LA-1407(Del.)

LOS ALAMOS SCIENTIFIC LABORATORY
of the
UNIVERSITY OF CALIFORNIA

Report written:
February 1952

Work performed under Contract No. W-7405-Eng-36.

PREPARATION OF URANIUM-COLUMBIUM ALLOYS BY BOMB REDUCTION

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ABSTRACT

High purity, homogeneous alloys of uranium and columbium have been produced by adding powdered columbium metal or columbium pentoxide to a regular reduction charge. Alloys up to 20.0 atomic percent columbium were produced. The preparation of the alloys, some of their properties, and casting results are described.

ACKNOWLEDGMENTS

Appreciation is expressed to C. G. Hoffman, CMR-6, for the preparation of the metallographic specimens, the photomicrographs, and for the hardness testing. The castings were made by D. Grobecker, CMR-6, and the analytical work was done by CMR-1.

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Introduction

In future reactor design, the necessity for high strength materials may be a major factor. The uranium-columbium alloy with 1 to 3 atomic % columbium shows a large increase in strength over unalloyed uranium. [7] The U-Cb phase diagram indicates solid solution in the area of interest. The melting point of columbium is 2415°C, [9] uranium, ~1133°C, [3] and the 1 to 3 atomic % alloy, ~1160°C. [2] The production of the 1 to 3 atomic % alloy by direct melting in an MgO crucible under vacuum has met with only limited success.

High purity unalloyed uranium metal [1] is prepared by reducing uranium tetrafluoride with calcium, using iodine as a booster. The product uranium metal forms a clean, solid, coherent mass of high purity and yield. The Ca + I_2 reaction, in addition to supplying more heat and a lower melting and more fluid slag, determines the starting temperature of the reaction mixture. This starting temperature is about 400°C.

The peak temperature in the reduction bomb is approximately 1650°C. [4] The peak temperature is present for a very short period, perhaps 2 to 3 sec. This is a long enough period to form the alloy, but not too long to cause excessive crucible reaction or failure as in the vacuum melting method. [7] It is possible that in small localized areas the reaction temperatures may be higher.

Analytical Procedure

The analytical procedure for assaying the columbium content of the U-Cb alloys was a modification of the method of Schoeller and Webb. [8] In analyses for columbium content, the presence of unalloyed columbium is indicated by an undissolved residue. The limits of accuracy for the columbium assay are approximately $\pm$ .02 weight %.

The procedure for determining the impurities in the alloyed metal was a modification of the general uranium spectrochemical method. The principal modification involved the change of the carrier from Ga_2O_3 to AgCl. [6]

Alloy Preparation

The U-Cb alloy has been made by the co-reduction of Cb_2O_5 and UF_4 with calcium, and by the direct melting of powdered columbium metal added to the reduction charge. (The co-reduction of columbium halides was considered, but their boiling points are all

below 300°C and they are not commercially available.) The alloying constituents were added to the reduction charge and thoroughly mixed. All reductions were made on the 1000 gm scale.

It was found that the powdered columbium metal contained 3000 to 4000 ppm of carbon. Consequently, in producing alloys made with the powdered columbium metal, it was necessary to consider carefully the carbon content of the alloyed button metal. Except for carbon, the impurities in the alloying constituents were so much diluted in the preparation of the alloy that they could be ignored. Pure Cb_2O_5 was prepared from powdered columbium metal by igniting in a muffle furnace at 1000°C. The resulting Cb_2O_5 was carbon-free.

Alloys containing 1.5, 5.0, 10.0, and 20.0 atomic % columbium were prepared using powdered columbium metal. Using Cb_2O_5, the alloys made contained 1.5, 5.0, and 10.0 atomic % columbium. Typical results of all alloy reductions are shown in Table I.

The button bottoms from the Cb_2O_5 reductions were rougher than those obtained when powdered columbium metal was used. With the 5.0 and 10.0 atomic % columbium reductions with Cb_2O_5, the rough bottoms caused a decrease in yield of 0.4% and 1.8%, respectively. All buttons had slightly porous top surfaces. In the higher percentage alloys made with powdered columbium metal, high yields were due to entrapped slag. The porosity of the top button surface was directly proportional to the columbium content. Reduction performance for both types of alloy tests was generally normal and comparable except that the slag was soft in the oxide tests because of the formation of CaO.

The button purity was barely satisfactory. Because of the porous top surfaces, impurities in the alloying constituents, and rough bottom surfaces, the calcium, carbon, magnesium, and iron contents in the button were higher than usual. The carbon contents of the buttons remained low in all alloys made with Cb_2O_5. With the powdered columbium metal reductions, the carbon content of the buttons increased in proportion to the columbium content. The carbon content was quite excessive in all of these reductions over 5.0 atomic % columbium.

The higher percent alloys showed marked segregation of both carbon and columbium. The top areas of the button were much higher in both carbon and columbium content than the bottom areas. It was considered that the carbon might nucleate a Cb-rich phase. Photomicrographs (Figs. 4 to 11) do not verify this. The carbon and columbium contents were high in the top areas and low in the bottom areas.

As expected, the segregation of the columbium increased as the quantity of columbium increased. There was no great difference between the segregation observed in the oxide reductions and that observed in the powdered metal reductions. In both types of reduction,

the top areas of the buttons were higher in columbium content than the bottom areas. The segregation was not distinctly apparent with alloys of 5.0 atomic % columbium and below. It was very difficult to take representative samples for analysis with the 10.0 and 20.0 atomic % columbium alloys.

A few reductions were made to observe the effect of using a 50-50 ratio of the alloying constituents, columbium and Cb_2O_5. Results were barely satisfactory. Considering purity primarily, the best master alloy made was the 5.0 atomic % with Cb_2O_5.

