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### CANADA

### DEPARTMENT OF MINES AND TECHNICAL SURVEYS

**OTTAWA** 

MINES BRANCH INVESTIGATION REPORT IR 64-15

# URANIUM ALLOY DEVELOPMENT FOR NON-NUCLEAR APPLICATION PROGRESS REPORT NO. 1A

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

by

PHYSICAL METALLURGY DIVISION



MARCH 3, 1964

#### Mines Branch Investigation Report IR 64-15

### URANIUM ALLOY DEVELOPMENT FOR NON-NUCLEAR APPLICATION

by

#### N.S. Spence\*, H.M. Skelly\*\* and C.F. Dixon\*\*\*

#### SUMMARY

This report describes work done to the end of 1962 on the development of high-strength uranium alloys. Several experimental compositions were investigated by preparing small (100 g) melts in a tungsten arc furnace and determining their mechanical properties and density. Tests were also carried out on larger alloy samples obtained from other sources. The uranium-2% molybdenum alloy was investigated the most fully, and an extensive heat treatment study was made of this alloy.

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INTRODUCTION

This report records the preliminary and early stages of an investigation of uranium alloys. It is in the form of a progress report to be followed by subsequent reports detailing more specific work based on results obtained in the laboratory.

During 1960 a program was under way in these laboratories to investigate and develop non-nuclear uses for uranium with the object of assisting the Canadian uranium mining industry. As part of this extensive project, an examination of uranium-base alloys of potential interest because of their combination of physical and mechanical properties was instituted.

#### EXPERIMENTAL PROCEDURE AND RESULTS

#### Alloys and Their Preparation

The alloys investigated consist of two groups: (a) those prepared as small (100 g) arc melts by the Nuclear Metallurgy Section and (b) those prepared elsewhere as comparatively large cast billets. The former consisted of several experimental compositions, whereas the latter consisted of only two compositions.

Table 1 gives details of the materials used in preparing the small arc melted alloys. The melts were made in an electric arc furnace in which the charge, contained in a water-cooled copper hearth, was melted by an arc struck between a tungsten electrode and the charge. Melting was carried out in argon at a pressure of about 38 cm mercury. The charge weighed 100 g and was melted four times and allowed to solidify "in situ" in the copper hearth after each melting. Most of the laboratory melts were made in a cigar-shaped hearth but a few melts were made in the form of "buttons".

Table 2 lists the nominal compositions of the alloys prepared in the above manner. As a check on composition, four melts (EF. EO. GA and GD) were analysed chemically and the results of the analyses are also given in Table 2. None of the melts was analysed for carbon. but. except where stated otherwise, the carbon content was probably about 500 ppm. TO determine the effect of carbon content on the mechanical properties. several melts were prepared using uranium of various carbon contents so as to obtain a range of carbon values in the alloys; the figures given in Table 2 for the carbon content of these particular alloys are nominal ones. A series of unalloyed uranium melts with a range of carbon contents was also prepared (melts HA, HB and HC). In melts GE and GF the zirconium was added as zircaloy-2, which is a zirconium-base alloy with a nominal composition of 1.5% tin, 0.12% iron, 0.10% chromium, and 0.05% nickel. Two melts of unalloyed uranium were made to provide data for comparison purposes (melts GG and HM).

Table 3 lists the alloys that were obtained from other sources. The billet obtained from the Refractory Metals Section (uranium-2% molybdenum alloy) was prepared in a consumable arc melting furnace. After the first melting, the resulting billet was machined into turnings which were then compressed into electrode form and remelted. The cast billet was 3 inches in diameter. The other materials listed in Table 3 were 1-5/8 inches and 2 inches diameter, but details of their preparation are not known.

#### Mechanical Properties of Alloys

The mechanical properties, hardness and density were determined for several of the melts prepared in the tungsten arc-melting furnace. Because of the smallness of these melts, there was a severe limitation on the size and number of test specimens that could be machined from one sample. Tensile specimens were machined longitudinally from some of the cigarshaped melts. These specimens were all machined to Physical Metallurgy Division drawing No. 100, which is a substandard size specimen with a gauge length of 0.447 inches and a gauge diameter of 0.126 inches. The tests were done at room temperature on an Instron machine and the results are listed in Table 4. Compression tests were carried out on most of the tungsten arc furnace melts. All compression tests were made with a 60,000 lb Baldwin machine, and the results are given in Table 5. All specimens were rectangular in shape, the dimensions of GA, GB, GC, GD, GE, GF, GG, GI and GJ being 0.25 inch by 0.50 inch by 0.50 inch, and the dimensions of the other specimens listed in Table 5 being 0.19 inch by 0.38 inch by 0.50 inch. The results for EF and EO are the averages of two determinations.

