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OTTAWA

MINES BRANCH INVESTIGATION REPORT IR 65-75

URANIUM ALLOY DEVELOPMENT FOR NON-NUCLEAR APPLICATION

PROGRESS REPORT NO. 3

by

H. M. SKELLY, C. F. DIXON & N. S. SPENCE

PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

The work reported here is part of a programme undertaken for the purpose of developing high-strength uranium-base alloys.

A procedure was established for the melting, alloying, and casting of small batches (about 1800 g) of experimental uranium alloys, and binary alloys of the following nominal compositions were prepared: U-1% Mo, U-2% Mo, U-3% Mo, U-1% Nb, U-2% Nb, U-3% Nb, U-2% V, U-3% V, U-0.5% Zr, U-2% Zr, U-0.5% Ti, and U-2% Ti. The quality of the resulting castings was assessed by chemical and X-ray fluorescence analyses, gamma radiography, and microexamination.

The response of the alloys to various heat treatments was determined by hardness measurements, and the results show that a large range of hardnesses can be obtained - from 264 to 677 VHN. The strength and hardness of the alloys are generally improved by heat treatment, but their ductility is seriously reduced.

The highest mechanical properties in the as-cast condition were given by the U-3% Nb alloy, viz. 180 kpsi UTS, 157 kpsi 0.2% YS, 3.4% elongation,

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370 kpsi compressive strength, 159 kpsi 0.2% compressive yield strength, and 412 VHN. The U-2% Mo alloy gave the highest heat-treated tensile properties, viz. 185 kpsi UTS, 180 kpsi 0.1% Y.S., 1% elongation. The compressive strengths of the heat treated alloys were all in the range of 313 to 365 kpsi, except for the U-2% Zr alloy, which gave 452 kpsi.

Densities ranged from 17.85 to 18.86 g/cc.

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1. INTRODUCTION

The work described in this report is part of an investigation being carried out for the Department of National Defence to develop high-strength, high-density alloys based on uranium. The high density of uranium is an asset for applications in which inertia or kinetic energy properties are important, as in ballistics, and development of high-strength uranium alloys for such uses would provide a welcome market for the metal; it is also possible that, if natural uranium were used for alloying, a material useful for ballistic applications might also have potential application in the nuclear fuel element field.

The work reported here is a continuation of earlier work carried out in these laboratories [1, 2], which investigated the effect of various alloying additions on the strength, heat treatability and density of uranium. Most of the previous work was of a preliminary nature in which small (100 g) melts of various compositions were prepared in a tungsten-arc furnace [1], and the data so obtained have been used in planning a more comprehensive investigation of uranium alloys in which considerably larger melts (about 1800 g) are prepared, enabling more testing to be carried out.

Uranium can be strengthened by alloying it with any one, or combination, of a variety of elements, and it was necessary that some selecting be done with regard to the compositions to be investigated. The following factors served as a guide:

(a) It was decided to confine the study to binary and ternary systems of low (i.e. $\leq$ 3%) alloy content. The reasons for this were to keep preparation of the alloys as simple as possible and to maintain a comparatively high density - 18 g/cc was arbitrarily chosen as the minimum density desirable.

(b) The alloys preferably had to be heat treatable so that a high hardness (minimum of about 500 VHN) could be developed in them.

(c) The level of impurities had to be kept to a minimum, especially carbon, as this element is thought to lower ductility. It was decided that the carbon level should be held below 150 ppm (0.0150%).

Based on these conditions and the published data on uranium alloy systems, the following binary alloys were chosen for investigation:

U-1% Mo	U-2% Mo
U-3% Mo	U-1% Nb
U-2% Nb,	U-3% Nb
U-2% V	U-3% V
U-0.5% Zr,	U-2% Zr
U-0.5% Ti,	U-2% Ti

All the alloying elements chosen have high solubility in gamma-uranium, except vanadium, which has a maximum solubility of about 3%. The alloys all form intermediate phases in which the alloying elements have varying solubility, giving promise of hardening possibilities. No true intermetallic compounds are known to be formed by any of the above alloys [3]. The uranium-molybdenum alloys are of special interest because of their comparatively high density and the fact that considerable work has already been done on them in connection with possible use in nuclear fuel elements.

Besides the above binary alloys, a list of ternary compositions was drawn up, but work on the ternary alloys is still in progress, and the present report is concerned solely with the binary compositions.

