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THE PROPERTIES OF HIGH-URANIUM ALLOYS
CONTAINING ZIRCONIUM OR CHROMIUM

by

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THE PROPERTIES OF HIGH-URANIUM ALLOYS
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Various physical and mechanical properties have been determined for high- and low-carbon base uranium, uranium-chromium, and uranium-zirconium alloys. These data complement those obtained at ANL on the same materials. Their data include studies of radiation damage. On the basis of the properties studied at BMI, the low-carbon chromium and low-carbon zirconium alloys appear to be comparable; both are much superior to beta-treated uranium. The high-carbon zirconium alloys are vastly inferior to the low-carbon zirconium alloys and also to the high-carbon chromium alloys. [High carbon content does not greatly affect the properties of the chromium alloys.] Similarly, high carbon content in the base uranium did not appreciably alter its properties, although the direction of growth during thermal cycling was reversed.]

These studies were made as Battelle's part of a cooperative program with ANL and KAPL.

INTRODUCTION

Early work on the grain refinement of low alloys of uranium revealed that chromium was the most prolific grain-refining element in the ranges of composition studied.[1]* Subsequently, study of the kinetics of transformation of uranium-chromium alloys provided a more complete understanding of the grain-refining characteristics of these alloys.[2]

On the basis of this information, a series of low-chromium samples was prepared and irradiated in the CP-3 at ANL. These samples turned out badly and were little, if any, better than beta-treated uranium. Samples of uranium-zirconium alloys, exposed in a similar fashion, showed considerable improvement over beta-treated uranium.

Evaluation of this situation revealed that, while the best practice possible was used on the low-chromium samples, undesired variables were involved. This situation apparently arose largely because of restrictions which then existed on the handling of uranium-235.

Representatives of Argonne National Laboratory (ANL), Battelle Memorial Institute (BMI), and Knolls Atomic Power Laboratory (KAPL) then met and planned a cooperative program to further evaluate and compare the low-chromium and the low-zirconium alloys. This program included base uranium and both types of alloys, each with high and low carbon contents.

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* References at end of report.

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The low-carbon alloys were to be prepared at KAPL, and the high-carbon alloys at BMI. All ingots were to be fabricated under constant conditions, by the best-known techniques, at BMI. Subsequently, each of the laboratories was to heat treat the fabricated materials and study certain properties: physical and mechanical properties for design, and irradiation-damage behavior for evaluation of the alloys in reactor applications.

The portion of the program undertaken by BMI is described in this report. It is expected that this information will complement the information obtained at ANL.

MATERIALS AND PREPARATION

At the time the program was planned, the base materials were selected and general procedures were agreed upon. These general procedures included the casting techniques, the fabrication practices, and recommended heat treatments. These details are described in the following sections.

Selection of Materials and Casting Techniques

In order to achieve as great a degree of uniformity as possible, it was agreed to use Grade 1 crystal-bar zirconium and electrolytic chromium in the preparation of all ingots. Biscuit uranium was to be used in the preparation of the low-carbon alloys, and project-grade uranium was to be used in the preparation of the high-carbon alloys.

Two separate casting procedures were used in preparing the low-carbon and high-carbon ingots. The low-carbon ingots were prepared at KAPL by induction melting the component metals in magnesia crucibles. The preparation and analyses of the resulting ingots are summarized in Table 1, Ingots 1 to 5.

Since no carbon would be picked up by melting in magnesia, the carbon content of the low-carbon ingots should be approximately that of biscuit uranium, 0.01 w/o carbon or less.

The low-carbon uranium-0.4 w/o chromium alloy, Ingot 3, was held 1/2 hr at 1065 F during cooling to avoid cracking.

The high-carbon ingots were prepared at BMI by induction melting the component metals in graphite crucibles and pouring into graphite molds.

TABLE 1. ANALYSES OF URANIUM AND URANIUM-ALLOY INGOTS

Ingot[a]	Nominal Composition, w/o	Analysis, w/o				Ingot Diameter, in.	Remarks
		Cr and Zr		Carbon			
		Top	Bottom	Top	Bottom		
1	Base U, low C	--	--	--	--	2-1/2	--
2	0.1 Cr, low C	0.094 Cr	0.086 Cr	--	--	2-1/2	--
3	0.4 Cr, low C	0.395 Cr	0.442 Cr	--	--	2-1/2	Held 1/2 hr at 1065 F during cooling
4	1.1 Zr, low C	1.35 Zr	1.08 Zr	--	--	2-1/2	--
5	2.2 Zr, low C	2.29 Zr	2.13 Zr	--	--	2-1/2	--
6	Base U, high C	--	--	0.06 C	0.07 C	2-1/2	--
7	0.1 Cr, high C	0.09 Cr	0.11 Cr	0.38 C	0.11 C	2-1/2	--
8	0.4 Cr, high C	0.37 Cr	0.36 Cr	0.16 C	0.10 C	4	Held 3/4 hr at 1020 F during cooling
9	1.1 Zr, high C	1.49 Zr	1.50 Zr	0.37 C	0.39 C	2	--
10	1.1 Zr, high C	1.55 Zr	1.66 Zr	0.33 C	0.33 C	2	--
11	2.2 Zr, high C	2.47 Zr	2.88 Zr	0.39 C	0.41 C	2	--
12	2.2 Zr, high C	2.29 Zr	2.45 Zr	0.39 C	0.40 C	2	--

(a) In subsequent tables, samples from ingots are referred to as Material, i.e., Material 1 is from Ingot 1.

The preparation and analyses of these ingots are summarized in Table 1, Ingots 6 to 12.

The uranium and uranium-chromium ingots were bottom poured without a stopper rod, by a process which is commonly termed "self-pouring". These ingots showed a tendency toward differential carbon compositions, presumably because of flotation of carbides during casting.

The uranium-0.4 w/o chromium ingot was held 3/4 hr at 1020 F during cooling to avoid cracking.

Homogeneous uranium-zirconium alloys having a high carbon content were very difficult to produce. This difficulty was probably the result of rapid flotation of zirconium carbide during casting. Vigorous inductive stirring, followed by top pouring into a 2-in.-diameter mold, minimized this flotation. Since vigorous inductive stirring was essential to the preparation of the uranium-zirconium alloys, rather high-carbon analyses resulted. Since the molds were smaller than the molds used for the other ingots, it was necessary to prepare two ingots of each of the high-carbon uranium-zirconium alloys.

