness of the precipitation of the U₂Ru and alpha phases from retained gamma. At 500°C (see Figure 16) all except the 8 w/o and 10 w/o Fs alloys exhibit precipitation hardening peaks at annealing times of one hour or less. For the 8 w/o and 10 w/o Fs alloys peaks occur at approximately 48 hr. In the U-10 w/o Fs alloy hardness is unchanged for annealing times up to 45 min, reflecting the stability of the retained gamma phase at low temperatures. At 375°C age hardening also occurs, with the U-5 w/o Fs alloy exhibiting two hardness plateaus shown in Figure 17. This behavior is consistent with that previously reported by Saller *et al.*⁽¹⁸⁾ for an alloy of similar composition. The first peak occurring within the first hour of annealing is thought to be due to the transformation of retained gamma to supersaturated alpha uranium. The second peak, occurring at approximately 16 hr, is related to the precipitation of the delta and U₂Ru phases. At 375°C, the hardness of the U-10 w/o Fs alloy is seen to increase only after 8 hr of annealing and appears to have not reached a maximum value after four weeks. This behavior demonstrates the sluggishness of the transformation of retained gamma to the low-temperature phases in the higher fissium alloys.

F. Density

The room-temperature densities of the alloys as cast and as heat treated at 825°C and 500°C are given in Table VI. In Figure 18 the densities of the alloys are plotted versus composition. One curve shows the as-cast data and the other gives the densities after annealing 11 days at 500°C. As is to be expected, density decreases with increasing fissium concentration. The densities of the 3, 5, and 8 w/o Fs alloys are higher after the 500°C anneal than in the as-cast condition because of the decomposition of retained gamma to the equilibrium alpha phase, which has a higher density. The density of the 10 w/o Fs alloy is not changed by the 500°C anneal, possibly because the aforementioned effect is counteracted by larger concentrations of the delta and U₂Ru phases, both of which are likely to have densities lower than either the alpha or gamma phases.

Fig. 14. Effect of Time of Annealing at 700°C upon Quenched Hardness of Uranium-Fissium Alloys. (Alloys previously annealed 66 hr at 825°C and water quenched.) Macro No. 27502.

Fig. 15. Effect of Time of Annealing at 600°C upon Quenched Hardness of Uranium-Fissium Alloys. (Alloys previously annealed 66 hr at 825°C and water quenched.) Macro No. 27499.

Fig. 16. Effect of Time of Annealing at 500°C upon Quenched Hardness of Uranium-Fissium Alloys. (Alloys previously annealed 66 hr at 825°C and water quenched.) Macro No. 27260.

Fig. 17. Effect of Time of Annealing at 375°C upon Quenched Hardness of Uranium-Fissium Alloys. (Alloys previously annealed 66 hr at 825°C and water quenched.) Macro No. 27259.

Fig. 18. Densities of Uranium-Fissium Alloys as a Function of Composition and Heat Treatment. Macro No. 24807.

G. Thermal Expansion

Dilation curves showing the thermal expansions behavior of the alloys on heating and cooling twice between room temperature and elevated temperatures are presented in Figures 19 through 23.

Fig. 19. Thermal Expansion of Uranium-3 w/o Fs Alloy. Macro No. 24803.

Fig. 20. Thermal Expansion of Uranium-5 w/o Fs Alloy. Macro No. 24804.

Fig. 21. Thermal Expansion of Uranium-8 w/o Fs Alloy. Macro No. 24810.

Fig. 22. Thermal Expansion of Uranium-10 w/o Fs Alloy. Macro No. 24806.

Fig. 23. Thermal Expansion of Uranium-5 w/o Fs-2.25 w/o Zr Alloy. Macro No. 24805.

The data for the curves and calculated linear thermal expansion coefficients for the alloys are given in Tables VII through XI. The marked contractions occurring in as-cast and gamma-quenched (825°C) alloys upon heating between approximately 400°C and 480°C are attributed to the irreversible decomposition of retained gamma to low-temperature phases of higher density.

Except for the 10 w/o Fs alloy, the contractions do not occur when the alloys are initially annealed at 500°C. In the case of the 10 w/o Fs alloy, contraction occurs only in the second heating cycle. This behavior results from the formation and retention of the gamma phase on the first cycle.

H. Thermal Conductivity

The method employed for measuring thermal conductivities⁽¹⁰⁾ consisted in joining a cylindrical bar of the uranium or a uranium-fissium alloy to a bar of the same diameter of Armco iron of known thermal conductivity and measuring longitudinal temperature gradients in both bars, while one end of the system was heated and the other end cooled. Radial heat flow by conduction, convection, or radiation is inhibited by the experimental technique, so that the constancy of heat flow along the length is optimized. When a steady-state condition is attained, the conductivity at any point whose temperature is known is inversely proportional to the temperature gradient at that point. Knowing the conductivity of the Armco iron standard, K_{STD} , the conductivity of the specimen under test, K_M , is calculated from the relation

$$K_M = K_{STD} \frac{[dT/dx]_{STD}}{[dT/dx]_M} ,$$

where $[dT/dx]_{STD}$ and $[dT/dx]_M$ are measured temperature gradients of the standard and unknown metals, respectively, and K_{STD} and K_M are their respective conductivities at the points at which the gradients are measured.

Measurements of temperature gradient were made for at least four thermal equilibria, each of which spanned a different temperature range. The results obtained on each equilibrium are given in Tables XII through XVII and plotted versus temperature in Figures 24 and 25. A least-squares analysis of the data yielded a relation between thermal conductivity and temperature of the form

$$K_T = a + bT + cT^2 ,$$

where K_T is the thermal conductivity at any temperature T within the studied temperature range, and a , b , and c are constants. The values for the constants and calculated values of K_T are included in Tables XII through XVII. Also included in the tables are standard deviations between experimental and calculated conductivities. Standard deviations, which are a measure of the precision of the method, were generally less than $\pm 0.0016 \text{ cal/}(\text{sec})(\text{cm})(^\circ\text{C})$ or $\pm 4\%$.

Fig. 24

Thermal Conductivity Versus Temperature for Uranium, U-3 w/o Fs and U-5 w/o Fs Alloys. Macro No. 27500.

Fig. 25.

Thermal Conductivity for U-8 w/o Fs, U-10 w/o Fs and U-5 w/o Fs-2.25 w/o Zr Alloys. Macro No. 27501.

The coefficients of thermal conductivity determined for uranium are in fair agreement with those determined earlier by Deem and coworkers at Battelle.⁽¹⁹⁾ Their data are given for comparison in Table XII and plotted in Figure 24. Their measurements were made by the same comparative method and in essentially the same type of apparatus.

The influence of fissium upon the thermal conductivity of uranium is apparent in Figure 26. It is clear that at all temperatures conductivity decreases with increasing fissium additions. It is also evident that addition of 2.25 w/o Zr to a 5 w/o Fs alloy increases conductivity slightly in the range from 100°C to 600°C but decreases it above this temperature range.

Fig. 26. Thermal Conductivity Versus Temperature for Uranium and U-Fs Alloys. Macro No. 27503.