2. EXPERIMENTAL PROCEDURE

2.1 Preparation of Alloys

The uranium metal used in preparing the alloys was low-carbon natural uranium, containing 35 ppm (0.0035%) carbon, obtained from Eldorado Mining and Refining Limited. The suppliers and purity of the alloying elements were as follows:

Alloying Element	Supplier	Purity (min)
Molybdenum	Sylvania Electric Products, Inc.	99.5%
Niobium	Fansteel Metallurgical Corporation	99.7%
Vanadium	Vanadium Corporation of America	99.5%
Zirconium	Wah Chang Corporation	99.5%
Titanium	Osaka Titanium Corporation	99.5%

Previous experience had shown that satisfactory alloy could not be obtained by merely adding the alloying element to the molten uranium - it was necessary, first, to prepare a hardener, or master alloy, of the alloying element with uranium. The master alloys were prepared in an electric arc furnace in which the metal charge was melted by striking an arc between a

tungstem electrode and the charge, which was contained in a water-cooled copper hearth; melting was carried out in an argon atmosphere at a pressure of 350 mm mercury, and each charge was remelted 4 to 6 times to ensure complete alloying and homogeneity. The quantity of master alloy prepared at a time was about 170 g. No chemical analyses were carried out on the hardeners as previous experience had shown that noting the weight loss during preparation was a satisfactory check on their composition. The hardeners were broken into pieces of about $\frac{1}{4}$ in. or less in size before being added to the melts. The following were the compositions of the master alloys prepared: U-20% Mo, U-10% Nb, U-15% Nb, U-20% Nb, U-20% V, U-20% Zr, and U-20% Ti.

The experimental alloys were prepared in a vacuum resistance furnace heated with a tantalum element and capable of reaching temperatures of up to 2,000°C (3630°F) at an absolute pressure of 0.1 micron mercury or less. Melting, alloying, and casting were all carried out under vacuum. Figure 1 is an illustration of the melting furnace.

The alloy charge, weighing 1700 or 1800 g, was contained in a fused zirconia crucible. Zirconia was chosen as crucible material after preliminary tests, which also involved crucibles of graphite and magnesia. Graphite crucibles resulted in excessive pick-up of carbon, which was unacceptable as the carbon content of the alloys had to be held below 150 ppm. Carbon pick-up from the crucible could be reduced considerably by coating the inside with a refractory wash and, of the washes tested, magnesium zirconate gave the best results; however, although it was considerably less, there was still

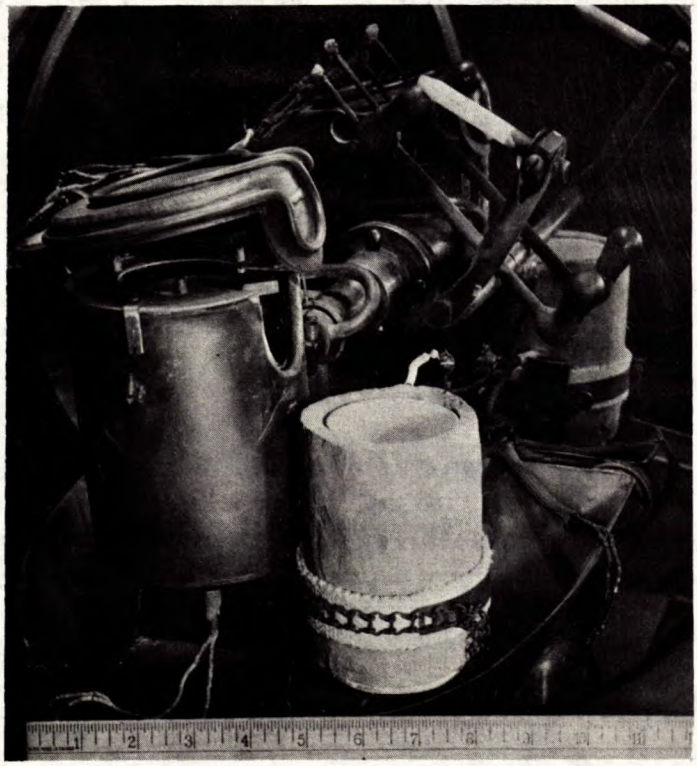


Figure 1. Vacuum melting furnace.

a slight pick-up of carbon, and the coating also tended to spall and peel off. Fused magnesium oxide crucibles were found to be satisfactory as long as the temperature was held below about 1300°C (2370°F), but above this temperature the molten uranium reduced the magnesium oxide to magnesium metal, which was evolved as vapour, causing violent agitation of the melt as it escaped and then deposited over the cooler parts of the furnace chamber. As a result, the viewing window was obscured, making it impossible to take optical pyrometer readings of the melt or, indeed, to see inside the furnace chamber. With fused zirconia crucibles there was no carbon pick-up, no objectionable fumes, and any reaction between melt and crucible was slight and did not result in serious contamination of the melt.

