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Evaluation of Uranium Alloys

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ABSTRACT

The oxidation resistance and mechanical properties of 23 uranium alloys have been evaluated. The U-Ti alloys had good mechanical properties, whereas U-Nb alloys had the best oxidation resistance.

I. INTRODUCTION

There are numerous applications in which uranium alloys must have a combination of strength and ductility and be resistant to both oxidation and stress corrosion. The Los Alamos Scientific Laboratory (LASL) Materials Technology Group initiated a uranium-alloy development program to develop and evaluate alloys to meet these requirements.

A review of the literature suggested several alloys that warranted further evaluation. We used unalloyed uranium as the standard for this work, though we found that by using a material that was very low in carbon and silicon, we obtained significant variations in mechanical properties. Mulberry (U-7.5Nb-2.5Zr) is known for its corrosion resistance, and was used as a comparison in the corrosion tests. Alloys of the related U-Nb system are also reputed to be corrosion resistant, and we evaluated alloys containing 2 to 6 wt% of niobium.

The Canadian Armament Research and Development Establishment (CARDE)[1] has studied several uranium alloys in a program whose objectives were (a) to determine the minimum alloy addition that would harden the alloy; (b) to determine certain mechanical, physical, and chemical properties of the alloys; and (c) to investigate the effect of heat treatment on the properties obtained. We selected two of these alloys, U-2Mo-2Nb and U-2Nb-2V, for further evaluation and modified two others slightly to yield nominal compositions of U-2Mo-3Nb and U-2Nb-1Zr.

The U.S. Army is working on development of a structural uranium alloy. Work reported by the U.S. Army Materials Research Agency[2] has involved the U-Mo-Nb-Zr-Ti alloy system. One of these alloys, U-1.5Mo-1.5Nb-1.5Zr-0.5Ti had properties that were of interest to LASL, and we included it in the present study.

Several other alloys were evaluated in this program. These include U-Ti alloys, U-0.5Ni, U-0.5Cr, U-0.5Ni-0.5Cr, U-1.5Mo-0.5Ni-0.5Cr, U-1.5Mo, and U-2Nb-2Ti.

The alloys were evaluated in the as-cast, homogenized, and wrought and heat-treated conditions. Evaluation of the as-cast and homogenized materials consisted of corrosion (oxidation) testing, hardness testing, and metallography. In addition to these tests, for wrought materials the mechanical properties were also determined.

This report summarizes the mechanical properties, metallography, hardness data, and corrosion data for the alloys. Sandstrom[3,4] has already made a more detailed presentation of the data.

II. PROCEDURES

Casting

The alloys investigated were induction melted using a high-frequency (3000-cycle) power supply and cast into 8- by 8- by 1/2-in. plates. Graphite crucibles flame-sprayed with a Mo-ZrO_2 coating were used for melting, and the molds were coated with a zirconium silicate mold wash to prevent carbon pickup by the uranium alloys. All casting was done under a rough vacuum of ~100 μ Hg.

Both elemental and prealloyed charges were used. The uranium, zirconium, titanium, nickel, and vanadium were added to the charge as the pure element. Prealloyed charge materials used were U-6.5Nb, U-10Mo, and U-5Cr.

Rolling

A Bliss two-high rolling mill with 8-in.-diam by 20-in.-wide rolls was used to roll the uranium alloys. The rolls were preheated to ~100°C by infrared lamps before rolling.

Alloys rolled in the alpha-phase range at 625°C were rolled from a 65% KCO_3-35% $LiCO_3$ salt bath. This salt melts at 510°C and reacts very little with the uranium. A fluid protective layer forms on the metal when it is removed from the salt pot. This layer protects the uranium from excessive oxidation and ignition when in contact with air.

Alloys rolled in the gamma-phase region (800°C) were heated in a Hoskins electric muffle furnace with an argon atmosphere. To minimize oxidation and the chances of ignition, the plates were preheated in the salt pot at 625°C before being transferred to the muffle furnace. This was done after each rolling pass.

Heat Treatment

The uranium alloys were annealed at 625°C in salt and in vacuum and at 800°C in vacuum. The KCO_3-$LiCO_3$ salt previously described was used for the 625°C salt anneals. For the vacuum cycles, the uranium was canned in copper and a vacuum was pulled continuously during the heat treatment. The samples treated to 625°C were air cooled, and those heated to 800°C were water quenched.

The effect of homogenization treatments on the microstructure was studied. The treatment depended on the alloy and was performed in a vacuum furnace. The alloys were vacuum cooled.

Metallographic Evaluation

Unalloyed uranium samples were electropolished and examined and photographed using polarized light. The alloyed samples were mechanically polished and chemically etched using standard metallographic techniques.

Mechanical Testing

Mechanical testing was performed on an Instron tensile testing machine using an Instron clamp-on strain-gauge extensiometer. A cross-heat speed of 0.050 in./min was used. Gauge marks at 1/4-in. increments were scribed on the specimens to determine elongation.

Flat tensile specimens ~ 4 in. long with a 1-1/8- by 3/8-in. reduced gauge length were used. The specimen thickness was 0.060 to 0.080 in. Specimens with two surface conditions were used. The first were eloxed from as-rolled and heat-treated material. The eloxed surfaces were then ground to remove any damaged or embrittled material. These specimens proved unsatisfactory because the oxide film flaked. This prevented accurate measurement of the specimen thickness and made determination of elongation impossible.

Subsequent specimens were also eloxed from the sheet, and their eloxed surfaces were ground. In addition, the reduced section of these specimens was milled to remove the oxide surface.

Corrosion Testing

The resistance to oxidation of the uranium alloys was tested at four different conditions; 260°C and atmospheric humidity, 120°C and atmospheric humidity, 120°C and 0.5-atm water-vapor pressure, and 60°C and 100% relative humidity. The tests were performed in thermostatically controlled convection ovens. Distilled water was used to obtain the 100% relative-humidity atmosphere, and a potassium acetate solution was used to maintain the 0.5-atm vapor pressure.

III. RESULTS

More than 20 uranium alloys, including unalloyed uranium, were cast and evaluated to varying degrees. The microstructure, hardness, and corrosion (oxidation) resistance of all the alloys were evaluated. Alloys that were predominantly two-phased and/or that showed poor corrosion resistance to moist air were not evaluated further. The mechanical properties of the remaining alloys were then determined.

Table I lists the alloys investigated and gives the analyses for the major alloying elements. The results of the complete spectrographic analyses are presented in the Appendix.

TABLE I

NOMINAL COMPOSITION OF URANIUM ALLOYS

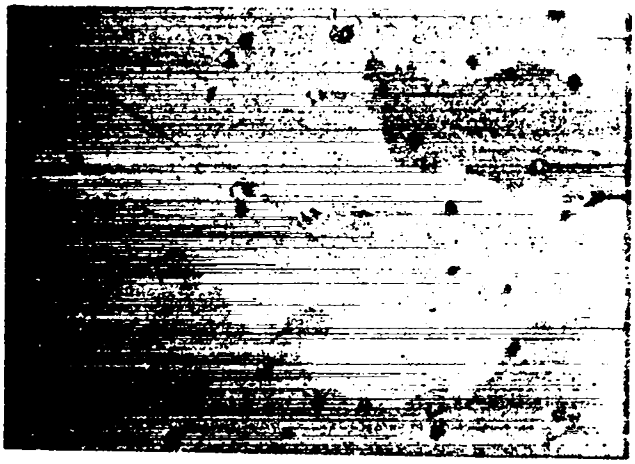
Alloy System	Item Number	Alloy Content (wt%) Nb	Mo	Ti	Zr	V	Ni	Cr
U	68165	-	-	-	-	-	-	-
U-Mo	52734	-	1.5	-	-	-	-	-
U-Ti	52712	-	-	0.7	-	-	-	-
	52710	-	-	0.8	-	-	-	-
	52711	-	-	1.6	-	-	-	-
	52770	-	-	1.6	-	-	-	-
U-Nb Binary	52702	2.2	-	-	-	-	-	-
	52701	3.4	-	-	-	-	-	-
	52704	4.0	-	-	-	-	-	-
	52771	4.7	-	-	-	-	-	-
	52705	5.1	-	-	-	-	-	-
	51193	6.0	-	-	-	-	-	-
U-Nb Polynary	52714	1.9	-	0.9	-	-	-	-
	52709	2.5	-	-	-	1.7	-	-
	52733	1.5	1.5	0.6	1.4	-	-	-
	52706	1.9	2.2	-	-	-	-	-
	52772	2.2	2.1	-	-	-	-	-
	52728	2.7	2.0	-	-	-	-	-
	52708	2.4	-	-	1.0	-	-	-
	52783	6.9	-	-	2.7	-	-	-
U-Ni-Cr-Mo	52727	-	-	-	-	-	2.0	-
	52729	-	-	-	-	-	-	2.2
	52698	-	-	-	-	-	0.5	0.5
	52697	-	1.5	-	-	-	0.5	0.5

The data are grouped according to the four alloying systems investigated: U-Ti, U-Ni-Cr-Mo, U-Nb, and polynary alloys based on the U-Nb base alloy. The unalloyed uranium and U-1.5Mo data are presented individually.

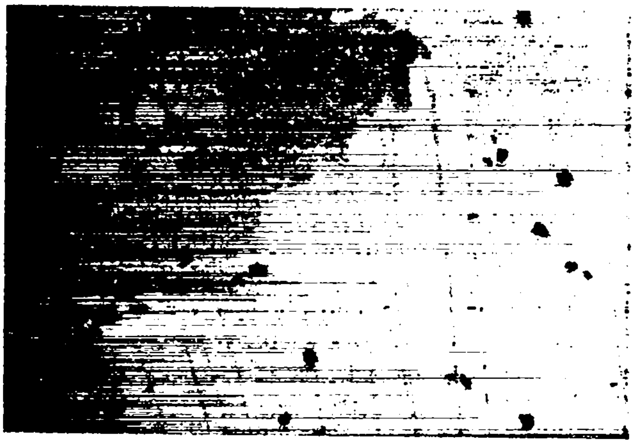
Unalloyed Uranium

A plate of unalloyed uranium was cast and used as a reference base. Uranium undergoes two phase transformations while cooling from its melting temperature. The first is the $\gamma \rightarrow \beta$ transformation at 772°C, and the second is the $\beta \rightarrow \alpha$ transformation at 662°C.

