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METALLURGY AND CERAMICS (M-3679, 20th Ed., Rev. 1)

UNITED STATES ATOMIC ENERGY COMMISSION

DIMENSIONALLY STABLE ALLOYS

Interim Report

By

A. L. Elss

H. S. Kalish

October 30, 1957

**Sylvania-Corning Nuclear Corporation
Bayside, New York**

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INTERIM REPORT

on

DIMENSIONALLY STABLE ALLOYS

By

A. L. Eiss

H. S. Kalish

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ABSTRACT

The development of dimensionally stable alloys for high temperature reactor application is discussed.

Preparation of alloys was accomplished by powder metallurgy techniques because of the ease of obtaining homogeneous material by a simple mixing process. Cold pressing followed by sintering was determined to be the most satisfactory method.

Evaluation of alloys by alpha-beta thermal cycling indicated the superiority of U-Mo and U-Nb alloys. Several other systems also appeared promising. A few specimens containing small additions of molybdenum, niobium and silicon were irradiation tested in the Materials Testing Reactor. Of these, the niobium alloy (1.6 w/o Nb) appeared to be most stable. The molybdenum alloys were somewhat less satisfactory and the alloys containing silicon were not stable.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to Dr. F. E. Bowman for his invaluable contributions in much of this work. They would also like to thank Mr. R. P. Wittmann and Mr. S. I. Megeff for their efforts on this project and cooperation in writing of this report.

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I. INTRODUCTION

The development of reactor fuel elements capable of sustained operation at high temperatures will be a significant step toward putting nuclear power costs on a level competitive with those of conventional electric power sources. The alpha-beta transformation temperature of uranium (650°C) is presently considered to be the peak fuel element temperature because of the dimensional instability problems.

Two phenomena cause the fuel element distortion that results from thermal fluctuations within the reactor. The first is the anisotropic nature of alpha uranium which appears as unequal thermal expansion along the crystallographic axes. The other is the 1.5% change in volume which accompanies the alpha-beta phase transformation. For operation entirely below 650°C , the second problem does not apply and the first may be overcome by an alloy with randomly oriented grains and a sufficiently fine grain size. Development of an alloy in which the isotropic gamma phase is stable at all temperatures would permit its use at even higher temperatures, since neither of the distortion-causing phenomena could come into play.

For thermal reactors, any alloy additions to uranium must be elements of low neutron capture cross section. For neutron economy in either thermal or fast reactors, the amount of addition should be kept to a minimum.

The use of powder metallurgy provides a method for the preparation of homogeneous alloys by a simple mixing procedure. Many of the compositions investigated are not readily amenable to normal melting and fabrication processes.

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The present work considered the advantages to be obtained from the preparation of fuel alloys by powder metallurgical techniques and the relative merits of several uranium alloys. Eleven elements were added to uranium to form various binary and ternary alloys. A few quaternary and one quinary alloys were also prepared.

Metallographic examination, tensile tests, and thermal cycling (both within the alpha phase and between the alpha and beta phases) were used to evaluate these alloys.

Thermal cycling between 200° and 720°C was determined to be a satisfactory method for elimination of the poorer alloys and almost all of the compositions prepared were tested in this way. Only actual irradiation tests in a reactor can decide the ultimate worth of any particular composition, and several of the alloys which showed satisfactory thermal cycling stability were tested in the Materials Testing Reactor to burn-ups up to 0.38 atomic per cent (1).

II. PREPARATION OF ALLOYS

Initial work was concentrated on the development of procedures for the preparation of alloys from metal powders^(2,3). Several methods were tried, including hot pressing and cold pressing followed by sintering, with both elemental and prealloyed powders being used.

Alloys of uranium with Al, Bi, Cr, Mo, Nb, Si, Sn, V, W and Zr were prepared by hot pressing and/or cold pressing and sintering. In addition, several ternary alloys based on uranium and containing the above elements were also made by the cold pressing and sintering technique. Carbon and titanium were used in a few ternary alloys. A few quaternary alloys and one quinary alloy were also prepared.

