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Addition of Rare Earths to
Uranium and Uranium Alloys

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

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Printed in the United States of America. Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

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Report written: April 1968
Report distributed: May 8, 1968

**Addition of Rare Earths to
Uranium and Uranium Alloys**

by

G. E. Jaynes

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ADDITION OF RARE EARTHS TO URANIUM AND URANIUM ALLOYS

by

G. E. Jaynes

ABSTRACT

The rare earths thulium, lutetium, and yttrium were added to uranium and uranium alloys in the range of 0.1-0.3 wt %. Nickel, cobalt, and rhodium were used as carrier metals for the rare earths. These carrier metals are partially soluble in uranium and also exhibit partial solubility for the rare earths.

The room temperature tensile strength, yield strength, elongation, calculated modulus, and hardness were obtained for both as-rolled and vacuum-annealed sheet stock. Grain size, hardness, and density values were obtained on the as-cast alloys for comparison.

INTRODUCTION

A development program was undertaken at the Los Alamos Scientific Laboratory (LASL) to determine the effect of rare-earth elements on the mechanical and physical properties of uranium and uranium alloys. The first samples were made by including the rare earths with the uranium at the time the crucible was loaded. However, only about 50-500 ppm of rare earths were retained in the melt. Further investigations indicated that three characteristics of the rare earths introduced problems in alloying with uranium. The first problem was created by the density extremes between uranium (18.93 g/cc) and the rare earths thulium (9.33 g/cc), lutetium (9.84 g/cc), and yttrium (4.47 g/cc). The second problem was that the high vapor pressure of some of the rare earths at the melting point of uranium (1130°C) resulted in losses during vacuum melting. A third problem was that of the limited solubility of the rare earths in uranium, as reported by Haeffling and Daane.¹ Their work indicated a maximum solubility of 0.04 wt % thulium at 1225°C, 0.40 wt % lutetium at 1200°C, and 0.14 wt % yttrium at 1225°C.

The density variation causes the lower-density rare earths either to float to the top of the casting or to remain in the crucible residue. A series of experiments showed that segregation of the rare earths could be overcome when the rare earths were added with a carrier metal that was soluble in molten uranium. This rare earth-carrier metal button was introduced into the uranium melt a few minutes prior to induction stirring and pouring. Chill casting prevented liquation of the rare earths during solidification of the melt.

This report describes the alloying and casting procedures developed at the Los Alamos Scientific Laboratory for producing homogeneous uranium and uranium alloys containing 0.1-0.3 wt % of the rare earths thulium, lutetium, and yttrium. Some physical property data were also obtained as a part of the program.

EQUIPMENT AND MATERIAL

The furnace used to melt and cast the uranium-rare earth alloys is shown in Figs. 1 and 2. The lid of the furnace contained a sight glass through which metal temperatures could be determined by an

Fig. 1. Steel tank vacuum and/or argon atmosphere furnace.

optical pyrometer. The argon supply valve was located such that the flow of argon prevented fogging of the sight glass. The lid was held in place by spring-loaded bolts which, for safety, were designed to open at 26-1/2 psi.

The metal charges were melted using a high-frequency (10 kc) power supply and inductively (60 cycle) stirred after the 10 kc power had been turned off.

The secondary graphite stopper rod or dispenser was attached to a movable tungsten rod which passed through a vacuum seal in the lid. The dispenser was made from a graphite rod approximately 2 in. diam x 4 in. long, with a through-hole drilled perpendicular to its axis. All the graphite surfaces were coated with Mold Wash A to prevent carbon pickup by the uranium melt. A 0.002-in.-thick piece of uranium foil was supported by graphite rings at each end of the dispenser cavity which contained the rare earth additions. The dispenser was screwed onto the movable tungsten rod and held above the surface of the uranium melt until the low-frequency induction stirring of the charge was begun. At this

Fig. 2. Schematic view of all metal induction type vacuum and/or argon atmosphere furnace.

time the dispenser was lowered into the melt and the metal was added to the molten uranium by melting of the uranium foils.

The carrier metal-rare earth additions were arc-melted buttons cast in a dc nonconsumable arc furnace utilizing a tungsten-2% thoria electrode and a power requirement of 300 amp at 20-30 V. An OFHC copper water-cooled mold having a button cavity 1-1/2 in. diam x 1/2 in. deep was used.

The melting procedure was to first melt the carrier metal under a positive argon pressure of 5 lb. The molten carrier metal was then moved by bringing the electrode into contact with the rare earth until the rare earth addition was completely absorbed. Care was taken not to strike the arc directly on the rare-earth metal. The buttons were then remelted twice using reverse stirring to ensure homogeneity of the melt. The dc reverse stirring coil was operated at 1/2 amp and reversed the stirring direction every 10 sec. The ratio of carrier metal to rare earth was approximately 2:1 and weight losses after melting were less than 1% in all cases.

The purity of the carrier metals rhodium, cobalt, and nickel was approximately 99.99%. The purity of the rare earths and the base-metal uranium to which they were added are shown in Table I.

Various coatings were applied to the graphite components of the induction furnace as shown in Table II. These coatings were either sprayed or brushed on the graphite to prevent carbon pickup and reaction with the melt.

EXPERIMENTAL PROCEDURE

Casting

The alloy charge of uranium and the arc-melted button of the carrier metal plus rare earth were loaded into the furnace and the furnace was pumped down to a pressure of 50 μ Hg or less. In melts under an argon atmosphere, the furnace was heated to approximately 800°C before the vacuum valve was closed and the argon was introduced into the furnace. The furnace was then pressurized to a maximum of 25 psi before the temperature of the uranium metal was increased.