Table 5 also gives the results of Vickers hardness measurements made on alloys prepared in the tungsten arc furnace. The values listed are the averages of five or more determinations.

Extensive tests were conducted on a sample of uranium-2% molybdenum alloy cast bar produced by National Lead Company, and Figure 1 shows the location and type of test specimens. Transverse and longitudinal test specimens were machined to determine if there was any significant difference in properties between these directions. Tables 6, 7 and 8 give details of the tensile, compression and impact tests, respectively. Tensile specimens E-1 and E-2 were tested on the Baldwin machine and D-1 and D-2 were tested on the Instron machine (Table 6). The impact tests (Table 8) were carried out on an Olsen machine of 15 ft-1bscapacity. The Vickers hardness of this material was 298 (30 kg load). The hardness of a machined core of uranium-2% molybdenum alloy (see Table 3) was 289 (30 kg load).

A transverse survey of hardness across the uranium-2% titanium cast bar (see Table 3), gave an average value of 366 Vickers hardness number (30 kg load), the individual values ranging from 348 to 393.

#### Density of Alloys

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Density determinations were carried out according to ASTM Designation B311-58. Table 9 gives the results for alloys prepared in the tungsten arc furnace, the determinations being carried out on complete cigars or on specimens machined from them.

Table 10 gives the results of density determinations on uranium-2% molybdenum alloy samples from various sources. The measurements on the machined cores were carried out on complete cores rather than on pieces cut from them.

The density of a slice cut from the uranium-2% titanium cast billet ( `e Table 3) was 17.91 g/cc.

#### Heat Treatment of Uranium-2% Molybdenum Alloy

An extensive heat treatment programme was carried out on the uranium-2% molybdenum alloy. This composition was chosen as a promising one for further study because of its good casting characteristics, high strength and ductility, and high density. An added interest in this composition was that uranium-molybdenum alloys have been extensively investigated for use as nuclear fuel elements. In the present work, the effect of various heat treatments was assessed by Vickers hardness determinations. The alloy was given seven different heat treatments, details of which are described in the following numbered sections. The materials used for the heat treatments are listed in Table 3.

(1) Samples about 1/2 inch cube of the uranium-2% molybdenum alloy, supplied by the Refractory Metals Section, were heated to 800°C (1470°F), 700°C (1290°F), 625°C (1155°F) and 550°C (1020°F) for 1/2 hour, then they were either water quenched, oil quenched or air cooled. All samples heat treated above 600°C (1110°F) were heated in Houghton 980 salt, and those heat treated below this temperature were heated in lead.

The hardness of this material before heat treating was 298 VHN and the hardnesses after heat treatment are shown in the graph, hardness versus heat treating temperature, in Figure 2. It can be seen that cooling from 800°C (1470°F) produced maximum hardness and the air cooled samples were hardest for all temperatures.

(2) Samples similar to the above were heat treated in Houghton 980 salt at 800°C (1470°F) for 2 hours then water quenched. This was followed by ageing in air at 500°C (930°F), 600°C (1110°F) and 690°C (1270°F) for times up to 1 hour.

The graph, hardness versus ageing time, for these samples is shown in Figure 3, which also shows the hardness of samples aged at 500°C (930°F) after they were stored at room temperature for 16 months. It is evident that the optimum ageing time for maximum hardness is in the order of 3 minutes, at 500°C (930°F). Storing at room temperature for 16 months increased the hardness of all but one of the samples aged at 500°C (930°F) in Figure 3.

(3) Samples in the form of 1/2 inch cubes of the cast billet obtained from the National Lead Company were heat treated in Houghton 980 salt at 800°C (1470°F) for 1/2 hour then water quenched, followed by ageing in air at 550°C (1020°F), 500°C (930°F) and 450°C (840°F) for times up to 4 minutes.