The cast material had a density of 18.932 g/cm^3 and an as-cast hardness of 220 DPH. This hardness decreased to 190 DPH after homogenization at 625°C for 8 h and vacuum cooling. The microstructure of this material was essentially single phase with what appears to be some carbides present (Fig. 1).



As-Cast.



Vacuum-annealed at 626°C for 8 h.

Fig. 1. Microstructure of cast unalloyed uranium, 100X.

TABLE II

MECHANICAL PROPERTIES OF WROUGHT, UNALLOYED URANIUM

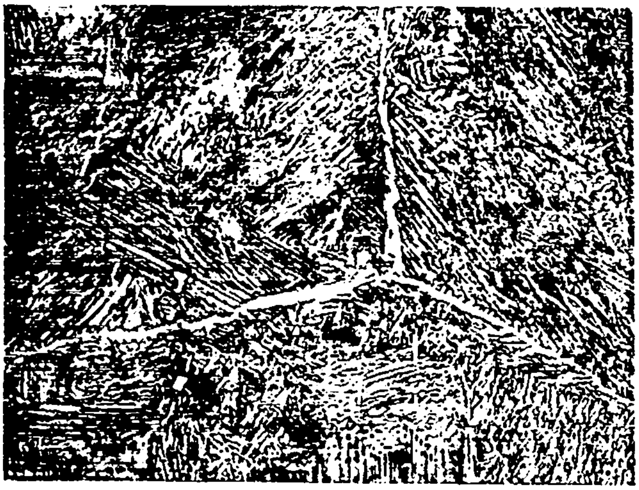
Condition	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 1 in. (%)
As-rolled	146.5	86.0	27.5
Salt-annealed at 625°C for 1/2 h	93.4	42.0	11.0
Vacuum-annealed at 625°C for 1/2 h	114.3	43.0	29.0
Water-quenched from 850°C	89.9	35.0	10.0
Water-quenched from 850°C and vacuum-annealed at 625°C for 1 h	94.3	39.5	10.0

The mechanical properties of wrought, unalloyed uranium in five different conditions are shown in Table II. Several values need further comment. First, the relative strengths and elongations of salt-annealed and vacuum-annealed materials are typical, the effects noted being due to the H_2 content of the metal. This behavior was previously documented by Hanks, Taub, and Doll.[5] We do not know the reason for the relatively small elongation (10% in 1-in. gauge length) of the gamma-quenched material, though it may be caused by increased interstitial content, increased grain size, or both. The 27.5% elongation of the as-rolled material seems extremely high for uranium of the strengths reported, and the validity of these data must be questioned.

Uranium-Molybdenum Alloys

The solubility of molybdenum in uranium is limited to ~0.2 wt% of molybdenum in alpha uranium at room temperature. Uranium-rich alloys undergo a $\gamma \rightarrow \alpha + \delta$ eutectoid reaction at 575°C, and an $\alpha \rightarrow \beta$ transformation at ~660°C. Alloys containing less than ~15 wt% of molybdenum are single phase γ at above ~770°C. Because of the limited solubility of molybdenum in uranium, additions of ~0.25 wt% of molybdenum are often used as a grain refiner in cast uranium.

The density of cast U-1.54Mo was determined to be 18.684 g/cm^3. Its hardness in this condition is 285 DPH, and it is not appreciably changed by vacuum annealing at 1000°C for 4 h and at 1050°C for 4 h. The microstructure of the as-cast and homogenized material is shown in Fig. 2.



As-Cast.

Homogenized at 1000°C for 4 h and at 1050°C for 4 h.

Fig. 2. Microstructures of cast U-1.5Mo alloy, 250X.

The U-1.5Mo alloy was rolled at either 625 or 800°C. Rolling at these temperatures produced two distinct microstructures as is shown in Fig. 3. The structure of the material rolled at 800°C has been recrystallized.

Annealing samples of this material at 850°C and water quenching them produced the microstructures shown in Figs. 3b and 3d. There are only slight differences between the as-rolled and heat-treated microstructures of the samples rolled at 800°C, though the differences in material rolled at 625°C are considerable.

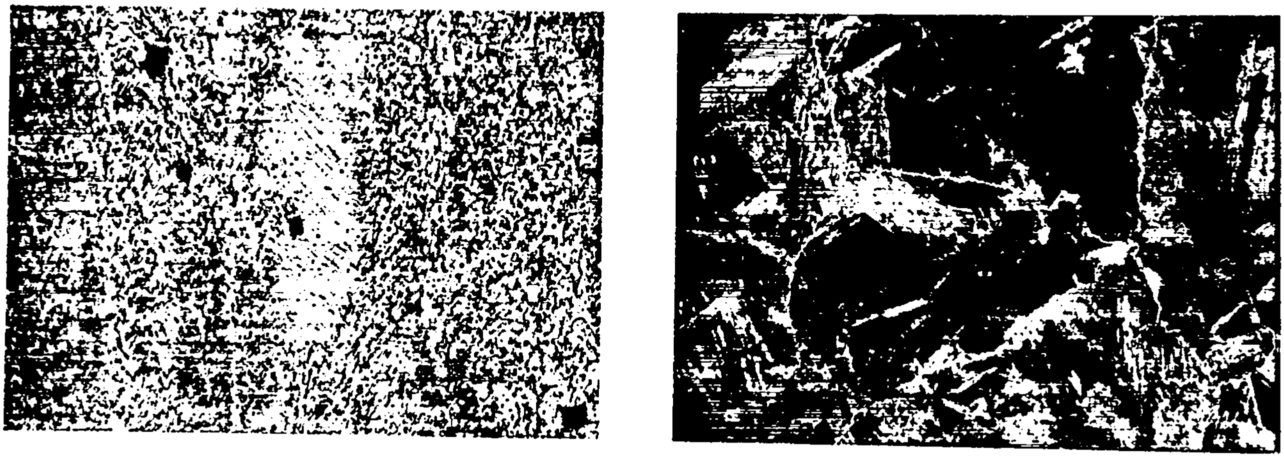
The effects of rolling temperature and heat treatment on the hardness and mechanical properties are shown in Table III. The ultimate and yield strengths of the 800°C as-rolled material are considerably higher than those of the 625°C as-rolled alloy. There was a corresponding decrease in elongation. These differences in properties are not seen in data from material rolled at both temperatures and subsequently γ-quenched from 800°C. Work done before this program showed that 125.1-ksi ultimate strength, 54.4-ksi yield strength, and 22% elongation can be obtained in the as-cast U-1.5Mo alloy.

Uranium-Titanium Alloys

Uranium-titanium alloys have complete solid solubility above ~890°C, and the lowest-melting-point constituent is uranium, which melts at 1130°C. For uranium-rich alloys, there is a eutectoid at 723°C and 0.8 wt% (4 at.%). There is essentially no solid solubility below the $\alpha \rightarrow \beta$ transition temperature of 667°C.

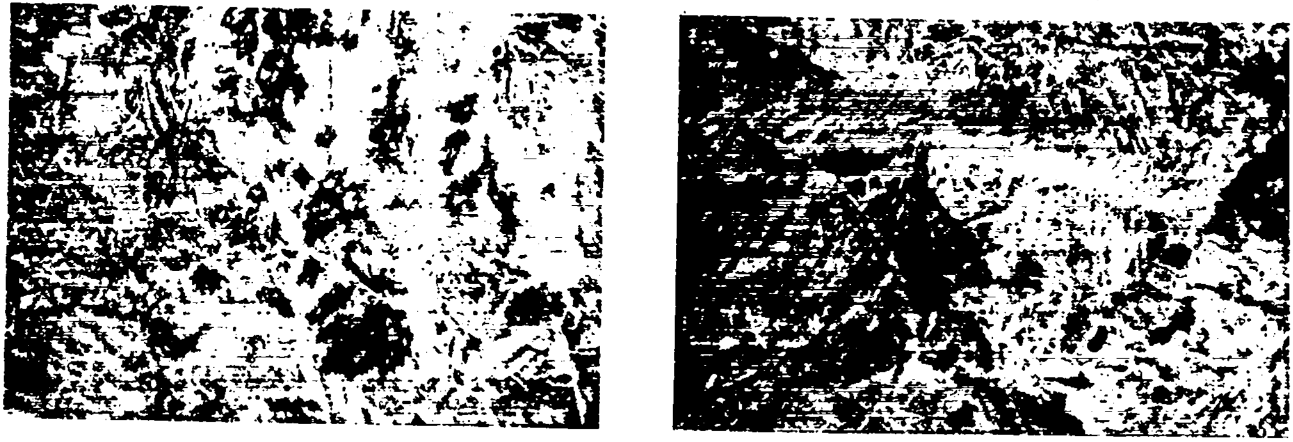
The titanium alloys (U-0.7Ti, U-0.8Ti, and U-1.5Ti) were rolled in the alpha-phase region at 625°C and did not crack. After rolling, they were heat treated at 625 or 800°C. Cast U-1.5Ti material was also homogenized at 1000°C for 4 h and at 1050°C for 4 h.

The as-cast density and hardness of the U-Ti alloys in the conditions described above are listed in Table IV. As can be seen, the hardness increases with increased titanium content. Also, the 800°C, water-quench, thermal treatment yields the highest hardness for all alloys. No significant change in hardness was noted when the as-cast U-1.5Ti alloy was homogenized.



a. As-Rolled at 625°C. 250X

b. Rolled at 625°C and annealed at 850°C. Water-quenched. 500X.



c. As-Rolled at 800°C. 250X.

d. Rolled at 800°C and annealed at 850°C. Water-quenched. 500X.