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Table I
COMPOSITIONS OF ARC-MELTED AND CAST URANIUM FISSION ALLOYS

Element	U 3 wt % Fs			U-5 wt % Fs			U 8 wt % Fs			U 10 wt % Fs			U 5 wt % Fs 2.25 t % Zr		
	σ (1)	2σ (2)	Ratio $\frac{X}{Mo}$	σ (1)	2σ (2)	Ratio $\frac{X}{Mo}$	σ (1)	2σ (2)	Ratio $\frac{X}{Mo}$	σ (1)	2σ (2)	Ratio $\frac{X}{Mo}$	σ (1)	2σ (2)	Ratio $\frac{X}{Mo}$
	(Casting No. 31)			(Casting No. 51)			(Casting No. 81)			(Casting No. 101)			(Casting No. 56)		
Pu	1.44	0.05	1.0	2.46	0.05	1.0	3.83	0.08	1.0	4.91	0.10	1.0	2.43	0.05	1.0
Ru	1.29	0.03	0.89	2.20	0.04	0.89	3.38	0.07	0.88	4.33	0.09	0.88	1.74	0.04	0.88
Rh	0.179	0.005	0.12	0.292	0.009	0.12	0.399	0.012	0.11	0.55	0.017	0.11	0.768	0.005	0.11
Pd	0.12	0.005	0.09	0.227	0.009	0.09	0.37	0.015	0.10	0.419	0.017	0.10	0.14	0.008	0.09
Zr	0.0130	0.0004	0.01	0.0784	0.002	0.03	0.0829	0.002	0.02	0.097	0.003	0.02	2.36	0.05	0.97
Nb	0.003 ⁽²⁾		0.034	0.010 ⁽²⁾		0.04	0.016 ⁽²⁾		0.004	0.020 ⁽²⁾		0.03	0.017 ⁽²⁾		0.004
Total % Fs	3.060			5.267			8.081			10.331			1.95		
U	Bal			Bal			Bal			Bal			Bal		
	(Casting No. 32)			(Casting No. 52)			(Casting No. 82)			(Casting No. 102)			(Casting No. 54)		
Pu	1.46	0.03	1.0	2.42	0.05	1.0	3.86	0.08	1.0	4.82	0.10	1.0	2.51	0.05	1.0
Ru	1.20	0.02	0.82	1.96	0.04	0.80	3.05	0.06	0.80	3.87	0.08	0.86	2.06	0.04	0.85
Rh	0.174 ⁽³⁾		0.12	0.291 ⁽³⁾		0.12	0.466 ⁽³⁾		0.11	0.51	0.017	0.12	0.254	0.008	0.10
Pd	0.115 ⁽³⁾		0.08	0.191 ⁽³⁾		0.08	0.304 ⁽³⁾		0.08	0.411	0.016	0.08	0.211	0.005	0.08
Zr	0.05 ⁽³⁾		0.04	0.059 ⁽³⁾		0.02	0.065 ⁽³⁾		0.03	0.215	0.003	0.04	2.5	0.05	0.99
Nb	0.006 ⁽³⁾		0.034	0.009 ⁽³⁾		0.004	0.017 ⁽³⁾		0.004	0.020 ⁽²⁾		0.034	0.010 ⁽³⁾		0.004
Total % Fs	2.990			4.950			7.823			9.927			1.45		
U	Bal			Bal			Bal			Bal			Bal		

(1) Average values of σ for three specimens from same casting.

(2) σ is the calculated standard deviation of the analytical method.

(3) No chemical analyses were made for these elements. Given percentages are calculated from weights of the elements charged for melting.

Table II
COMPOSITIONS OF VARIOUS INDUCTION-MELTED AND CAST URANIUM FISSION ALLOYS

Element	U 3 wt % Fs				U 5 wt % Fs				U 8 wt % Fs				U 10 wt % Fs				U 5 wt % Fs 2.5 t % Zr			
	Top	Bottom	Average	Ratio $\frac{X}{Mo}$	Top	Bottom	Average	Ratio $\frac{X}{Mo}$	Top	Bottom	Average	Ratio $\frac{X}{Mo}$	Top	Bottom	Average	Ratio $\frac{X}{Mo}$	Top	Bottom	Average	Ratio $\frac{X}{Mo}$
Pu	1.48	1.46	1.47	1.0	2.23	1.88	2.06	1.0	3.72	3.74	3.73	1.0	4.60	4.65	4.63	1.0	1.86	1.82	1.85	1.0
Ru	1.22	1.22	1.22	0.82	1.91	1.81	1.86	0.90	2.99	3.25	3.12	0.84	3.95	4.0	4.00	0.86	1.75	1.71	1.73	0.95
Rh	0.167	0.160	0.164	0.11	0.218	0.182	0.195	0.09	0.465	0.425	0.445	0.11	0.57	0.510	0.54	0.12	0.182	0.195	0.189	0.10
Pd	0.119	0.123	0.120	0.08	0.150	0.121	0.136	0.07	0.270	0.290	0.280	0.08	0.380	0.335	0.355	0.09	0.131	0.139	0.135	0.07
Zr	0.031	0.033	0.032	0.02	0.062	0.063	0.063	0.03	0.096 ⁽²⁾	0.096 ⁽²⁾	0.096 ⁽²⁾	0.02	0.118 ⁽²⁾	0.118 ⁽²⁾	0.118 ⁽²⁾	0.04	2.61	2.47	2.54	1.37
Nb	0.006 ⁽²⁾	0.006 ⁽²⁾	0.006 ⁽²⁾	0.034	0.010 ⁽²⁾	0.013 ⁽²⁾	0.010 ⁽²⁾	0.005	0.017 ⁽²⁾	0.017 ⁽²⁾	0.017 ⁽²⁾	0.005	0.020 ⁽²⁾	0.020 ⁽²⁾	0.020 ⁽²⁾	0.004	0.010 ⁽²⁾	0.010 ⁽²⁾	0.010 ⁽²⁾	0.005
Total % Fs	3.032	2.999	3.016		4.571	4.066	4.324		7.498	7.618	7.658		9.68	9.683	9.686		6.54	6.414	6.454	
U	Bal	Bal	Bal		Bal	Bal	Bal		Bal	Bal	Bal		Bal	Bal	Bal		Bal	Bal	Bal	

(1) Ratios of $\frac{X}{Mo}$ were calculated using average w_o of the elements.

(2) w_o analyses were made for these elements. Given percentages are calculated from weights of the elements charged for melting.

Table III
CHEMICAL ANALYSIS OF HIGH-PURITY URANIUM
(CASTING NO. 747)

Element	Parts per Million by Weight	Element	Parts per Million by Weight
C	10-12	Cu	1
Si	20	Mg	3
Fe	3-5	Sb	4

Other elements present in amounts less than spectrographic limits were as follows:

Ag - < 1	Bi - < 1	Li - < 1	Pb - < 1
Al - < 5	Ca - < 20	Mo - < 20	Sn - < 5
As - < 10	Co - < 5	Na - < 10	Ti - < 50
B - < 0.1	Cr - < 1	Ni - < 5	Zn - < 50
Be - < 5	K - < 50	P - < 50	