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A. Hot Pressing

The hot pressing operation consisted of compacting blended powders in vacuum at about 600°C for 1/2 hour. A pressure of 10 tsi was normally applied. The resultant compacts consisted essentially of discrete particles of uranium and the alloy element. These alloys could be homogenized by isothermal heat treatment at higher temperatures. Two hours at 900°C was a frequently used procedure.

Hot pressed compacts had the advantages of a very fine grain size, random orientation and high density. The grain size attained was approximately that of the particles of powder used. In the case of -325 mesh powder, hot pressing resulted in grain sizes of 4 to 18 microns. The resultant densities were very close to the theoretical values calculated on the basis of ideal mixtures. Data on the hot pressing of several alloys are recorded in Table I.

The use of prealloyed powders gave hot pressed compacts which appeared to be truly alloyed. High density and fine grain size were easily obtained. The procedure followed in this laboratory was to prepare a solid alloy by cold pressing and sintering. The alloy was then hydrided by means of the same procedures normally applied to uranium. The decomposed hydride was ground to a powder, which could be used in the usual hot pressing operation. Very little work was done with prealloyed powders because of the rather complex procedure involved which could not be easily applied to the manufacture of large numbers of alloys of many compositions.

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TABLE I.

DENSITY AND GRAIN SIZE OF TYPICAL
HOT PRESSED URANIUM ALLOYS

<u>Alloy</u> <u>Addition</u>	<u>w/o</u>	<u>Calculated</u> <u>Density,</u> <u>gm/cm³</u>	<u>Actual</u> <u>Density,</u> <u>gm/cm³</u>	<u>Grain</u> <u>Size,</u> <u>microns</u>
Al	1.0	17.87	17.53	8 - 12
Al	1.0	17.87	17.47	12 - 18
Bi	1.0	18.78	18.63	8 - 12
Cr	1.0	18.63	18.57	8 - 12
Cr	1.0	18.63	18.37	12 - 18
*Cr	1.0	18.63	18.33	8 - 25
Mo	0.35	18.90	18.88	12 - 18
Mo	0.35	18.90	18.80	12 - 18
Nb	1.6	18.58	18.50	4 - 18
Nb	1.6	18.58	18.21	8 - 12
Si	0.42	18.41	17.98	12 - 18
Si	0.42	18.41	18.32	9 - 18
Si	0.42	18.41	18.37	8 - 12
Si	0.49	18.30	18.41	8 - 12
Si	0.49	18.30	17.77	12 - 18
Sn	2.0	18.36	18.01	8 - 12
Sn	2.0	18.36	18.05	12 - 18

All alloys hot pressed at 600° - 610°C.

*Prealloyed Powder used in this compact.

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B. Cold Pressing and Sintering

In the case of alloys prepared by cold pressing, the proper elemental powders were weighed out and tumble-mixed in glass bottles for two hours. Because of the pyrophoric nature of uranium powder, all operations with this material were carried out under an argon atmosphere. Most of the specimens were pressed in a rectangular single-action V-block die. Compacts were pressed to a size of $1\frac{3}{4}$ " x $\frac{3}{4}$ " x $\frac{3}{4}$ " at 50 tsi in a press which was enclosed in a dry box. The compacts were loaded into a graphite boat which was covered and then inserted into a mullite furnace tube. The furnace was evacuated, and the compacts were sintered. The exact sintering time and temperature depended on the composition of the alloy. For many uranium alloys with less than 1.5 w/o of other elements, four hours at 1100°C were satisfactory.

In a later modification of the cold pressing operation, the elemental powders were placed in tubes of plastisol or surgical rubber. These tubes were sealed with aluminum end plugs and were then placed in a hydrostatic die and pressed at 50 tsi. Paraffin oil was the medium used in the hydrostatic vessel, since it will not react with uranium in the event that the tube accidentally opens. The compacts were removed from the molds in a dry box and were then dipped in a 0.5% solution of camphor in benzene. This rendered the compacts temporarily non-pyrophoric and permitted them to be loaded into the vacuum furnace in air. The benzene solution was drawn off by the vacuum pumps.