Fig. 3. Microstructure of wrought U-1.5Mo alloy.

TABLE III

MECHANICAL PROPERTIES OF U-1.5Mo

Alloy	Condition	Hardness (DPH)	Ultimate Tensile Strength (ksi)	0.2% Offset Yield Strength (ksi)	Elongation in 1 in. (%)
U-1.5Mo	As-rolled at 625°C	310	134.0	54.1	9.0
	As-rolled at 800°C	345	155.4	88.9	3.0
	Rolled at 600°C and γ-quenched from 850°C	380	170.5	102.3	9.0
	Rolled at 800°C and γ-quenched from 850°C	100	177.4	93.4	8.0

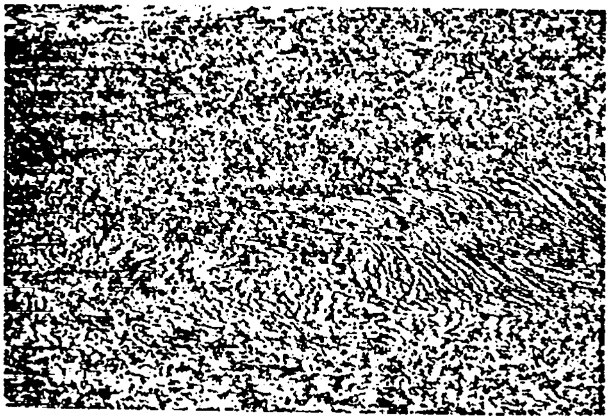
TABLE IV

DENSITY AND HARDNESS OF U-Ti ALLOYS

Composition	Cast Density (g/cm³)	Hardness (DPH)				
		As-Cast	Homogenized	As-Rolled	625°C, AC	800°C, WQ
U-0.7Ti	18.654	285	-	395	315	415
U-0.8Ti	18.602	310	-	320	335	435
U-1.5Ti	18.229	390	380	400	310	615

The metallography of the as-cast 0.8% titanium alloy is shown in Fig. 4. As can be seen, the alloy composition is slightly hypoeutectoid. The as-rolled structure is similar to that shown for the material annealed at 625°C. Heating to 800°C recrystallizes the wrought structure.

As-Cast.



625°C, air-cooled, wrought material.

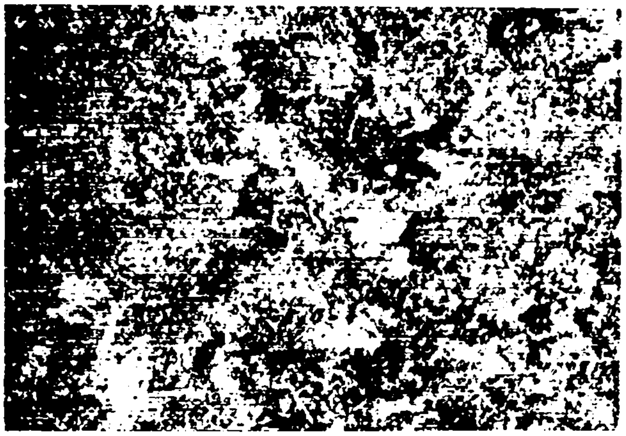
800°C, water quenched, wrought material.

Fig. 4. Microstructures of U-0.8Ti alloy, 250X.

The homogenized structure of the 1.5% titanium alloy is shown in Fig. 5. There was essentially no difference from the as-cast material. The wrought 1.5% titanium alloy was similar to the 0.8% titanium alloy, with recrystallization occurring at 625°C. An equiaxed structure containing a grain-boundary precipitate like that shown in Fig. 5 was developed by heating into the gamma-phase region at 800°C and water quenching.

The properties of the U-Ti alloys can be altered by aging. The hardnesses of the near-eutectoid alloys (0.7 and 0.8 wt% Ti) were essentially identical and were considered the same for this discussion. All alloys were water-quenched from the gamma range (800°C) before aging.

The hardness results of this aging study are shown in Fig. 6. The maximum hardnesses were



Microstructure of cast alloy homogenized at 1050°C maximum temperature.

Wrought alloy heat treated at 800°C and water quenched.

Fig. 5. Microstructures of U-1.5Ti alloy, 250X.

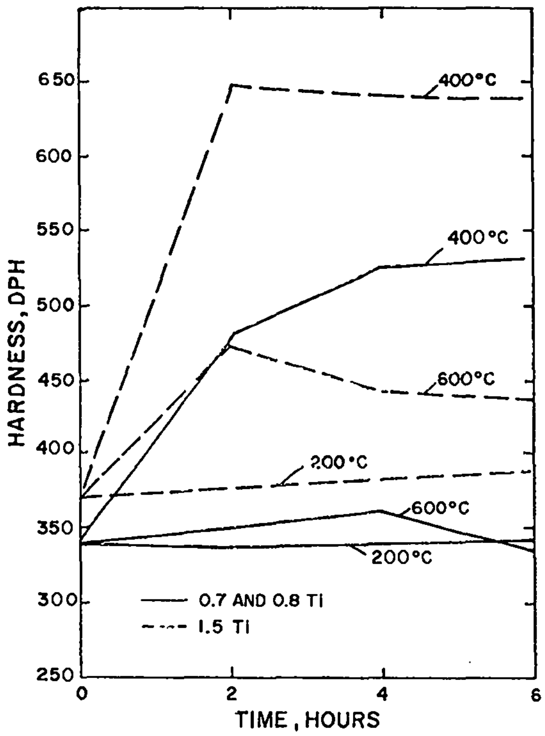


Fig. 6. Effect of aging time and temperature on the hardness of U-Ti alloys.

recorded for the 400°C aging treatments. Aging at 600°C produced an over-aged material, whereas 200°C was insufficient to produce appreciable aging in up to 6 h. At the 400°C aging temperature, the maximum hardness was reached in 2 to 4 h, depending on alloy content. The 1.5 wt% titanium alloy attained a hardness of ~640 DPH in 2 h, and the 0.7-0.8 wt% titanium alloys attained a hardness of 525 DPH in 4 h.

The mechanical properties developed in the wrought U-Ti alloys are listed in Table V. The data show that both the ultimate and yield strengths can be significantly increased by aging the U-0.8Ti alloys at 400°C for 2 h. An accompanying decrease in elongation occurs, but a minimum elongation of 10.5% was still recorded. The average yield and ultimate strengths for this alloy heat-treated at 400°C for 2 h were 133.3 and 221.6 ksi, respectively.

Increasing the titanium content to 1.5 wt% embrittled the material so that no yield strength could be recorded for any wrought specimen. The ultimate strength of the γ-quenched and 200°C-aged material remained the same, but that of the material aged at 300°C decreased. The elongations were decreased to 1% in all cases.

TABLE V

MECHANICAL PROPERTIES OF WROUGHT U-Ti ALLOYS

Alloy	Condition	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 1 in. (%)
U-07Ti	γ-quenched from 800°C	176.5	85.1	18.0
	and aged at 200°C for 2 h	175.6	98.5	11.5
	and aged at 300°C for 2 h	178.7	94.5	15.0
	and aged at 400°C for 4 h	212.2	125.4	12.0
U-0.8Ti	γ-quenched from 800°C	191.8	97.0	16.5
	and aged at 200°C for 2 h	190.53	93.3	13.0
	and aged at 300°C for 2 h	194.9	99.5	14.0
	and aged at 400°C for 2 h	221.6	133.3	10.5
U-1.5Ti	γ-quenched from 800°C	192.0	-	1
	and aged at 200°C for 2 h	194.4	-	1
	and aged at 300°C for 2 h	187.9	-	1

Uranium-Niobium Binary Alloys

Uranium-niobium alloys have complete solid solubility above ~980°C. Alloys containing less than ~5 wt% of niobium undergo a peritectoid reaction at 663°C, whereas those containing ~1 to ~53 wt% of niobium undergo a eutectoid reaction at 647°C; the eutectoid composition is ~6 wt%. Uranium-rich alloys at room temperature have essentially no solid solubility.

Uranium-niobium alloys ranging from 2.2 to 6.0 wt% of niobium were cast and rolled at 800°C. The as-cast U-4.7Nb alloy was homogenized at a maximum temperature of 1050°C in attempts to improve its chemical homogeneity.

The hardness and density survey results are reported in Table VI. The hardness of the as-cast, as-rolled, and 625°C heat-treated materials increased with increasing niobium to ~4 wt% of niobium and then remained essentially constant. The material annealed at 800°C decreased in hardness with increasing niobium content. The increasing hardness for the as-cast, as-rolled, and 625°C air-cooled materials is attributed to their increased ability to age during cooling. The effect of aging treatments on the hardness of the 6 wt% niobium alloy is shown in Fig. 7.

Figure 8 shows typical structures developed in as-cast; as-rolled, 625°C-annealed, and 800°C-annealed alloys containing 4 to 6 wt% of niobium. These photomicrographs show the grain-boundary precipitate formed by aging during cooling in all but the 800°C water-quenched material. The precipitate is not so readily discernible in the as-cast as in the wrought material, but it is present. The microstructure developed in the aging studies

TABLE VI

DENSITY AND HARDNESS OF URANIUM-NIOBIUM ALLOYS

Composition	As-Cast Density (g/cm^3)	As-Cast	Homogenized	As-Rolled	625°C, AC	800°C, WQ
U-2.2Nb	18.492	315	-	430	365	455
U-3.4Nb	18.199	390	-	490	450	375
U-4.0Nb	18.079	400	-	510	435	340
U-4.7Nb	17.811	400	400	-	-	-
U-5.0Nb	17.568	410	-	505	435	230
U-6.0Nb	-	-	-	-	-	155[a]

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[a] Water-quenched from 850°C.