The alloys were cast into a graphite mould, 4-7/8 in. long by 2-3/8 in. diameter, which contained seven cavities, each about 3 in. long and tapering from 0.58 in. to 0.44 in. diameter. The top part of the mould consisted of a pouring basin, 1-$\frac{1}{4}$ in. deep, into which was fitted a graphite distributor disc. The latter fulfilled the following functions: (a) it controlled the flow of metal into the mould, permitting a head of metal to be maintained in the pouring basin and so reducing turbulence; (b) it produced a smooth uniform flow down the centre of the mould cavities; and (c) it prevented the casting from shrinking on to the mould proper. Figures 2 and 3 are illustrations of the mould with distributor disc, and the resulting casting, respectively.

The graphite mould was heated to prevent cold-shuts and to induce directional solidification, the top part of the mould being maintained at about 650°C (1200°F) and the bottom at 430°C (805°F). The inside of the pouring basin, and the distributor disc, were coated with a wash of magnesium zirconate to minimize carbon pick-up and to assist in keeping the feeder metal molten and so prevent the formation of large shrinkage cavities at the top of the bars. The wash was applied by suspending the magnesium zirconate in water and spraying the mixture with an atomizer on to the mould, which was pre-heated to about 200°C (390°F). Preliminary tests showed that there was no significant pick-up of carbon from the mould.

It was found necessary to thoroughly degas the mould beforehand to prevent the formation of gross blowholes in the casting. This degassing was accomplished by heating the mould in vacuo to 1350°C (2460°F) for 2-$\frac{1}{2}$ hours and then holding overnight at 480°C (895°F).

The melt temperature was determined by taking optical pyrometer readings through a viewing window in the furnace cover. The crucible temperature was checked by means of a platinum-platinum/rhodium thermocouple placed in contact with the outside bottom of the crucible. The mould temperature was determined with an iron-constantan thermocouple inserted into the bottom of the mould.

Melting and casting details for all melts are given in Table 1.

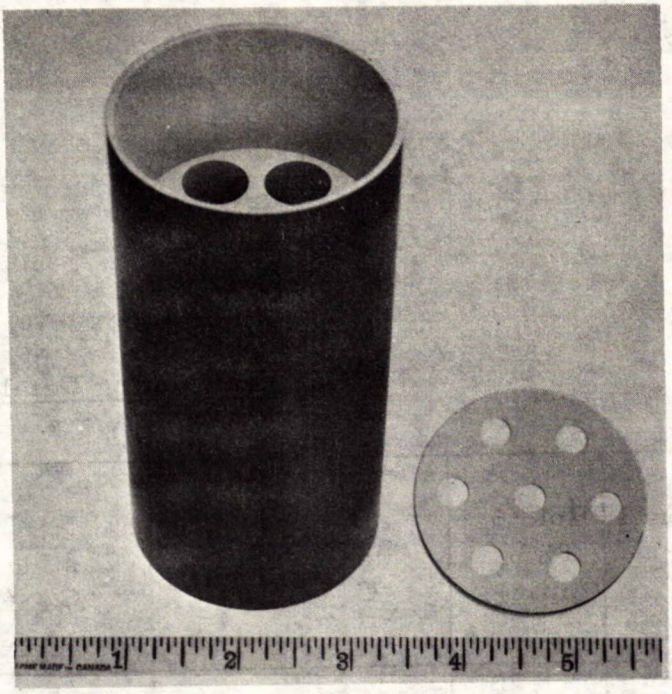


Figure 2. Graphite mould and distributor disc.

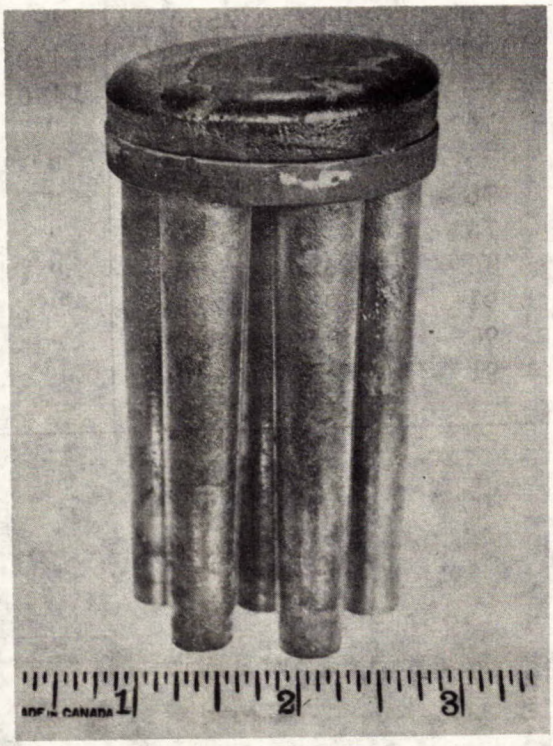


Figure 3. Uranium alloy casting.