An extensive study of the effects of charge variation was not undertaken. Tests showed that an increase in the I_2 content of the charge was detrimental. The resulting buttons had rougher bottoms and more porous tops than usual.

Casting Results

A number of castings were made and sampled, using master alloys that were diluted. Both static and centrifugal castings were made. Some previous experience by the casting group indicated the possibility of gravity segregation. This effect was carefully considered. It was expected that the analyses would show that the castings were more homogeneous than the reduction buttons. This is, however, subject to the ratio of the dilution. A larger variation in alloy composition can be expected when a higher percent master alloy is diluted. Excellent results were obtained in the initial castings (Table II).

Some Properties of the Alloyed Buttons

Photomicrographs (Figs. 1 to 11) show the structural formations and some physical properties found in the U-Cb alloy buttons as compared to normal unalloyed uranium buttons. The alloy made in the reduction process is in the molten state for only a short time. The metal initially solidifies at the metal-crucible interface. The last area of the button to solidify is the top center area immediately beneath the slag. It is very possible for impurities to be entrapped, especially in the top surface. The rapid solidification (within less than 1 min after the bomb fires) probably does not permit much diffusion and mixing to take place. The vacuum remelting of the alloy buttons in the fabrication process releases some of the trapped impurities. This, together with the distillation of some light element impurities, produces a pure, homogeneous metal mass. The casting, as well as the button, may show different solid phases, depending on the heat treatment.

All buttons were sectioned vertically along a radius, and the sections were examined

microscopically. The change in grain size and hardness from unalloyed uranium to the 20 atomic % columbium alloy is shown in Table III.

The hardness and grain size studies were made because hardness and grain size are related to the increased strength of the U-Cb alloy. The U-Cb phase diagram is shown in Fig. 12. [2]

The photomicrographs of the different alloys are shown at various magnifications. They show grain boundary precipitations and the forms of known and unknown constituents throughout the buttons. There appear to be no noticeable differences between the alloys made with Cb_2O_5 and the alloys made with powdered columbium metal.

Preparation of Metallographic Samples

Each button was sectioned vertically along a radius. The piece was then mounted in Bakelite so that the entire plane of the radius was polished and examined. The rough polishing was done on a Buehler polishing wheel using "Wet-or-Dry" silicon carbide paper. It was always done "wet." This grinding was carried through 100, 150, 320, 400, and 600 grit paper.

The sample was then lapped on a kitten's ear type broadcloth using "Gamal," a pH-controlled water suspension of alumina.

The sample was then electrolytically polished, using a solution made up of the following:

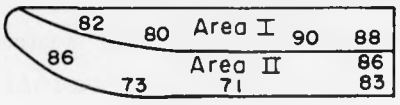
CH_3COOH - 240 cc (glacial)
CrO_3 - 50 gm
H_2O - 60 cc

The solution was used at $<42^{\circ}F$ and at a current density of 4 to 12 amp/in.^{2}. In etching, the same solution was used at a current density of 0.3 to 2 amp/in.^{2} for 1 to 7 sec.

Normal Unalloyed Uranium Button (Figures 1 to 3)

This button, No. 10,941, is a high purity unalloyed button.

It was sectioned as shown in the sketch. There were two distinct areas indicated. The hardness values on the sketch are Rockwell B scale. Area I is ~3/32 in. thick.

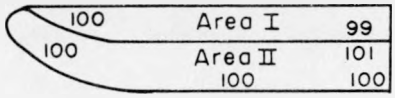


Area I has a higher concentration of carbides as shown in Plate 138-1-2 (Fig. 1) than Area II as shown in Plate 138-1-3 (Fig. 1). The top portion is somewhat harder than the bottom, probably due to the presence of the carbides. The grain size of this material is about 0.5 mm or over.

Plate 138-1-1 (Fig. 2) shows the microstructure at 100X. The carbides are shown at 1000X in Plate 138-1-4 (Fig. 2). The background constituent in Plates 138-1-5, 138-1-6, 138-1-7, 138-1-9 (Fig. 3), when examined at higher magnification, appears to be a eutectic, probably calcium. There seems to be more eutectic in Area II than Area I, and it does not have any relationship to the present grains in the metal. The straight lines in Plates 138-1-1, 138-1-6, and 138-1-9 are strain lines caused by phase changes.

Uranium-Columbium Alloy, 1.5 Atomic % Columbium (Figures 4 and 5)

This button, No. 20,009, was made by adding powdered columbium metal as the alloying constituent. The hardness values on the sketch are Rockwell B scale.



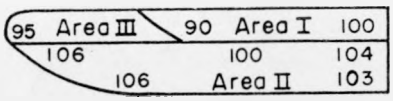
The hardness appears quite uniform throughout. It is about 20 points higher R_B than the unalloyed uranium.

Area I shows a higher concentration of carbides than does Area II. (See Plates J-112-1-3 and J-112-1-4, Fig. 4.)

The grain size is about 0.1 mm in Area I and 0.15 mm in Area II. The grain size appears to be about the same for all U-Cb buttons. The top areas have finer grains than the lower portions, probably caused by nucleation by the carbides.

Uranium-Columbium Alloy, 5.0 Atomic % Columbium (Figures 6 and 7)

This button, No. 20,036, was prepared with Cb_2O_5. The hardness values on the sketch are Rockwell B scale.

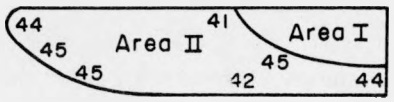


The hardness values are slightly higher in Area II than for lower content columbium alloys. Area I is very porous as shown in Plate 142-1-3 (Fig. 6), and contains fewer carbides than Area III, which is less porous (see Plate 142-1-2, Fig. 6). Area II has the fewest carbides and least porosity (see Plate 142-1-1, Fig. 6).