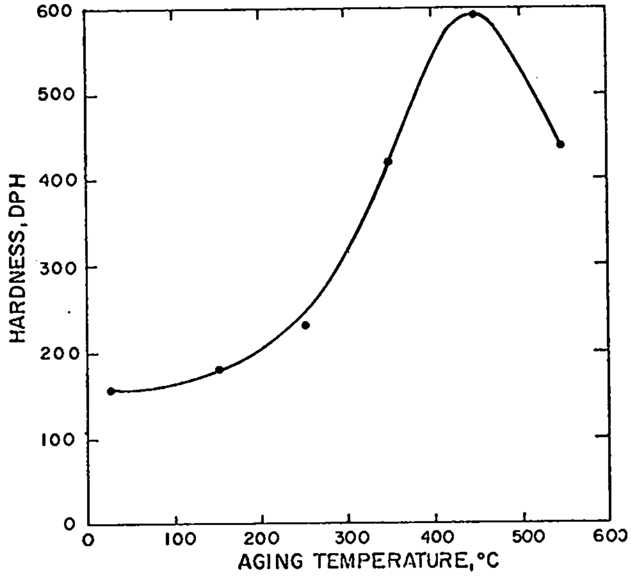


Fig. 7. Effect of aging temperature on the hardness of U-6Nb alloys.

previously mentioned is equiaxed and contains a grain-boundary precipitate like that in the as-rolled material. Quenching from the gamma-phase region produces a single-phase, equiaxed structure. Some carbide particles are present.

One of the main problems encountered in preparation of U-Nb alloys is segregation of the niobium. Metallography showed this to occur on both the macro- and microscale. Areas of what appeared to be elemental niobium were found, in addition to single-phase areas rich in niobium. The latter areas were extremely difficult to etch.

Both parent-metal and cross-weld yield and ultimate strengths and elongations were determined for the U-4Nb and U-5Nb alloys (Table VII). Tensile data were not obtained for any other U-Nb alloy.

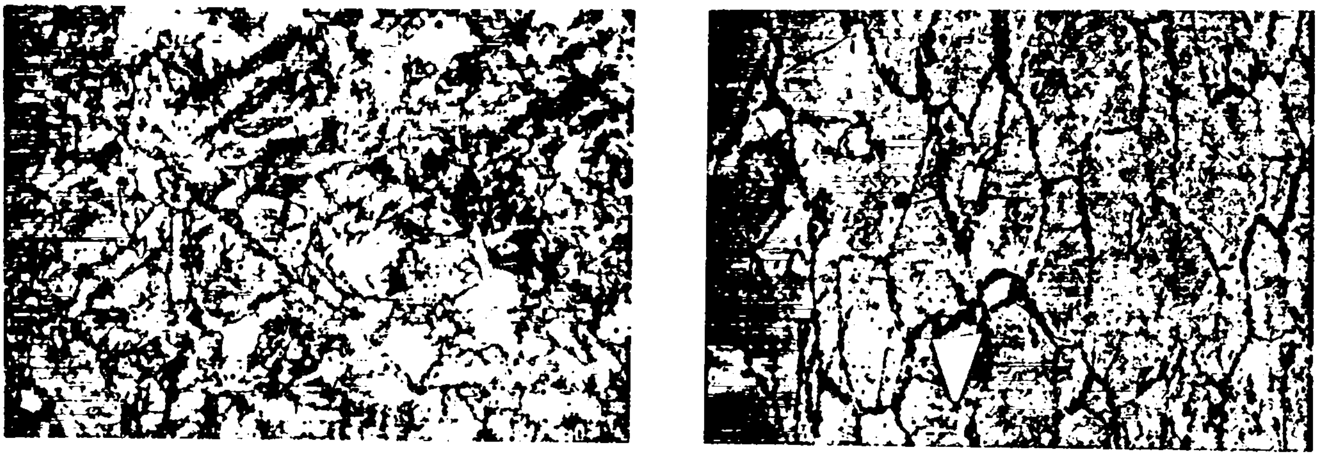
There was little difference in the strengths of correspondingly heat-treated materials, though the parent-metal ultimate strengths of the U-5Nb alloy tended to be slightly higher.

In all cases, increasing the aging temperature drastically increased the yield strength. Increases in ultimate strengths were also noted, but not of the same magnitude. As expected, the elongations decreased correspondingly.

Cross-weld properties of electron beam-welded sheet samples were obtained. In all cases, the weld buildup was removed by machining. The ultimate and yield strengths actually increased over the parent-metal values, and a reasonable elongation was also retained in the welded U-4Nb samples. A slight decrease in ultimate strength of the U-5Nb alloy was noted when comparing parent-metal and cross-weld values; the yield strengths were essentially the same. However, the elongation of the U-5Nb alloy was reduced considerably more than that of the U-4Nb alloy. It is interesting that in the cross-weld samples, all failures occurred in either the parent metal or at the parent metal-weld fusion line. There were no failures in the weld metal itself.

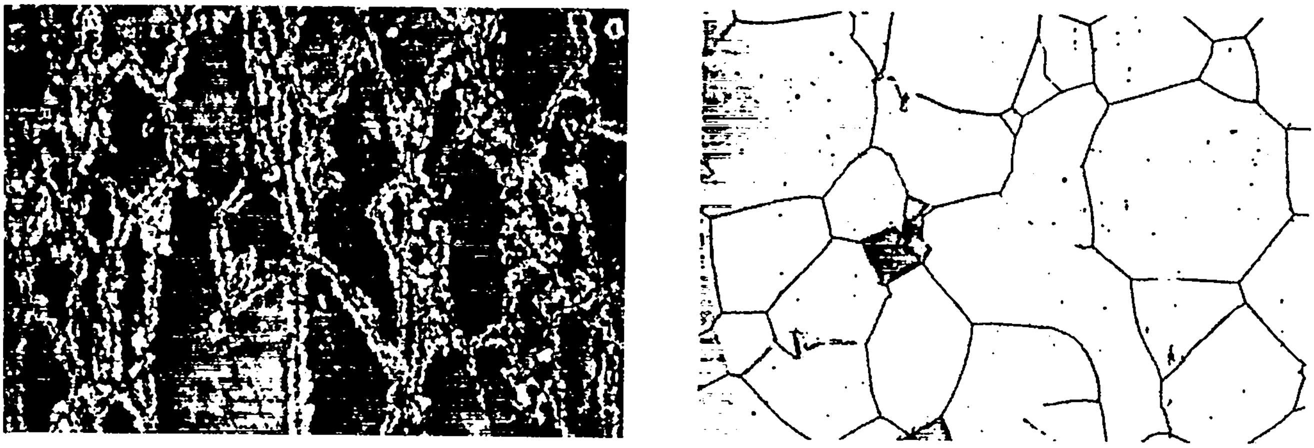
Uranium-Niobium Polynary Alloys

The niobium alloys gave definite promise of corrosion resistance as shown later in this report. However, it is advantageous to add a minimum quantity of alloying element to achieve this corrosion protection. Therefore, we cast a series of alloys containing a nominal 2 wt% of niobium plus additions of titanium, zirconium, molybdenum, and vanadium. For reporting purposes, Mulberry (U-7.5Nb-2.5Zr) and the Army alloy U-1.5Mo-1.5Nb-1.5Zr-0.5Ti are included in this group.



As-Cast.

As-Rolled.



Rolled and air-cooled at 625°C.

Rolled and water-quenched at 800°C.

Fig. 8. Microstructures of U-4.0Nb alloy, 250X.

TABLE VII

MECHANICAL PROPERTIES OF U-Nb ALLOYS

		Parent Metal			Cross Weld[a,b]		
Alloy	Heat Treatment	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 1 in. (%)	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 1 in. (%)
U-4Nb	γ-quenched from 800°C	163.7	42.0	16	167.2[c]	47.5	10
	and aged at 200°C for 2 h	158.7	56.1	18	167.7	65.5	12
	and aged at 300°C for 2 h	187.1	124.3	12	199.0	173.0	5
	and aged at 400°C for 2 h	237.0	200.4	1	-	-	-
	and aged at 260°C for 80 h	186.2	142.7	11	195.8	164.0	7
U-5Nb	γ-quenched from 800°C	154.1	37.7	20	147.2[c]	38.2	12
	and aged at 200°C for 2 h	157.8	56.9	16	142.5	59.0	9
	and aged at 300°C for 2 h	182.8	148.2	8	-	-	-
	and aged at 260°C for 80 h	182.3	149.5	9	186.0	-	2

---

a. Material welded in the γ-quenched condition. The only postweld heat treatment was the indicated aging cycle.

b. Failure always occurred in parent metal or parent-metal-to-weld-metal fusion line.

c. As-welded condition.

All these alloys except the U-6.9Nb-2.7Zr were rolled at 800°C in the gamma-phase range. The U-6.9Nb-2.7Zr was used in this program only as an oxidation-test standard and was not rolled.

The hardnesses of these alloys in various conditions and their as-cast densities are shown in Table VIII. The hardnesses of the U-2.2Nb alloy are included for comparison. The addition of titanium, molybdenum, and vanadium and the Mo-Zr-Ti combination decreased the hardness of the γ-quenched material. Only zirconium increased the hardness. A hardness of 180 DPH was recorded for the U-2.7Nb-2.0Mo alloy quenched from 800°C. This was slightly lower than the 190-DPH hardness recorded for unalloyed uranium vacuum-annealed at 625°C.

The opposite trend was noted for the as-cast, as-rolled, and 625°C-annealed material, whose hardness increased with additions of alloying element. The one exception was the U-2.7Nb-2.0Mo alloy whose hardnesses were below that of U-2.2Nb in the as-rolled and 625°C-annealed conditions.

We used the U-2.2Nb alloy as a base line for comparing the microstructures in the U-Nb-X alloys. Figure 9 shows the U-2.2Nb microstructures. The results show that the coarse intergranular precipitate does not form so readily as it does in the higher niobium alloys. However, if a rapid quench is not obtained after treating at 800°C, the precipitate will form.