Table IV
PHASE TRANSFORMATIONS IN URANIUM-FISSIUM ALLOYS

Transformation	Transformation Temperatures (°C)				
	U-3 w/o Fs ⁽¹⁾	U-5 w/o Fs ⁽¹⁾	U-8 w/o Fs ⁽¹⁾	U-10 w/o Fs ⁽¹⁾	U-5 w/o Fs - 2.25 w/o Zr ⁽¹⁾
$\text{Gamma} \rightleftharpoons \text{Gamma} + \text{Beta}$	682 ± 2				
$\text{Gamma} + \text{Beta} \rightleftharpoons \text{Gamma} + \text{Beta} + \text{U}_2\text{Ru}$	660 ± 3				
$\text{Gamma} + \text{Beta} + \text{U}_2\text{Ru} \rightleftharpoons \text{Gamma} + \text{Alpha} + \text{U}_2\text{Ru}$	636 ± 2				
$\text{Gamma} \rightleftharpoons \text{Gamma} + \text{U}_2\text{Ru}$		725 ± 3	812 ± 10	832 ± 3	
$\text{Gamma} + \text{U}_2\text{Ru} \rightleftharpoons \text{Gamma} + \text{Alpha} + \text{U}_2\text{Ru}$		642 ± 2	607 ± 7	580	
$\text{Gamma} + \text{Alpha} + \text{U}_2\text{Ru} \rightleftharpoons \text{Alpha} + \text{Delta} + \text{U}_2\text{Ru}$	552 ± 3	552 ± 3	552 ± 3	552 ± 3	
$\text{Gamma}^{(2)} \rightleftharpoons \text{Gamma} + \text{ZrRu}$					above 975 ⁽²⁾
$\text{Gamma} + \text{ZrRu} \rightleftharpoons \text{Gamma} + \text{Alpha} + \text{ZrRu}$					662 ± 3
$\text{Gamma} + \text{Alpha} + \text{ZrRu} \rightleftharpoons \text{Alpha} + \text{Delta} + \text{ZrRu}$					552 ± 3

⁽¹⁾Detailed compositions of the alloys as determined by chemical analysis are given in Table I.

⁽²⁾Whether gamma exists as a single phase in this alloy was not determined. The presence of ZrRu was detected as high as 975°C.

Table V
HARDNESS OF URANIUM-FISSIUM ALLOYS (VHN-10 Kg)

Heat Treatment ⁽¹⁾		U-3 w/o Fs	U-5 w/o Fs	U-8 w/o Fs	U-10 w/o Fs	U-5 w/o Fs - 2.25 w/o Zr
Temp, °C	Time, hr					
825	As Cast	300	214	271	292	375
	66	260	156-219	250	271-289	261-289
700 ⁽²⁾	1	316	151	281	321	322
	5	311	146	281	306	316
	16	310	150	276	305	317
	40	307	141	277	301	318
	168 (1 week)	308	151	261	290	310
	672 (4 weeks)	306	145	260	293	307
600 ⁽²⁾	1	349	342	290	368	409
	5	323	332	295	352	393
	16	306	319	291	341	388
	40	304	317	287	325	368
	168 (1 week)	287	306	294	312	320
	672 (4 weeks)	264	277	282	298	292
500 ⁽²⁾	(5 min)		455		287	561
	(15 min)		549		277	546
	(25 min)		542		287	536
	(45 min)		546		334	537
	1	497	552	533	453	553
	5	457	529	561	527	507
	16	428	505	576	566	505
	40	398	494	583	588	474
	168 (1 week)	365	414	546	572	446
	672 (4 weeks)	344	362	448	474	411
375 ⁽²⁾	(5 min)		252		274	452
	(15 min)		256		275	481
	(25 min)		261		274	493
	(45 min)		268		270	506
	1		272		278	521
	5		553		278	549
	16		584		305	571
	40		570		317	571
	258		549		446	575
	672 (4 weeks)		534		467	562

(1) All heat treatments were followed by water quenching.

(2) Heat treatments at 700°C, 600°C, 500°C and 375°C were preceded by heat treatment for 66 hr at 825°C and water quenched.

Table VI
DENSITIES OF URANIUM-FISSIUM ALLOYS

Alloy	Casting No	As Cast	Density (g cc)	
			As Annealed 66 Hr at 825°C Water Quenched	As Annealed 11 days at 500°C, Water Quenched
U-3 w/o Fs	3-1	18.373	18.362	-
	3-2	18.383	18.395	18.503
	3-3	18.390	18.388	-
U-5 w/o Fs	5-1	17.988	17.968	-
	5-2	17.996	18.001	18.210
	5-3	17.983	-	-
U-8 w/o Fs	8-1	17.629	-	17.832
	8-2	17.652	-	-
	8-3	17.640	-	-
U-10 w/o Fs	10-1	17.408	-	-
	10-2	17.397	-	17.385
	10-3	17.373	-	-
U-5 w/o Fs - 2.25 w/o Zr	5-4	17.467	-	17.701
	5-5	17.465	-	-
	5-6	17.498	-	-

Table VII
DILATOMETRIC DATA FOR U-3 w o Fs ALLOY (CASTING NO. 3-2)

	As Cast			As Annealed 48 Hr at 852°C; w.q.			As Annealed 11 Days at 500°C; w.q.		
	Temperature (°C)	Dilation ⁽¹⁾ (in./in.) (x 10 ⁴)	TEC ⁽²⁾ (in./in./°C) (x 10 ⁶)	Temperature (°C)	Dilation ⁽¹⁾ (in./in.) (x 10 ⁴)	TEC ⁽²⁾ (in./in./°C) (x 10 ⁶)	Temperature (°C)	Dilation ⁽¹⁾ (in./in.) (x 10 ⁴)	TEC ⁽²⁾ (in./in./°C) (x 10 ⁶)
1st Cycle ⁽³⁾ (Heating)	L ₀ = 0.9743 in.			L ₀ = 0.9737 in.			L ₀ = 0.9674 in.		
	100	15.9371	15.94	100	13.9415	13.94	100	12.5159	12.52
	200	29.9402	14.97	200	29.9581	14.98	200	27.1202	13.56
	300	43.9857	14.66	300	43.5107	14.50	300	42.7759	14.26
	400	51.0540	12.76	400	49.0786	12.27	400	59.4777	14.87
	421	51.5551	12.25	418	49.6898	11.89	500	78.7014	15.74
	448	46.5502	10.39	442	43.8144	9.91	533	85.4294	
	480	52.6102	10.96	500	55.1475	11.03	600	106.9906	17.83
				600	80.7507	13.46	666*	153.7674	23.09
				656*	104.5729	15.94	710	161.5270	17.37
1st Cycle ⁽³⁾ (Cooling)	400	35.0217	15.81	729	120.0012	(24.90)	710	161.5270	(21.51)
	300	17.4322	15.20	700	112.3314	(20.54)	632*	144.5092	24.81
	200	0.3808	14.25	634*	98.4569	23.74	600	101.9451	19.03
	100	-14.1227	13.97	600	55.1834	17.81	500	70.6280	16.56
	0	-28.0565		500	25.0680	15.32	400	50.3952	15.64
				400	6.4664	14.47	300	33.1882	15.12
				300	-11.6342	13.23	200	16.5235	14.33
				200	-27.1919	12.03	100	1.4152	13.54
				100	-41.2035	9.98	0	-12.1098	
				0	-51.1346				
2nd Cycle ⁽³⁾ (Heating)	L ₀ = 0.9716 in.			L ₀ = 0.9687 in.			L ₀ = 0.9662 in.		
	L ₀ - L _{0f} = 0.0027 in.			L ₀ - L _{0f} = 0.0050 in.			L ₀ - L _{0f} = 0.0012 in.		
	100	15.4779	15.48	100	13.5074	13.51	100	13.5413	13.54
	200	32.0305	16.01	200	29.1004	14.55	200	29.1734	14.58
	300	47.1183	15.70	300	45.7436	15.25	300	45.8583	15.28
	400	64.2527	16.06	400	63.9353	15.98	400	62.2801	15.64
	500	84.4009	16.88	500	83.6385	16.73	500	83.3432	16.67
	600	108.5518	18.09	600	109.3711	18.23	600	108.1306	18.02
	634	125.1310	19.74	666*	160.0919	24.04	661*	155.9139	23.59
	650	137.1885	21.11	670	161.6135	(37.45)	707	164.2351	(17.81)
2nd Cycle ⁽³⁾ (Cooling)	650	137.1885	22.68	670	161.6135	(24.61)	707	164.2351	(28.84)
	600	98.5028	18.11	631*	151.8693	24.07	633*	148.6916	24.62
	500	70.8358	16.19	600	120.4569	20.08	600	108.1306	19.21
	400	52.1952	15.57	500	81.1185	16.22	500	75.7650	16.58
	300	33.5537	14.55	400	62.4237	15.61	400	56.5174	15.91
	200	17.0373	14.02	300	43.2242	14.41	300	38.2800	15.13
	100	2.9181	12.98	200	27.5888	13.79	200	22.1004	14.59
	0	-10.0480		100	12.4996	12.50	100	6.9735	14.06
				0	0.0000		0	-6.8334	
	L _{0f} = 0.9706 in. L ₀ - L _{0f} = 0.0010 in.			L _{0f} = 0.9687 in. L ₀ - L _{0f} = 0.0000 in.			L _{0f} = 0.9655 in. L ₀ - L _{0f} = 0.0007 in.		