The rare earth additions were made between the induced stirring and the pour. Alloying took place

TABLE I
CHEMICAL ANALYSIS OF RAW MATERIALS

Impurity Elements	U	Tm	Lu	Y
U	major			
Li	<0.2			<3
Be	<0.2			<3
B	<0.2			<10
Na	<1			<10
Al	20			30
Si	100	<100	<100	10
P	<50			
Ca	<2	<100	1	30
V	<20			<10
Cr	1			10
Mn	15			10
Fe	60	<100	1	300
Co	<5			<30
Ni	15			100
Cu	5			20
Mo	<25			30
Cd	<1			<100
Sn	<1			<10
Pb	<1			<10
C	60			
Tm		major		<20
Yb		1		5
Er		5	5	<10
Dy		500	1	50
Y		100	3	major
Mg		<100	<100	30
Lu			major	
Ta			1-2%	<1000
Eu				<3
Sc, Ti, Ag, Bi				<10
La, Gd, Tb, Ho				<30
Ce, Pr, Nd				<100
Zn, Nb, Th				<300
Sr				<1

TABLE II
COATING USED ON GRAPHITE COMPONENTS (a)

Description	Type of Coating	Application of Coating	Thickness of Coating (in.)
Crucible	ZrO ₂ (b)	Brush	0.030
Stopper rod	ZrO ₂ (b)	Brush	0.030
Dispenser	Zirconite Mold Wash A (c)	Spray	0.010
Mold	Zirconite Mold Wash A	Spray	0.010

(a) All graphite parts were prefired in vacuum (1350°C) to eliminate any presence of moisture.

(b) ZrO₂ (grade TAM-powder R) calcia stabilized and milled, purchased from National Lead Co., Titanium Alloy Mfg. Division.

(c) Zirconium silicate (ZrSiO₄) purchased from National Lead Co., Titanium Alloy Mfg. Division.

between the superheat temperature (1550-1750°C) and the final pour temperature (1450°C). The stirring time was dependent upon the temperature differential between superheat and pour temperature. Superheat temperatures, pour temperatures, and stirring times for the various alloy compositions are shown in the Appendix, Tables A-I through A-VI.

To reduce segregation, low-frequency induction stirring of the molten metal in the crucible was used in all casting work reported. The low-frequency stirring unit consists of a 60-cycle source attached to the leads of the primary coil. It is not feasible to run the high-frequency (10 kc) motor generator unit and the 60-cycle source simultaneously. In so doing, it was found that the feedback from the high-frequency motor generator caused the 60-cycle transformer to heat up. Therefore, the high-frequency heating unit was turned off and the low-frequency stirring unit was started after the metal had attained the desired superheat temperature. Stirring was continued until the pour temperature was reached.

The temperature of the coated graphite mold was controlled from 1000°C at the top to 400°C at the bottom. This allowed the melt to solidify rapidly, proceeding from the bottom of the casting to the riser. The ingot cast in each test was 1-11/16 in. diam x 6 in. long and weighed approximately 4.0 kg. Three different methods were used for making the rare earth additions:

1. The rare-earth metal was distributed in the charge with the uranium and the two were melted together.
2. The rare-earth metal additions were placed in a cavity machined into the bottom of the graphite crucible. A secondary graphite stopper rod attached to the movable tungsten rod was placed over the cavity. The stopper rod was raised at the proper temperature to release the addition into the melt.
3. The rare-earth metal addition was placed in a graphite dispenser unit, which was lowered into the melt at a predetermined time.

These addition methods are discussed in detail later in the report.

Rolling

The cast bars were sectioned and machined from the as-cast dimension of 1-11/16 in. diam x 6 in. long to 1-1/2 in. diam x 1/2 in. thick plates. The plate was heated in a salt bath at 625°C and hot rolled (60% reduction) to a thickness of 0.200 in. The plates were then salt annealed at 625°C for 1/2 h and warm rolled (99% reduction) from an oil bath (340°C) to a final thickness of 0.020 in. Some edge cracking was evident on the alloys containing rhodium as the carrier metal. No cracking was evident with nickel or cobalt as the carrier metal.

Sample Preparation and Testing

Modified ASTM sheet tensile specimens, 4-1/4 in. long x 9/16 in. wide x 0.020 in. thick with a 1.000 ± 0.010 in. reduced section, were prepared from each sheet. All specimens were taken parallel to the rolling direction. Data on tensile strength, yield strength, calculated modulus, elongation, and hardness were obtained from tensile specimens in both as-rolled and annealed conditions. The blanked specimens were ground on the reduced section to eliminate stress risers.

The tensile specimens were pulled on a 10,000-lb Instron tensile machine at a cross-head speed of 0.050 in. per min. The elongation values are a strain rate on a 1 in. gauge length.

Hardness tests in accordance with ASTM specifications (ASTM designation: E92-65) were made on as-cast material and on as-rolled and annealed sheet stock specimens to determine the hardness values on the Rockwell C scale.

Results and Discussions

When it was first decided to study the effect of rare-earth elements on the mechanical and physical properties of uranium, the alloys were cast by adding the rare earths to the uranium charge at room temperature and heating the charge to the pouring temperature under vacuum. Chemical analysis of these heats indicated that only 50-500 ppm of the 1000 ppm rare earth added was retained and that the distribution of the rare earth throughout the casting was not uniform. It soon became evident that three problems existed; a large difference in density (4.47-9.84 g/cc for the rare earths as

compared to 18.93 g/cc for uranium), the high vapor pressures of the rare earths at the melting point of uranium, and the limited solubility of the rare earths in γ -uranium.