Standardization of Fabrication Practices

In the fabrication of rods from the cast ingots, it was considered necessary to strive toward uniformity of handling of all the ingots. It was also important to select a final rolling temperature which would produce anisotropic properties in the rolled product and would permit the fabrication of high-quality rod.

It was not feasible to maintain completely uniform handling throughout, since experience indicated that two different forging temperatures should be used for the two different alloys. The rolling temperature, however, was maintained constant for all materials.

The uranium-chromium ingots were forged at 1500 F to 1-1/4-in.-square billets. These were held 1 hr at 1020 F during cooling to avoid cracking. The uranium-zirconium ingots were forged at 1110 F to 1-1/4-in.-square billets. These alloys were hard but workable at this temperature.

All of the forged billets were rolled through hand-round rolls from 1-1/4-in.-square to 0.4-in.-diameter rods. This rolling was done at 1020 F from a salt bath composed of 50 w/o Li_2CO_3 and 50 w/o K_2CO_3. The salt bath gave good temperature control and also minimized oxidation during the rolling. During rolling, the rods were reheated in the salt bath for 10 min

after each pass. They were also returned to the salt bath for 10 min after the last pass through the rolls and were then straightened.

Good-quality rolled rod was obtained from all of the ingots by these procedures.

Use of Recommended Heat Treatments

Standard heat-treating procedures were selected on the basis of the best information available at the time the program was planned. These heat treatments were to be used at all of the laboratories.

The heat treatments which were selected are summarized in Table 2. Those for the base uranium and uranium-zirconium alloys were selected from data obtained at ANL, and those for the uranium-chromium alloys were selected from data obtained at KAPL.

TABLE 2. SELECTED HEAT TREATMENTS

Nominal Composition, w/o	Heat Treatment	Material
Uranium	1/2 hr 735 C in vacuum, and water quench, 2 hr 575 C, air cool	1, 6
0.1 Cr	Step (a) 15 min 715 C ± 10, quench to 575 C ± 10 for 15 min, water quench; Step (b) 15 min 715 C ± 10, quench to 500 C ± 10 for 20 min, water quench	2, 7
0.4 Cr	Step (a) 15 min 715 C ± 10, quench to 575 C ± 10 for 25 min, water quench; Step (b) 15 min 715 C ± 10, quench to 500 C ± 10 for 90 min, water quench	3, 8
1.1 Zr	1 hr 725 C in vacuum, and water quench	4, 9, 10
2.2 Zr	1 hr 800 C in vacuum followed by isothermal treatment of 1 hr at 500 C, air cool	5, 11, 12

It should be pointed out that the heat treatments for the uranium-zirconium alloys were based primarily upon thermal-cycling data. Subsequent work indicates that samples with these heat treatments do not give the best results during exposure to radiation.[3] There does not appear to be any reason to believe that this is also true of the heat treatment of the uranium-chromium alloys, since the heat treatments were selected primarily on the basis of grain-refining data, rather than on thermal-cycling data.

RESULTS AND DISCUSSIONS

After careful analysis of the rolled product, alloy rod was shipped to each of the cooperating laboratories. Studies at BMI included determination of resistivity, of microstructure and grain size, of tensile properties, and of performance during thermal cycling.

Analysis of Rolled Rod

The analyses of rolled-rod specimens indicate that the materials are more uniform and closer to the nominal compositions than the ingot analyses presented earlier would suggest. Analyses of lead-end, center, and trail-end samples of all of the rolled rods are summarized in Table 3. The carbon analyses of the low-carbon materials should be very nearly that of the biscuit uranium; about 0.01 w/o or less.

Electrical Resistivity and Thermal Conductivity

The electrical resistivity of each of the materials was determined, and the relationship of electrical resistivity and thermal conductivity was examined briefly. The thermal conductivities of the uranium-zirconium alloys have been obtained by interpolation from existing graphs of data and are also included in this report.

Measurements of electrical resistivity on samples of all the materials are summarized in Table 4. Temperature coefficients of resistivity are shown in Table 5.

In the low-carbon materials, the resistivity increases slightly with increasing chromium content and with increasing zirconium content. A similar trend occurs in the high-carbon materials, but the 0.11 w/o chromium alloy has a higher resistivity than the 0.51 w/o chromium alloy.

TABLE 3. ANALYSES OF URANIUM AND URANIUM-ALLOY RODS

Material	Nominal Composition, w/o	Analyses[a], w/o		
		Cr	Zr	C
1	Base U, low C	--	--	(b)
2	0.1 Cr, low C	0.10	--	(b)
	--	0.10	--	(b)
	--	0.10	--	(b)
3	0.4 Cr, low C	0.46	--	(b)
	--	0.42	--	(b)
	--	0.42	--	(b)
4	1.1 Zr, low C	--	1.13	(b)
	--	--	1.15	(b)
	--	--	1.11	(b)
5	2.2 Zr, low C	--	2.19	(b)
	--	--	2.24	(b)
	--	--	2.24	(b)
6	Base U, high C	--	--	0.08
	--	--	--	0.07
	--	--	--	0.10
7	0.1 Cr, high C	0.10	--	0.38
	--	0.11	--	0.35
	--	0.11	--	0.34
8	0.4 Cr, high C	0.46	--	0.03
	--	0.51	--	0.10
	--	0.45	--	0.11
9	1.1 Zr, high C	--	1.25	0.38
	--	--	1.25	0.38
10	1.1 Zr, high C	--	1.19	0.32
	--	--	1.25	0.31
11	2.2 Zr, high C	--	2.29	0.40
	--	--	2.22	0.39
12	2.2 Zr, high C	--	2.23	0.41
	--	--	2.14	0.38

(a) Analyses represent samples from lead ends, centers, and trail ends of rolled rods.
(b) Low carbon, probably less than 0.01 C.