Plate 142-1-4 (Fig. 7) shows that the alpha phase has about disappeared from the grain boundaries and the darker Cb-rich phase is present, indicating approximate eutectoid composition. (Near eutectoid composition is evidenced by the lack of nucleation by the carbides of any other phase.) This is in disagreement with the eutectoid shown in the phase diagram, Fig. 12.[2] This may be influenced by impurities in the metal but a more likely explanation is the effect of rapid cooling which would prevent equilibrium conditions from being reached. The data from which Fig. 12 was derived were obtained under equilibrium conditions.

Uranium-Columbium Alloy, 10.0 Atomic % Columbium (Figures 8 and 9)

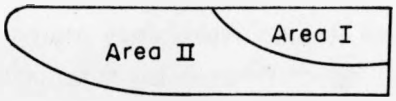
This button, No. 20,070, was prepared with powdered columbium metal. The hardness values indicated on the sketch are Rockwell C scale.



Area I is very porous as shown in Plate 170-1-5 (Fig. 8). The structure of Area II is shown in Plate 170-1-6 (Fig. 8). Referring to the phase diagram (Fig. 12) of U-Cb with these photomicrographs in mind, it is seen that the Cb-rich phase is precipitating at the grain boundaries in Area II and almost all over in Area I and may account for the wider segregation in this alloy. This also suggests that 10.0 atomic % Cb is hypereutectoidal but, as pointed out above, such a conclusion is not tenable in view of the lack of equilibrium conditions. Plate 170-1-5 also suggests that there is a higher concentration of Cb near the top of the button. Plate 170-1-8 (Fig. 9) shows the very fine structure of the Cb-rich material. Plate 170-1-2 (Fig. 9) shows the uranium carbides (gray rectangles) and the acicular unidentified phase. The grain size is about 90 μ.

Uranium-Columbium Alloy, 20.0 Atomic % Columbium (Figures 10 and 11)

This button, No. 20,057, was prepared with powdered columbium metal.



No hardness values were determined due to the porosity in both areas. The microstructure of Areas I and II are shown in Plates 185-1-14 and 185-1-8 (Fig. 10), respectively. It will be noted that the high columbium content has reduced the grain size to about 50μ.

Plate 185-1-8 shows the Cb-rich phase thrown out chiefly at the grain boundaries. This phase is, for the most part, unresolvable with visible light, as shown in Plate 185-1-15 (Fig. 11). Plate 185-1-13 (Fig. 11) shows the carbides at a higher power than Plate 185-1-14 and also shows the unidentified acicular phase, presumably a compound.

References

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2. Buzzard, R. W. and Cleaves, H. E., "The Binary Alloys of Uranium," TID-65, p. 33.
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6. Monthly Progress Reports, CMR-1-11, June, July 1950.
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9. Yntema, L. F., Metals Handbook, 1948 Edition, p. 1137. The American Society for Metals, Cleveland.

This work was done under Project Authorization CMR-8-1. Reference: LA Notebook 3317.

Table I

TYPICAL URANIUM-COLUMBIUM ALLOY RESULTS

Reduction Number	Form Cb Added	Est. % Cb At.	Est. % Cb Wt.	Anal. Wt. % Cb Top	Anal. Wt. % Cb Bottom	Button Yield (%)	Carbon (ppm)	Button Appearance
20013	Powd. metal	1.5	.59	.59 .62	.62 .59	99.90	150	Excellent, slightly porous top
20014	Powd. metal	1.5	.59	.57 .57	.57 .56	99.79	150	Excellent, slightly porous top
20015	Powd. metal	1.5	.59	.52 .54	.52 .53	99.76	170	Excellent, slightly porous top
Average	Powd. metal	1.5	.59	.57	.57	99.82	155	Excellent, slightly porous top
20027	Cb_2O_5	1.5	.59	.60 .60	.59 .56	99.83	145	Excellent, slightly porous top
20028	Cb_2O_5	1.5	.59	.60 .59	.60 .60	99.72	140	Excellent, slightly porous top
20051	Cb_2O_5	1.5	.59	.63		99.89	170	Excellent, slightly porous top
Average	Cb_2O_5	1.5	.59	.60	.60	99.81	150	Excellent, slightly porous top
20054	Powd. metal	5.0	2.01	1.97 - 2.00		99.86	270	Normal bottom, slightly porous top
20055	Powd. metal	5.0	2.01	1.96 - 2.03		99.83	270	Normal bottom, slightly porous top
20064	Powd. metal	5.0	2.01	2.01 - 2.02		99.83	275	Normal bottom, slightly porous top
Average	Powd. metal	5.0	2.01	2.00		99.84	270	Normal bottom, slightly porous top
20082A	Cb_2O_5	5.0	2.01	2.01 - 2.00		99.44	105	Slightly porous top, slightly rough bottom
20083A	Cb_2O_5	5.0	2.01	2.01 - 2.00		99.48	130	Slightly porous top, slightly rough bottom
20084A	Cb_2O_5	5.0	2.01	2.00 - 2.02		99.46	140	Slightly porous top, slightly rough bottom
Average	Cb_2O_5	5.0	2.01	2.00		99.46	125	Slightly porous top, slightly rough bottom
20076	Powd. metal	10.0	4.15	5.03 - 5.05	4.01B- 3.87B*	99.94	530	Normal bottom, slightly porous top
20077	Powd. metal	10.0	4.15	4.84 - 4.82	3.82B- 3.72B	99.98	500	Normal bottom, slightly porous top
20078	Powd. metal	10.0	4.15	5.00 - 4.92	3.66B- 3.82B	>100.0	620	Normal bottom, slightly porous top
Average	Powd. metal	10.0	4.15	4.94 - 3.82B		~ 99.98	550	Normal bottom, slightly porous top
20037	Cb_2O_5	10.0	4.15	3.14 4.58	4.15 4.04	97.91	---	Slightly porous top, rough bottom
20129	Cb_2O_5	10.0	4.15	4.96 5.34	4.26 4.58	98.46	210T 120B 280T 180B	Slightly porous top, rough bottom
Average	Cb_2O_5	10.0	4.15	4.51	4.26	98.19	245T 150B	Slightly porous top, rough bottom
20057	Powd. metal	20.0	8.89	12.42 12.39	7.52 7.50	>100.0	3570T 350B 3920T 380B	Quite porous top, slightly rough bottom
20130	Powd. metal	20.0	8.89	11.68 12.12	8.85 8.97	>100.0	1930T 730B 1140T 570B	Quite porous top, slightly rough bottom
Average	Powd. metal	20.0	8.89	12.15	8.21	<100.0	2640T 510B	Quite porous top, slightly rough bottom
20101	Powd. metal + Cb_2O_5 (1:1)	5.0	2.01	1.98 - 1.99		99.66	210	Slightly porous top, slightly rough bottom
20102	Powd. metal + Cb_2O_5 (1:1)	5.0	2.01	1.99 - 2.00		99.68	205	Slightly porous top, slightly rough bottom
20103	Powd. metal + Cb_2O_5 (1:1)	5.0	2.01	1.99 - 1.99		99.77	215	Slightly porous top, slightly rough bottom
Average	Powd. metal + Cb_2O_5 (1:1)	5.0	2.01	1.99		99.70	210	Slightly porous top, slightly rough bottom