TABLE 1

Melting and Casting Details

Melt Identification and Nominal Composition	Holding Time (min)	Max. Temp. °C	(°F)	Casting Temp. °C	(°F)	Pressure at Casting (μ)
R-BA (2% Mo)	120	1455	(2650)	1450	(2640)	0.035
R-BB (2% Nb)	120	1510	(2750)	"	"	0.019
R-BC (3% Nb)	90	1515	(2760)	"	"	0.016
R-BD (2% V)	120	1460	(2660)	"	"	0.052
R-BE (3% V)	100	1445	(2635)	1440	(2625)	0.026
R-BF (1% Mo)	90	1470	(2680)	1450	(2640)	0.032
R-BG (3% Mo)	76	1485	(2705)	"	"	0.028
R-BH (0.5% Zr)	76	1495	(2725)	"	"	0.010
R-BJ (2% Zr)	76	1465	(2670)	"	"	0.010
R-BK (0.5% Ti)	76	1450	(2640)	"	"	0.032
R-BL (2% Ti)	86	1455	(2650)	"	"	0.061
R-BM (1% Nb)	91	1495	(2725)	"	"	0.010
R-BN (2% Nb)	96	1505	(2740)	"	"	0.008
R-BO (3% Nb)	91	1505	(2740)	"	"	0.008

It can be seen from Table 1 that all melts were cast at about 1450°C (2640°F), holding time (i.e., total time the melt was molten) varied from 76 to 120 mins, and the maximum temperature to which the melts were heated ranged from 1445°C (2635°F) to 1515°C (2760°F). Pressure at casting was in all cases well below 0.1 micron of mercury. The melts could not be thoroughly stirred, but a graphite rod coated with magnesium zirconate was used to produce some slight stirring of the melt, and the long holding times and high temperatures assisted in dissolving the master alloy additions.

The metal yield from the melts ranged from 93.2% to 97.3% and averaged 95.4%. The feeder-head, or riser, contained, on an average, 22.8% of the total casting weight for the 1800 g melts and 17.9% for the 1700 g melts. It is usually recommended that, in the case of uranium alloys, the riser should contain 20 to 25% of the casting volume [4], but it was found that both the above percentages gave satisfactory feeding of the casting.

2.2 Analysis of Alloys

All alloys were analysed chemically for the alloying element and for carbon. In addition, some alloys were checked for possible pick-up of zirconium from the zirconia melting crucible and for possible contamination due to pick-up of copper and tungsten by the hardeners during preparation in the arc furnace. Samples for chemical analysis were in the form of lathe turnings that were machined from the castings.

A check for homogeneity was carried out on the 1% and 2% Mo alloys by X-ray fluorescence analysis of the top and bottom of the castings.

2.3 Mechanical Testing

Tensile and compressive tests were carried out on the alloys in the as-cast and heat treated conditions.

Hounsfield-type tensile specimens were machined to PMD drawing No. 107, the approximate dimensions being 0.18 in. gauge diameter, 0.63 in. gauge length and 1.5 in. total length. The tensile tests were carried out on an Instron machine.

For determination of compressive yield strength, the specimens were about 1-1/8 in. long by 3/8 in. diameter. To determine the ultimate compressive strength, these specimens were cut to give two specimens $\frac{1}{2}$ in. long by 3/8 in. diameter. The compressive tests were carried out on a 60,000 lb Baldwin machine.

As most of the alloys were too hard to machine in the fully heat-treated condition, preparation of the test specimens presented a problem. The

procedure used was to machine the test specimens from the alloys in the "soft" condition (as-cast or solution heat treated) leaving the specimens slightly oversize, and then to harden the specimens and machine them to final dimensions by grinding.

Vickers hardness determinations were used to assess the response of the alloys to various heat treatments.

2.4 Density Determinations

Density determinations were carried out by the procedure described in ASTM Designation B311-58, which is based on displacement of water by the specimen. The compression test specimens were useful for this purpose, and their densities were determined prior to testing.

2.5 Microexamination

Microexamination was carried out on as-cast specimens of each alloy to assess the quality of the castings with respect to inclusions and porosity.

To prepare them for microexamination, specimens were first polished on silicon carbide paper up to 600 grit and then with Linde 'A' and Linde 'B' alumina polishing powders on silk cloth and microcloth, respectively. Manual polishing was followed by electropolishing in a solution consisting of 4 parts acetic acid and one part of a solution of 118 g chromium trioxide in 100 ml distilled water; the solution was contained in a water-cooled stainless steel vessel which served as the cathode, and a current density of 2 amp/sq cm was applied for $\frac{1}{2}$ minute.