TABLE 4. ELECTRICAL RESISTIVITY[a] OF URANIUM AND URANIUM ALLOYS

Material	Interpolated Analysis, w/o	Resistivity, microhm-cm									
		20 C	100 C	150 C	200 C	250 C	300 C	350 C	400 C	450 C	500 C
1	Base U, low C	28.8	33.7	36.7	39.5	42.1	44.5	46.6	48.5	50.0	51.4
2	0.10 Cr, low C	30.0	35.2	38.2	41.1	43.9	46.4	48.6	50.6	52.3	53.8
3	0.42 Cr, low C	32.5	38.1	41.6	44.8	47.6	50.4	52.8	55.0	56.9	58.5
4	1.13 Zr, low C	33.3	38.7	41.9	44.8	47.4	49.9	52.0	54.0	55.7	57.3
5	2.19 Zr, low C	33.8	39.4	42.6	45.7	48.4	50.9	53.1	55.2	57.0	58.6
6	Base U, 0.08 C	30.2	35.3	38.3	41.2	43.9	46.5	48.7	50.7	52.4	53.9
7	0.11 Cr, 0.36 C	31.5	37.6	41.0	44.2	47.1	49.7	52.1	54.3	56.4	58.1
8	0.51 Cr, 0.10 C	31.6	37.0	40.3	43.4	46.3	48.9	51.3	53.4	55.2	56.8
10	1.19 Zr, 0.32 C	32.7	38.1	41.3	44.4	47.3	50.0	52.4	54.5	56.4	58.0
11	2.29 Zr, 0.40 C	33.5	39.3	42.6	45.7	48.6	51.1	53.4	55.4	57.3	58.9

(a) Data obtained from 0.080-in.-diameter by 12-in.-long wires using potentiometric method of measurement. Measurements were made after 15 min at each thermal equilibrium.

(b) Samples were heat treated as described in section "Use of Recommended Heat Treatments".

TABLE 5. TEMPERATURE COEFFICIENT OF ELECTRICAL RESISTIVITY OF URANIUM AND URANIUM ALLOYS

Material	Interpolated Analysis, w/o	Temperature Coefficient of Resistivity, 10^{-6} per deg C, Over Indicated Temperature Range, C								
		20 to 100	20 to 150	20 to 200	20 to 250	20 to 300	20 to 350	20 to 400	20 to 450	20 to 500
1	Base U, low C	21.3	21.1	20.6	20.1	19.5	18.7	18.0	17.1	16.4
2	0.10 Cr, low C	21.7	21.0	20.6	20.1	19.5	18.8	18.1	17.3	16.5
3	0.42 Cr, low C	21.5	21.5	21.0	20.2	19.7	18.9	18.2	17.5	16.7
4	1.13 Zr, low C	20.3	19.9	19.2	18.4	17.8	17.0	16.4	15.5	15.0
5	2.19 Zr, low C	20.7	20.0	19.6	18.8	18.1	17.3	16.7	16.0	15.3
6	Base U, 0.08 C	21.1	20.6	20.2	19.7	19.3	18.6	17.9	17.1	16.4
7	0.11 Cr, 0.36 C	24.2	23.2	22.4	21.5	20.6	19.8	19.1	18.4	17.6
8	0.51 Cr, 0.10 C	21.4	21.2	20.7	20.2	19.6	18.9	18.2	17.4	16.6
10	1.19 Zr, 0.32 C	20.6	20.2	19.9	19.4	18.9	18.3	17.5	16.9	16.1
11	2.29 Zr, 0.40 C	21.6	20.9	20.2	19.6	18.8	18.0	17.2	16.5	15.8

This exception may be the result of the higher carbon content in the 0.11 w/o chromium alloy. The same material, 0.11 chromium-0.36 carbon, shows the greatest difference in resistivity when the high-carbon materials are compared with the corresponding low-carbon materials, Table 4. It also exhibits the greatest variation in the temperature coefficient of resistivity, Table 5.

An attempt was made to relate electrical resistivity and thermal conductivity of the zirconium alloys, on the basis of electrical resistivity and thermal conductivity data for 5 to 100 w/o zirconium. It was found that available data were not sufficient to form a basis for a relationship. However, the Lorentz ratios agreed fairly well for uranium and for 5, 10, and 20 w/o zirconium alloys.

In order to obtain data for design applications, the thermal conductivities of the 1.1 and 2.2 w/o zirconium alloys were obtained by interpolation from existing data.[4] These data are tabulated below along with experimental data for arc-melted uranium.

| Temperature, C	U	Thermal Conductivity, w/(in.)(sec)	
		U-1.1 w/o Zr	U-2.2 w/o Zr
20	0.26	--	--
100	0.27	--	--
200	0.285	0.271	0.258
300	0.305	0.292	0.280
400	0.330	0.317	0.306
500	0.360	0.345	0.334

Since these are interpolated data, they should be used with caution.
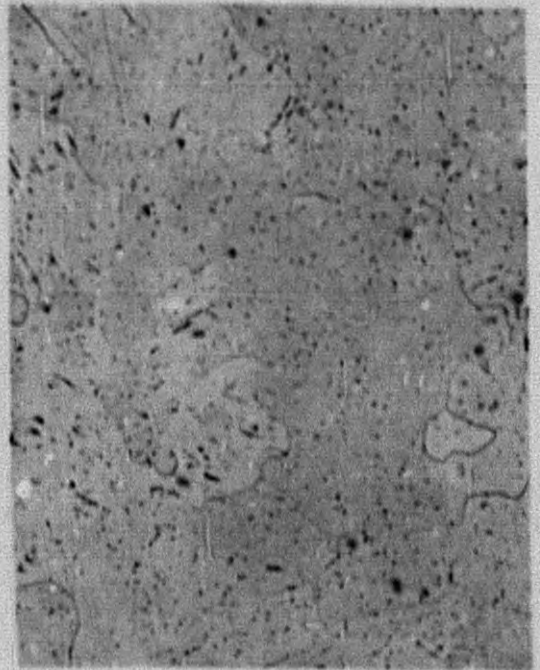
Microstructure

Specimens of all of the heat-treated rods were prepared for metallographic examination and were photographed by means of bright-field techniques. The grain sizes were determined under both bright-field and polarized illumination.[5] Vickers hardness numbers were obtained from all metallographic samples with a 10-kg load.