Unless otherwise noted in the proper columns the analytical results are from composite samples (top and bottom).
*B = bottom sample.

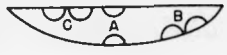
Table II

URANIUM-COLUMBIUM CASTING RESULTS

Button Specimen Number	% Cb Added At.	% Cb Added Wt.	Analytical Results, Wt. % Cb A	B	C	D
20013	1.5	0.59	.59	.62	.62	
			.62	.59	.61	
20014	1.5	0.59	.57	.57	.56	
			.57	.56	.57	
20015	1.5	0.59	.52	.52	.54	
			.54	.53	.55	
Casting 38215 (undiluted)	1.5	0.59	.58	.58	.58	.59
			.59	.60	.57	.57
20030	5.0	2.01	2.55 2.19	2.10	2.05	
			2.26 2.21	2.10	2.15	
Casting 48215 diluted to	1.5+	0.60	.58	.58	.59	.58
			.57	.57	.61	.57
20052	10.0	4.15	4.60	3.97	4.37	
			4.74	3.62	4.16	
Casting 53215 diluted to	1.5+	0.60	.64	.60	.61	.62
			.58	.55	.64	.54
20054	5.0	2.01	1.97	Composite sample		
			2.00			
20055	5.0	2.01	1.96	Composite sample		
			2.03			
20058	5.0	2.01	2.09	Composite sample		
			2.08			
Casting 56215 diluted to	1.5+	0.60	.72			
			.73			
20074	10.0	4.15	4.48	Composite sample		
			4.61			
20071	10.0	4.15	4.84	Composite sample		
			4.83			
Casting 60215	1.5+	0.60	.62	.70		
			.63	.69		
20072	10.0	4.15	4.52	Composite sample		
			4.57			
20073	10.0	4.15	4.56	Composite sample		
			4.71			
20074	10.0	4.15	4.48	Composite sample		
			4.61			
Casting 61215	1.5+	0.60	.60	.56		
			.60	.55		
20074	10.0	4.15	4.48	Composite sample		
			4.61			
20072	10.0	4.15	4.52	Composite sample		
			4.57			
20036	5.0	2.01	1.98	1.96	1.97	
			2.00	2.02	2.01	
Casting 62215 diluted to	1.5+	0.60	.56	.56		
			.56	.58		

Note: The casting estimates of weight % columbium are based on the button estimates of weight % columbium, not the analytical results, which are considered non-representative. The sample locations A, B, C from the buttons bear no relation to the location of samples A, B, C, D from the casting. Composite samples = A + B + C, mixed.

Analytical button sample origin:



Note: 1.5 atomic % = 0.59 weight %.

Table III

GRAIN SIZE AND HARDNESS

Specimen	Grain Size Mean Diam. (μ)	Average Rockwell Hardness	Hardness, Brinell*
Pure Uranium	500	82B	155
1.5 atomic % Cb	150	100B	240
5.0 atomic % Cb	120	100B	240
10.0 atomic % Cb	90	44C	405
20.0 atomic % Cb	50		Too porous for accurate measurement

* The hardness values were converted from Rockwell to Brinell to obtain an approximate comparison between specimens. Brinell scale: 10 mm standard steel ball, 3000 kg load. [5]

Plate 138-1-2. 0% Cb. 250X.

Electrolytic polish; not etched. High concentration of carbides in Area I.

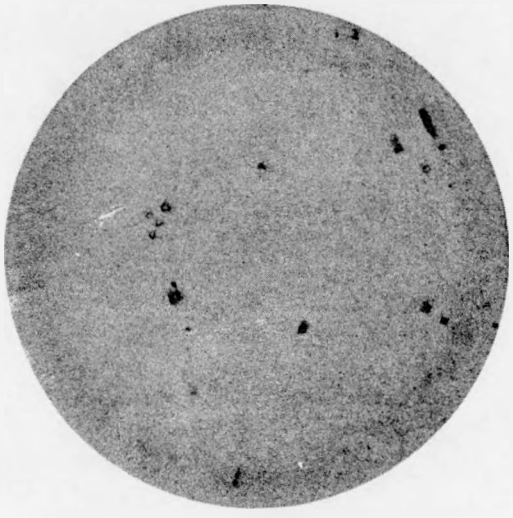


Plate 138-1-3. 0% Cb. 250X.