Two modifications to the casting procedure were then tried. First, the induction stirring unit was used in hopes that it would overcome the difference in density. Second, the furnace was modified to allow the charge to be melted under a pressure of 25 psi argon. This modification was a major factor in the development of a casting procedure for uranium-rare earth alloys. These two modifications improved the recovery to 240-785 ppm. However, chemical analyses indicated that the rare earths were not uniformly distributed throughout the casting.

To overcome the nonuniform distribution, the rare earths were prealloyed with a metal in which rare earths had some solubility and which itself was soluble in uranium. These prealloyed buttons were prepared by arc melting as described earlier. They were then added to the charge at room temperature and melted with the uranium. This procedure produced a more uniform distribution of the rare earths in the uranium, but the recovery was not appreciably improved. Where the rare earth was added to a uranium alloy, two alloy buttons were prepared. One consisted of the rare earth and the carrier metal and the other consisted of the alloy addition and uranium. Typical results for lutetium are given in Table III. A more detailed tabulation

TABLE III

TYPICAL ANALYSIS OF CASTINGS MADE BY ADDING LUTETIUM TO THE URANIUM CHARGE

Method of Casting	Charge Comp., wt %	Lu Recovery, %
Melted in vacuum; induction stirred	U- 99.90 Lu- 0.10	6.0
Melted under 25 psi Ar; induction stirred until solidified	U- 99.90 Lu- 0.10	59.2
Melted under 25 psi Ar; induction stirred; Lu prealloyed with 1 wt % Rh	U- 98.85 Rh- 1.00 Lu- 0.15	32.9
Lu prealloyed with Rh; cast under Ar atmosphere; U-Nb alloy	U- 99.10 Nb- 0.50 Rh- 0.30 Lu- 0.30	21.1

is presented in Tables A-I through A-IV of the Appendix.

It was felt that further improvements in recovery could be made if the rare earth was added to the melt near the pouring temperature to shorten the time during which the rare earths could vaporize. Two methods of accomplishing this were employed. The first consisted of machining a small cavity in the bottom of the crucible and controlling the additional time through a second stopper rod (Fig. 3).

A series of castings was made using this method. The rare earth additions were made both as the pure element and as a prealloyed button. It is again shown (Table IV below and Tables A-V to A-VII in the

TABLE IV

TYPICAL RESULTS FOR LUTETIUM ADDITIONS MADE BY DISPENSING THE LUTETIUM FROM A CAVITY IN THE CRUCIBLE

Method of Casting	Charge Comp., wt %	Lu Recovery, %
Lu added to melt in elemental form under Ar atmosphere	U- 99.90 Lu- 0.10	11.8
Lu prealloyed with Ni; cast under Ar atmosphere	U- 99.40 Ni- 0.50 Lu- 0.30	66.1
Lu prealloyed with Rh; cast under Ar atmosphere; U-Nb alloy	U- 99.21 Nb- 0.39 Rh- 0.30 Lu- 0.30	32.4

Fig. 3. Crucible arrangement for adding rare earth to uranium by means of cavity in crucible bottom with secondary stopper rod.

Appendix) that the prealloying increased the rare-earth recovery and in general, gave a more uniform distribution of the elements. This method has the disadvantage of the rare earth addition being heated to the casting temperature of the uranium melt. Although the vapor pressure effect is partially overcome by the stopper rod confining the addition to a small volume, the problem could be further reduced by holding the addition at a lower temperature.

In the second method, to avoid heating the rare earth addition during the melting of the uranium charge, a graphite dispenser (Fig. 4) was designed and tested. A limited number of tests were made using this apparatus; the results are shown in Table V. As can be seen, the difference between vacuum and argon atmosphere casting are considerably smaller than for other methods.

TABLE V

CHEMICAL COMPOSITION OF ARC-MELTED BUTTON OF RARE EARTH PLUS CARRIER METAL ADDED TO URANIUM BY MEANS OF GRAPHITE DISPENSER

Item	Heat No. 26	Heat No. 27
Nominal Composition, wt %	U-99.30 Rh- 0.40 Lu- 0.30	U-99.30 Rh- 0.40 Lu- 0.30
Composition of Rare Earth + Carrier Metal Button, wt %	Rh-57.0 Lu-43.0	Rh-57.0 Lu-43.0
Atmosphere	Ar, 25 psi	Vacuum, ~ 50 μ
Superheat Temperature, °C	1550	1550
Pour Temperature, °C	1450	1450
Stirring Time, min	1-1/4	1-1/4
Chemical Analysis, wt %	Lu Rh	Lu Rh
Top	0.08 0.32	0.07 0.37
Center	0.09 0.31	0.08 0.36
Bottom	0.06 0.31	0.08 0.37
Lu Recovery, %	24.9	24.8

Density Values

Table VI is a tabulation of the as-cast densities obtained with the various alloying elements and rare earth additions. Nickel and cobalt are more desirable than rhodium as a carrier metal on a weight basis if the amount of carrier metal is limited in a given composition. A limit of 2 at. % carrier metal for density considerations in a given alloy would then use only 0.5 wt % cobalt or nickel as compared to 0.875 wt % rhodium.

Fig. 4. Crucible arrangement for adding rare-earth to uranium by means of graphite dispenser.