- 4 -

The as-received hardness of this material was 289 VHN and the hardness of these samples after heat treatment is plotted in the graph, hardness versus ageing time, in Figure 4. Of the three temperatures, 500°C (930°F) was the optimum ageing temperature for maximum hardness (506 VHN), which occurred after ageing for 3 minutes.

(4) Two samples of the same material were heat treated in Houghton 980 salt at 800°C (1470°F) for 1/2 hour then water quenched, followed by ageing for 3 minutes at 500°C (930°F). One sample was a 1/2 inch cube and had a hardness of 511 VHN after heat treatment. The other sample was 1 inch long by 1-5/8 inch diameter, had a hardness between 371 and 402 VHN but cracked during quenching.

(5) From the machined cores obtained from AEE, two sets of samples, 1 inch by 1-5/8 inch diameter were heat treated in Houghton 980 salt at 800°C (1470°F) for 5, 15 and 30 minutes. One sample heated for each of the above times was water quenched and the other was air cooled. The water quenched samples cracked during quenching.

The hardness of this material before heat treatment was 280 VHN. Results of hardness surveys across the diameter of the heat treated samples after they were cross-sectioned 1/2inch along the length are shown in the graphs in Figures 5 to 10. These graphs also show the hardness results after storing the samples at -40 °C (-40 °F) for 8 days.

The graphs show that the water quenched samples were softer at the edges and hard in the centres and storing these samples at -40°C (-40°F) had the greatest effect on the samples heated for 30 minutes in which the overall hardness was increased.

Samples that were air cooled had a more uniform hardness throughout and the samples held at temperature for 5 minutes were a little softer than those held for 15 and 30 minutes. Storing at -40 °C (-40 °F) for 8 days caused a decrease of up to 10 VHN hardness points in the centre of the samples and an increase of about 10 VHN at the surface.

(6) Other samples of the same size cut from the same material were heated in Houghton 980 salt at 800°C (1470°F) for 1 hour then quenched in lead at 500°C (930°F) and held for 5 minutes and for 1 hour before water quenching from the lower temperature. There were no cracks in these samples and the average hardness for the samples was 394 VHN for the sample held for 5 minutes at 500°C (930°F) and 398 VHN for the sample held for the 1 hour.

(7) A section of a machined core, 1 inch by 1-5/8 inches in diameter, of the material obtained from AEEE was heat treated at 400°C (750°F) for 24 hours. The average hardness of the sample after heat treating was 302 VHN.

#### DISCUSSION

#### Alloy Compositions

The chief attraction of uranium for the application under investigation is its high density and it is therefore important that any alloying carried out to strengthen the metal should not materially lower this property. A density of 18.0 g/cc was arbitrarily chosen as being the minimum below which it would be undesirable to go unless there was an outstanding improvement in some other property. Broadly speaking, the purpose of alloying is to increase the mechanical strength of the uranium, especially the compressive strength and hardness.

Most of the alloy compositions investigated involved additions of the elements molybdenum, titanium and zirconium. These elements are known to alloy with, and to strengthen, uranium and, of the three, molybdenum is the most attractive from the density viewpoint.

#### Mechanical Properties of Alloys

Most of the compositions listed in Table 4 have ultimate tensile strengths in the range of 170-190 kpsi. Apart from the unalloyed uranium, the only result considerably below this range is that for melt HH (1.0% zirconium), which has an ultimate tensile strength of 133.5 kpsi; it is interesting to note that this is the only alloying composition listed in the table that does not contain molybdenum. The three highest ultimate tensile strengths were obtained from melt GW (1.5% molybdenum, 0.5% zirconium, 73.5 ppm carbon), melt HI (1.5% molybdenum, 0.25% zirconium, 0.25% niobium) and melt HK (1.5% molybdenum, 0.5% niobium). These alloys did not have the highest yield strengths - that was provided by melt HF (1.75% molybdenum, 0.25% titanium). The elongations varied from 3 to 15% and the reduction of area from 3 to 22%. The most ductile alloy composition was melt HH (1.0% zirconium) and the least ductile compositions were melt HF (1.75% molybdenum, 0.25% titanium) and melt HJ (1.5% molybdenum, 0.25% titanium, 0.25% niobium).