We developed a variety of as-cast microstructures for the U-2Nb-X alloys. The microstructure in the U-1.9Nb-0.9Ti alloy (Fig. 10) can be considered typical for additions of 1.7 wt% of vanadium, 1 wt% of zirconium, and 0.9 wt% of titanium to the U-Nb base alloy. The most noticeable difference from the U-2.2Nb is the absence of the Widmenstatten-type second phase at the grain boundaries.

The as-cast microstructure can be altered by homogenizing the as-cast material at 950 to 1050°C for 8 h. The types of changes resulting from homogenization can best be shown using the U-2.2Nb-2.0Mo alloy. As Fig. 11 shows, a microstructure more closely resembling a single-phase structure is developed, and some grain growth is apparent.

The microstructure of wrought alloys vacuum annealed at 800°C and water quenched is shown in Fig. 12. It appears that additions of molybdenum, vanadium, zirconium, and titanium tend to stabilize the gamma phase. Of these alloys, the U-1.9Nb-0.9Ti alloy has what might be considered optimum single-phase structure. A grain-boundary precipitate was noted in the U-Nb-Mo alloy.

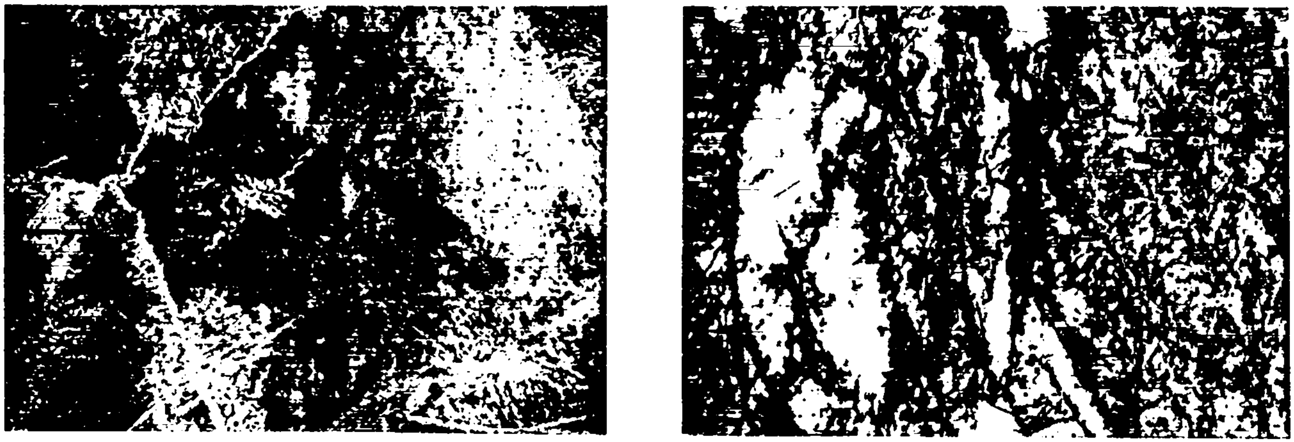
The microstructure developed by heat treating the wrought U-1.5Nb-1.5Mo-1.4Zr-0.6Ti alloy at 800°C was identical to that developed in the U-Nb-Ti alloy. The as-cast, homogenized, as-rolled, and 625°C-annealed samples differed from the other alloys in this group in that a more definite grain structure was present. Some segregation was noted metallographically.

The U-6.9Nb-2.7Zr alloy had a completely different microstructure, as shown in Fig. 13. Again the effects of the 1000 to 1050°C homogenization treatment are very evident.

TABLE VIII

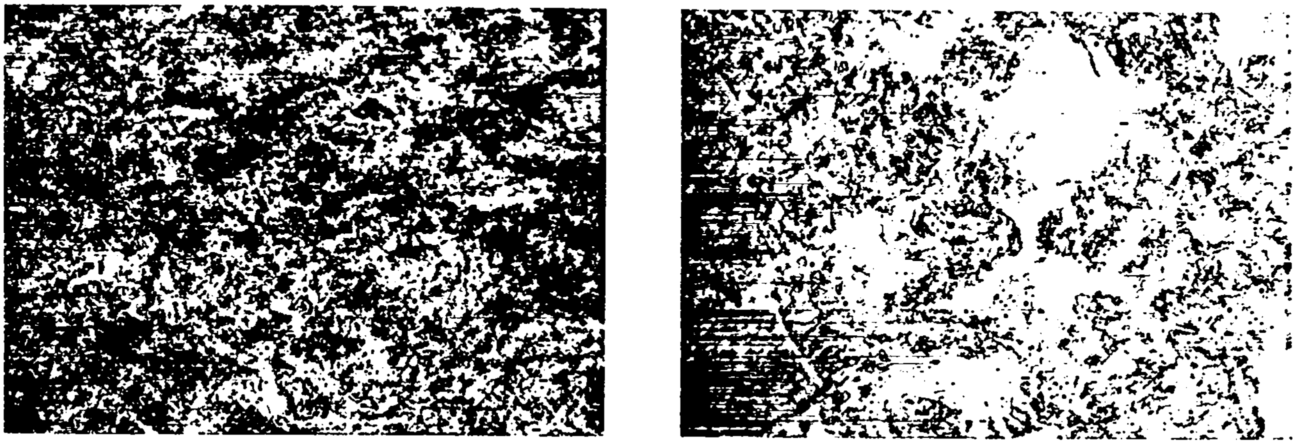
DENSITY AND HARDNESS OF U-Nb-X ALLOYS

Alloy	As-Cast Density (g/cm^3)	Hardness, (DPH)				
		As-Cast	Homogenized, VC	As-Rolled	625°C, AC	800°C, WQ
U-2.2Nb	18.492	315	-	430	365	455
U-1.9Nb-0.9Ti	18.084	440	-	590	435	335
U-1.9Nb-2.2Mo	18.151	430	-	460	375	245
U-2.2Nb-2.0Mo	18.137	420	550	-	-	-
U-2.7Nb-2.0Mo	17.889	435	165 to 310	360	350	180
U-2.4Nb-1.7V	18.153	425	445	510	425	315
U-2.4Nb-1.0Zr	17.628	335	-	500	425	520
U-6.9Nb-2.7Zr	-	420	550	-	-	-
U-1.5Nb-1.5Mo-1.4Zr-0.6Ti	17.618	475	570	470	390	235



As-Cast.

As-Rolled.



625°C for 3/4 h, air-cooled.

800°C for 3/4 h, water-quenched.

Fig. 9. Microstructure of U-2.2Nb alloy, 250X.

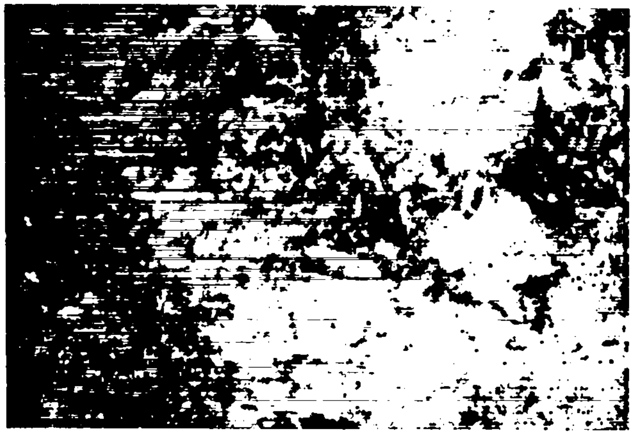
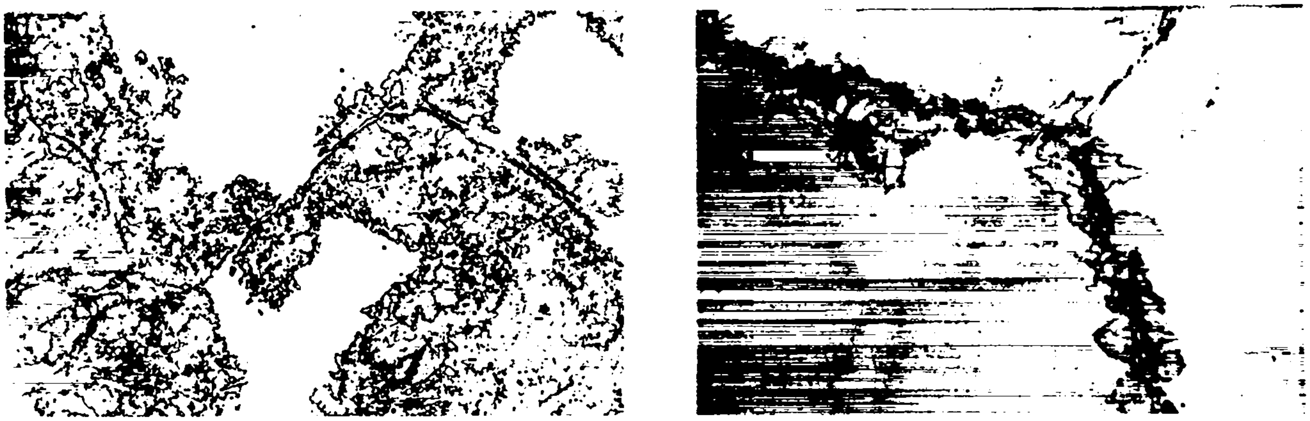


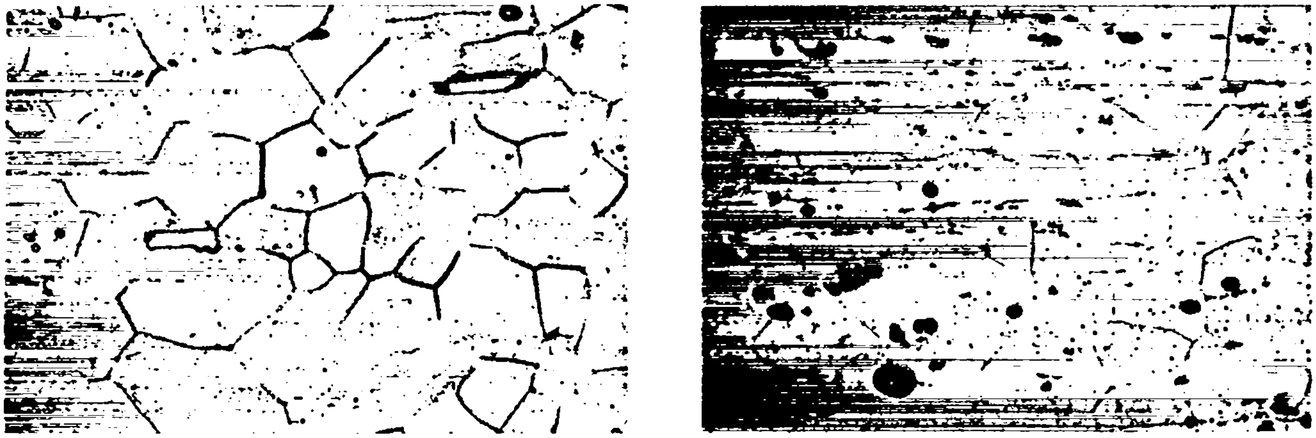
Fig. 10. As-Cast microstructure of the U-1.9Nb-0.9Ti alloy. 250X.