TABLE VI

DENSITY VALUES OF URANIUM ALLOYS COMBINED WITH RARE EARTHS; THULIUM, LUTETIUM, AND YTTRIUM

Heat No.	Composition, wt %	Density, g/cc ^(a)
0	U-99.99	18.932
20	U-99.31 Co- 0.48 Lu- 0.21	18.830
27	U-99.56 Rh- 0.37 Lu- 0.08	18.827
21	U-99.28 Co- 0.50 Tm- 0.22	18.827
24	U-99.44 Ni- 0.44 Y- 0.12	18.803
10	U-99.40 Ni- 0.51 Lu- 0.09	18.777
25	U-99.29 Co- 0.50 Y- 0.22	18.748
13	U-99.06 Rh- 0.68 Y- 0.26	18.736
19	U-99.48 Ni- 0.41 Tm- 0.11	18.702

(a) Density samples were machined to 3/8 in. diam x 3/8 in. long cylinders and were free of defects larger than 0.020 in. diam as determined by radiography.

TABLE VII
PHYSICAL DATA ON AS-CAST URANIUM ALLOYS COMBINED WITH RARE EARTHS (THULIUM, LUTETIUM, AND YTTRIUM)

Heat No.	Composition, wt %	Rockwell C	Grain Size, mm	Structure
		Hardness As-Cast		
10	U-98.00 Mo- 1.89 Lu- 0.04	36	0.32	Two primary phases (see Fig. 6 - sample A)
11	U-98.98 Rh- 0.97 Lu- 0.05	27	N.A. (a)	Two-phase dendritic structure (see Fig. 6 - sample B)
13	U-99.06 Rh- 0.68 Y- 0.26	26	N.A.	Large amount of spherical nonmetallic particles (see Fig. 6 - sample C)
14	U-98.93 Rh- 1.00 Tm- 0.07	30	N.A.	Two primary phases
15	U-98.78 Nb- 1.09 Lu- 0.02	24	0.50	Large beta grains (see Fig. 6 - sample D)
16	U-99.22 Ni- 0.50 Lu- 0.28	31	N.A.	Massive second phase (see Fig. 7 - sample A)
17	U-99.12 Ni- 0.55 Tm- 0.33	27	N.A.	Massive second phase (see Fig. 7 - sample B)
20	U-99.31 Co- 0.48 Lu- 0.21	21	N.A.	Two phases
21	U-99.28 Co- 0.50 Tm- 0.22	22	N.A.	Two phases (see Fig. 7 - sample C)
24	U-99.44 Ni- 0.44 Y- 0.12	32	N.A.	Massive uniform fine nonmetallic particles (see Fig. 7 - sample D)
25	U-99.29 Co- 0.50 Y- 0.22	21	N.A.	Two phases
31	U-98.87 Nb- 0.62 Rh- 0.25 Lu- 0.26	25	0.40	Large amount of nonmetallic particles
32	U-97.80 Zr- 0.95 W- 0.55 Rh- 0.32 Tm- 0.38	32	N.A.	Nonmetallics present

(a) None apparent.

Hardness, Grain Size, and Structure

Table VII lists the effect of various alloying elements and rare earths on the hardness and grain size of uranium alloys in the as-cast condition. The increase in hardness is dependent on the alloying element rather than the rare earth addition. Rockwell C hardness values varied from a minimum of

21 for alloys containing cobalt to a maximum of 36 for alloys containing molybdenum. The same trend (hardness controlled by alloy element as opposed to rare earth addition) also was evident in the as-rolled condition (Table VIII) and the annealed condition (Table IX). However, for both the as-rolled and annealed material, specimens containing

TABLE VIII

MECHANICAL DATA ON AS-ROLLED URANIUM ALLOYS COMBINED WITH RARE EARTHS (THULIUM, LUTETIUM, AND YTTRIUM)

Heat No.	Composition, wt %	Tensile Strength (psi)	Yield Strength (psi) ^(b)	% Elongation			Calculated Modulus ^(c)	Rockwell C As Rolled
				1/4 in.	1/2 in.	1 in.		
13	U-99.04 Rh- 0.69 Y- 0.27	219,900	143,133	7	5	2	27.9 x 10 ⁶	40
6	U-99.98 Tm- 0.02	203,100	148,566	12	9	6	21.4 x 10 ⁶	38
0	U-99.99	201,500	137,300	18	14	11	21.5 x 10 ⁶	38
4	U-99.94 Tm- 0.06	191,766	125,266	36	25	16	23.1 x 10 ⁶	37
14	U-98.93 Rh- 1.00 Tm- 0.07	171,633	162,850	4	2	1	24.1 x 10 ⁶	43
12	U-98.99 Rh- 0.97 Tm- 0.04	139,033	(d)	4	2	1	23.9 x 10 ⁶	42
25	U-99.28 Co- 0.50 Y- 0.22	135,433	129,600	4	2	1	23.4 x 10 ⁶	39
11	U-99.00 Rh- 0.96 Lu- 0.04	127,200	(d)	3	1.5	1	23.8 x 10 ⁶	42
21	U-99.28 Co- 0.50 Tm- 0.22	124,100	154,600	4	2	1	22.6 x 10 ⁶	35
20	U-99.31 Co- 0.48 Tm- 0.21	123,633	(d)	4	2	1	23.3 x 10 ⁶	38
28	U-99.10 Nb- 0.54 Rh- 0.30 Lu- 0.06	101,733	(d)	4	2	1	22.8 x 10 ⁶	39
16	U-99.30 Ni- 0.48 Lu- 0.22	92,100	(d)	4	2	1	22.3 x 10 ⁶	40
17	U-99.30 Ni- 0.47 Tm- 0.23	77,800	(d)	4	2	1	22.3 x 10 ⁶	39
24	U-99.59 Ni- 0.32 Y- 0.09	74,833	(d)	4	2	1	22.8 x 10 ⁶	37

(a) Rolled to 0.020 in. in thickness with a warm rolled finish reduction of about 85-90%. The tests were made using a cross-heat speed of 0.05 in. per min. Values listed are an average of three specimens tested.