Electrolytic polish; not etched. Fewer carbides in Area II.

Fig. 1. Uranium button No. 10,941.

Plate 138-1-1. 0% Cb. 100X.
Electrolytic polish; polarized light.

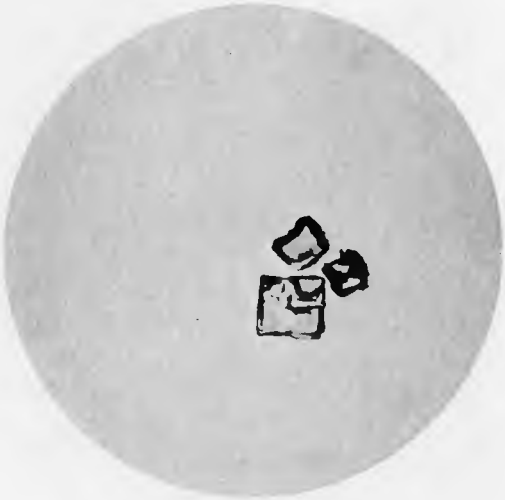


Plate 138-1-4. 0% Cb. 1000X.
Electrolytic polish; not etched. Carbide in uranium.

Fig. 2. Uranium button No. 10,941.

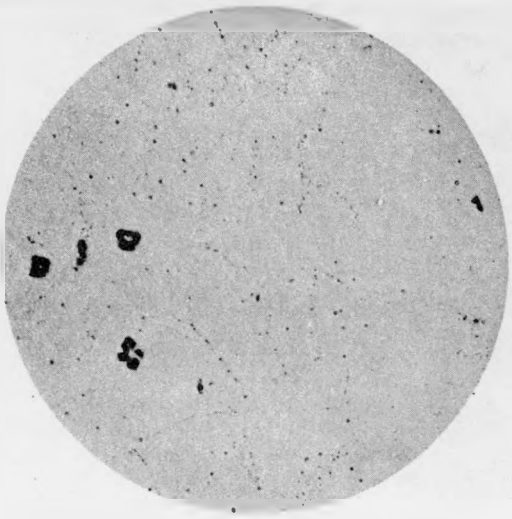


Plate 138-1-7. 0% Cb. 250X.

Electrolytic polish; not etched. Eutectic just under Area I, probably calcium.

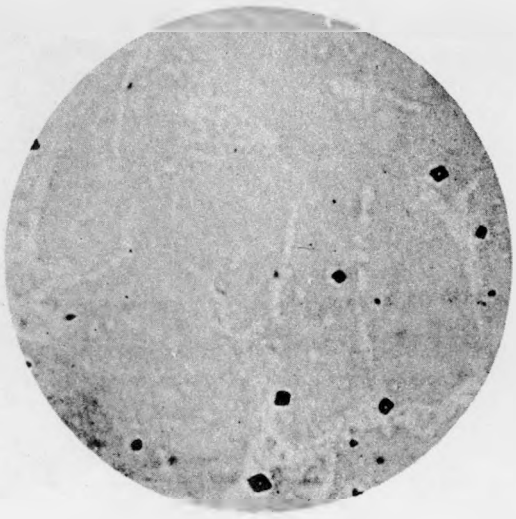


Plate 138-1-5. 0% Cb. 250X.

Electrolytic polish; not etched. Eutectic near bottom of button, probably calcium.

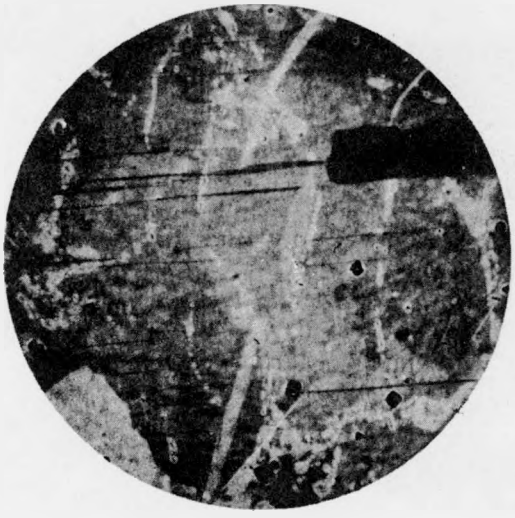


Plate 138-1-6. 0% Cb. 250X.

Electrolytic polish; polarized light. Same field as 138-1-5. Shows the eutectic not related to present grains.

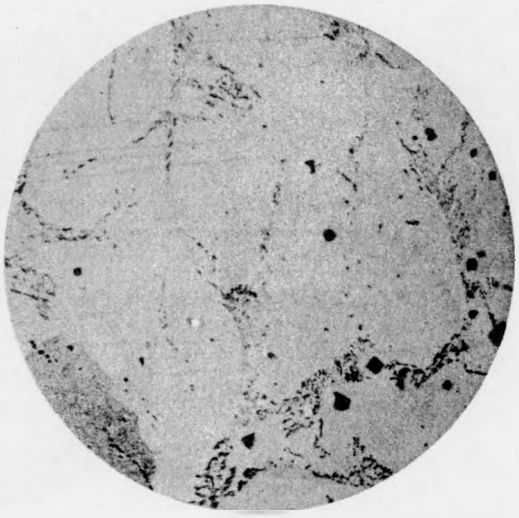


Plate 138-1-9. 0% Cb. 250X.

Electrolytic polish; etched. Same field as preceding but etched showing structure of eutectic.

Fig. 3. Uranium button No. 10,941.