The advantage of this second method lay in the fact that the specimens produced were cylindrical in shape. This simplified the machining operations which were necessary to produce thermal cycling and irradiation specimens from the sintered alloys.

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Metallographic examination of cold pressed and sintered alloys showed that the alloying element reacted completely with the uranium. Grain size was larger than that obtained by hot pressing but, in most of the alloys studied, was smaller than that found in pure uranium (8-800 microns for beta-treated wrought material).

The use of prealloyed powders in the cold-pressing operation showed no apparent advantage over elemental powders; hence, the higher cost of the former process did not justify its use.

Tables II and III record densities and grain sizes of several cold-pressed and sintered alloys.

C. Other Methods

Several binary uranium alloys were produced by induction melting followed by casting into a graphite crucible and by arc-melting techniques. Powder rolling was also used for one or two alloys. The specimens prepared by these methods were intended for comparison with powder metallurgical specimens in thermal cycling tests.

III. EVALUATION OF ALLOYS

A. Thermal Cycling

A thermal cycling test consists of alternately heating and cooling a specimen between two pre-set temperatures for a specified number of cycles. At the start and conclusion of the test, measurements are made of such factors as dimensions, density, hardness and grain size. Variables which affect the behavior of a specimen in a thermal cycling test include:

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TABLE II

DENSITY AND GRAIN SIZE OF TYPICAL COLD
PRESSED AND SINTERED BINARY URANIUM ALLOYS

<u>Alloy Addition</u>	<u>w/o</u>	<u>Sintering Temperature, °C</u>	<u>Calculated Density, gm/cm³</u>	<u>Actual Density, gm/cm³</u>	<u>Grain Size, microns</u>
Mo	1.0	1100	18.78	18.67	38-70
Mo	1.0	1100	18.78	18.08	38-70
Mo	1.0	1100	18.78	18.74	20-175
Mo	1.0	1100	18.78	18.68	20-175
Mo	9	1150	17.58	17.19	50-100
Mo	9	1150	17.58	17.17	50-100
Mo	10	1100	17.44	16.84	38-70
Mo	12	1150	17.18	16.70	38-70
Nb	1.4	1100	18.63	18.06	25-70
Nb	1.5	1100	18.60	18.07	25-70
Nb	1.6	1100	18.58	18.34	13-38
Nb	1.6	1100	18.58	18.18	13-38
Nb	1.7	1100	18.56	18.15	13-38
Nb	1.8	1100	18.54	17.87	13-38
Nb	1.9	1100	18.51	18.20	13-38
Nb	2.0	1120	18.49	18.26	13-38
Nb	3.0	1170	18.28	17.88	13-38
Nb	8.0	1225	17.32	16.34	9-16
Si	0.36	980	18.53	17.09	400+
Si	0.62	980	18.19	16.82	400+
Si	3.0	960	15.70	15.12	100+
Si	3.7	960	15.02	13.37	35-50
Si	3.9	960	14.85	14.05	35-50
Si	3.9	960	14.85	12.52	35-50

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TABLE III

DENSITY AND GRAIN SIZE OF TYPICAL COLD
PRESSED AND SINTERED TERNARY URANIUM ALLOYS

<u>Alloy Additions</u>	<u>w/o</u>	<u>Sintering Temperature, °C</u>	<u>Calculated Density, gm/cm³</u>	<u>Actual Density, gm/cm³</u>	<u>Grain Size, microns</u>
Cr, Mo	1.0, 1.0	950	18.48	18.05	125
Cr, Si	1.0, 0.3	925	18.26	16.04	100-250
Cr, V	1.0, 0.5	950	18.50	17.51	10-60
Mo, Nb	0.5, 0.5	1100	18.75	18.52	100-300
Mo, Nb	0.75, 0.5	1100	18.71	18.26	38-70
Mo, Nb	0.5, 0.75	1100	18.69	18.34	38-70
Mo, Nb	1.0, 1.0	1100	18.56	18.03	18-38
Mo, Si	1.0, 0.42	1100	18.25	17.59	25-50
Mo, V	0.5, 0.5	1100	18.72	18.31	20-300
Mo, Zr	1.0, 1.5	1100	18.26	18.17	9-38
Nb, Si	1.6, 0.42	1000	18.07	17.00	200+
Nb, Zr	1.5, 5.0	1100	17.01	16.89	9-25
Nb, Zr	1.5, 5.0	1170	17.01	16.98	9-25
Nb, Zr	2.0, 4.0	1230	17.21	17.11	13-38
Si, Zr	0.42, 1.5	1000	17.91	16.29	200+