The microstructures of the low-carbon materials are shown in Figures 1 through 5. These include longitudinal and transverse photomicrographs for each material. Marked grain refinement was obtained in all these alloys (Figures 2-5).
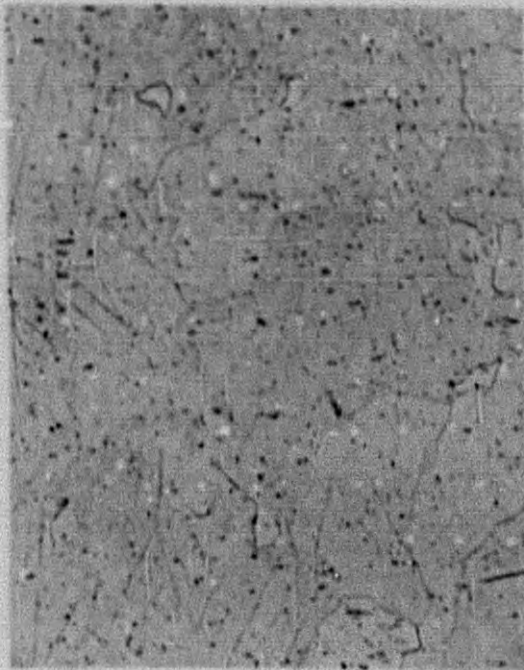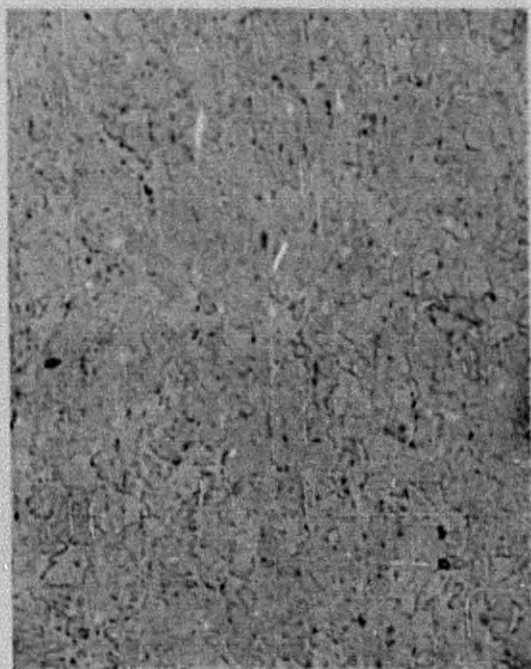
100X   N3161   100X   N3162
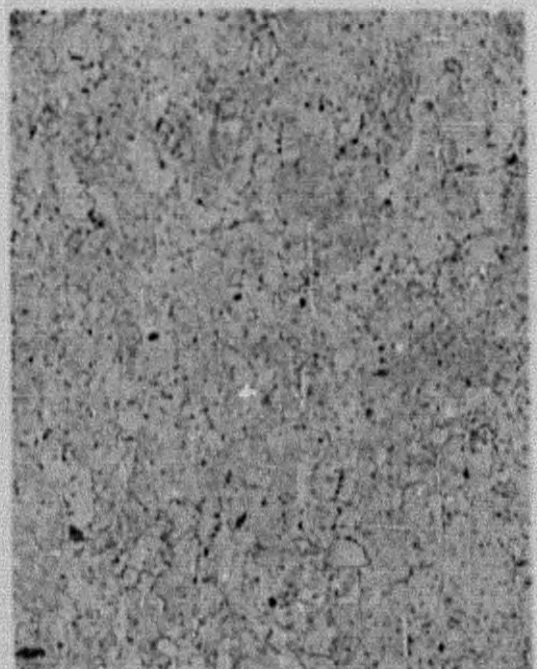
Longitudinal Section, VHN 214   Transverse Section, VHN 213

FIGURE 1. LOW-CARBON URANIUM

100X   N8302   100X   N8303
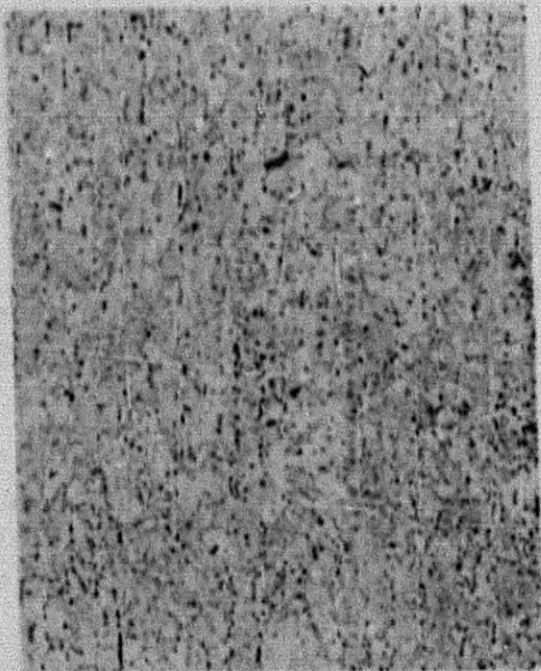
Longitudinal Section, VHN 332   Transverse Section, VHN 350
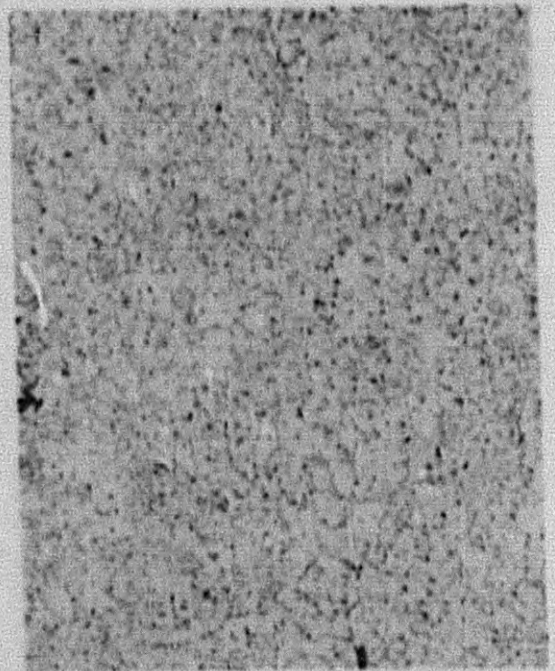
FIGURE 2. LOW-CARBON URANIUM-0. 1 w/o CHROMIUM
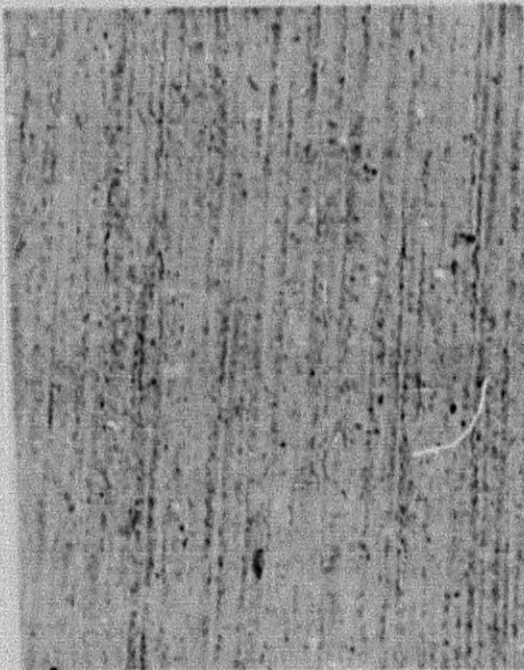
100X N8307
Longitudinal Section, VHN 329