2.6 Gamma-Ray Inspection

The as-cast bars and the machined test specimens were examined for inclusions and flaws by gamma radiography using a cobalt-60 source.

2.7 Heat Treatment

One of the main objectives of the investigation was to produce alloys of high hardness and, in order to determine the response of the alloys to heat treatment, half-inch long specimens were cut from the cast bars for heat treating and hardness determinations. The specimens were solution heat treated and then given various ageing treatments.

The solution heat treatment consisted of heating to 800°C (1470°F) for $\frac{1}{2}$ hour, followed by water quenching; this temperature put the 3% V alloy in the gamma plus delta region and all other alloys in the gamma region. Heat treatment was carried out in a fused salt bath (Houghton '980'

salt), the specimens being first coated with graphite to prevent attack from the salt.

Ageing was carried out on the solution heat treated specimens by immersing them in molten lead-11% Sb alloy, the specimens being again coated with graphite. All compositions (except U-1% Nb) were aged at 400°C (750°F) and at 500°C (930°F) for $\frac{1}{2}$, 1, 3, 5 and 10 min. In addition, the 2% and 3% Nb, 2% and 3%V and 0.5% and 2% Ti alloys were aged at 600°C (1110°F) for $\frac{1}{2}$, 1, 3, 5 and 10 min, and the 0.5% and 2% Zr alloys were aged at 550°C (1020°F) for the same times. The U-1% Nb alloy was given one ageing treatment, viz. 500°C (930°F) for $\frac{1}{2}$ min. The specimens were quenched in water after ageing. The ageing temperatures for the alloys containing Mo, V and Zr were in the alpha plus delta phase region and the ageing temperatures for the U-Nb alloys were in the alpha plus gamma - 2 phase region, while the U-0.5% Ti alloy was aged in the alpha region and the 2% Ti alloy in the alpha plus delta region.

Based on the results of the heat treatment investigation, one treatment was chosen for each alloy for determination of mechanical properties in the hardened condition. Except for the 1% Nb, 3% V and 2% Ti alloys, the heat treatment chosen was the one giving the highest hardness. As stated above, the 1% Nb alloy was given only one ageing treatment. The 3% V specimen had cracked on quenching into water from the solution heat treating temperature, and the mechanical tests were therefore carried out on material that was given a modified heat treatment, which involved an "isothermal" quench into molten lead-11% Sb at 400°C (750°F), holding for 5 min and then water quenching. The heat treatment given to the 2% Ti alloy for subsequent mechanical testing was not the one giving the highest hardness as it was thought that there would be an advantage in sacrificing some hardness for ductility, especially as this alloy gave the highest hardness of the series, and a heat treatment giving slightly less than maximum hardness was therefore chosen in this case.

The 2% V and 2% Ti tensile specimens were sealed in vacuo in quartz for solution heat treatment rather than being immersed in the salt bath because these were repeat tests and it was more convenient to use this method for heat treating when the specimens were few in number.

3. RESULTS

3.1 Composition and Quality of Castings

Table 2 gives the results of the chemical analyses carried out on

the castings for the alloying element and for carbon.

TABLE 2

Uranium Alloy Analyses

Melt Identification	Nominal Composition (wt %)	Actual Composition (wt %)	Carbon (ppm)
R-BF	1% Mo	1% Mo	70
R-BA	2% Mo	2% Mo	80
R-BG	3% Mo	3.1% Mo	50
R-BM	1% Nb	1% Nb	40
R-BB	2% Nb	2% Nb	55
R-BN	2% Nb	2.1% Nb	50
R-BC	3% Nb	3.1% Nb	75
R-BO	3% Nb	2.8% Nb	60
R-BD	2% V	2% V	65
R-BE	3% V	3.1% V	80
R-BH	0.5% Zr	0.9% Zr	40
R-BJ	2% Zr	1.8% Zr	50
R-BK	0.5% Ti	0.5% Ti	40
R-BL	2% Ti	1.9% Ti	40

Of four castings that were analysed to check possible pick-up of zirconium from the crucible, three analysed 0.001% Zr and one analysed 0.002% Zr. One casting, which was analysed to check possible pick-up of tungsten and copper from the hardener, gave less than 0.02% W and 3 ppm (0.003%) Cu.

X-ray fluorescence analysis of melts R-BA (2% Mo) and R-BF (1% Mo) gave the following results:

		% Mo
R-BA	Top of casting	1.9
"	Bottom of casting	2.1
R-BF	Top of casting	1.0
"	Bottom of casting	1.0

These results show no evidence of segregation and confirm previous work done on a 3% Mo alloy, which gave a range of 3.0% Mo to 3.2% Mo on chemical analyses of twelve samples taken from the top, centre, and bottom of a casting.