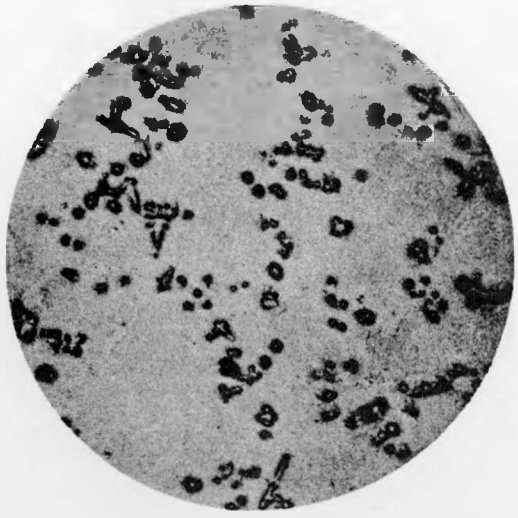


Plate J-112-1-3 1.5 atomic % Cb. 250X.

Electrolytic polish; not etched. Shows high concentration of carbides in Area I.

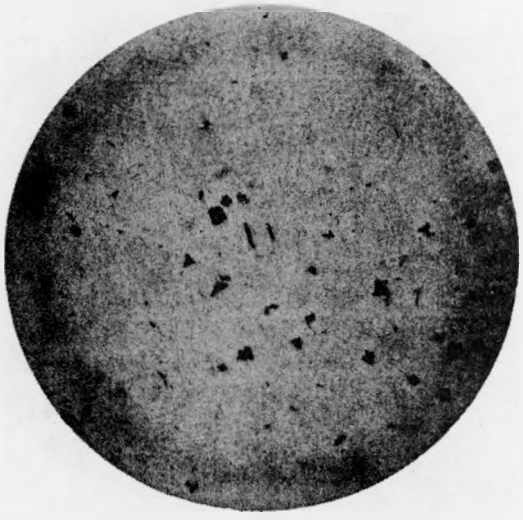


Plate J-112-1-4 1.5 atomic % Cb. 250X.

Electrolytic polish; not etched. Shows the structure typical of Area II.

Fig. 4. Uranium-columbium (1.5 atomic %) button No. 20,009.

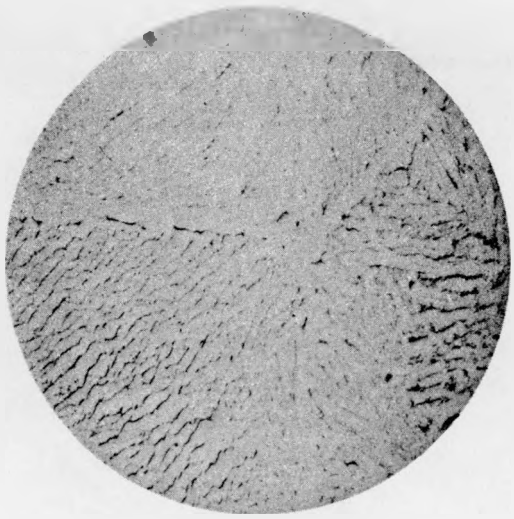


Plate J-112-1-7 1.5 atomic % Cb. 2000X.

Electrolytic polish. Shows hypo-eutectoid character of the U-Cb alloy.

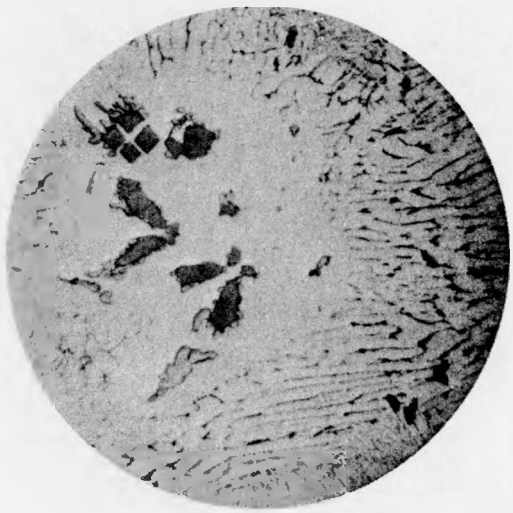


Plate J-112-1-6. 1.5 atomic % Cb. 1000X.

Electrolytic polish. Shows carbides to which are attached particles of alpha (α) phase.

Fig. 5. Uranium-columbium (1.5 atomic %) button No. 20,009.

Plate 142-1-3. 5 atomic % Cb. 250X.

Electrolytic polish; etched. Porous structure found in Area I. Relatively few carbides.

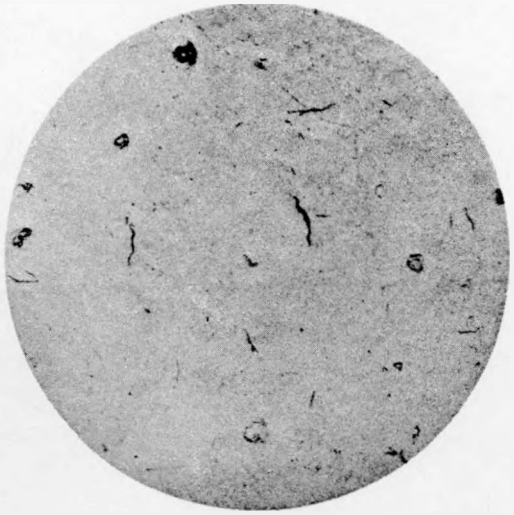


Plate 142-1-1. 5 atomic % Cb. 250X.

Electrolytic polish; etched. Structure of Area II, relatively few carbides. Irregular stringers may be stain resulting from microcracks.