(1) $\frac{L_T - L_0}{L_0}$, where L_T = length at temperature and L_0 = length at 0°C at start of heating cycle.

(2) Mean thermal expansion coefficients between 0°C and indicated temperatures: on heating, $TEC = \frac{L_T - L_0}{L_0 \times \Delta T}$;

on cooling, $TEC = \frac{L_T - L_{0f}}{L_{0f} \times \Delta T}$, where L_{0f} = length at 0°C at end of cooling cycle.

(Coefficients in parentheses are for range between phase transformation arrest temperatures indicated by * and higher temperatures.)

$TEC = \frac{L_T - L_a}{L_a \times \Delta T}$, where L_a = length at arrest temperature.

(3) As-cast alloy was heated and cooled at approximately 1.8°C/min. Others were heated and cooled at approximately 1.0°C/min.

Table VIII

DILATOMETRIC DATA FOR U 5 w o Fs ALLOY (CASTING NO 5-2)

	As Cast			As Annealed 48 Hr at 852°C w q			As Annealed 11 Days at 500°C w q		
	Temperature (°C)	Dilation(1) (in in x 10 ⁴)	TEC ⁽²⁾ (in in °C) (x 10 ⁶)	Temperature (°C)	Dilation(1) (in in x 10 ⁴)	TEC ⁽²⁾ (in in °C) (x 10 ⁶)	Temperature (°C)	Dilation(1) (in in x 10 ⁴)	TEC ⁽²⁾ (in in °C) (x 10 ⁶)
1st Cycle ⁽³⁾ (Heating)	L ₀ 0.6798 in			L ₀ 0.6772 in			L ₀ 0.6740 in		
	100	12.612	12.61	100	11.9393	11.94	100	10.5448	10.54
	200	27.450	13.72	200	26.8311	13.42	200	26.2200	13.12
	300	42.329	14.11	300	41.7651	13.92	300	42.6810	14.23
	376	51.296	13.64	400	59.6245	14.91	400	58.4447	14.61
	400	47.910	11.98	437	44.6824	10.22	500	77.1053	15.42
	468	40.528	8.66	468	50.6195	10.82	600	111.6818	18.62
	500	45.592	9.12	494	45.7274	9.26	637*	143.0045	22.45
	600	77.006	12.83	500	47.9197	9.58	700	156.3592	(20.90)
	650*	105.259	16.19	600	78.0108	13.00	704	157.1034	(20.75)
1st Cycle ⁽³⁾ (Cooling)	731	120.017	(18.03)	728	118.2939	(14.44)			
	700	111.972	(22.42)	700	110.9462	(22.97)	704	157.1034	(22.34)
	603*	91.381	21.82	600	89.5439	(25.73)	700	156.3592	(22.46)
	600	88.495	21.66	583*	85.1221	23.00	600	133.4091	(21.73)
	500	35.539	15.35	554	48.9313	17.63	573*	127.4675	21.10
	400	15.597	14.19	500	32.7828	16.29	546	97.6343	16.68
	300	0.036	13.68	400	12.0455	15.16	500	80.7263	14.83
	200	14.197	13.42	300	2.9248	15.20	400	60.6181	13.52
	100	28.316	12.66	200	18.5796	14.93	300	47.0261	13.50
	0	40.929		100	33.4714	14.89	200	32.0234	12.75
2nd Cycle ⁽³⁾ (Heating)	L ₀ 0.6670 in			L ₀ 0.6739 in			L ₀ 0.6744 in		
	L ₀ L _{0f} 0.0026 in			L ₀ L _{0f} 0.0033 in			L ₀ L _{0f} -0.0004 in		
	100	13.454	13.45	100	13.4443	13.44	100	9.8149	9.81
	200	29.793	14.89	200	29.1309	14.57	200	25.4913	12.75
	300	44.731	14.91	300	44.8599	14.97	300	41.9327	13.98
	400	64.033	16.01	400	62.7997	15.70	400	57.6874	14.42
	500	84.055	16.81	500	81.4621	16.29	500	76.3373	15.27
	600	110.550	18.42	600	108.8007	18.13	600	105.1028	17.52
	642*	147.570	22.88	642*	143.7795	22.40	637*	136.4067	21.41
	700	157.915	(18.54)	700	155.6575	(20.19)	700	149.7539	(20.90)
2nd Cycle ⁽³⁾ (Cooling)	733	163.831	(18.21)	705	156.4018	(19.75)	704	150.4976	(20.75)
	733	163.831	(22.20)	705	156.4018	(24.97)	704	150.4976	(22.29)
	700	155.751	(21.63)	700	155.6575	(25.43)	700	149.7539	(22.42)
	603*	135.797	21.47	600	129.8061	(24.64)	600	126.8177	(21.42)
	600	132.902	21.30	588*	126.8117	22.07	576*	121.6140	21.75
	500	79.008	14.78	500	74.9435	15.57	500	74.1661	15.56
	400	59.707	13.66	400	55.5550	14.67	400	54.7924	14.61
	300	44.731	13.22	300	39.7899	14.23	300	38.3139	13.98
	200	29.793	12.36	200	24.7851	13.85	200	22.5955	13.11
	100	15.618	10.57	100	9.8219	12.72	100	7.6437	11.27
	0	5.047		0	2.8972		0	3.6188	
2nd Cycle ⁽³⁾ (Cooling)	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		
	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		
	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		
	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		
	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		
	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		
	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		
	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		
	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		
	L ₀ L _{0f} 0.0003 in			L ₀ L _{0f} 0.0002 in			L ₀ L _{0f} 0.0002 in		

(1) $\frac{L_T - L_0}{L_0}$ where L_T length at temperature and L_0 length at 0°C at start of heating cycle

(2) Mean thermal expansion coefficients between 0°C and indicated temperatures on heating $TEC = \frac{L_T - L_0}{L_0 \times \Delta T}$
on cooling $TEC = \frac{L_T - L_{0f}}{L_{0f} \times \Delta T}$ where L_{0f} length at 0°C at end of cooling cycle