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1. Temperature range
2. Time of each cycle (i.e., quenching vs. slow cooling)
3. Number of cycles
4. Initial dimensions of the specimen

In the present work, two distinct temperature ranges were used. The first was from 100° to 500°C, which was entirely below any transformation temperature in uranium or the alloys tested. This is referred to as alpha cycling. The other temperature range used involved passing through the alpha-beta transformation temperature of uranium, and is therefore called alpha-beta cycling. Typical temperatures used were from 200° to 720°C. Small variations in these end temperatures appeared to have little effect on the dimensional stability of uranium alloys.

All alloys studied were slow cycled. Initial experiments provided for a 30-minute heating and 30-minute cooling cycle. It was later found that comparable results could be obtained with the shorter cycle of 10.5 minutes heating and 4.5 minutes cooling.

Five hundred cycles was chosen as a standard test of the dimensional stability of a material and almost all specimens were given such a treatment. In several alloys, measurements of distortion were made at intervals between 0 and 500 cycles but, in most cases, only the initial and final dimensions were measured.

All thermal cycling specimens were cylindrical in shape. Prior to the construction of the Sylvania-Corning Nuclear Corporation cycling apparatus, several powder-compacted specimens were tested by North American Aviation as part of a cooperative program with this company⁽⁴⁾. These alloy specimens were 3/4" to 1" in

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length and 1/2" to 3/4" in diameter. In the later work carried out here, 3/4" long specimens were used. One group of these was 3/8" in diameter, and another 1/5" in diameter. A few specimens of intermediate diameter were also tested.

The results from these various specimens were not identical, dimensional changes being most severe in the samples of smallest diameter. Qualitative comparisons can be made, however, and since thermal cycling is used mainly as a method of screening alloys, the use of any diameter specimen is valid.

1. Cycling Performed at North American Aviation ⁽⁴⁾

A series of binary uranium alloys prepared by powder metallurgical techniques at the Sylvania-Corning Nuclear Corporation were thermal cycled by North American Aviation. Included were hot-pressed and cold-pressed and sintered samples.

Hot-pressed alloys containing high-melting point additions (chromium, molybdenum, niobium and silicon) were not completely alloyed because of the low diffusion rates of their constituents at the hot-pressing temperature. The other hot-pressed alloys and all those that were cold-pressed and sintered appeared to be homogeneous.

The specimens were sealed in evacuated vycor tubes and cycled in a low heat capacity resistance furnace operated by a program controller.

All of these alloys were first alpha cycled (100° to 500°C) and showed good dimensional stability. Alpha-beta thermal cycling (200° to 700°C) proved to be a more discriminating test and clearly demonstrated the superiority of some of the alloys over the others. Typical results of alpha-beta thermal cycling are recorded in Table IV.

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TABLE IV

TYPICAL RESULTS OF ALPHA-BETA THERMAL CYCLING OF
URANIUM ALLOYS TESTED AT NORTH AMERICAN AVIATION
 (500 Cycles 200° to 720°C)