(b) Based on 0.2% offset from the calculated modulus.

(c) Based on the most applicable straight line starting at the origin of a curve traced from signals from a 1 in. gauge length extensometer and load values.

(d) Brittle failure occurred before the desired 0.2% offset was obtained. The elongation figures for these specimens are not absolute but indicative of this brittle failure.

TABLE IX
MECHANICAL DATA ON ROLLED AND ANNEALED URANIUM ALLOYS COMBINED
WITH RARE EARTHS (THULIUM, LUTETIUM, AND YTTRIUM)

Heat No.	Composition, wt %	Tensile Strength (psi)	Yield Strength (psi) ^(b)	% Elongation			Calculated Modulus ^(c)	Rockwell C Hardness Annealed
				1/4 in.	1/2 in.	1 in.		
13	U-99.04 Rh- 0.69 Y- 0.27	152,400	73,550	17	13	9	22.0 x 10 ⁶	29
11	U-99.00 Rh- 0.96 Lu- 0.04	149,500	67,366	6	5	3	27.7 x 10 ⁶	29
12	U-98.99 Rh- 0.97 Tm- 0.04	144,233	81,033	4	4	2	23.4 x 10 ⁶	29
6	U-99.98 Tm- 0.02	137,700	57,500	23	20	16	26.8 x 10 ⁶	21
4	U-99.94 Tm- 0.06	137,500	70,950	10	8	6	22.7 x 10 ⁶	23
14	U-98.93 Rh- 1.00 Tm- 0.07	136,600	71,533	6	5	3	18.5 x 10 ⁶	28
0	U-99.99	133,000	47,000	34	31	28	26.4 x 10 ⁶	22
21	U-99.28 Co- 0.50 Tm- 0.22	118,133	58,933	4	2	1	21.0 x 10 ⁶	27
20	U-99.31 Co- 0.48 Lu- 0.21	107,866	62,933	4	2	1	27.8 x 10 ⁶	25
16	U-99.30 Ni- 0.48 Lu- 0.22	106,666	63,566	3	3	2	23.9 x 10 ⁶	28
17	U-99.30 Ni- 0.47 Tm- 0.23	101,066	58,733	3	2	1	25.7 x 10 ⁶	27
24	U-99.59 Ni- 0.32 Y- 0.09	101,000	61,400	4	2	1	21.9 x 10 ⁶	25

(a) Annealed under vacuum for 1 h at 650°C. Values listed are an average of three specimens tested.

(b) Based on 0.2% offset from the calculated modulus.

(c) Based on the most applicable straight line starting at the origin of a curve traced from signals from a 1 in. gauge extensometer and load values.

rhodium had the highest hardness (R_C 40-43 and R_C 28-29, respectively).

Representative as-cast microstructures are shown in Figs. 5 and 6. As can be seen, there is no apparent grain size for the majority of the alloys. Some of the alloys exhibited a considerable amount of a second phase. For the nickel alloys (Fig. 6A and 6B) the second phase appears to be a low melting point liquid present in the grain boundaries. The microstructures indicate that the

rare earth is present as fine, evenly dispersed particles throughout the material.

Preliminary annealing tests at 625°C for 1 h indicated that part of the material recrystallized. However, by increasing the vacuum annealing temperature to 650°C for 1 h, all alloys were recrystallized. The microstructures of several annealed alloys are shown in Figs. 7 and 8.

Mechanical Properties

The mechanical properties of as-rolled and

A. Heat No. 10: U with 1.89 Mo-0.04 Lu wt % addition. X250

B. Heat No. 11: U with 0.97 Rh-0.05 Lu wt % addition. X250

C. Heat No. 13: U with 0.68 Rh-0.26 Y wt % addition. X250

D. Heat No. 15: U with 1.09 Nb-0.13 Lu wt % addition. X250

Fig. 5. Microstructure of uranium alloys combined with rare earth additions in the as-cast condition. Chromic acetic electrolytic etchant.

A. Heat No. 16: U with 0.50 Ni-0.28 Lu wt % addition. X250

B. Heat No. 17: U with 0.55 Ni-0.33 Tm wt % addition. X250

C. Heat No. 21: U with 0.50 Co-0.22 Tm wt % addition. X250

D. Heat No. 24: U with 0.44 Ni-0.12 Y wt % addition. X250

Fig. 6. Microstructure of uranium alloys combined with rare earth additions in the as-cast condition. Chromic acetic electrolytic etchant.

A. Heat No. 4: U with 0.04 Tm wt % addition. X250

B. Heat No. 12: U with 0.97 Rh-0.04 Tm wt % addition. X250

C. Heat No. 13: U with 0.68 Rh-0.26 Y wt % addition. X250

D. Heat No. 16: U with 0.48 Ni-0.22 Lu wt % addition. X250

Fig. 7. Microstructure of uranium alloys combined with rare earth additions; hot rolled (60% reduction) at 625°C, warm rolled (99% reduction) at 340°C to final thickness of 0.020 in. thick. Annealed at 650°C for 1 h. Chromic acetic electrolytic etchant.