(Coefficients in parentheses are for range between phase transformation arrest temperatures indicated by * and higher temperatures)

$TEC = \frac{L_T - L_a}{L_a \times \Delta T}$ where L_a length at arrest temperature

(3) Heated and cooled at approximately 10°C/min

Table IX

DILATOMETRIC DATA FOR U-8 wt % FS ALLOY (CASTING NO. 8-1)

	As Cast			As Annealed 48 Hr at 850°C; w.q.			As Annealed 11 Days at 500°C; w.q.		
	Temperature (°C)	Dilation ⁽¹⁾ (in. in. $\times 10^4$)	TEC ⁽²⁾ (in. in. $^{\circ}\text{C}$) $\times 10^6$	Temperature (°C)	Dilation ⁽¹⁾ (in. in. $\times 10^4$)	TEC ⁽²⁾ (in. in. $^{\circ}\text{C}$) $\times 10^6$	Temperature (°C)	Dilation ⁽¹⁾ (in. in. $\times 10^4$)	TEC ⁽²⁾ (in. in. $^{\circ}\text{C}$) $\times 10^6$
1st Cycle ⁽³⁾ (Heating)	$L_0 = 0.6413$ in.			$L_0 = 0.6407$ in.			$L_0 = 0.6380$ in.		
	100	11.8229	11.82	100	10.3100	10.31	100	11.8820	11.88
	200	26.0003	13.00	200	24.4993	12.25	200	24.5992	12.30
	300	40.9804	13.66	300	39.4938	13.12	300	40.4201	13.47
	400	55.2362	13.81	400	55.2861	13.82	400	57.0420	14.26
	444	60.7940	13.69	500	67.2686	13.45	500	73.6630	14.73
	500	58.0738	11.61	572	82.1152	14.36	559	88.5218	15.84
	508	55.0794	10.84	600	99.0425	16.51	600	108.6303	18.11
	533	55.1993	10.36	615*	107.4873	17.48	620*	122.5320	19.76
	563	62.2094	11.05	700	124.6832	(20.02)	700	138.9685	(20.33)
	600	70.5679	11.76	715	127.0348	(19.34)			
	639*	96.8793	15.16						
	700	107.8244	(17.77)						
	732	113.3083	(17.50)						
1st Cycle ⁽³⁾ (Cooling)	732	113.3083	(24.26)	715	127.0348	(23.91)	700	138.9685	(21.34)
	700	102.4966	(22.39)	700	123.1595	(23.76)	600	116.2817	(19.49)
	600	79.9239	(22.33)	600	101.3289	(26.50)	540*	104.4688	18.35
	541*	66.6629	19.14	523*	80.7604	17.71	500	87.4348	16.50
	500	44.3728	16.24	500	73.3632	16.52	454	72.6390	14.82
	400	21.7446	14.62	464	60.1922	14.98	400	62.3973	14.25
	300	5.2054	13.96	400	46.9051	14.02	300	46.5404	13.72
	200	-9.7737	13.43	300	30.3510	13.18	200	31.4856	13.06
	100	-24.7123	11.86	200	16.1192	12.64	100	18.7683	13.41
	0	-36.5361		100	1.1680	10.32	0	5.3553	
				0	-9.1419				
	$L_{of} = 0.6390$ in. $L_0 - L_{of} = 0.0023$ in.			$L_{of} = 0.6401$ in. $L_0 - L_{of} = 0.0006$ in.			$L_{of} = 0.6383$ in. $L_0 - L_{of} = -0.0003$ in.		
2nd Cycle ⁽³⁾ (Heating)	$L_0 = 0.6390$ in.			$L_0 = 0.6401$ in.			$L_0 = 0.6383$ in.		
	100	11.8640	11.86	100	12.6077	12.61	100	10.3471	10.35
	200	26.0908	13.04	200	28.3349	14.16	200	25.3538	12.67
	300	40.3590	13.45	300	44.1047	14.70	300	40.4017	13.47
	400	57.7196	14.43	400	59.1489	14.79	400	55.4866	13.87
	500	75.8443	15.17	500	72.6671	14.53	500	70.5709	14.11
	562	85.3404	15.19	551	82.8421	15.03	574	87.0113	15.16
	600	104.6457	17.44	600	105.2337	17.54	600	100.1681	16.70
	626*	120.8175	19.30	617*	114.4588	18.55	615*	110.1799	17.92
	700	135.7092	(19.87)	700	132.4229	(21.40)	700	125.9041	(18.30)
	732	141.2033	(19.00)	710	135.5272	(22.40)			
2nd Cycle ⁽³⁾ (Cooling)	732	141.2033	(23.60)	710	135.5272	(22.19)	700	125.9041	(20.89)
	700	132.6448	(23.02)	700	133.9480	(22.63)	600	103.9909	(19.08)
	639	116.2983	(20.80)	600	113.6226	(27.98)	555*	95.3238	18.56
	600	108.4649	(21.41)	543*	100.3423	18.48	500	72.8650	16.12
	542*	95.9252	18.98	500	81.8185	16.36	485	66.6484	15.33
	500	72.7879	15.94	476	70.9730	15.10	400	49.3682	14.27
	492	69.6934	15.57	400	56.0987	14.03	300	32.7539	13.48
	400	49.3163	14.06	300	40.2920	13.43	200	16.9413	12.30
	300	33.4834	13.46	200	25.2848	12.64	100	4.2297	11.89
	200	19.2152	13.05	100	11.0817	11.08	0	-7.6469	
	100	4.9894	11.87	0	0.0000				
	0	6.8746							
	$L_{of} = 0.6386$ in. $L_0 - L_{of} = 0.0004$ in.			$L_{of} = 0.6401$ in. $L_0 - L_{of} = 0.0000$ in.			$L_{of} = 0.6376$ in. $L_0 - L_{of} = 0.0005$ in.		

$$(1) \frac{L_T - L_0}{L_0} \text{ where } L_T = \text{length at temperature and } L_0 = \text{length at } 0^{\circ}\text{C at start of heating cycle.}$$

$$(2) \text{ Mean thermal expansion coefficients between } 0^{\circ}\text{C and indicated temperatures: on heating, } \text{TEC} = \frac{L_T - L_0}{L_0 \times \Delta T}.$$

$$\text{on cooling } \text{TEC} = \frac{L_T - L_{of}}{L_{of} \times \Delta T} \text{ where } L_{of} = \text{length at } 0^{\circ}\text{C at end of cooling cycle.}$$

(Coefficients in parentheses are for range between onase transformation arrest temperatures indicated by * and higher temperatures.)

$$\text{TEC} = \frac{L_a - L_0}{L_0 \times \Delta T}, \text{ where } L_a = \text{length at arrest temperature}$$

(3) Heated and cooled at approximately 1.0°C/min.