<u>Alloy</u> <u>Addition</u>	<u>w/o</u> <u>Added</u>	<u>Preparation</u>	<u>% Change/500 Cycles</u>		<u>Hardness, DPH</u>		<u>Surface Appearance</u>	<u>Internal</u> <u>Structure</u>
			<u>Length</u>	<u>Diameter</u>	<u>Initial</u>	<u>Final</u>		
Nb	1.6	HP	+65	+27	278	238	bumpy, porous	very porous
Cr	1.0	HP	-9*	+8*	283	365	slightly rough	solid
Bi	1.0	HP	+16	+17	273	257	badly cracked	very porous
Sn	2.0	HP	+8	+36	245*	307*	badly cracked	very porous
Al	1.0	HP	-13	+23	288	249	badly cracked	slightly porous
Si	0.5	HP	+3	+5	297	347	slightly rough	solid
Mo	0.4	HP	+7	+9	272	278	slightly rough	slightly porous
Nb	1.6	CPS	+4	+0.5	435	308	slightly rough	solid
Cr	1.0	CPS	+1	+2	317	378	slightly rough	solid
Si	0.4	CPS	+5	+4	373	259	slightly rough	solid
Mo	1.2	CPS	+0.6	+1.2	329	323	smooth	solid
Zr	7.0	CPS	+2	+3	329	274	rough	solid

* wide variations
 HP = hot pressed
 CPS = cold pressed and sintered

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The relatively stable hot-pressed alloys contained chromium, molybdenum and silicon. Cold-pressed and sintered alloys with the same additions proved to be even more stable. A striking example is the hot-pressed 1.6 w/o Nb alloy which distorted severely during the test, while the same alloy, when cold pressed and sintered, proved to be fairly stable.

The results obtained in these experiments showed the more selective nature of alpha-beta cycling as compared with alpha cycling. Also demonstrated was the superiority of cold-pressed and sintered alloys, as compared with hot-pressed alloys. Because of this, thermal cycling performed at Sylvania-Corning Nuclear Corporation on powder metallurgy alloys was almost entirely restricted to specimens made by cold pressing and sintering, using an alpha-beta cycling test.

2. Cycling Performed at Sylvania-Corning Nuclear Corp.

Construction of a thermal cycling apparatus at the Sylvania-Corning Nuclear Corporation made possible an expansion of thermal stability tests on uranium alloys. Construction features of this apparatus differed from those of the North American Aviation thermal cyclers described above. At Sylvania-Corning Nuclear Corporation the specimens were sealed in evacuated vycor or stainless steel capsules which were placed in a stainless steel boat. An electric clock mechanism activated an air pressure operated piston which moved the boat between a Kanthal-wound furnace (held at 720° to 750°C) and an air blast at room temperature. A standard cycle consisted of 10.5 minutes in the furnace and 4.5 minutes in the air blast. This sequence could be altered by replacing a cam in the timing mechanism.

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About seventy different alloy compositions were tested. Emphasis was placed on binary and ternary alloys based on the U-Mo and U-Nb systems. Most of the specimens were prepared by cold-pressing and sintering elemental powders. Some cast, and cast and wrought samples were cycled for comparison.

Several pure uranium specimens were prepared and thermal cycled both for controls and for comparison with the alloyed material. The results obtained with unalloyed uranium are recorded in Table V.

a. U-Mo and U-Mo-X Alloys

Tables VI and VII show typical results of thermal cycling of cold-pressed and sintered binary uranium-molybdenum alloys. Addition of molybdenum markedly increased the stability of uranium and in amounts greater than 4 w/o results in an alloy essentially unaffected by thermal cycling. Powder metallurgy alloys appear to be superior to those cast or cast and wrought, as can be seen from Table VIII and Fig. 1, which give results obtained for the 1.4 w/o molybdenum composition.

One specimen containing 2.5 w/o Mo was prepared by the hot rolling of elemental powders and was then tested by thermal cycling. The surface of the specimen became rough and it elongated 15.3%. The diameter decreased 2.2%. This result can be explained by the incomplete alloying which took place at the hot rolling temperature of 600°C and the preferred orientation caused by the rolling.