As-Cast. 100X.

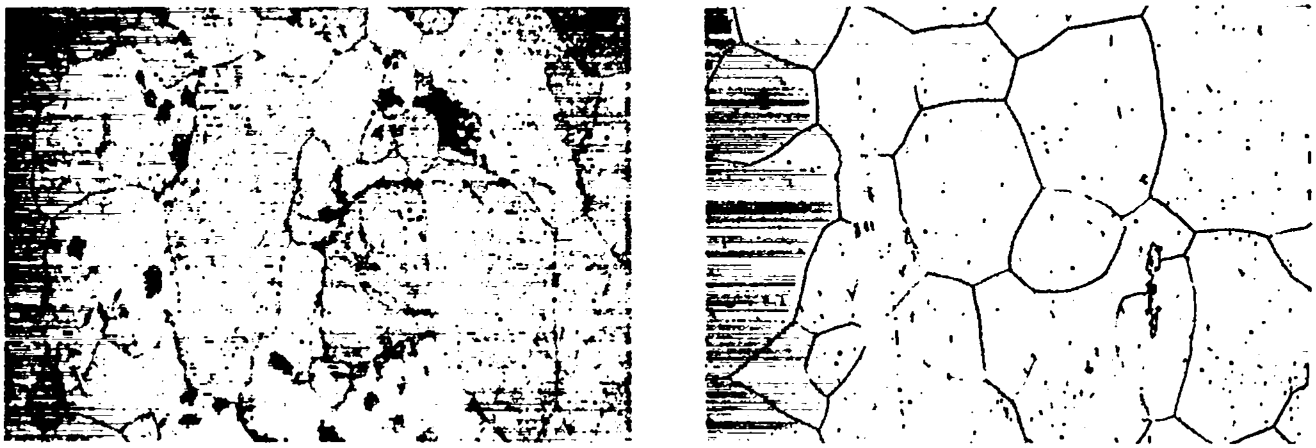
Homogenized at 1000°C for 4 h and at 1050°C for 4 h, vacuum-cooled. 250X.

Fig. 11. Effect of homogenization treatments on as-cast microstructures of the U-2.2Nb-2.1Mo alloy.



U-2.2Nb-2.0Mo.

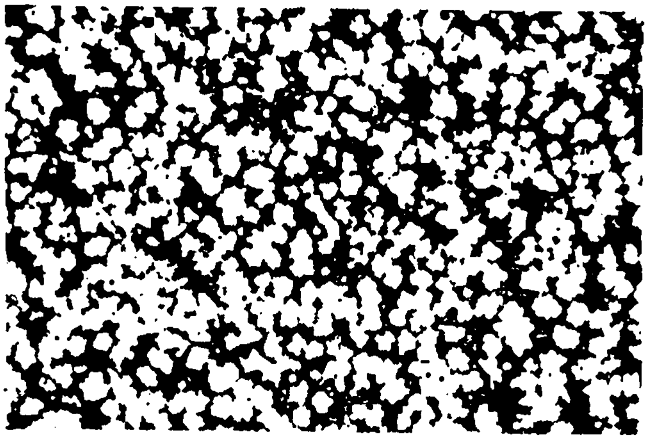
U-2.4Nb-1.7V.



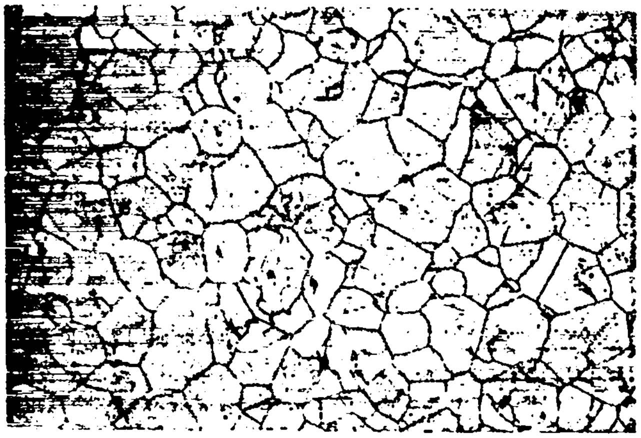
U-2.4Nb-1.0Zr.

U-1.9Nb-0.9Ti.

Fig. 12. Microstructure of wrought U-Nb-X alloys annealed at 800°C and water quenched, 250X.



As-Cast. 100X.



Homogenized at 1000°C for 4 h and at 1050°C for 4 h, vacuum cooled. 250X

Fig. 13. Microstructures of Mulberry alloy (U-6.9Nb-2.7Zr).

We determined the mechanical properties of five of the U-Nb-X alloys. (See Table IX.) These alloys were U-1.9Nb-0.9Ti, U-1.9Nb-2.2Mo, U-2.7Nb-2.0Mo, U-2.4Nb-1.7V, and U-1.5Mo-1.5Nb-1.4Zr-0.5Ti. The best combination of strength and ductility was shown by the U-1.5Mo-1.5Nb-1.4Zr-0.5Ti alloy that was γ-quenched and aged at 200°C for 2 h. The U-1.9Nb-0.9Ti alloy had similar strengths, but its elongation was lower by a factor of 2 in the aged condition.

The U-2.7Nb-2.0Mo and U-1.9Nb-2.2Mo alloys had some ductility (8-9% elongation) when aged, but their yield and ultimate strengths were low compared to those of the above alloys. The opposite was true for the U-2.4Nb-1.7V alloy which had the highest strengths (207.8-ksi ultimate strength and 158.0 yield strength), but essentially no ductility (1% elongation).

We determined the cross-weld mechanical properties of three of these alloys. The welding process did not lower the strengths or ductility of the welded and aged U-1.9Nb-0.91Ti and U-2.7Nb-2.0Mo specimens. This behavior is very similar to that of the U-Nb alloys. This was not true of the U-Mo-Nb-Zr-Ti alloy. The cross-weld yield and ultimate strengths of this material were decreased significantly, and its elongation was somewhat less.

TABLE IX

MECHANICAL PROPERTIES OF WROUGHT U-Nb-X ALLOYS

					Cross Weld[a]		
Alloy	Heat Treatment	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 1 in.(%)	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 1 in.(%)
U-1.9Nb-0.9Ti	γ-quenched from 800°C	190.0	87.4	11	184.7[b]	154.8	2
	and aged at 200°C for 2 h	173.5	116.8	3	183.0	145.0	4
	and aged at 260°C for 80 h	202.7	159.3	-	-	-	-
U-1.9Nb-2.2Mo	γ-quenched from 800°C	137.2	42.2	8	-	-	-
	and aged at 200°C for 2 h	134.2	60.0	9	-	-	-
	Vacuum-annealed at 625°C	167.8	111.3	-	-	-	-
U-2.7Nb-2.0Mo	γ-quenched from 800°C	142.0	34.5	8	125.5[a]	33.8	8
	and aged at 200°C for 2 h	137.1	51.0	9	135.5	64.5	6
	and aged at 300°C for 2 h	173.1	103.7	6	-	-	-
	and aged at 260°C for 80 h	172.3	125.8	6	-	-	-
U-2.4Nb-1.7V	γ-quenched from 800°C	207.8	158.0	1	-	-	-
U-1.5Mo-1.5Nb-1.4Zr-0.5Ti	γ-quenched from 800°C	200.0	106.4	5	157.2[b]	67.3	4
	and aged at 200°C for 2 h	198.0	110.5	7	163.2	73.3	4

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a. Material was welded in the γ-quenched condition and given postweld aging treatments as indicated. The weld bead was removed before testing.

b. As-welded values.

Uranium-Chromium and Uranium-Nickel Alloys

Uranium-chromium alloys form a low-melting-point eutectic at ~859°C and 5 wt% of chromium. Subsequent solid-state transformations include eutectoids at 752 and 640°C. The eutectoid compositions are less than 1 wt% chromium; there is very limited solid solubility at room temperature.

A uranium-nickel eutectic forms at ~12 wt% of nickel and 740°C. Uranium-rich alloys experience a peritectic reaction at 790°C and a eutectoid reac- at ~775°C, and undergo an $\alpha \longrightarrow \beta$ phase transformation at 670°C. Nickel in uranium has essentially no solid solubility below 600°C.

We tried to roll the U-2Ni alloy at 725°C, but found severe edge cracking. Because of the low eutectic temperature, we could not use higher temperatures.

The U-2.2Cr alloy was rolled successfully at 625°C from the salt bath. We tried higher temperatures, but this alloy is pyrophoric at 800°C. Both the U-0.5Cr-0.5Ni and the U-0.5Cr-0.5Ni-1.5Mo alloys were rolled successfully at 625°C. The hardnesses and densities of these alloys in various conditions are shown in Table X.