Increasing the carbon content of the unalloyed uranium from 75 to 735 ppm resulted in an increase in tensile and compressive strengths with decrease in ductility. The tensile properties of the uranium-2% molybdenum alloy were relatively unaffected up to 441 ppm carbon, but there was a slight drop in strength at 735 ppm; the highest compressive yield strength was obtained with the lowest carbon content. The uranium-1.5% molybdenum-0.5% zirconium alloy showed highest tensile strength at the lowest carbon content, but there was no consistent correlation between carbon content and compressive yield strength. The rapid solidification occurring in the preparation of the melts could have had a stronger influence than varying carbon Also, it would have been more satisfactory to have content. analysed the actual melts for carbon, but there was insufficient material for this purpose.

It should be made clear that, because of the small amount of material available, the compression tests listed in Table 5 were carried out on test specimens of a shape and size that would not give the greatest accuracy. The highest compressive yield strength was 226 kpsi from melt GE (1.5% molybdenum, 0.5% zirconium); values of 190 kpsi and greater were also obtained from melts GA (1.5% molybdenum, 0.5% titanium), GB (1.75% molybdenum, 0.25% titanium), GS (2.0% molybdenum), HJ (1.5% molybdenum, 0.25% titanium, 0.25% niobium) and HK (1.5% molybdenum, 0.5% niobium). The compressive yield strength of the 2.0% molybdenum alloy was greatest at the low and high carbon contents. The various carbon contents investigated showed no significant influence on the compression properties.

The hardness values listed in Table 5 are for asprepared material made in small batches in the tungsten arc furnace and these values could be considerably changed by working and heat treating the alloys. The highest hardness value listed in Table 5 is 492 VHN for melt EF (2.0% titanium). Hardnesses of 400 VHN or over were also given by melt HF (1.75% molybdenum, 0.25% titanium), GD(1.75% molybdenum, 0.25% zirconium), GS and GT (2.0% molybdenum), GY (1.5% molybdenum, 0.5% zirconium), HJ (1.5% molybdenum, 0.25% titanium, 0.25% niobium) and HK (1.5% molybdenum, 0.5% niobium). Again, no obvious trend resulted from varying the carbon content, although there was a slight drop in hardness of the 1.5% molybdenum-0.5% zirconium alloy at 224 ppm carbon (melt GX).

As might be expected, because of the slower cooling rate, the ultimate tensile and yield strengths of the uranium-2% molybdenum cast bar (National Lead Company) were considerably below those of the tungsten arc furnace material, and the cast bar was considerably more ductile (see Table 6). The compressive yield strength of the cast bar (see Table 7) was also appreciably lower than that of the arc melts - 96 kpsi compared with 140-190 kpsi. The impact values (Table 8) show that the influence of size of test specimen was much stronger than the direction from which it was machined (i.e., longitudinal or transverse).

The hardness of the National Lead Company's cast bar was lower than that of the same alloy as prepared in the tungsten arc furnace (298 VHN versus 336 to 424 VHN).

#### Density of Alloys

The densities of all the tungsten arc furnace alloys, listed in Table 9, are 18 g/cc or greater except for the 2.0% titanium composition (melt EF), which is only slightly less than this value. The density of the 2% molybdenum alloy from different sources (Table 10) varies, as would be expected, and tends to be lower than the density of the tungsten arc furnace material.

#### Heat Treatment of Uranium-2% Molybdenum Alloy

Interest in uranium-molybdenum alloys as a fuel for atomic reactors has resulted in considerable work being done on the effect of heat treatment on the transformation reactions and physical properties of these alloys, and the heat treatments carried out in this investigation can be discussed with reference to some of these reports (1-4).

In considering the samples quenched from the various temperatures (Table 11), G.H. May(1) showed that uranium-5 at% molybdenum ( $\simeq 2.2$  wt % Mo) samples, water quenched from 800°C (1470°F) had a microstructure of martensitically formed alpha prime and M.Kawasaki et al(2) showed that samples water quenched after being held for a short period of time in the beta plus gamma phase region, which would be at 700°C (1290°F) in this investigation, contained a structure consisting of what Lehmann and Hills<sup>(4)</sup> called alpha double prime, plus some gamma phase. Then, H.A. Salter et al<sup>(3)</sup> showed that samples of uranium-5 at % molybdenum alloy, water quenched from the alpha plus gamma phase at 580°C (1075°F), contained alpha plus gamma phases in the quenched structure. From consideration of these reports, it appears that samples of the uranium-2% molybdenum alloy, water quenched from the various temperatures contain phase structures as indicated in Table 11.