Several ternary alloys containing Al, C, Nb, Si, Ti, V, and Zr, in addition to U and Mo, were thermal cycled. These results are shown in Table IX. The 2 w/o Mo + 0.5 w/o Zr

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TABLE V

RESULTS OF ALPHA-BETA THERMAL CYCLING
OF UNALLOYED URANIUM
(3/8" Diameter Specimens)

<u>Specimen Number</u>	<u>Preparation</u>	<u>Density, gm/cm³</u>		<u>% Change/500 Cycles</u>		<u>Appearance after cycling</u>
		<u>Initial</u>	<u>Final</u>	<u>Length</u>	<u>Diameter</u>	
U-2	Beta-treated wrought	18.85	18.54	+31.6	+13.2	growth in all directions
U-3	Beta-treated wrought	18.82	17.95	+56.7	-	spiny, cactus-like
U-4	Beta-treated wrought	18.82	18.70	+ 9.09	+18.40	completely distorted
U-5	CPS	18.49	13.34	+12.98	+16.76	mushroomed severely, one end, wrought

CPS = cold pressed and sintered

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TABLE VI

TYPICAL RESULTS OF ALPHA-BETA THERMAL CYCLING OF
COLD PRESSED AND SINTERED U-Mo ALLOYS
 (3/8" Diameter Specimens)

Specimen Number	w/o Mo	Density, gm/cm ³			% Change/500 Cycles		Appearance after cycling
		Calculated	before cycling	after cycling	Length	Diameter	
B-18	1.2	18.81	18.56	18.49	-1.33	+1.72	Slightly rough
B-38	1.4	18.77	18.52	18.43	+0.80	+1.07	Smooth, one end slightly rounded
B-42	1.75	18.72	17.97	17.73	+0.66	+0.87	Smooth
B-45	2.0	18.68	18.57	18.36	-0.93	-1.33	Smooth
B-46	2.5	18.60	18.24	17.97	+1.86	+1.32	Slightly rough
B-47	2.5	18.60	18.30	18.13	-0.13	+0.88	Smooth and shiny
B-54	3.0	18.52	18.09	18.03	+2.66	+0.96	Rough, slightly oval
B-55	3.5	18.44	18.12	17.98	+0.26	-0.54	Smooth
B-57	3.75	18.40	17.62	17.73	-1.07	+0.35	Smooth
B-59	4.0	18.37	16.78	16.77	+0.67	+0.61	Slightly wrinkled
B-62	4.5	18.29	17.57	17.48	+0.60	0	Smooth

TABLE VII

TYPICAL RESULTS OF ALPHA-BETA THERMAL CYCLING OF
COLD PRESSED AND SINTERED U-Mo ALLOYS
 (1/5" Diameter Specimens)

Specimen Number	w/o Mo	Density, gm/cm ³			% Change/500 Cycles		Appearance after cycling
		Calculated	before cycling	after cycling	Length	Diameter	
C-1	0.5	18.92	17.57	17.12	+11.3	+1.04	Badly warped, rough
C-2	1.0	18.84	17.88	17.42	+0.97	+1.60	Bulge in center, slightly rough
E-18	1.2	18.81	18.41	18.83	-1.6	+1.7	Slight warp, slightly rough
E-21	1.4	18.77	18.39	18.86	-1.2	+1.75	Smooth
E-26	1.75	18.72	18.17	16.86	-0.5	+1.4	Rough, ends cupped
E-28	2.0	18.68	17.33	17.46	-2.1	-0.4	Slightly rough
E-31	2.5	18.60	17.51	17.20	+1.0	+1.0	Smooth
E-36	6.0	18.06	16.75	16.71	+0.1	0	Unchanged
C-4	6.0	18.06	17.73	17.60	+0.21	+0.51	Unchanged
C-5	11.0	17.35	16.91	16.94	-0.03	0	Unchanged

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TABLE VIII

RESULTS OF ALPHA-BETA THERMAL CYCLING
OF U + 1.4 w/o Mo ALLOYS
(3/8" diameter specimens)