A. Heat No. 17: U with 0.047 Ni-0.23 Tm wt % addition. X250

B. Heat No. 20: U with 0.48 Co-0.21 Lu wt % addition. X250

C. Heat No. 21: U with 0.050 Co-0.22 Tm wt % addition. X250

D. Heat No. 24: U with 0.32 Ni-0.09 Y wt % addition. X250

Fig. 8. Microstructure of uranium alloys combined with rare earth additions; hot rolled (60% reduction) at 625°C, warm rolled (99% reduction) at 340°C to final thickness of 0.020 in. thick. Annealed at 650°C for 1 h. Chromic acetic electrolytic etchant.

annealed sheet are shown in Tables VIII and IX. Excellent ductility was exhibited in uranium containing only thulium. Elongations as high as 36% in a 1/4 in. gauge length were recorded for this material in the as-rolled condition and 23% for annealed material. However, as soon as an alloying element was added, the elongations dropped to a maximum of 7% for both as-rolled and annealed material. The one exception to this was a value of 17% recorded for a U-Rh-Y alloy.

For both the as-rolled and annealed material, rhodium was the strongest strengthening agent followed by thulium, cobalt, and nickel (see Tables VIII and IX). Thulium appeared to act as a dispersion strengthener. Data were not available to establish if the other rare earths investigated had the same effect, although one would expect this from a dispersion strengthening addition. When thulium or the other rare earths were added in solution with the carrier metal, they were not effective strengtheners and the carrier metal was the dominant addition.

These observations are based on a limited amount of data and, although definite trends are present, the values recorded should be taken as preliminary. A word should be said about the calculated modulus listed in these tables. This value is determined from the most applicable straight line starting from the origin of a curve traced from signals from a 1 in. gauge length extensometer and load values. This should not be interpreted as Young's Modulus.

Conclusion

Rare earth additions of thulium, lutetium, and yttrium can be made to uranium in limited quantities. Noncarbide-forming carrier metals such as rhodium, nickel, or cobalt, prealloyed with the rare earths under controlled conditions, can improve the quantity and distribution of the rare earths in uranium.

The maximum rare earth additions realized were:

Method 1. The rare earth distributed in the charge with the uranium and melted together: 0.042 wt % thulium (vacuum), 0.077 wt % thulium (argon); 0.070 wt % lutetium (argon) and 0.26 wt % yttrium (vacuum).

Method 2. The rare-earth metal addition placed in a cavity machined into the bottom of the

graphite crucible: 0.19 wt % thulium (vacuum), 0.23 wt % thulium (argon); 0.19 wt % lutetium (vacuum), 0.21 wt % lutetium (argon) and 0.35 wt % yttrium (argon).

Method 3. The rare earth addition placed in a graphite dispenser unit and lowered into the melt at a predetermined time: 0.089 wt % lutetium (vacuum) and 0.082 wt % lutetium (argon).

No runs were made by the third method for thulium or yttrium additions. This method can be used where the charge weight is a factor and only a vacuum system is available.

Melting under argon pressure instead of vacuum results in an increase in the amount of retained rare earth in uranium, particularly if the rare earth possesses a high vapor pressure relative to that of uranium.

The distribution of the rare earth throughout the uranium casting was improved significantly by the use of the carrier metal technique.

Density values are not appreciably lowered by the use of a carrier metal for the rare earth addition.

The greatest increase in tensile strength resulted in specimens containing rhodium and yttrium additions.

References

1. Haefling, J. F., and Daane, A. H., "The Immiscibility Limits of Uranium With the Rare-Earth Metals," Trans. Met. Soc. AIME, 215, 336-338, April 1959.

Acknowledgments

The author is indebted to J. M. Taub, Group Leader, CMB-6, for his guidance and counsel in this work; to the Powder Metallurgy Section, CMB-6, under the direction of R. E. Riley, for the arc-melted buttons; to T. I. Jones of the Physical Metallurgy Section, CMB-6, for the physical and mechanical data and metallography of the various alloys; to R. W. Keil of the Fabrication Section, CMB-6, for the rolling of the rare earth-uranium alloys; and to CMB-6 under the direction of C. F. Metz for the analytical chemistry.

The author also wishes to acknowledge the help of W. C. Erickson in preparing the report.

APPENDIX

TABLE A-I

CHEMICAL COMPOSITION OF RARE EARTHS MELTED WITH URANIUM

Heat No.	Nominal Composition, wt %	Amount of Rare Earth Added, wt %	Superheat Temperature, °C	Pour Temperature, °C	Stirring Time min		Chemical Analysis, wt %			% Recovery
							Top	Center	Bottom	
1 (a)	U-99.90 Tm- 0.10	0.10	1450	1335	1-1/2	Tm	0.005	0.005	0.005	5.0
2 (a)	U-99.90 Lu- 0.10	0.10	1450	1335	1-1/2	Lu	0.006	0.006	0.006	6.0
3 (a)	U-99.90 Y- 0.10	0.10	1450	1335	1-1/2	Y	0.050	0.050	0.050	50.0

(a) Vacuum ~ 50μ pressure.