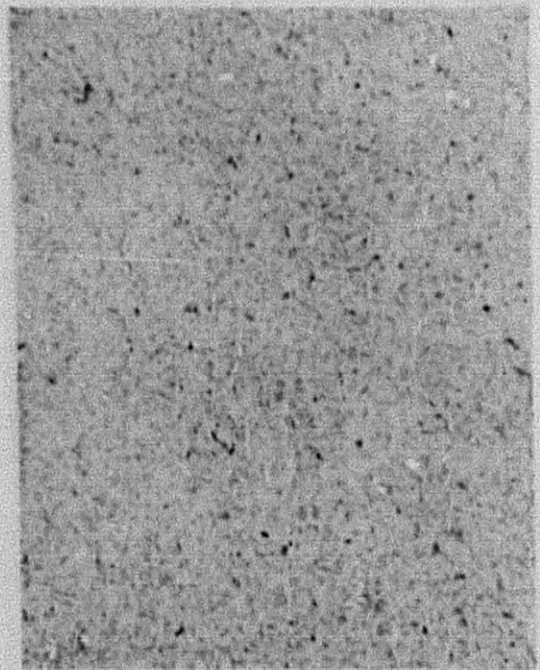100X N8309
Transverse Section, VHN 337

FIGURE 3. LOW-CARBON URANIUM-0.4 w/o CHROMIUM

100X N3165
Longitudinal Section, VHN 302
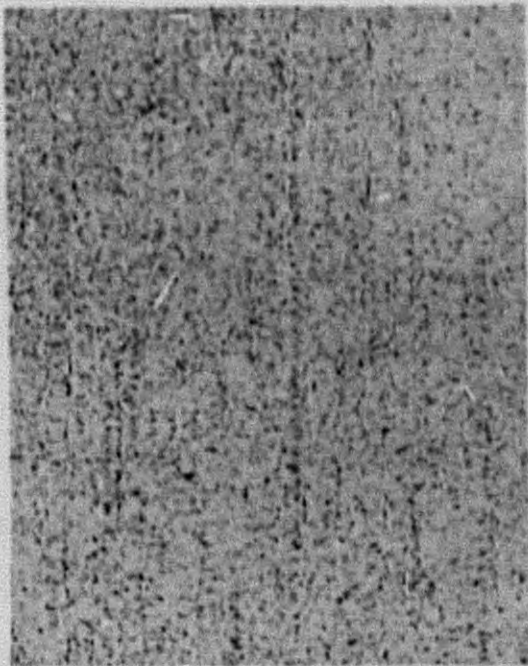
100X N8298
Transverse Section, VHN 328

FIGURE 4. LOW-CARBON URANIUM-1.1 w/o ZIRCONIUM

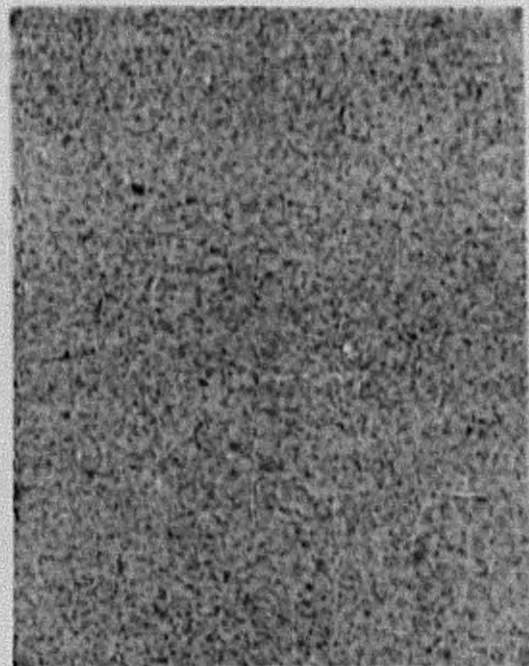| 100X | N8300 | 100X | N8301 |

Longitudinal Section, VHN 393   Transverse Section, VHN 387

FIGURE 5.   LOW-CARBON URANIUM-2.2 w/o ZIRCONIUM

The longitudinal and transverse structures appear to be the same in most of the alloys, except for a slight stringering of inclusions in some of the longitudinal sections.

In the 1.1 w/o zirconium alloy, shown in Figure 4, a segregation effect was observed under bright-field illumination. It appears that the specimen was in the beta-plus-gamma region, resulting in a microsegregated structure. In the longitudinal section the microsegregation causes a banded appearance. The grain structure under polarized light appeared to be more regular, although the grains tended to be elongated in the longitudinal direction.

The microstructures of the high-carbon materials are shown in Figures 6 through 10. The greater quantities of inclusions in these materials, principally carbides, resulted in a marked stringering in the longitudinal direction. This effect is greatest in the 0.1 w/o chromium alloy and in the zirconium alloys, because of the high carbon contents. This stringering effect can be observed in Figures 7, 9, and 10.

The microsegregation, resulting from heat treating the low-carbon 1.1 w/o zirconium samples in the beta-plus-gamma two-phase region, was not observed in the corresponding high-carbon samples (Figure 9). This absence is probably the result of the removal of zirconium from solid solution by the formation of zirconium carbide.