Figures 4 and 5 are photomicrographs of the unalloyed uranium base-metal and of the 3% Mo alloy, respectively, and they illustrate the soundness of the alloy and the fact that the melting and alloying introduced very little additional impurities into the metal. Most of the inclusions in both photomicrographs are carbides, the particles being fewer in number, but larger, in the unalloyed uranium.

The gamma-graphs showed the castings to be sound.

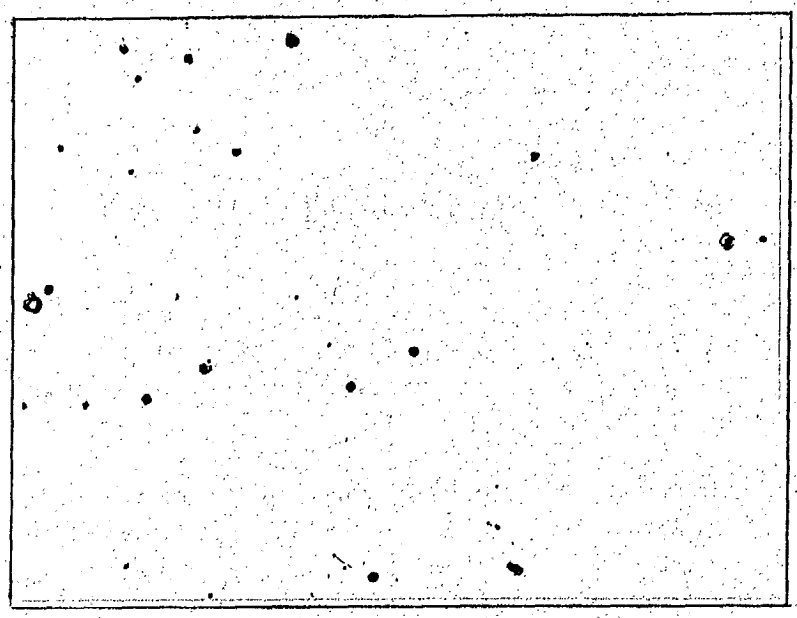
3.2 Response to Heat Treatment

Table 3 lists the Vickers hardnesses of the alloys in the as-cast, solution heat treated, and solution heat treated and aged conditions. Each value is the average of at least three determinations.

A large range of hardnesses was obtained, from 264 VHN for the as-cast 0.5% Zr alloy to 677 VHN for the solution heat treated and aged 2% Ti alloy.

The hardness values chosen for mechanical testing are underlined in Table 3 and, except in the case of the 2% Ti alloy, these are the highest hardnesses in each case. As noted above (page 9), the 3% V alloy was given an isothermal quench-age heat treatment, which hardened it to 377 VHN, lower than the maximum of 498 VHN for solution heat treating followed by ageing at 400°C (750°F) for 5 mins.

The 2% Ti and 2% V alloy test bars that were heat treated in vacuo in quartz (as opposed to molten salt) hardened to 600 VHN and 399 VHN respectively - that is, the titanium alloy was as hard as in Table 3 (600 vs. 606) but the vanadium alloy was softer (399 vs. 502).



X150

Figure 4. Unalloyed uranium, as-polished.

X150

Figure 5. Uranium-3% Mo alloy, as-polished.

TABLE 3

Results of Hardness Tests on Uranium Alloys (VHN)

Condition	U-1% Mo	U-2% Mo	U-3% Mo	U-1% Nb	U-2% Nb	U-3% Nb	U-2% V	U-3% V	U-0.5% Zr	U-2% Zr	U-0.5% Ti	U-2% Ti
As-cast	275	317	340	297	344	412	307	279	264	274	274	362
HT 800°C (1470°F)	407	381	308	376	389	316	502	488*	269	414	318	419
Aged 400°C (750°F) ½ min	400	447	406		423	432	447	480	270	425	330	549
" " 1 min	429	460	487		432	447	460	494	294	442	325	593
" " 3 min	441	460	509		461	438	466	480	289	446	317	579
" " 5 min	415	457	498		447	460	487	498	292	453	312	603
" " 10 min	441	476	509		446	457	487	495	283	453	319	603
Aged 500°C (930°F) ½ min	441	496	461	422	498	470	420	473	279	432	337	677
" " 1 min	463	441	473		509	473	423	476	270	432	341	670
" " 3 min	462	402	486		490	476	473	483	287	432	347	610
" " 5 min	450	375	463		463	502	432	460	342	457	353	606
" " 10 min	457	366	450		463	494	429	457	336	450	367	606
Aged 550°C (1020°F) ½ min									294	447		
" " 1 min									302	447		
" " 3 min									299	444		
" " 5 min									304	423		
" " 10 min									302	409		
Aged 600°C (1110°F) ½ min					494	435	487	470			343	579
" " 1 min					443	438	487	460			350	588
" " 3 min					435	436	474	450			383	566
" " 5 min					412	412	420	396			380	520
" " 10 min					407	412	420	394			390	516

* Broke on quenching.