TABLE A-II

CHEMICAL COMPOSITION OF RARE EARTHS MELTED IN CONJUNCTION WITH URANIUM; INDUCTION STIRRED IN PLACE UNTIL SOLIDIFIED

Heat No.	Nominal Composition, wt %	Amount of Rare Earth Added, wt %	Superheat Temperature, °C	Pour Temperature, °C	Stirring Time min		Chemical Analysis, wt %			% Recovery
							Top	Center	Bottom	
4 (a)	U-99.90 Tm- 0.10	0.10	1550	None	13	Tm	0.044	0.024	0.064	43.8
5 (a)	U-99.90	0.10	1750	None	15	Lu	0.064	0.035	0.078	59.2

(a) Argon atmosphere (25 psi).

TABLE A-III

CHEMICAL COMPOSITION OF ARC-MELTED BUTTON OF RARE EARTH PLUS CARRIER METAL ADDED TO URANIUM BY PLACING BUTTON IN BOTTOM OF CRUCIBLE

Heat No.	Nominal Composition, wt %	Composition of Rare Earth + Carrier Metal Button, wt %	Superheat Temperature, °C	Pour Temperature, °C	Stirring Time min		Chemical Analysis, wt %			% Recovery
							Top	Center	Bottom	
10 (a)	U-97.90 Mo- 2.00 Lu- 0.10	Mo-95.0 Lu- 5.0	1600	1450	5	Lu Mo	0.029 1.87	0.029 1.90	0.030 1.89	29.5 93.5
11 (b)	U-98.85 Rh- 1.00 Lu- 0.15	Rh-87.0 Lu-13.0	1550	1450	2	Lu Rh	0.048 0.96	0.050 0.98	0.051 0.97	32.9 97.0
12 (a)	U-98.85 Rh- 1.00 Tm- 0.15	Rh-87.0 Tm-13.0	1550	1450	2	Tm Rh	0.034 0.97	0.043 0.99	0.032 0.98	24.0 98.0
13 (a)	U-97.00 Rh- 1.00 Y- 2.00	Rh-33.0 Y-67.0	1550	1450	3-1/2	Y Rh	0.26 0.68	0.26 0.68	0.26 0.68	13.0 68.0
14 (b)	U-98.85 Rh- 1.00 Tm- 0.15	Rh-87.0 Tm-13.0	1550	1450	3	Tm Rh	0.066 1.00	0.073 0.98	0.070 1.00	46.3 99.3
15 (a)	U-99.20 Nb- 0.50 Lu- 0.30	Nb-62.0 Lu-38.0	1750	1450	7-1/2	Lu Nb	0.038 0.46	0.064 0.59	0.033 0.55	14.0 100.0

(a) Vacuum ~ 50μ pressure.

(b) Argon atmosphere (25 psi).

TABLE A-IV

CHEMICAL COMPOSITION OF ARC MELTED BUTTON (1) RARE EARTH PLUS CARRIER METAL AND BUTTON (2) URANIUM PLUS ALLOYING ELEMENT ADDED TO URANIUM BY PLACING BOTH BUTTONS IN BOTTOM OF CRUCIBLE

Heat No.	Nominal Composition, wt %	Composition of Arc Melted Buttons, wt %	Superheat Temperature, °C	Pour Temperature, °C	Stirring Time min	Chemical Analysis, wt %				% Recovery
						Top	Center	Bottom		
28(a)	U-99.10	Arc melted	1750	1450	7	Lu	0.059	0.071	0.061	21.1
	Nb- 0.50	button (1)				Nb	0.53	0.52	0.52	100.0
	Rh- 0.30	(U+Nb)				Rh	0.29	0.29	0.28	95.5
	Lu- 0.30	U-90.0								
		Nb-10.0								
		Arc melted								
		button (2)								
		(Rh+Lu)								
		Rh-50.0								
		Lu-50.0								
29(a)	U-98.76	Arc melted	1750	1450	7	Tm	0.054	0.074	0.062	21.0
	W- 0.61	button (1)				W	0.44	0.40	0.43	69.3
	Zr- 0.29	(U+W+Zr)				Zr	0.20	0.22	0.20	71.2
	Rh- 0.33	U-83.0				Rh	0.30	0.29	0.30	100.0
	Tm- 0.30	W-13.0								
		Zr- 4.0								
		Arc melted								
		button (2)								
		(Rh+Tm)								
		Rh-53.0								
		Tm-47.0								
30(a)	U-98.76	Arc melted	1750	1450	6	Tm	0.077	0.075	0.073	24.9
	W- 0.61	button (1)				W	0.37	0.36	0.37	60.0
	Zr- 0.29	(U+W+Zr)				Zr	0.17	0.16	0.15	55.2
	Rh- 0.33	U-83.0				Rh	0.32	0.32	0.31	95.9
	Tm- 0.30	W-13.0								
		Zr- 4.0								
		Arc melted								
		button (2)								
		(Rh+Tm)								
		Rh-53.0								
		Tm-47.0								

(a) Argon atmosphere (25 psi).

TABLE A-V

CHEMICAL COMPOSITION OF RARE EARTHS ADDED TO URANIUM BY MEANS OF CAVITY IN CRUCIBLE BOTTOM WITH SECONDARY STOPPER ROD

Heat No.	Nominal Composition, wt %	Amount of Rare Earth Added, wt %	Superheat Temperature, °C	Pour Temperature, °C	Stirring Time min	Chemical Analysis, wt %			% Recovery	
						Top	Center	Bottom		
6 (a)	U-99.90 Tm- 0.10	0.10	1550	1450	2	Tm	0.021	0.027	0.023	23.5
7 (a)	U-99.90 Lu- 0.10	0.10	1750	1450	5	Lu	0.014	0.011	0.011	11.8
8 (a)	U-99.85 Tm- 0.15	0.15	1550	1450	2	Tm	0.040	0.039	0.039	26.2
9 (a)	U-99.85 Tm- 0.15	0.15	1550	1450	2	Tm	0.034	0.039	0.033	23.7

(a) Argon atmosphere (25 psi).