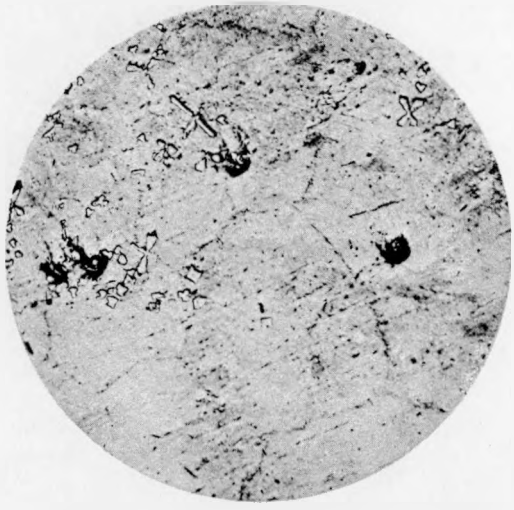


Plate 142-1-2. 5 atomic % Cb. 250X.

Electrolytic polish; etched. Carbides greater in number in Area III.

Fig. 6. Uranium-columbium (5 atomic %) button No. 20,036.

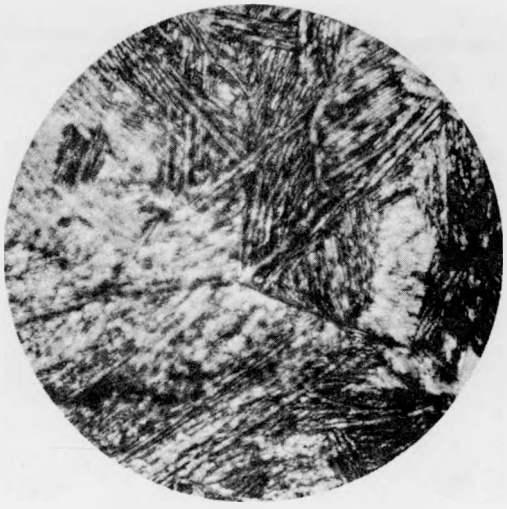


Plate 142-1-4 5 atomic % Cb. 2000X.

Electrolytic polish; etched. Portions of three grains with dark constituent (Cb-rich phase) in grain boundary. Appears to be about eutectoid composition.

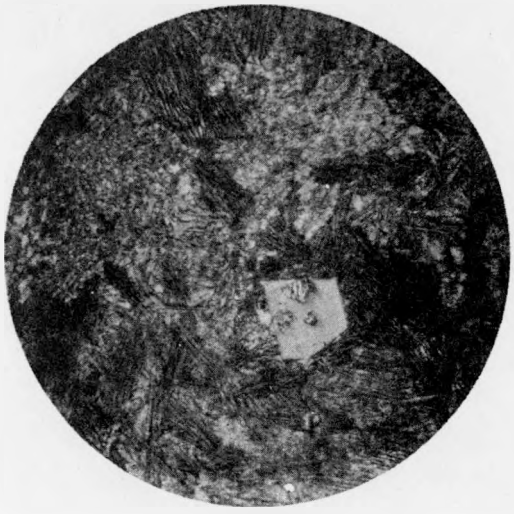


Plate 142-1-5 5 atomic % Cb. 1000X.

Electrolytic polish; etched. Carbide does not appear to have nucleated any precipitation.

Fig. 7. Uranium-columbium (5 atomic %) button No. 20,036.

Plate 170-1-5. 10 atomic % Cb. 250X.

Electrolytic polish; etched. Porous portion, Area I, shows carbides (rectangular gray) and unidentified compound (needles). Matrix is largely Cb-rich phase.

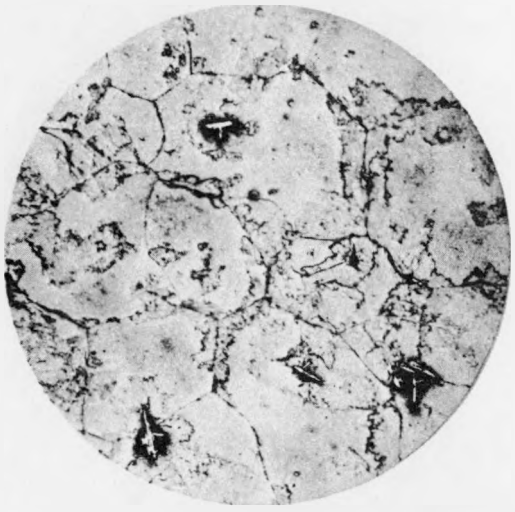


Plate 170-1-6 10 atomic % Cb. 250X.

Electrolytic polish; etched. Area II contains fewer carbides and unidentified compound. Cb-rich phase is precipitated at grain boundaries.

Fig. 8. Uranium-columbium (10 atomic %) button No. 20,070.

Plate 170-1-8 10 atomic % Cb. 2000X.

Electrolytic polish; etched. Structure of the Cb-rich phase.

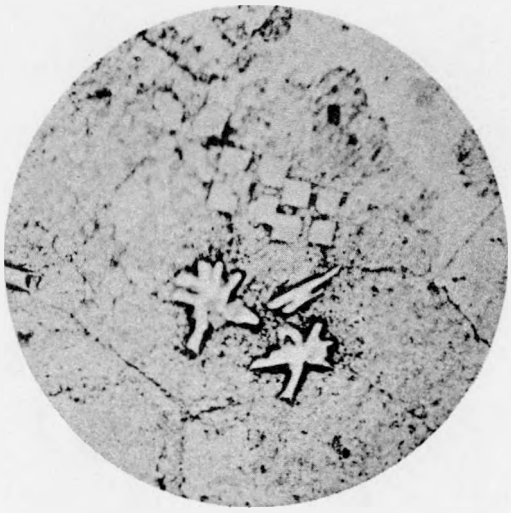


Plate 170-1-2. 10 atomic % Cb. 1000X.

Electrolytic polish; etched. Shows carbides (rectangular gray) and the needle-like unidentified phase.