The as-cast microstructures of all the alloys in this group except the U-Cr-Ni-Mo alloy are typical of hypoeutectic alloys. The structures do differ in the amount of primary phase (in this case transformed gamma), coring, and eutectic present. Figure 14 shows typical microstructures of these alloys. The U-Cr-Ni-Mo structures more closely resemble the molybdenum-base alloys.

Results of Corrosion Tests

We tested the uranium alloys at 260, 120, and 60°C to determine whether they could withstand up to 3 months' exposure at these temperatures. Failure was arbitrarily taken at the point at which loose corrosion products developed.

At 120 and 260°C, the oxidation was uniform and flaking occurred after about 0.001 in. of metal had been oxidized. Oxidation of 0.001 in. of metal in 90 days corresponds to an oxidation rate of 0.063 mg/cm^2/day. Specimens tested at 60°C and 100% relative humidity did not corrode uniformly. Deep pits formed on the surface, and the corrosion products were light and fluffy. Thus a loose corrosion product was formed when total corrosion was much less than that of the specimens tested at 120 and 260°C.

Corrosion at 260°C. The corrosion tests at 260°C and ambient humidity revealed a definite effect of both composition and material conditions. At this temperature, only the homogenized U-6.9Nb-2.7Zr alloy (Mulberry) had an acceptable corrosion rate. An oxide layer ~0.002 in. thick had formed on the surface after 5 month's exposure. This corresponds to an oxidation rate of 0.0186 mg/cm^2/day. No as-cast Mulberry sample was tested.

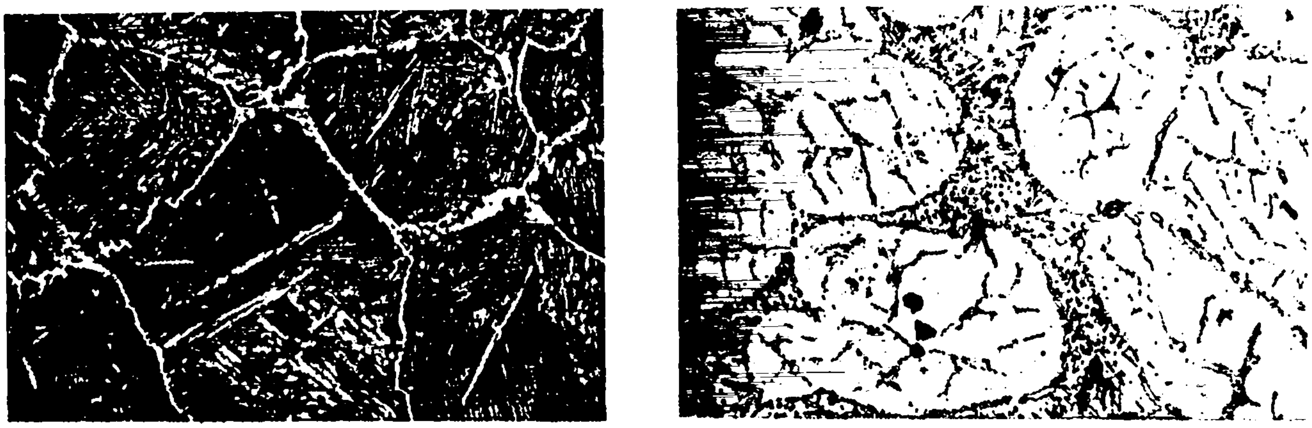
None of the other alloys had oxidation rates of less than 0.063 mg/cm^2/day. However, we noted some trends relative to material condition and alloy content (Table XI). The data show the beneficial effect of niobium additions and of procedures (homogenization and mechanical working) that tend to produce a more homogeneous material. Thermal treatments can be beneficial, if they do not produce an over-aged structure.

Corrosion at 120°C. At 120°C and ambient humidity, the trends noted at 260°C become more clearly defined. The beneficial results of homogenization and mechanical working are clear, as is shown in Table XII. Segregation of the niobium is evident in the U-5.1Nb alloy, two supposedly identical samples of which had drastic variations in oxidation rates.

TABLE X

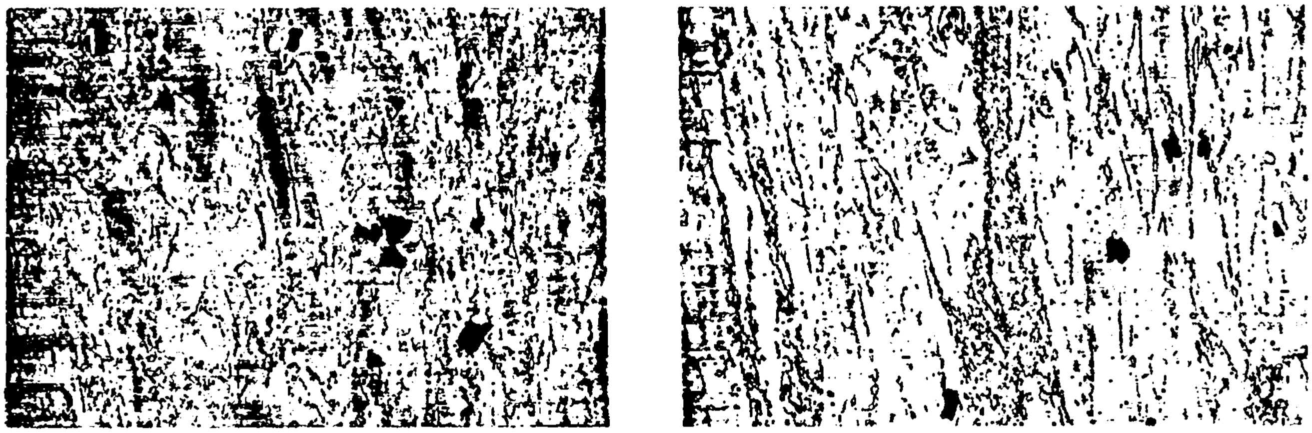
DENSITY AND HARDNESS OF U-Cr-Ni ALLOYS

Alloy	As-Cast Density (g/cm^3)	As-Cast	As-Rolled	625°C Air-Cooled	800°C Water-Quenched
U-2.2Cr	18.418	385	270	250	-
U-2Ni	18.345	350	-	-	-
U-0.5Cr-0.5Ni	18.642	295	370	290	405
U-0.5Cr-0.5Ni-1.5Mo	18.395	330	415	365	485



As-Cast U-0.5Cr-0.5Ni-1.5Mo.

As-Cast U-2.2Cr.



As-Rolled U-2.2Cr.

Wrought U-2.2Cr annealed at 625°C in salt for 3/4 h, air cooled.

Fig. 14. Microstructures of U-Cr-Ni-Mo alloy system, 250X.

TABLE XI

OXIDATION OF URANIUM ALLOYS AT 260°C

	Oxidation rate (mg/cm²/day)							
Alloy	As-Cast	Homogenized	As-Rolled	As-Quenched 800°C	200°C 2 h	260°C 80 h	300°C 2 h	Other
U-5.1Nb	-	-	0.217	0.248	2.186	0.217	0.264	
U-4.0Nb	-	-	0.651	0.279	0.279	-	0.310	1.21[a]
U-2.7Nb-2.0Mo	> 2.2	0.279	-	0.357	0.543	0.543	0.248	-
U-2.5Nb-1.7V	-	-	0.357	0.512	-	-	-	-
U-1.9Nb-2.2Mo	> 2.2	0.620	-	1.71	0.806	-	-	32.6[b]
U-1.9Nb-0.9Ti	-	3.57	-	3.44	4.26	2.44	-	
U-1.5Nb-1.5Mo-1.4Zr-0.6Ti	10.5	-	-	1.04	1.10	-	-	

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[a] Aged at 400°C for 2 h.

[b] Aged at 600°C for 45 min.

TABLE XII

OXIDATION RATES OF URANIUM ALLOYS AT 120°C AND AMBIENT HUMIDITY

	Oxidation Rate ($mg/cm^2/day$)		
Alloy	As-Cast	Homogenized	As-Rolled
U	2.15	0.62	-
U-1.5Mo	0.60	-	-
U-0.5Cr-0.5Ni	1.32	-	-
U-2.2Cr	1.16	-	-
U-2.0Ni	0.39	-	-
U-1.5Mo-0.5Cr-0.5Ni	0.59	-	-
U-0.7Ti	0.31	-	-
U-0.8Ti	0.40	-	-
U-1.6Ti	0.25	0.17	0.37
U-2.2Nb	0.51	-	-
U-3.4Nb	0.34	-	-
U-4.0Nb	0.25	0.07	nil
U-5.1Nb	0.02-0.11	-	nil
U-1.9Nb-2.2Mo	0.14	0.08	0.19
U-2.7Nb-2.0Mo	0.17	0.02	-
U-2.5Nb-1.7V	0.16	0.11	nil
U-2.4Nb-1.0Zr	0.37	-	-
U-1.5Nb-1.5Mo-0.5Ti-1.4Zr	0.07	-	-

The wrought structure and increased homogeneity generated by hot-rolling is particularly beneficial in reducing the oxidation rate of niobium-containing alloys. The three samples (U-4.0Nb, U-5.1Nb, and U-2.5Nb-1.7V) for which essentially no oxidation of the as-rolled material was reported were held at temperature for 5 months.

These three alloys plus the U-1.6Ti and U-2.2Nb-2.1Mo alloys were also tested at 120°C and 0.5-atm water-vapor pressure. Both the U-1.6Ti and U-1.9Nb-2.2Mo alloys caught fire after 2 weeks' exposure. In contrast, the U-4.0Nb, U-5.1Nb, and U-2.5Nb-1.7V alloys experienced essentially no oxidation (oxidation rate = 0.0031 $mg/cm^2/day$).