The hardness associated with the samples, water quenched from 800°C (1470°F) and 700°C (1290°F) in Figure 2, was considered to be the result of strains caused by the martensitic transformation of the gamma phase to the alpha prime or double prime phase during quenching. The reason for the higher hardnesses of the samples with slower cooling rates was evidently due to ageing occurring during cooling. To investigate the optimum temperatures and times for maximum benefit from ageing, heat treatments number 2 and 3 were conducted (See page 4).

The graphs in Figures 3 and 4 show that to obtain maximum hardness in the uranium-2% molybdenum alloy, the optimum ageing temperature of those investigated was 500°C (930°F) and the ageing time was in the order of 3 minutes.

To explain this hardening effect G.H.  $May^{(1)}$  suggests that during ageing in the temperature range 425°C (800°F) to 550°C (1020°F) prior to the appearance of any gamma precipitate, molybdenum segregated in the orthorhombic lattice of the alpha prime phase to form molybdenum-rich zones with monoclinic phase structures. The interaction of these molybdenum-rich zones and the molybdenum-impoverished matrix, which were still coherent, resulted in increased elastic and plastic strains that caused hardening.

G.H. May<sup>(1)</sup> also showed that on further ageing, hardnesses decreased because the matrix recrystallized to an unstrained alpha structure with an incoherent gamma precipitate when the above-mentioned coherency strains added to the strains of heating the specimen to the ageing temperature reached a critical value. Maximum hardnesses were obtained just before reaching the critical value and this occurred in the samples in this investigation after ageing for 3 minutes.

Samples aged at 500°C (930°F) showed, (see Figure 3), a general increase in hardness after they were stored at room temperature for 16 months but because the overaged samples were included it is unlikely that this increase was the result of any ageing effect.

The tests in heat treatments number 2 and 3 had been carried out on 1/2 inch cubes and the tests in heat treatment number 4 were therefore carried out to determine the feasibility of heat treating larger sections to maximum hardness. The cracking of the 1 inch diameter samples in this test was thought to be the result of stresses developed by difference in cooling rates between the interior of the sample and the surface.

In the number 5 heat treatment, the larger waterquenched samples again cracked and a hardness survey across an interior diameter showed a wide variation in hardnesses (Figure 5). However, in general, the slower cooling rate of the center of the samples evidently permitted some ageing to take place during quenching thus causing an increase in hardness as compared to the more rapidly cooled surface. Because of the variation in the hardness across the samples it is difficult to compare the results of holding for 5, 15 or 30 minutes at temperature, or to assess the effect of holding the samples for 8 days at -40°C (-40°F).

The more uniform cooling of the air cooled samples in heat treatment number 5 permitted a uniform hardness distribution and no cracking was observed (Figures 8, 9 and 10). Because the overall hardnesses of these samples are considerably lower than for the smaller samples similarly treated in heat treatment number 1 (Figure 2), it appears that the larger samples cooled more slowly and permitted more overageing to occur.

Holding the samples for 15 and 30 minutes appeared to cause an increase of a few hardness points over those held for 5 minutes. The change in hardness after holding for 8 days at -40 °C (-40 °F) is not understood at present.

In an attempt to obtain a quenched and aged structure without any cracking, samples in heat treatment number 6 were quenched from 800°C (1470°F) into lead at 500°C (930°F) then water quenched from the lead bath. Hardnesses obtained from this treatment were higher (398 VHN) than for the samples air cooled from 800°C (1470°F) and no cracking occurred. There also appeared to be little difference in hardness between the samples held in the lead bath for 5 minutes and those held for 1 hour.

The heat treatment listed as number 7 was carried out to determine if the as-cast material would increase in hardness on ageing. It is evident that this did not occur.