TABLE A-VI

CHEMICAL COMPOSITION OF ARC MELTED BUTTON OF RARE EARTH PLUS CARRIER METAL ADDED TO URANIUM BY MEANS OF CAVITY IN CRUCIBLE BOTTOM WITH THE SECONDARY STOPPER ROD

Heat No.	Nominal Composition, wt %	Composition of Arc Melted Buttons, wt %	Superheat Temperature, °C	Pour Temperature, °C	Stirring Time min	Chemical Analysis, wt %			% Recovery
						Top	Center	Bottom	
16(a)	U-99.20	Ni-63.0	1550	1450	2-1/4	Lu	0.22	0.22	66.1
	Ni- 0.50	Lu-37.0				Ni	0.47	0.47	94.0
	Lu- 0.30								
17(a)	U-99.20	Ni-63.0	1550	1450	2-1/4	Tm	0.21	0.23	72.2
	Ni- 0.50	Tm-37.0				Ni	0.47	0.47	93.3
	Tm- 0.30	Tm-37.0							
18(b)	U-99.20	Ni-63.0	1550	1450	2-1/4	Lu	0.084	0.087	28.4
	Ni- 0.50	Lu-37.0				Ni	0.51	0.50	100.0
	Lu- 0.30								
19(b)	U-99.20	Ni-63.0	1550	1450	2-1/4	Tm	0.12	0.14	40.0
	Ni- 0.50	Tm-37.0				Ni	0.41	0.43	83.3
	Tm- 0.30								
20(a)	U-99.20	Co-63.0	1550	1450	2	Lu	0.17	0.21	59.4
	Co- 0.50	Lu-37.0				Co	0.48	0.48	96.0
	Lu- 0.30								
21(a)	U-99.20	Co-63.0	1550	1450	2	Tm	0.21	0.22	70.0
	Co- 0.50	Tm-37.0				Co	0.51	0.51	100.0
	Tm- 0.30								
22(b)	U-99.20	Co-63.0	1550	1450	2-1/4	Lu	0.16	0.19	52.2
	Co- 0.50	Lu-37.0				Co	0.42	0.42	83.3
	Lu- 0.30								
23(b)	U-99.20	Co-63.0	1550	1450	2-1/2	Tm	0.14	0.19	55.5
	Co- 0.50	Tm-37.0				Co	0.49	0.49	98.0
	Tm- 0.30								
24(a)	U-98.50	Ni-33.0	1550	1450	3	Y	0.087	0.085	8.3
	Ni- 0.50	Y-67.0				Ni	0.32	0.32	63.3
	Y- 1.00								
25(a)	U-98.50	Co-33.0	1550	1450	2	Y	0.35	0.22	23.3
	Co- 0.50	Y-67.0				Co	0.52	0.50	100.0
	Y- 1.00								

(a) Argon atmosphere (25 psi).

(b) Vacuum ~ 50μ pressure.

TABLE A-VII

CHEMICAL COMPOSITION OF ARC MELTED BUTTON (1) URANIUM PLUS ALLOYING ELEMENT ADDED TO URANIUM AND BUTTON (2) RARE EARTH PLUS CARRIER METAL PLACED IN CAVITY IN CRUCIBLE BOTTOM WITH SECONDARY STOPPER ROD

Heat No.	Nominal Composition, wt %	Composition of	Superheat Temperature, C	Pour Temperature, C	Stirring Time min	Chemical Analysis, wt %			% Recovery		
		Arc Melted Buttons, wt %				Top	Center	Bottom			
31 (a)	U-99.21	Button 1	1750	1450	2	Lu	0.082	0.12	0.090	32.4	
	Nb- 0.39	U-96.0				Rh	0.26	0.26	0.26	86.6	
	Rh- 0.30	Nb- 4.0				Nb	0.40	0.43	0.40	100.0	
	Lu- 0.30										
		Button 2									
		Rh-50.0									
		Lu-50.0									
32 (a)	U-98.66	Button 1	1750	1450	7	Tm	0.079	0.18	0.086	38.3	
	W- 0.60	U-92.0				W	0.56	0.56	0.56	23.3	
	Zr- 0.29	W- 6.0				Zr	0.20	0.21	0.20	70.1	
	Rh- 0.33	Zr- 2.0				Rh	0.30	0.29	0.28	97.8	
	Tm- 0.30										
						Button 2					
						Rh-53.0					
						Tm-47.0					

(a) Argon atmosphere (25 psi).

TABLE A-VIII

MAXIMUM RECOVERY (WT %) OF RARE EARTH ADDITIONS UNDER VACUUM OR ARGON ATMOSPHERES

Method	Condition		Rare Earth Recovery, wt. %	
			Vacuum	Argon
1	The rare earth distributed in the charge with the uranium and melted together	Lu	(a)	0.070
		Tm	0.042	0.077
		Y	0.26	(a)
2	The rare earth metal addition placed in a cavity machined into the bottom of the graphite crucible	Lu	0.19	0.21
		Tm	0.19	0.23
		Y	(a)	0.35
3	The rare earth addition placed in a graphite dispenser unit and lowered into the melt at a predetermined time	Lu	0.089	0.082
		Tm	(a)	(a)
		Y	(a)	(a)

(a) No tests made by this method.