Corrosion at 60°C. The niobium alloys again demonstrated their superior corrosion resistance in the tests conducted at 60°C and 100% relative humidity. After 5 months exposure, the U-4.0Nb, U-5.1Nb, U-2.2Nb-2.1Mo, U-2.5Nb-1.7V, and U-2.7Nb-2.0Mo alloys showed only slight corrosion. However, if these alloys were used at this temperature in an environment where the water vapor could condense on the surface of the uranium, corrosion would be more severe.

This was demonstrated by tests in which the specimens were set on a plastic grid. The grid absorbed moisture, and the specimens corroded so much that only the Mulberry could be recommended for use under these conditions. Replacing the plastic grid with a nonabsorbing Teflon grid gave the completely different results mentioned above. (Mulberry was not tested using the Teflon grid).

All alloys corroded at more nearly the same rate than at higher temperatures. We noted little difference in the corrosion resistance of alloys tested in various conditions (as-cast, homogenized, as-rolled).

IV. SUMMARY AND CONCLUSIONS

This report summarizes uranium-alloy work performed by the Materials Technology Group of the Los Alamos Scientific Laboratory. Typical properties of over 20 alloys were presented. On the basis of these data, some general observations can be made.

1. The homogeneity of the cast material can be improved by thermal processing and mechanical working. These treatments significantly improve the observed properties.
2. Additions of less than 1 wt% of titanium or 2 wt% of molybdenum produce material with yield strength in excess of 100,000 psi and with good ductility (> 9% elongation).
3. The mechanical properties of the titanium alloys can be controlled by aging. Optimum properties were obtained by aging at 400°C for 4 h.
4. Niobium additions are required to achieve corrosion (oxidation) resistance. Only the Mulberry alloy could withstand exposure to temperatures of 260°C, but binary alloys containing 4 and 5 wt% of niobium and the ternary alloy U-2.5Nb-1.7V had excellent corrosion resistance at 120°C when hot-rolled.
5. The oxidation rate was drastically affected by the condition of the material. Treatments that increased the homogeneity of the material significantly increased the corrosion resistance.

ACKNOWLEDGMENTS

We wish to thank the following groups and individuals for their contributions to this program: Group CMB-1 for the chemical analyses and density measurements, T. I. Jones and C. A. Javorsky for the metallographic and tensile data, A. G. Fox and B. W. Powell for help in performing the corrosion tests, and B. Daly and J. Ellis for typing the report.

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5. G. S. Hanks, J. M. Taub, and D. T. Doll, "Effect of Annealing Media on the Mechanical Properties of Uranium," Los Alamos Scientific Laboratory report LA-1619 (1953).

APPENDIX

RESULTS OF COMPLETE SPECTROGRAPHIC ANALYSES

	Alloy Content (ppm) unless otherwise noted						
Element	68165	52734	52712	52710	52711	52770	52702
Cr	2	2	< 10	< 10	< 10	1	1
Nb	-	-	-	-	-	-	2.20 wt%
Ni	-	10	10	10	< 10	15	5
Mo	5	1.55 wt%	10	< 10	< 10	30	-
Ti	< 25	-	0.69 wt%	0.79 wt%	1.60 wt%	1.55 wt%	-
V	-	< 25	< 20	< 20	< 20	< 1	< 2
Zr	< 25	-	-	-	-	-	-
C	360	210	300	210	160	65	95
Li	< 0.1	< 0.1	< 1	< 1	< 1	< 0.1	< 0.1
Be	< 0.5	< 0.5	< 1	< 1	< 1	< 0.1	< 0.1
B	< 0.5	< 0.5	< 1	< 1	< 1	< 0.1	< 0.5
Na	3	< 1	10	7	15	< 1	< 1
Mg	3	< 1	5	< 5	< 5	< 1	< 1
Al	20	20	< 10	< 10	< 10	< 10	< 5
Si	300	300	70	50	40	50	70
P	< 50	< 100	< 100	< 100	< 100	< 200	-
Ca	10	< 2	70	50	70	< 2	< 2
Mn	3	1	10	10	10	5	5
Fe	50	250	200	300	300	50	50
Co	-	< 5	< 5	< 10	< 5	-	< 1
Cu	10	6	40	-	10	5	2
Zn	< 25	-	-	-	-	< 25	-
Sr	< 20	-	-	-	-	< 2	-
Ag	< 1	-	-	-	-	-	-
Cd	< 2	< 2	< 1	< 1	< 1	< 0.2	-
Sn	< 1	< 1	< 5	< 5	< 5	< 1	-
Sb	10	-	-	-	-	< 5	-
Ba	< 5	-	-	-	-	< 1	-
Tl	-	-	-	< 5	-	-	-
Pb	< 1	< 1	5	-	< 5	1	-
Bi	< 1	-	-	-	-	< 2	-

Alloy Content (ppm) unless otherwise noted

Element	52701	52704	52771	52705	51193	52714	52709
Cr	2	< 2	3	< 3	6	2	1
Nb	3.43 wt%	4.01 wt%	4.70 wt%	5.20 wt%	6.00 wt%	1.93 wt%	2.53 wt%
Ni	10	15	20	15	60	25	5
Mo	-	-	< 100	-	< 0.1 wt%	-	-
Ti	-	-	-	-	-	0.86 wt%	-
V	< 3	< 4	< 200	< 6	< 6	< 2	1.68 wt%
Zr	-	-	-	-	-	-	-
C	140	90	150	90	195	190	420
Li	0.2	< 0.2	< 0.1	0.3	< 0.3	< 0.1	< 0.5
Be	< 0.2	< 0.2	0.6	< 0.3	< 0.3	< 0.1	< 0.1
B	< 1	< 1	< 0.5	< 2	< 0.3	< 0.5	< 0.5
Na	< 2	< 0.5	1	< 0.5	6	5	7
Mg	< 2	< 2	< 1	< 3	< 3	1	< 1
Al	< 10	< 10	15	< 15	< 30	< 5	5
Si	100	60	80	30	45	2	20
P	-	-	< 50	-	-	-	-
Ca	8	< 2	< 25	< 3	9	7	< 2
Mn	10	8	5	15	6	5	7
Fe	100	60	50	900	90	200	300
Co	< 2	< 2	-	< 3	< 3	< 1	< 1
Cu	10	5	10	3	75	20	5
Zn	-	-	< 25	-	-	-	-
Sr	-	-	< 100	-	-	-	-
Ag	-	-	< 1	-	-	-	-
Cd	-	-	< 1	-	-	-	-
Sn	-	-	< 1	-	< 0.001	-	-
Sb	-	-	< 5	-	-	-	-
Ba	-	-	< 10	-	-	-	-
Tl	-	-	-	-	-	-	-
Pb	-	-	< 1	-	< 0.001	-	-
Bi	-	-	< 1	-	-	-	-

Alloy Content (ppm) unless otherwise noted

Element	52733	52706	52772	52728	52708	52783	52727
Cr	< 100	10	10	10	2	< 2	5
Nb	1.55 wt%	1.95 wt%	2.54 wt%	2.75 wt%	2.36 wt%	6.92 wt%	-
Ni	< 100	15	25	20	7	10	2.03 wt%
Mo	1.54 wt%	2.20 wt%	2.11 wt%	2.00 wt%	-	25	50
Ti	0.57 wt%	-	-	-	-	-	-
V	< 100	3	< 200	< 25	< 1	< 5	< 50
Zr	1.40 wt%	-	-	-	-	2.73 wt%	-
C	55	185	460	350	175	250	1270
Li	< 100	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Be	< 100	< 0.1	< 0.5	< 0.5	< 0.1	< 0.5	< 0.5
B	< 100	< 0.5	< 0.5	< 0.5	< 0.5	0.6	< 0.5
Na	< 100	< 1	< 1	15	1	1	10
Mg	< 100	< 1	< 1	2	< 1	< 1	1
Al	< 100	70	< 10	5	< 5	5	50
Si	< 300	300	120	200	15	200	120
P	-	-	< 50	< 200	-	< 100	< 200
Ca	-	200	< 10	2	< 2	< 10	15
Mn	< 100	3	1	3	7	8	2
Fe	< 100	150	80	200	70	80	100
Co	< 100	< 1	-	< 5	< 1	-	-
Cu	< 100	8	8	25	7	5	25
Zn	< 0.1	-	< 25	-	-	< 10	-
Sr	< 100	-	< 100	-	-	< 40	-
Ag	< 100	-	< 1	-	-	< 1	-
Cd	< 100	-	< 1	< 2	-	< 1	< 2
Sn	< 500	-	< 1	< 1	-	< 1	< 1
Sb	-	-	< 5	-	-	< 5	< 100
Ba	< 100	-	< 10	-	-	< 10	-
Tl	-	-	-	-	-	-	-
Pb	< 100	-	< 1	8	-	< 1	1
Bi	< 100	-	< 1	-	-	< 1	< 10

	Alloy Content (ppm) unless otherwise noted		
Element	52729	52698	52697
Cr	2.44 wt%	0.52 wt%	0.50 wt%
Nb	-	-	-
Ni	8	0.50 wt%	0.50 wt%
Mo	< 25	< 25	1.46 wt%
Ti	-	-	-
V	< 25	< 25	< 50
Zr	-	-	-
C	950	270	320
Li	< 0.1	< 0.1	< 0.1
Be	< 0.5	< 0.5	< 0.5
B	< 0.5	< 0.5	0.5
Na	5	1	2
Mg	2	2	1
Al	40	10	10
Si	200	300	500
P	< 100	< 50	< 50
Ca	5	< 5	< 5
Mn	3	5	7
Fe	80	40	50
Co	< 10	-	-
Cu	5	10	15
Zn	-	< 25	-
Sr	-	< 20	-
Ag	-	< 1	-
Cd	1	< 2	< 1
Sn	< 1	< 2	< 1
Sb	-	< 5	-
Ba	-	< 2	-
Tl	-	-	-
Pb	1	3	5
Bi	-	< 1	-

KT/je:325(100)