<u>Specimen Number</u>	<u>Preparation</u>	<u>Density, gm/cm³</u>		<u>% Change/500 Cycles</u>		<u>Appearance after cycling</u>
		<u>before cycling</u>	<u>after cycling</u>	<u>Length</u>	<u>Diameter</u>	
B-21	cast	18.53	-	-3.86	+6.63	Rough, oval, bent, warped
B-27	cast	18.48	18.55	-2.60	+5.33	Slightly rough, rounded at one end
B-20	cast and hot rolled	18.45	-	-3.67	+8.48	Rough, bent, warped, oval shape
B-38	CPS	18.52	18.43	+0.80	+1.07	Smooth, slightly rounded one end
B-31	CPS	18.44	18.29	-2.06	0	Smooth

CPS = Cold pressed and sintered

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Plate No. 10,003

Fig. 1 Uranium alloys after cycling 500 times
 between the alpha-beta phases.
 From left to right:

U-3 B-treated wrought uranium

B-31 Cold pressed and sintered 1.4 w/o
 Mo-U alloy

B-28 As-cast 1.4 w/o Mo-U alloy

B-20 Cast and wrought 1.4 w/o
 Mo-U alloy

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TABLE IX

TYPICAL RESULTS OF ALPHA-BETA THERMAL CYCLING OF COLD PRESSED
AND SINTERED U-Mo-X ALLOYS

Specimen Number	Alloy Additions	w/o	Initial diameter, inches	Density, gm/cm ³			% Change/500 Cycles		Appearance after cycling
				Calculated	before cycling	after cycling	Length	Diameter	
C-8	Mo, Al	0.5, 0.5	1/5	18.37	17.62	14.40	+7.47	+3.85	Slightly rough, ends cupped
C-7	Mo, Al	1.0, 0.5	1/5	18.29	17.25	17.54	-1.46	+1.36	Surface good
E-39	Mo, C	0.5, 0.1	1/5	18.78	18.23	10.46	+32.1	+40.0	Swollen, many cracks
C-11	Mo, C	1.0, 0.1	1/5	18.70	17.56	17.74	+0.13	+0.74	Smooth, ends cupped
E-42	Mo, Si	0.5, 0.25	1/5	18.59	17.89	12.29	Too distorted to measure		Swollen and distorted
B-100	Mo, Si	0.5, 0.5	3/8	18.27	-	-	+1.01	+0.09	Smooth, many small points on surface
E-44	Mo, Zr	2.0, 0.5	1/5	18.50	17.79	17.99	-0.1	+0.7	Slight graininess
E-45	Mo, Zr	2.0, 0.5	1/4	18.50	17.72	17.92	-0.2	+0.4	Slight graininess
E-47	Mo, Zr	2.0, 0.5	1/4	18.50	17.69	17.91	-0.5	+0.5	Slight graininess
B-97	Mo, Nb	0.5, 0.5	3/8	18.80	18.40	18.31	+1.3	+3.4	Slightly rough
B-98	Mo, Nb	0.75, 0.75	3/8	18.71	18.34	17.83	+8.5	+6.1	Slightly rough, ends cupped
B-99	Mo, Nb	0.75, 0.75	3/8	18.71	18.27	18.31	+3.3	+0.9	Wrinkled surface
B-101	Mo, Ti	0.5, 0.5	3/8	18.62	-	-	+3.04	+2.84	Slightly rough
B-102	Mo, V	0.5, 0.5	3/8	18.72	-	-	+1.29	+1.46	Slightly rough
B-103	Mo, V	0.5, 0.5	3/8	18.72	-	-	+1.80*	-0.45*	Smooth, ends cupped, slight warp *

*400 cycles

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composition is the best of those tested and is a promising fuel element material. The stability of this alloy is comparable to that of a 6 w/o Mo binary, while the use of less addition element atoms makes it more desirable than the latter, from a nuclear standpoint.

With the exception of the 2 w/o Mo + 0.5 w/o Zr alloy, only one or two specimens of each composition were tested. Therefore, the results must be somewhat inconclusive. However, uranium alloys containing molybdenum plus niobium, vanadium or carbon appear to be promising.

b. U-Nb and U-Nb-X Alloys

Niobium, like molybdenum, serves to stabilize the gamma phase and greatly increases the thermal cycling stability of uranium if a sufficient amount is added. As can be seen from Table X, alloys containing more than 4.6 w/o niobium are stable while those with 1.6 w/o niobium or less are unsatisfactory in alpha-beta cycling. No work was done with intermediate compositions. Arc-melted samples of a few alloys appeared to be virtually the same as the cold-pressed and sintered specimens. Several of these specimens are shown in Fig. 2.