3.3 Mechanical Properties

The tensile and compressive properties of the alloys in the as-cast condition are listed in Table 4; the results listed are the averages of two determinations except where indicated otherwise by the numbers in brackets. Also included are the appropriate Vickers hardness numbers.

Only two alloys (U-3% Mo and U-3% Nb) exhibited an ultimate compressive strength - the other alloys flattened without breaking at a definite load.

The mechanical properties, including hardness, of the heat treated alloys are listed in Table 5. Here again, the tensile and compressive figures are the averages of two determinations except where indicated otherwise by the numbers in brackets.

TABLE 4

Mechanical Properties of As-cast Uranium Alloys

Alloy (Nominal) Composition	Tensile Properties				Compressive Properties		VHN
	UTS (kpsi)	0.1% YS (kpsi)	0.2% YS (kpsi)	% El. $4\sqrt{A}$	UCS (kpsi)	0.2% CYS (kpsi)	
1% Mo	131.8	87.2	91.8	30	*	81.5	275
2% Mo	152.0	115.5	118.0	18	*	103.6	317
3% Mo	171.0(1)	165.0(1)	169.0(1)	6(1)	314.0(1)	145.4	340
1% Nb	135.1	88.5	97.1	6.3	*	82.2	297
2% Nb	155.2(3)	113.3(4)	120.9(4)	4(4)	*	114.5(4)	344
3% Nb	179.8(4)	149.8(4)	156.8(4)	3.4(4)	370.2(4)	158.7(4)	412
2% V	129.2	83.6	86.6	7	*	83.4	307
3% V	135.0	84.1	87.4	14	*	84.2	279
0.5% Zr	135.5(1)	58.5	60.8	14.5	*	53.9	264
2% Zr	135.0(1)	81.7	85.3	23	*	70.2(1)	274
0.5% Ti	132.5	81.2	83.4	12	*	98.0	274
2% Ti	142.8	113.0	122.0	2.5	*	136.9	364

* Specimens flattened

TABLE 5

Mechanical Properties of Heat Treated Uranium Alloys

Alloy (Nominal) Composition	Tensile Properties				Compressive Properties		VHN
	UTS (kpsi)	0.1% YS (kpsi)	0.2% YS (kpsi)	% El. $4\sqrt{A}$	UCS (kpsi)	0.2% CYS (kpsi)	
1% Mo	173.0(1)	150.4(1)	158.5(1)	3.0(1)	327.5	175.5	463
2% Mo	184.6	180.4(1)	*	1.5	365.0	228.4	496
3% Mo	165.5	*	*	1.0	313.2	204.0	509
1% Nb	173.2(1)	138.2(1)	147.2(1)	2.0(1)	339.0	137.0	422
2% Nb	NA	NA	NA	NA	NA	224.0(1)	509
3% Nb	111.0	*	*	1.0	348.8(4)	212.8(4)	502
2% V	NA	NA	NA	NA	353.3	215.1	399
3% V	150.4(1)	130.4(1)	139.5(1)	2.0(1)	352.3	124.0	377
0.5% Zr	136.4	73.4	79.4	12.0	**	87.2	342
2% Zr	148.8(1)	139.8(1)	147.8(1)	2.0(1)	452.3(1)	170.8	457
0.5% Ti	125.2(1)	118.0(1)	125.2(1)	1.0(1)	**	128.6	390
2% Ti	NA	NA	NA	NA	331.7(1)	310.1	600

* Specimens broke before 0.1% or 0.2% offset reached.
** Specimens flattened.
NA Not available.

3.4 Density

The results of the density determinations are listed in Table 6.

TABLE 6

Densities of Uranium Alloys

Alloy (Nominal) Composition	Density (g/cc)
1% Mo	18.86
2% Mo	18.54
3% Mo	18.42
1% Nb	18.75
2% Nb	18.46
3% Nb	18.22
2% V	18.23
3% V	17.85
0.5% Zr	18.79
2% Zr	18.30
0.5% Ti	18.72
2% Ti	17.96

DISCUSSION

The examinations and tests carried out on the castings demonstrate that the melting, alloying and casting procedure developed for preparing these experimental uranium alloys resulted in sound material of low impurity content. The chemical analyses show that, except for the 0.5% Zr alloy, the alloys were on, or close to, the desired composition. The reason for the high zirconium content of the nominal 0.5% Zr alloy is not known.