The grain sizes of the various specimens are summarized in Table 6. The low-carbon 2.2 w/o zirconium alloy had the finest grain size of any of the materials. The next finest grain size was found in the 0.4 w/o chromium alloy.

In comparing the low-carbon and high-carbon materials, it can be seen that carbon had little effect on the grain size of uranium or of the chromium alloys. On the other hand, a serious coarsening effect was observed in the high-carbon zirconium alloys. This effect was greatest in the high-carbon 2.2 w/o zirconium alloy.

Tensile Properties

The tensile properties of both the low- and the high-carbon materials were determined at 20 C and 500 C. The resulting data are summarized in Tables 7 and 8.

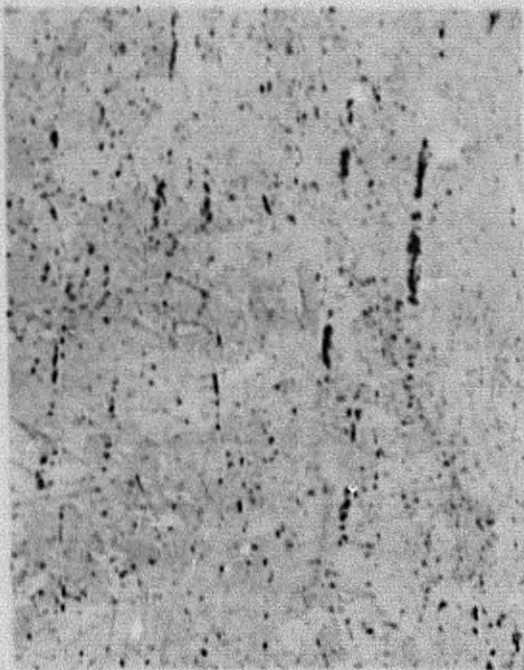It is apparent that at 20 C (Table 7) the low-carbon zirconium alloys are the strongest materials studied. The low-carbon chromium alloys are the most ductile and are also very strong alloys. At 500 C (Table 8) the

100X   N3163   100X   N3164

Longitudinal Section, VHN 226   Transverse Section, VHN 228
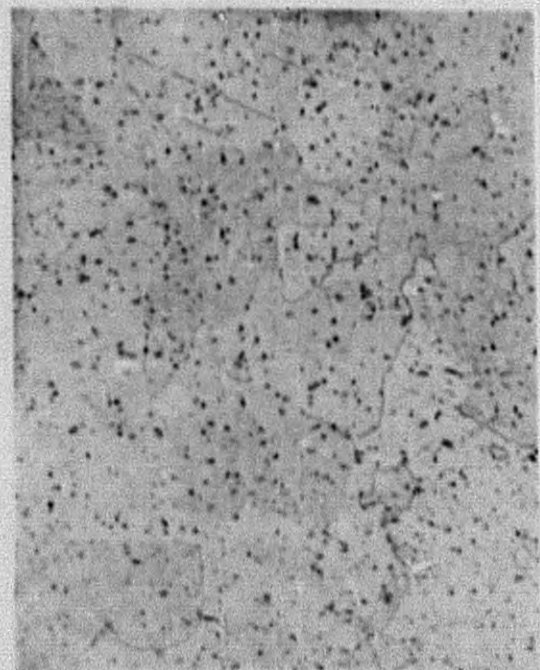
FIGURE 6. HIGH-CARBON URANIUM

| 100X | N8304 | 100X | N8305 |

Longitudinal Section, VHN 336   Transverse Section, VHN 364
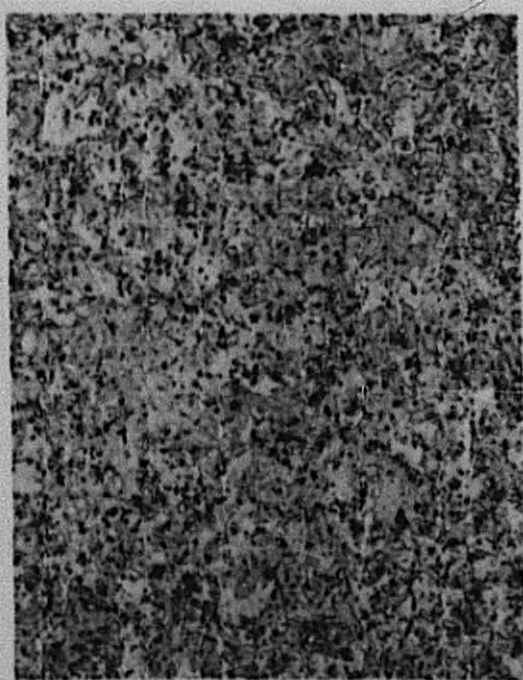
FIGURE 7. HIGH-CARBON URANIUM-0.1 w/o CHROMIUM
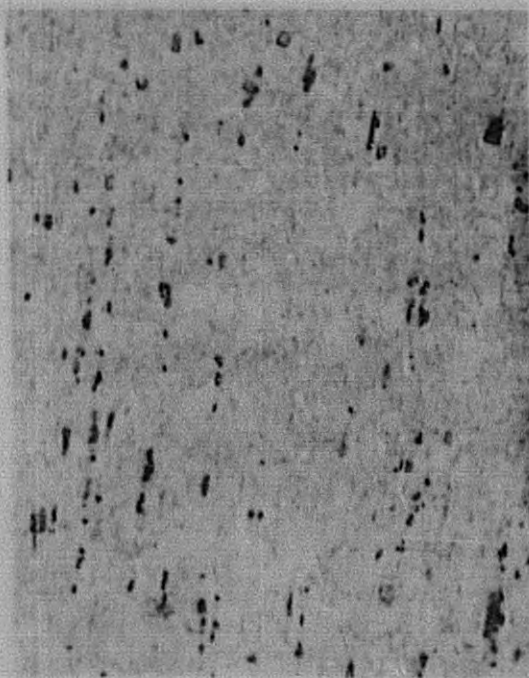
| 100X | N8311 | 100X | N8313 |