Fig. 9. Uranium-columbium (10 atomic %) button No. 20,070.

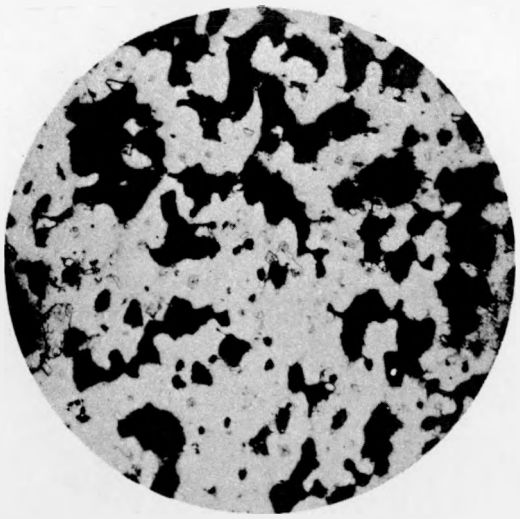


Plate 185-1-14. 20 atomic % Cb. 250X.

Electrolytic polish; etched. Structure of Area I, carbides gray, and unidentified acicular phase.

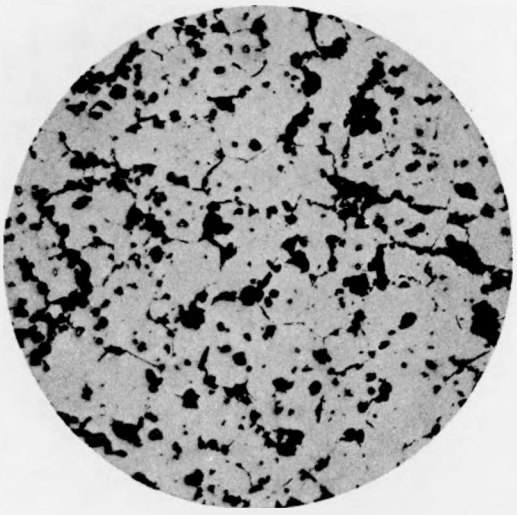


Plate 185-1-8. 20 atomic % Cb. 250X.

Electrolytic polish; etched. Shows Cb-rich phase being thrown out at the grain boundaries.

Fig. 10. Uranium-columbium (20 atomic %) button No. 20,057.

Plate 185-1-15. 20 atomic % Cb. 2000X.

Electrolytic polish; etched. Cb-rich phase, thrown out at the grain boundaries.

Plate 185-1-13. 20 atomic % Cb. 1000X.

Electrolytic polish; etched. Carbides (gray rectangular phase) and unidentified needles.

Fig. 11. Uranium-columbium (20 atomic %) button No. 20,057.

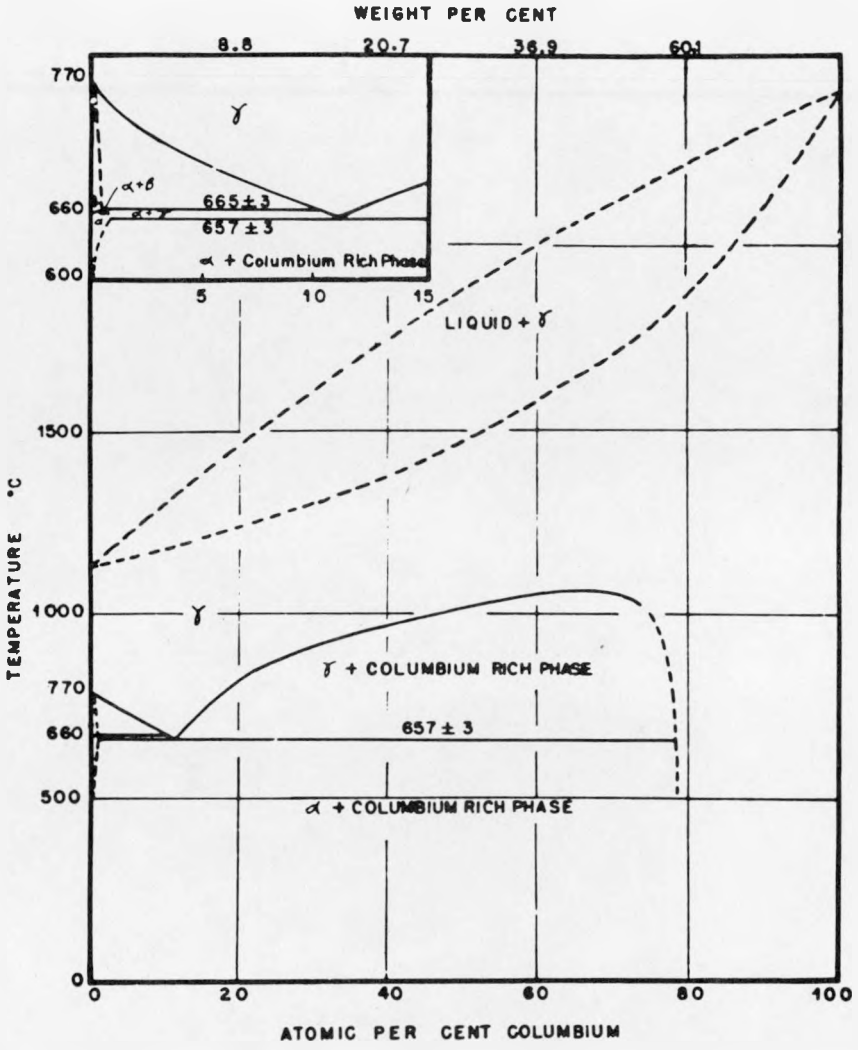


Fig. 12. Uranium-columbium phase diagram.