The results of the heat treatment tests (Table 3, page 13) show that the hardness of most of the alloys increased on solution heat treating at 800°C (1470°F), but two alloys (U-3% Mo and U-3% Nb) were softer than in the as-cast condition. The as-cast hardness of the nominal 0.5% Zr alloy (analysed 0.9% Zr) was little affected by solution heat treatment. It is evident from Table 3 that, with the exception of the 0.5% Zr and 0.5% Ti

composition, all the alloys examined can be hardened to values above 420 VHN by appropriate heat treatment. Five alloys (U-3% Mo, U-2% Nb, U-3% Nb, U-2% V and U-2% Ti) hardened to over 500 VHN, and of those the U-2% Ti alloy hardened to 677 VHN.

The alloys with the highest tensile and compressive properties in the as-cast condition were U-3% Mo and U-3% Nb (See Table 4, page 15). These two alloys were also the only ones that exhibited a definite value for the ultimate compressive strength in the as-cast condition.

In the heat treated condition (Table 5, page 16) all alloys showed poor elongation except the nominal 0.5% Zr alloy. In contrast to the as-cast condition, the highest tensile strength was shown by the U-2% Mo alloy and the highest compressive strength by the U-2% Zr alloy; the 0.2% compressive yield strength for the U-2% Zr alloy was comparitively low, and it is possible that the high value for the ultimate compressive strength is an anomalous result. It is interesting to note that, apart from the U-2% Zr alloy, and the U-0.5% Zr and U-0.5% Ti alloys, both of which flattened, the ultimate compressive strengths all fell within a narrow range, from 313 to 365 kpsi. The U-3% Mo, and U-3% Nb alloys showed a drop in tensile and compressive strength on heat treating, and the 0.5% Ti alloy showed a drop in tensile strength. Some of the heat treated alloys (U-2% Mo, U-3% Mo and U-2% Nb) were so brittle that they broke without exhibiting a 0.2% offset. The U-1% Mo alloy showed useful strength in the heat treated condition - especially as it had the highest elongation (apart from the weak U-0.5% Zr composition).

The comparatively low tensile values for the heat treated alloys are considered to be spurious in some cases (e.g. U-3% Nb) and a consequence of the difficulty of carrying out accurate tensile tests on brittle material. No tensile values could be obtained for the 2% Nb, 2% V and 2% Ti alloys. As already mentioned, the 3% V alloy cracked on quenching into water from the solution heat treating temperature; trouble was also experienced with cracking in the 1% Mo and 2% Nb alloys. Thus, although the alloys could be heat treated to 500 VHN, and better, the resulting mechanical properties were not satisfactory. The cause of the brittleness is thought to be hard, brittle phases formed during ageing, and a variation in the heat treatment procedure, such as an isothermal treatment, might produce better results. However it may be impossible to avoid formation of the brittle phases when high hardness is required. Other possible ways of improving ductility are to break up the embrittling constituents by working the alloys and/or to increase the alloy content so as to stabilize the gamma phase at room temperature, but neither method has been explored in the present investigation which was aimed at producing a strong cast alloy of high density.

The density values (Table 6, page 17) followed the expected pattern. The highest density (18.86 g/cc) was shown by the U-1% Mo alloy, and two

densities were below 18 g/cc - U-3% V (17.85 g/cc) and U-2% Ti (17.96 g/cc).

5. CONCLUSIONS

1. The technique described in this report for the preparation of uranium alloys gives castings of good quality and low carbon content.

2. It is possible to prepare binary alloys of uranium with hardnesses ranging from 264 to 677 VHN.

3. The U-3% Mo and U-3% Nb alloys have the highest as-cast strength.

4. Although the alloys can be hardened by heat treatment, poor ductility is a problem.

6. FUTURE WORK

It is planned to do more work on improving the ductility of the hardened binary alloys and to investigate selected ternary alloys.

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REFERENCES

1. N.S. Spence, H.M. Skelly and C.F. Dixon, "Uranium Alloy Development for Non-Nuclear Application: Progress Report No. 1A" - Mines Branch Investigation Report IR 64-15 (March 3, 1964).

2. N.S. Spence, H.M. Skelly, and C.F. Dixon, "Uranium Alloy Development for Non-Nuclear Application: Progress Report No. 2" - Mines Branch Investigation Report IR 64-40 (May 4, 1964).

3. W.D. Wilkinson, "Uranium Metallurgy Vol. 2: Uranium Process Metallurgy", Interscience Publishers p. 859 (1962).

4. W.D. Wilkinson, "Uranium Metallurgy Vol. 1: Uranium Process Metallurgy", Interscience Publishers p. 272 (1962).

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