#### CONCLUSIONS

- (1) This preliminary investigation has not revealed any one alloy composition with properties that are outstandingly superior with respect to the other compositions examined, but the uranium-2% molybdenum alloy appears to offer attraction as being easily prepared and capable of response to heat treatment.
- (2) Additions of zirconium and/or niobium increase the tensile strength of the uranium-molybdenum alloys.
- (3) The compressive strength of uranium-molybdenum alloys is improved by additions of zirconium, titanium, or niobium.
- (4) Greatest hardness is obtained from the uranium-2% titanium alloy. Alloys of uranium-molybdenum and uranium-molybdenum with titanium, zirconium, and niobium also give high hardness.

- (5) No significant directionality of properties occurs in a cast billet (about 2 inches diameter) of the uranium-2% molybdenum alloy.
- (6) By heat treating the uranium-2% molybdenum alloy, hardnesses ranging from 280 to 500 Vickers can be obtained. However, when large samples (1-5/8 inches diameter) are heat treated to maximum hardness cracking occurs as a result of cooling stresses set up during quenching.
- (7) Large samples (1-5/8 inches diameter) of the uranium-2% molybdenum alloy can be heat treated to a hardness of about 400 Vickers without cracking by quenching from the gamma phase into a lead bath at 500°C (930°F) followed by quenching into water at room temperature.

#### FUTURE WORK

A vacuum resistance furnace, which can attain a temperature of 2000°C and which has a capacity of 2 kilograms of uranium, has become available. This furnace will make it possible to melt and cast in vacuo melts that are considerably larger than the 100 g arc melts described in this report, and will also permit the preparation of material that is more representative of production billets. Also, with the larger size of casting it will be possible to carry out more mechanical tests on bigger test specimens.

It is planned to investigate the heat treatment of the uranium-2% molybdenum alloy with a view to developing a procedure that will produce a hardness greater than 400 Vickers without cracking the material. The effect of varying the temperature of the lead bath will be investigated.

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More extensive work will be done on various alloy compositions based on additions of the following elements: molybdenum, titanium, tantalum, niobium, zirconium and tungsten.

#### REFERENCES

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### Materials Used for Alloys Prepared in Tungsten Arc Melting Furnace

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Metal	Duritu	Source
metar		bour ce
Uranium	Reactor grade	AECL, Chalk River (NRU Flat Rods)
Uranium	75 ppm carbon 450 ppm carbon 750 ppm carbon	Eldorado Mining and Refining Company
Molybdenum	99.5%	Sylvania Electric Products Inc.
Titanium	100 Brinell Sponge	Osaka Titanium Corp.
Zirconium	Crystal Bar	Foote Mineral Co.
Iron	99.9% (Electro)	A.D. MacKay Inc.
Nickel	Electrolytic	International Nickel Company of Canada Ltd.
Silicon	97.5% Si, 0.65% Fe	Electro-Metallurgical Co. of Canada Ltd.
Niobium ·	99.7%	Fansteel Metallurgical Corp.

TABLE	2
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## Alloys Prepared in Tungsten Arc Melting Furnace

•		Nom	inal Com	positi	on (Wt	%)	<del></del> .	<del>,,,,,,</del>	
Melt Ident	· Mo	Ti	Zr	Zr-2*	Nb	Fe	Si	Ni	ppm C
EI EK EH EL						3.0 8.0	3.0	6.0	
EJ EP EF Analysis:		0.5 2.0 (1.99)				3.0 3.3	1.0		
EO EO Analysis: GA Analysis:	2.0 (1.97) 1.5 (1.43)	0.5 (0.53)						• •	
GB HF GI HH GJ	1.75 "	0.25	1.0 " 2.0						
GC HG GD Analysis:	1.5 1.75 (1.74)	· · ·	0.5 " 0.25 (0.26)	0 5					
GE GF GS GT GU	1.5     1.75     2.0     2.0     2.0     2.0     2.0     2.0     2.0     3			0.25					73.5224441
GV GW GX GY GZ HA	$2.0 \\ 1.5 \\ 1.5 \\ 1.5 \\ 1.5 \\ 1.5 \\ 1.5 $		$0.5 \\ 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \\ 0.5$						735 73.5 224 441 735 75
HB HC HI HJ HK HL	1.5 1.5 1.5	0.25	0.25		$0.25 \\ 0.25 \\ 0.50 \\ 0.25$				441 735
GG HM	Unal	loyed Ur	anium "				•		