Longitudinal Section, VHN 312   Transverse Section, VHN 350
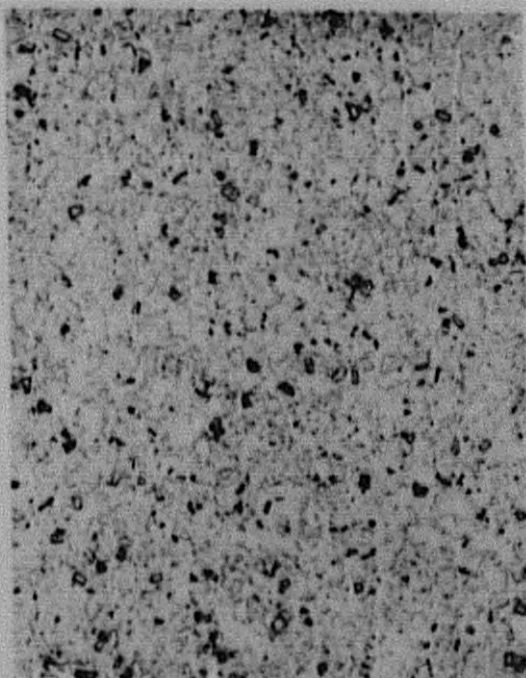
FIGURE 8. HIGH-CARBON URANIUM-0.4 w/o CHROMIUM

100X   N8315   100X   N8316

Longitudinal Section, VHN 274   Transverse Section, VHN 285
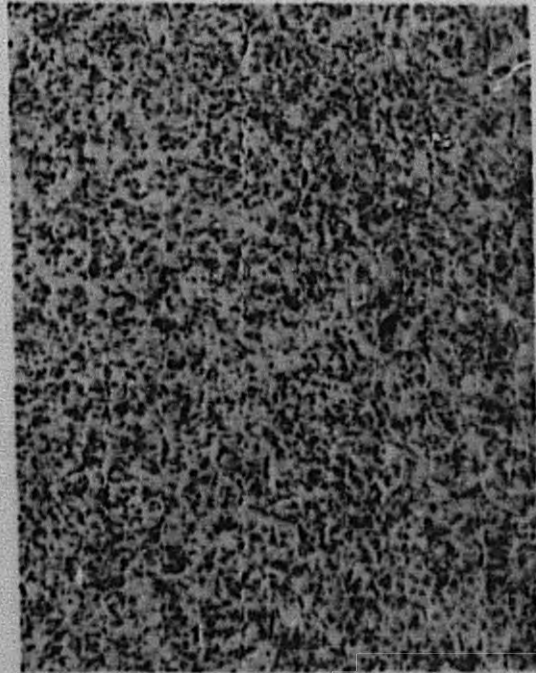
FIGURE 9. HIGH-CARBON URANIUM-1.1 w/o ZIRCONIUM

100X   N8317   100X   N8318

Longitudinal Section, VHN 265   Transverse Section, VHN 294

FIGURE 10. HIGH-CARBON URANIUM-2.2 w/o ZIRCONIUM

TABLE 6. GRAIN SIZE OF URANIUM AND URANIUM ALLOYS

| Material | Interpolated Analysis, w/o | Grain Size, mm | | Remarks |
		Longitudinal	Transverse[a]	
1	Base U, low C	>0.118	--	--
2	0.10 Cr, low C	0.057	--	--
3	0.42 Cr, low C	0.025	--	--
4	1.14 Zr, low C	0.033	0.049	Some grains as large as 0.05-0.06 mm
5	2.19 Zr, low C	0.009	--	--
6	Base U, 0.08 C	>0.118	--	--
7	0.10 Cr, 0.38 C	0.049	--	--
8	0.50 Cr, 0.08 C	0.025	--	--
10	1.19 Zr, 0.32 C	0.057	--	--
11	2.29 Zr, 0.40 C	>0.118	--	--

(a) Same as longitudinal except where indicated otherwise.

TABLE 7. TENSILE PROPERTIES OF URANIUM AND
URANIUM ALLOYS AT 20 C

Material	Interpolated Analysis, w/o	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation in 2 In., per cent	Reduction of Area, per cent
1	Base U, low C	72,000	42,300	11.0	9.5
		100,700	35,000	12.0	11.6
2	0.10 Cr, low C	158,500	82,700	20.5	18
		156,200	81,300	17.7	14.4
3	0.42 Cr, low C	156,500	79,800	23.0	13.8
		156,000	81,000	23.0	13.8
4	1.12 Zr, low C	172,500	95,000	9.0	8.7
		184,900	86,200	14.0	10.9
5	2.24 Zr, low C	183,000	91,400	10	9.7
		187,900	95,800	13.9	11.8
6	Base U, 0.08 C	104,200	38,700	17.5	17.2
7	0.11 Cr, 0.34 C	132,600	88,400	10.5	9.3
		121,500	85,800	11.5	9.3
8	0.48 Cr, 0.11 C	146,700	80,400	16.0	13.8
10	1.19 Zr, 0.32 C	109,000	52,800	15.5	13
		111,800	53,000	17.0	13.5
11	2.14 Zr, 0.38 C	102,700	51,600	7.5	8.9
		99,900	50,700	10.5	7.9

TABLE 8. TENSILE PROPERTIES OF URANIUM AND
URANIUM ALLOYS AT 500 C

Material	Interpolated Analysis, w/o	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation in 2 In., per cent	Reduction of Area, per cent
1	Base U, low C	11,260	8,330	36	~78
		12,460	7,900	29	~87
2	0.10 Cr, low C	32,050	23,300	24.5	~57
		25,980	15,300	25.5	~85
3	0.42 Cr, low C	38,750	24,600	23	82
		37,100	23,800	23	82
4	1.11 Zr, low C	43,300	31,400	11.3	61
		61,000	48,200	21	94
5	2.21 Zr, low C	46,100	41,300	18	85
		52,400	45,000	24	94
6	Base U, 0.08 C	12,020	9,000	26.5	~79
		14,320	10,950	33	71
7	0.11 Cr, 0.35 C	29,050	18,200	27.5	90
		30,100	20,400	23.5	66
8	0.48 Cr, 0.11 C	36,100	26,200	19.0	65
	0.45 Cr, 0.11 C	33,400	24,000	18.5	59
10	1.23 Zr, 0.31 C	16,200	12,300	25.0	61
		16,450	12,000	27.0	65
11	2.14 Zr, 0.38 C	20,500	15,600	17.5	49
		20,270	15,200	17.4	48.5

low-carbon zirconium alloys are still the strongest, but there is little differ-
ence among the ductilities of the low-carbon zirconium, low-carbon chro-
mium, and high-carbon chromium alloys.