Table X

DILATOMETRIC DATA FOR U-10 w/o FS ALLOY (CASTING NO 10 2)

	As Cast			As Annealed 48 Hr at 850°C w q			As Annealed 11 Days at 500°C w q		
	Temperature (°C)	Dilation ⁽¹⁾ (in in)(x 10 ⁴)	TEC ⁽²⁾ (in in)(°C)(x 10 ⁶)	Temperature (°C)	Dilation ⁽¹⁾ (in in)(x 10 ⁴)	TEC ⁽²⁾ (in in)(°C)(x 10 ⁶)	Temperature (°C)	Dilation ⁽¹⁾ (in in)(x 10 ⁴)	TEC ⁽²⁾ (in in)(°C)(x 10 ⁶)
1st Cycle ⁽³⁾ (Heating)	L ₀ 0.9747 in			L ₀ 0.9452 in			L ₀ 0.9716 in		
	100	11.9245	11.92	100	9.1856	9.19	100	11.4589	11.46
	200	25.9221	12.96	200	22.5718	11.28	200	25.4994	12.75
	300	40.4623	13.49	300	34.9689	11.66	300	40.5869	13.53
	400	53.0369	13.26	400	51.0159	12.75	400	54.7071	13.68
	452	60.3184	13.35	480	68.5023	14.27	500	71.8406	14.37
	500	64.1079	12.82	500	70.6893	14.14	567	85.7568	15.12
	563	71.9501	12.78	530	69.2907	13.07	600*	106.5413	17.75
	600	83.1754	13.86	550	69.3981	12.62	612	111.6194	(41.87)
	622*	89.7893	14.44	575*	73.5578	12.79	700	129.1458	(22.37)
	700	105.2084	(19.59)	600	81.5445	(31.71)	705	130.1758	(22.14)
	730	111.3634	(19.77)	700	99.6019	(20.68)			
				733	105.9638	(20.62)			
1st Cycle ⁽³⁾ (Cooling)	730	111.3634	16.71	733	105.9638	15.88	705	130.1758	15.15
	700	102.7045	16.19	700	97.5363	15.43	700	129.6482	15.19
	646	89.9993	15.56	600	73.2815	13.95	600	109.0537	14.29
	600	80.1702	15.13	500	55.1855	13.12	570	103.8632	14.14
	500	61.6041	14.44	400	39.1381	12.38	513	97.0118	14.37
	400	42.0194	13.15	300	23.0898	11.15	500	93.4442	14.04
	300	26.4401	12.33	200	8.6278	9.49	400	77.3155	13.52
	200	12.9009	11.72	100	2.9882	8.17	300	61.6381	12.83
	100	1.4077	9.93	0	10.3286		200	48.1075	12.47
	0	10.5168					100	34.5697	11.43
							0	23.1101	
	L _{0f} 0.9737 in L ₀ L _{0f} 0.0010 in			L _{0f} 0.9442 in L ₀ L _{0f} 0.0010 in			L _{0f} 0.9738 in L ₀ L _{0f} 0.0022 in		
2nd Cycle ⁽³⁾ (Heating)	L ₀ 0.9737 in			L ₀ 0.9442 in			L ₀ 0.9738 in		
	100	11.4350	11.44	100	11.2627	11.26	100	11.4340	11.43
	200	24.9453	12.47	200	23.6287	11.81	200	24.4410	12.22
	300	40.0011	13.33	300	38.1055	12.70	300	38.4934	12.83
	400	56.0972	14.02	400	52.1023	13.03	400	54.0867	13.52
	478	69.0557	14.45	435	56.3329	12.95	486	65.0784	13.39
	500	71.1898	14.24	500	61.9622	12.39	500	65.6686	13.13
	569	81.5771	14.34	550	67.3876	12.25	513	65.7196	12.81
	600	90.2758	15.05	588*	83.1140	14.14	560	72.5063	12.95
	700	113.3340	16.19	600	85.7638	(21.90)	600*	87.2594	14.54
	730	119.9965	16.44	700	103.3229	(17.90)	700	105.8036	(18.38)
				730	108.6420	(17.83)			
2nd Cycle ⁽³⁾ (Cooling)	730	119.9965	(21.51)	730	108.6420	16.32	700	105.8036	14.94
	700	111.8301	(19.87)	700	100.7376	15.88	600	86.7582	14.29
	600*	91.7802	14.71	632	82.8211	14.76	500	71.1828	14.03
	500	73.6953	14.03	600	78.0090	14.74	400	54.0867	13.27
	400	56.0972	13.14	500	59.3768	13.96	300	37.9922	12.33
	300	41.5056	12.66	400	42.7966	13.30	200	24.9428	11.97
	200	26.9504	11.71	300	27.2490	12.54	100	12.4364	11.43
	100	13.9415	10.43	200	13.8050	12.08	0	1.0625	
	0	3.5090		100	0.9231	10.24			
				0	10.3395				
	L _{0f} 0.9740 in L ₀ L _{0f} 0.0303 in			L _{0f} 0.9432 in L ₀ L _{0f} 0.0010 in			L _{0f} 0.9739 in L ₀ L _{0f} 0.0001 in		

(1) $\frac{L_T - L_0}{L_0}$ where L_T length at temperature and L_0 length at 0°C at start of heating cycle(2) Mean thermal expansion coefficients between 0°C and indicated temperatures on heating $TEC = \frac{L_T - L_0}{L_0 \times \Delta T}$
on cooling $TEC = \frac{L_T - L_{0f}}{L_{0f} \times \Delta T}$ where L_{0f} length at 0°C at end of cooling cycle

(Coefficients in parentheses are for range between phase transformation arrest temperatures indicated by * and higher temperatures)

 $TEC = \frac{L_T - L_*}{L_* \times \Delta T}$ where L_* length at arrest temperature

(3) Heated and cooled at approximately 10°C/min

Table XI

DILATOMETRIC DATA FOR U 5 w o F s 2 2 5 w o 7 r ALLOY (CASTING NO 5 4)