\*Zircaloy-2

### Alloys from Other Sources

Alloy	Form of Material	Source
U-2% Mo U-2% Mo U-2% Mo U-2% Ti	As-cast billet As-cast billet Machined core (Approx. 1-5/8 in. dia by 5 in. long) As-cast billet	Refractory Metals Section, PMD National Lead Company Army Equipment Engineering Establishment (AEEE) National Lead Company

#### TABLE 4

	Nominal Composition (Wt %)				Tensile Propert:					
Melt		•			ppm	$\mathtt{UTS}$	0.2% YS	0.1% YS	% <u>El</u>	
Ident	Mo	Ti	Zr	Nb	<u> </u>	kpsi	kpsi	kpsi	4VArea	% RA
GS	20				73.5	185.5	157.9	152.0	5*	5
СТ СТ	20				224	188.5	161.8	154.0	5*	7
GI	2.0				441	187.5	157.9	150.0	6	7
GV	2.0		•		735	176.7	148.0	138.2	7	7
GW	1.5		0.5		73.5	193.4	153.8	142.0	10	10
GX	1.5		0.5		<b>224</b>	173.0	138.2	130,2	10	10
GY	1.5		0.5		441	185.5	158.2	142.0	6*	6
GZ	1.5		0.5		735	182.5	ND	ND	7	7
HA					75	61.6	33.9	29.2	12	20**
HB					441	68	39.4	33.9	8	18**
HC					735	75.1	58.5	54.1	8	8
HF	1.75	0.25				185.0	175.2	167.2	3	2
HG	1.5		0.5			185.5	163.9	157.9	10	15
HH			1.0		ļ	133.5	79.2	75.5	15	22
HI	1.5		0.25	0.25		191.5	165.5	157.8	6	6
HJ	1.5	0.25		0.25		172.5	162.5	152.5	3	3
HK	1.5			0.50	1	189.5	165.7	158.0	4	4
HL	1.5		ł	0,25		171.5	145.5	137.5	7	7
HM	Unalloyed Uranium			nium		75.6	49.7	45.7	10	10
	1	v					· ·	1	1	1

Results of Tensile Tests on Alloys Prepared in Tungsten Arc Melting Furnace

\*Broke at shoulder \*\*Measured on smaller diameter ND == not determined

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Melt	Nomi	.nal Co	mposit	ion (W	t %)	ppm ·	VHN (30 kg load)	0.2% CYS
Ident	Mo	Ti	Zr	Zr-2*	Nb	Ĉ	(Averages)	kpsi
EF EO GA GB HF GI HH	2.0 1.5 1.75 1.75 1.75	2.0 0.5 0.25 0.25	1.0				492 336 395 399 412 257 266	$177.6 (2) \\ 136.4 (2) \\ 200.0 \\ 191.3 \\ 166.3 \\ 79.2 \\ 91.5 \\$
GJ GC HG GD GE GF	$   \begin{array}{r}     1.5 \\     1.5 \\     1.75 \\     1.5 \\     1.75 \\     1.75 \\   \end{array} $		2.0 0.5 0.5 0.25	0.5			316 391 395 401 378 351	ND 168.1 162.7 184.4 226.0 168.5
GS GT GU GV	$2.0 \\ 2.0 \\ 2.0 \\ 2.0 \\ 2.0 $					73.5224441735	424 401 384 376	$     190.5 \\     164.0 \\     155.3 \\     185.4 $
GW GX GY GZ	1.5 1.5 1.5 1:5		0.5 0.5 0.5 0.5			73.5224441735	398 358 419 399	158.5 141.2 169.8 167.0
HA HB HC					· · · · · · · · · · · · · · · · · · ·	75 441 735	193 214 226	$46.6 \\ 40.1 \\ 63.1$
HI HJ HK HL GG HM	1.5 1.5 1.5 1.5 Una	0.25 lloyed	0.25 Urani	um	0.25 0.25 0.5 0.25		396 427 428 380 208 279**	175.5190.2192.7139.080.362.3