There appears to be little advantage in strength or ductility to be ob-
tained by the addition of 0.4 w/o chromium instead of 0.1 w/o chromium,
or by the addition of 2.2 w/o zirconium instead of 1.1 w/o zirconium. This
condition might be expected, since the solid solubility of both chromium and
zirconium in alpha uranium is quite limited.

Comparison of the data for the low-carbon and high-carbon materials
reveals that carbon has a drastic effect on the properties of the zirconium
alloys, but has relatively little effect on the properties of uranium and of
the chromium alloys.

At both 20 and 500 C the strength of the high-carbon zirconium alloys
is much less than the strength of the low-carbon zirconium alloys. This
low strength is probably the result of the formation of zirconium carbide and
corresponding removal of zirconium from solid solution. The absence of
zirconium apparently affects not only the solution strengthening but the grain
size of the alloy.

Thermal-Cycling Experiments

Specimens of all of the materials were cycled 500 times between 100
and 500 C. The results are summarized in Table 9. These tests were not
intended to serve as a "stand in" for radiation-damage experiments, but
merely to evaluate the relative stability of the materials to a particular set
of thermal-cycling conditions. Thermal-expansion coefficients were ob-
tained on the same specimens before thermal cycling. Resulting data are
summarized in Table 10.

The thermal-cycling data indicate the existence of a transient behav-
ior during the first few hundred cycles in many of the samples. For example,
the specimen of Material 4, low-carbon 1.1 w/o-zirconium, had a total
length change of 0.003 per cent after 500 cycles. Actually, it shrank in
length quite rapidly during the first 100 cycles and then began to grow, and
by coincidence had come back to its original length after 500 cycles. Perhaps
a good indication of the stability during thermal cycling is the growth ex-
hibited between 300 and 500 cycles. These values of growth, along with the
surface condition after 500 cycles, should provide a fairly good measure of
the relative merits of this set of samples. On this basis, it is apparent that
the best materials are the low-carbon chromium and low-carbon zirconium
alloys.

TABLE 9. LONGITUDINAL GROWTH OF URANIUM AND URANIUM ALLOYS DURING THERMAL CYCLING FROM 100 TO 500 C

Material	Interpolated Composition, w/o	Growth Per Hundred Cycles[a], per cent				Total Length Change, per cent	Surface Condition After 500 Cycles
		After 100 Cycles	100–200 Cycles	200–300 Cycles	300–500 Cycles		
1	Base U, low C	−0.288	−0.568	−0.144	−0.223	−1.44	Warped and bumped
2	0.10 Cr, low C	−0.057	−0.017	−0.013	+0.010	−0.07	Good surface
3	0.42 Cr, low C	−0.046	−0.021	−0.011	−0.004	−0.086	Good surface
4	1.12 Zr, low C	−0.146	+0.020	+0.037	+0.046	+0.003	Very good surface
5	2.20 Zr, low C	+0.072	−0.047	+0.025	+0.027	+0.10	Very good surface
6	Base U, 0.08 C	+0.376	+0.094	+0.190	+0.211	+1.09	Warped and bumped
7	0.11 Cr, 0.35 C	+0.010	+0.115	+0.188	+0.204	+0.72	Good surface
8	0.48 Cr, 0.11 C	+0.004	+0.055	+0.088	+0.155	+0.46	Good surface
10	1.21 Zr, 0.32 C	−0.063	+0.073	+0.083	−0.050	+0.043	Warped and bumped
11	2.24 Zr, 0.39 C	0.00	−0.076	+0.347	−0.271	−0.27	Warped and bumped

(a) Time for one cycle was about 30 min.

TABLE 10. LONGITUDINAL-THERMAL-EXPANSION COEFFICIENTS OF
URANIUM AND URANIUM ALLOYS

Material	Interpolated Composition, w/o	Thermal-Expansion Coefficients, 10^{-6} per deg C	
		50 C	Mean 40 to 500 C
1	Base U, low C	12.17	13.53
	--	--	13.75
2	0.10 Cr, low C	12.68	14.66
	--	--	15.00
3	0.42 Cr, low C	12.41	15.00
4	1.12 Zr, low C	12.75	15.50
5	2.20 Zr, low C	12.08	14.40
6	Base U, 0.08 C	11.17	12.66
	--	--	12.58
7	0.11 Cr, 0.35 C	13.91	15.73
	--	--	15.73
8	0.48 Cr, 0.11 C	13.17	15.83
10	1.21 Zr, 0.32 C	12.17	12.83
	--	--	13.41
11	2.24 Zr, 0.39 C	12.00	13.50
	--	--	13.33

The zirconium-alloy samples had slightly better surfaces after cycling than did the chromium alloys. This superiority does not correlate directly with the grain-size measurements: the 1.1 w/o zirconium alloy had a coarser grain size than did the chromium alloys; the 2.2 w/o zirconium alloy had a finer grain size.

The low-carbon chromium alloys underwent less growth between cycles 300 and 500 than did the low-carbon zirconium alloys. This may mean that the randomization during heat treatment was more complete in the chromium alloys. On the other hand, other factors, such as the strength of the alloys and surface condition of the specimens, could be involved.

From the preceding discussion, it is apparent that the merits of the low-carbon chromium and low-carbon zirconium samples were about equal in these thermal-cycling experiments. The low-carbon and high-carbon base-uranium samples were numerically similar in behavior, but the low-carbon uranium shrank while the high-carbon uranium grew in length.

SIGNIFICANCE OF RESULTS

The full value of these results can probably be obtained only by comparison with the results of ANL. However, several observations can be made.

On the basis of the tensile properties, grain size, and behavior during thermal cycling, the low-carbon uranium-chromium and low-carbon uranium-zirconium alloys are roughly comparable. These alloys are the best of the materials which were studied.

High-carbon content was detrimental to the zirconium alloys, but had less detrimental effect on the chromium alloys and the base uranium.

The ultimate criterion for evaluation of these alloys is, of course, actual irradiation. However, on the basis of the effectiveness of grain refinement in producing stability during irradiation, reasonably good behavior can probably be expected from both the low-carbon zirconium and low-carbon chromium alloys.

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