	As Cast			As Annealed 48 Hr at 850°C w q			As Annealed 11 Days at 500°C w q		
	Temperature (°C)	Dilation(1) (in/in)(x 10 ⁴)	TEC(2) (in/in/°C) (x 10 ⁶)	Temperature (°C)	Dilation(1) (in/in)(x 10 ⁴)	TEC(2) (in/in/°C) (x 10 ⁶)	Temperature (°C)	Dilation(1) (in/in)(x 10 ⁴)	TEC(2) (in/in/°C) (x 10 ⁶)
1st Cycle ⁽³⁾ (Heating)	L ₀ = 0.9334 in			L ₀ = 0.9335 in			L ₀ = 0.9305 in		
	100	11.3883	11.39	100	10.8388	10.84	100	12.9962	13.00
	200	23.8919	11.94	200	26.5044	13.25	200	28.1607	14.08
	300	38.0073	12.67	300	36.4347	13.14	300	44.4167	14.81
	400	47.9756	11.99	400	41.6956	10.45	400	60.1844	15.05
	428	50.2124	11.73	442	42.9665	9.72	500	78.0509	15.61
	500	51.6673	10.33	462	39.4064	8.53	600	101.6701	16.95
	600	72.0777	12.01	500	43.2954	8.65	670*	145.5552	21.72
	661*	112.1172	16.96	600	67.3638	11.23	700	152.5295	(22.91)
	700	124.8728	(32.34)	663*	107.9319	16.28	705	154.6539	(25.62)
1st Cycle ⁽³⁾ (Cooling)	732	131.3038	(26.74)	700	112.3103	(11.72)			
	700	123.3040	(20.39)	638*	96.3081	21.99	705	154.6539	(21.19)
	648*	112.5801	21.87	600	59.5201	17.40	700	153.5789	(21.19)
	600	72.6006	16.94	500	32.3145	15.42	640*	140.6841	22.23
	500	44.8693	13.28	400	13.4586	14.54	600	105.8672	17.91
	400	26.5336	13.86	300	4.3518	13.42	500	76.4766	15.61
	300	10.8132	13.23	200	20.0332	12.26	400	58.6107	15.05
	200	4.3474	12.24	100	33.5830	10.91	300	41.7932	14.46
	100	17.3747	11.42	0	44.4472		200	26.0624	13.82
	0	28.7631					100	11.4226	13.00
2nd Cycle ⁽³⁾ (Heating)	L ₀ = 0.9307 in L ₀ L _{of} = 0.0027 in			L ₀ = 0.9294 in L ₀ L _{of} = 0.0041 in			L ₀ = 0.9304 in L ₀ L _{of} = 0.0001 in		
	100	11.9447	11.94	100	13.0111	13.01	100	12.9975	13.00
	200	25.5320	12.76	200	26.0922	13.04	200	26.5897	13.29
	300	42.3090	14.10	300	41.3159	13.77	300	42.3222	14.10
	400	58.0741	14.57	400	58.1527	14.54	400	59.1414	14.79
	500	76.4607	15.29	500	75.5139	15.10	500	75.4354	15.08
	600	95.8799	15.98	600	98.1104	16.35	600	99.5821	16.60
	694*	152.9775	22.04	660*	130.9678	19.84	673*	145.5805	21.63
	700	154.5962	(26.57)	700	136.9495	(14.76)	700	150.4474	(17.77)
	753	166.9144	(23.27)				705	151.5218	(18.30)
2nd Cycle ⁽³⁾ (Cooling)	753	166.9144	(20.93)	700	136.9495	(4.82)	705	151.5218	(21.21)
	700	156.1695	(22.45)	640*	134.0189	21.69	700	149.3982	(19.62)
	667*	148.6520	21.88	600	99.6859	17.40	635*	136.4714	21.74
	600	102.6976	16.68	500	71.8376	15.32	600	105.8781	17.91
	500	79.6080	15.39	400	53.9513	14.68	500	77.0092	15.72
	400	61.7459	14.77	300	37.1145	13.95	400	58.0922	14.65
	300	45.4563	14.28	200	20.8398	12.79	300	40.7484	14.11
	200	29.7282	13.55	100	7.2335	11.97	200	25.0153	13.30
	100	15.0913	12.47	0	4.7266		100	10.8991	12.47
	0	2.6222					0	1.5783	
2nd Cycle ⁽³⁾ (Cooling)	L ₀ L _{of} = 0.0002 in			L ₀ L _{of} = 0.0004 in			L ₀ L _{of} = 0.0001 in		

(1) $\frac{l_T - L_0}{L_0}$ where l_T = length at temperature and L_0 = length at 0°C at start of heating cycle(2) Mean thermal expansion coefficients between 0°C and indicated temperatures on heating $TEC = \frac{l_T - L_0}{L_0 \times \Delta T}$
on cooling $TEC = \frac{l_T - L_{of}}{L_{of} \times \Delta T}$ where L_{of} = length at 0°C at end of cooling cycle

(Coefficients in parentheses are for range between phase transformation arrest temperatures indicated by * and higher temperatures)

 $TEC = \frac{l_T - L_a}{L_a \times \Delta T}$ where L_a = length at arrest temperature

(3) Heated and cooled at approximately 10°C/min

Table XII
THERMAL CONDUCTIVITY OF URANIUM
(Casting No. 747)

Equilibrium No.	Temperature, °C	Thermal Conductivity, cal/(sec)(cm)(°C)		
		ANL (exp) ⁽¹⁾	ANL (calc) ⁽²⁾	BMI ⁽³⁾
	0	-	0.068 (extrapolated)	
	100	-	0.069 (extrapolated)	0.062
1	150	0.068		
1	200	0.070	0.071	0.067
2	200	0.070		
1	250	0.071		
2	250	0.072		
3	250	0.074		
2	300	0.074	0.074	0.072
3	300	0.076		
4	300	0.076		
2	350	0.076		
3	350	0.078		
4	350	0.078		
2	400	0.078	0.080	0.076
3	400	0.080		
4	400	0.081		
2	450	0.081		
3	450	0.083		
4	450	0.084		
3	500	0.086	0.086	0.084
4	500	0.087		
3	550	0.089		
4	550	0.091		
3	600	0.092	0.094	0.093
4	600	0.095		
3	650	0.096		
4	650	0.100		
4	700	0.105	0.104	0.103
4	750	0.112	0.110	
	800	-	0.115 (extrapolated)	0.112
	900	-	0.128 (extrapolated)	0.124

(1) Experimental coefficients: $K_U = K_{STD} \left(\frac{\left[\frac{dT}{dx} \right]_{STD}}{\left[\frac{dT}{dx} \right]_U} \right)$

(2) $K(\text{calc}) = a + bT + cT^2$, where $a = 0.0679$, $b = 9.215 \times 10^{-7}$, and $c = 7.543 \times 10^{-8}$. Standard deviation between experimental and calculated coefficients is 0.0014 cal/(sec)(cm)(°C).

(3) Battelle Memorial Institute, Progress Report BMI-902 (January 1954).

Table XIII
THERMAL CONDUCTIVITY OF U-3 w/o Fs ALLOY
(Casting No. 678)

Equilibrium No.	Temperature, °C	Thermal Conductivity, cal/(sec)(cm)(°C)	
		K (exp) ⁽¹⁾	K (calc) ⁽²⁾
	0	-	0.053 (extrapolated)
	100	-	0.056 (extrapolated)
1	150	0.056	
2	175	0.059	
1	200	0.058	0.060
3	200	0.061	
5	225	0.062	
2	250	0.062	
3	250	0.063	
4	259	0.062	
1	275	0.061	
6	275	0.066	
2	300	0.064	0.065
3	300	0.065	
5	300	0.065	
3	350	0.068	
5	350	0.067	
6	350	0.069	
4	358	0.069	
3	400	0.070	0.071
5	400	0.070	
6	400	0.072	
5	450	0.074	
6	450	0.075	
4	451	0.073	
5	500	0.078	0.079
6	500	0.079	
6	550	0.083	
5	575	0.085	
6	600	0.088	0.088
6	675	0.096	
-	700	-	0.098 (extrapolated)

(1) Experimental coefficients:

$$K_{\text{U-3 w/o Fs}} = K_{\text{STD}} \left(\frac{\left[\frac{dT}{dx} \right]_{\text{STD}}}{\left[\frac{dT}{dx} \right]_{\text{U-3 w/o Fs}}} \right)$$

(2) $K(\text{calc}) = a + bT + cT^2$, where $a = 0.0535$, $b = 1.764 \times 10^{-5}$, and $c = 6.571 \times 10^{-8}$. Standard deviation between experimental and calculated coefficients is $0.0010 \text{ cal}/(\text{sec})(\text{cm})(^\circ\text{C})$.