### Results of Hardness and Compression Tests on Alloys Prepared in Tungsten Arc Melting Furnace

TABLE 5

\*Zircaloy-2 \*\*20 kg load +1

### Results of Tensile Tests on Uranium-2% Molybdenum Cast Bar (Ex National Lead Company)

Test	Direction of Test with	Test Spec.		Tensile	Properties	
Spec. Ident	Respect to Bar	Drawing No.	UTS kpsi	0.2% YS kpsi	% Elong.	% RA
E-1	Longitudinal	PMD DRWG	135.0	74.2	$\frac{4\mathrm{D}}{25.0}$	36.8
E-2	Longitudinal	No. 12	136.5	80.6	20.0	34.7
D-1	Transverse	PMD DRWG	135.8	89.2	$\frac{4\sqrt{\text{Area}}}{22.0}$	32.0
D-2	Transverse	No. 100	136.0	94.6	23.0	32.0

#### TABLE 7

### Results of Compression Tests on Uranium-2% Molybdenum Cast Bar (Ex National Lead Company)

Test Spec. Ident	Direction of Test With Respect to Bar	Size of Test Spec.	0.2% CYS (kpsi)
B-1 B-2 G-1 G-2	Transverse Transverse Longitudinal Longitudinal	0.44" Dia. x 1.25" 0.44" Dia. x 1.25" 0.44" Dia. x 1.50" 0.44" Dia. x 1.50" 0.44" Dia. x 1.25"	ND 98.9 96.4 94.3

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ND = not determined .

### Results of Impact Tests on Uranium-2% Molybdenum Cast Bar

(Ex National Lead Company)

Test Spec. Ident	Direction of Test with Respect to Bar	Test Spec. Drawing No.	Impact Strength (Charpy) ft-lb
C-1	Longitudinal	PMD	3
C-2	Longitudinal	Drawing No. 19	3
F-1	Transverse	PMD Drawing	9
F-2	Transverse	No. 4 Modified*	9
H-1	Transverse	PMD Drawing	3
H-2	Transverse	No. 19	3

\*Width halved

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### Density of Alloys Prepared in Tungsten Arc Melting Furnace

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Melt	· No	ominal Co	ompositi	on (Wt %)		ppm	Density
Ident	Mo	Ti	Zr	Zr-2*	Nb	Ċ	(g/cc)
EF EO GA GB HF GI HH GJ GC HG GD GE	$2.0 \\ 1.5 \\ 1.75 \\ 1.75 \\ 1.5 \\ 1.5 \\ 1.75 \\ 1.5 \\ 1$	2.0 0.5 0.25 0.25	1.0 1.0 2.0 0.5 0.5 0.25	0.5			$17.94 \\ 18.52 \\ 18.25 \\ 18.31 \\ 18.01 \\ 18.70 \\ 18.20 \\ 18.38 \\ 18.46 \\ 18.06 \\ 18.47 \\ 18.52 \\ 18.52 \\ 17.94 \\ 18.52 \\ 18.5$
GF	1.75			0.25			18.44
GS GT GU GV GW	$ \begin{array}{c} 2.0 \\ 2.0 \\ 2.0 \\ 2.0 \\ 1.5 $		0.5			73.522444173573.5224	$     18.62 \\     18.56 \\     18.65 \\     18.62 \\     18.62 \\     18.62 \\     18.61 $
GX GY GZ	1.5		0.5			441 735	18.64 18.58
HA HB HC						75 441 735	$19.14 \\ 19.07 \\ 19.02$
HI HJ HK HL GG HM	1.5 1.5 1.5 1.5 U	nalloyed	0.25 Uranium	1	0.25 0.25 0.50 0.25		$18.07 \\ 18.03 \\ 18.07 \\ 18.13 \\ 18.86 \\ 18.31$
*****							

\*Zircaloy-2

### Density of Uranium-2% Molybdenum Alloys

Source of Material	Density* (g/cc)				
National Lead Company	18.26 (3)				
Stock No. NPN Machined Core	18.49				
Stock No. NPN Machined Core	18.13				
ex DND	18.47 (5)				
*Figures in brackets are number of determinations carried out.					

### TABLE 11

Phase Structures of Uranium-2% Molybdenum Alloy After Water Quenching

Quenching Temperature	Phase Region	Quenched Structure
800°C (1470°F)	gamma	alpha prime
700°C (1290°F)	beta + gamma	alpha double prime + gamma
625°C (1155°F)	alpha + gamma	alpha + gamma
550°C (1020°F)	alpha + epsilon	alpha + epsilon



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