Table XIV
THERMAL CONDUCTIVITY OF U-5 w/o Fs ALLOY
(Casting No. 870)

Equilibrium No.	Temperature, °C	Thermal Conductivity, cal/(sec)(cm)(°C)	
		K (exp) ⁽¹⁾	K (calc) ⁽²⁾
	0	-	0.044 (extrapolated)
5	100	0.048	0.047
1	150	0.046	
2	150	0.049	
5	150	0.050	
1	200	0.049	0.052
2	200	0.051	
3	200	0.054	
5	200	0.052	
1	250	0.053	
2	250	0.054	
3	250	0.056	
4	250	0.059	
5	250	0.055	
1	300	0.058	0.058
2	300	0.057	
3	300	0.059	
4	300	0.061	
5	300	0.059	
2	350	0.061	
3	350	0.061	
4	350	0.063	
2	400	0.065	0.065
3	400	0.064	
4	400	0.066	
2	450	0.071	
3	450	0.068	
4	450	0.069	
3	500	0.072	0.073
4	500	0.072	
3	550	0.078	
4	550	0.076	
3	600	0.085	0.083
4	600	0.081	
4	650	0.086	
4	700	0.093	0.094
4	750	0.102	0.099

(1) Experimental coefficients:

$$K_{\text{U-5 w/o Fs}} = K_{\text{STD}} \left(\frac{\left[\frac{dT}{dx} \right]_{\text{STD}}}{\left[\frac{dT}{dx} \right]_{\text{U-5 w/o Fs}}} \right)$$

(2) $K(\text{calc}) = a + bT + cT^2$, where $a = 0.0435$, $b = 3.0483 \times 10^{-5}$ and $c = 5.8673 \times 10^{-8}$. Standard deviation between experimental and calculated coefficients is $0.0016 \text{ cal}/(\text{sec})(\text{cm})(^\circ\text{C})$.

Table XV

THERMAL CONDUCTIVITY OF U-8 w/o Fs ALLOY
(Casting No. 743)

Equilibrium No.	Temperature °C	Thermal Conductivity, cal/(sec)(cm)(°C)	
		K (exp) ⁽¹⁾	K (calc) ⁽²⁾
	0	-	0.037 (extrapolated)
	100	-	0.041 (extrapolated)
1	140	0.042	
5	150	0.040	
1	200	0.047	0.046
2	200	0.046	
4	200	0.045	
5	200	0.044	
6	200	0.046	
1	250	0.053	
2	250	0.049	
3	250	0.053	
4	250	0.048	
5	250	0.048	
6	250	0.048	
7	250	0.051	
2	300	0.052	0.052
3	300	0.055	
4	300	0.051	
6	300	0.050	
7	300	0.053	
2	350	0.055	
3	350	0.057	
4	350	0.054	
6	350	0.053	
7	350	0.056	
2	400	0.059	0.059
3	400	0.059	
4	400	0.058	
6	400	0.056	
7	400	0.058	
2	450	0.064	
3	450	0.062	
4	450	0.063	
6	450	0.060	
7	450	0.061	
2	500	0.069	0.066
3	500	0.066	
6	500	0.065	
7	500	0.065	
3	550	0.069	
6	550	0.071	
7	550	0.069	
3	600	0.074	0.075
7	600	0.075	
3	650	0.080	
7	650	0.081	
3	700	0.087	0.085

(1) Experimental coefficients:

$$K_{\text{U-8 w/o Fs}} = K_{\text{STD}} \left(\frac{\left[\frac{dT}{dx} \right]_{\text{STD}}}{\left[\frac{dT}{dx} \right]_{\text{U-8 w/o Fs}}} \right)$$

(2) $K(\text{calc}) = a + bT + cT^2$, where $a = 0.0375$, $b = 3.2300 \times 10^{-5}$, and $c = 5.0910 \times 10^{-8}$. Standard deviation between experimental and calculated coefficients is $0.0017 \text{ cal}/(\text{sec})(\text{cm})(^\circ\text{C})$.

Table XVI
THERMAL CONDUCTIVITY OF U-10 w/o Fs ALLOY
(Casting No. 744)

Equilibrium No.	Temperature, °C	Thermal Conductivity, cal/(sec)(cm)(°C)	
		K (exp)(1)	K (calc)(2)
	0	-	0.033 (extrapolated)
1	100	0.037	0.038
1	150	0.039	
2	150	0.039	
1	200	0.043	0.043
2	200	0.042	
5	225	0.046	
1	250	0.047	
2	250	0.045	
3	250	0.047	
4	250	0.050	
2	300	0.050	0.049
3	300	0.049	
4	300	0.051	
5	300	0.049	
2	350	0.056	
3	350	0.051	
4	350	0.053	
5	350	0.051	
3	400	0.053	0.055
4	400	0.055	
5	400	0.054	
3	450	0.056	
4	450	0.058	
5	450	0.057	
3	500	0.059	0.061
4	500	0.061	
5	500	0.060	
3	550	0.063	
4	550	0.064	
5	550	0.065	
3	600	0.067	0.068
4	600	0.067	
5	600	0.070	
3	650	0.073	
4	650	0.072	
4	700	0.077	0.075

(1) Experimental coefficients:

$$K_{\text{U-10 w/o Fs}} = K_{\text{STD}} \left(\left[\frac{dT}{dx} \right]_{\text{STD}} \left[\frac{dT}{dx} \right]_{\text{U-10 w/o Fs}} \right)$$

(2) $K(\text{calc}) = a + bT + cT^2$, where $a = 0.0331$, $b = 4.6728 \times 10^{-5}$, and $c = 1.9534 \times 10^{-8}$. Standard deviation between experimental and calculated coefficients is $0.0016 \text{ cal}/(\text{sec})(\text{cm})(^\circ\text{C})$.

Table XVII
THERMAL CONDUCTIVITY OF U-5 w/o Fs - 2.25 w/o Zr ALLOY
(Casting No. 896)

Equilibrium No.	Temperature °C	Thermal Conductivity, cal/(sec)(cm)(°C)	
		K (exp)(1)	K (calc)(2)
	0	-	0.046 (extrapolated)
	100	-	0.050 (extrapolated)
1	150	0.050	
2	150	0.051	
6	175	0.054	
1	200	0.054	0.055
2	200	0.053	
6	200	0.055	
7	200	0.056	
1	250	0.057	
2	250	0.056	
3	250	0.059	
4	250	0.059	
5	250	0.060	
6	250	0.057	
7	250	0.058	
2	300	0.059	0.060
3	300	0.061	
4	300	0.061	
5	300	0.062	
6	300	0.060	
7	300	0.060	
2	350	0.063	
3	350	0.063	
4	350	0.063	
5	350	0.064	
6	350	0.064	
7	350	0.063	
3	400	0.066	0.066
4	400	0.066	
5	400	0.067	
6	400	0.068	
7	400	0.067	
2	425	0.069	
3	450	0.069	
4	450	0.068	
5	450	0.069	
7	450	0.070	
3	500	0.072	0.073
4	500	0.071	
5	500	0.072	
7	500	0.075	
7	525	0.078	
3	550	0.075	
4	550	0.075	
5	550	0.076	
3	600	0.079	0.081
4	600	0.079	
5	600	0.080	
3	650	0.084	
4	650	0.084	
5	650	0.085	
3	675	0.091	
4	675	0.090	
5	700	0.090	0.089
	800	-	0.099 (extrapolated)

(1) Experimental Coefficients:

$$K_{\text{U-5 w/o Fs - 2.25 w/o Zr}} = K_{\text{STD}} \left(\frac{\left[\frac{dT}{dx} \right]_{\text{STD}}}{\left[\frac{dT}{dx} \right]_{\text{U-5 w/o Fs - 2.25 w/o Zr}}} \right)$$

(2) $K(\text{calc}) = a + bT + cT^2$, where $a = 0.0464$, $b = 3.3975 \times 10^{-5}$, and $c = 3.9067 \times 10^{-8}$. Standard deviation between experimental and calculated coefficients is 0.0014 cal/(sec)(cm)(°C).