As with the binary compositions, ternary uranium-niobium alloys with low niobium content were not stable. The only exceptions to this were the U-Mo-Nb specimens mentioned in the previous section and the U + 0.5 w/o Nb + 0.5 w/o V specimen. Thermal cycling results for U-Nb-X alloys are reported in Table XI.

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TABLE X

TYPICAL RESULTS OF ALPHA-BETA THERMAL CYCLING OF
URANIUM-NIOBIUM ALLOYS
(1/5" Diameter Specimens)

Specimen Number	w/o Nb	Density,			% Change/500 Cycles		Appearance after cycling
		Calculated	before cycling	after cycling	Length	Diameter	
E-49	0.5	18.88	18.19	12.11	+25.1	+19.3	Rough, elongated
C-12	1.0	18.77	17.82	15.73	+16.0	+5.70	Rough, ends cupped
E-53	1.6	18.64	17.84	15.85	+5.2	+7.1	Rough, one end cupped
E-56 (1)	1.6	18.64	18.51	17.96	+7.0	+5.1	Rough, warped
E-59	4.6	17.99	17.76	17.64	+0.13	+1.0	Slight graininess
E-60	6.0	17.71	16.76	16.86	+1.1	-0.07	Slight graininess
E-61 (2)	6.0	17.71	16.85	16.97	-0.13	+0.48	Slight graininess
E-62 (1)	6.0	17.71	17.45	17.43	+0.3	+0.8	Smooth, slight warp
E-64	8.0	17.31	16.28	16.09	+0.4	+0.4	Unchanged
E-66 (1)	8.0	17.31	16.86	16.86	0	+0.6	Unchanged
E-69	10.0	16.84	15.62	15.45	+0.3	+0.3	Unchanged
E-73 (1)	10.0	16.84	16.17	16.12	0	+0.2	Unchanged
E-74 (1)	14.0	16.23	14.69	14.67	+0.2	+0.2	Unchanged

(1) Arc melted specimen.

(2) Prepared with niobium hydride powder.

All others cold-pressed and sintered from elemental powders.

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TABLE XI

TYPICAL RESULTS OF THERMAL CYCLING OF COLD-PRESSED
AND SINTERED U-Nb-X ALLOYS

Specimen Number	Alloy Additions	w/o added	Initial Diameter, inches	Density, gm/cm^3		% Change/500 cycles		Appearance after cycling
				Calculated	before cycling	after cycling	Length Diameter	
E-76	Nb, Al	0.5, 0.5	1/5	18.34	17.63	12.30	+7.4 +25.1	Enlarged diameter, several vertical cracks
C-13	Nb, Al	1.0, 0.5	1/5	18.23	17.20	16.86	+2.67 +4.97	Rough, slight warp
C-15	Nb, C	0.5, 0.1	1/4	18.74	17.30	13.22	+13.7 +13.2	Smooth, surface cracked
C-16	Nb, C	1.0, 0.1	1/4	18.63	17.05	13.84	+10.0 +13.6	Surface cracked, ends cupped
E-80	Nb, Si	0.5, 0.25	1/5	18.56	17.73	9.75	+29.5 +27.8	Swollen
E-84	Nb, Si	1.0, 0.25	1/5	18.45	17.47	10.64	+29.5 +42.2	Swollen, rough, cracked
B-97	Nb, Mo	0.5, 0.5	3/8	18.80	18.40	18.31	+1.3 +3.4	Slightly rough
B-98	Nb, Mo	0.75, 0.75	3/8	18.71	18.34	17.83	+8.5 +6.1	Slightly rough, ends cupped
B-99	Nb, Mo	0.75, 0.75	3/8	18.71	18.27	18.31	+3.3 +0.9	Wrinkled surface
B-104	Nb, Ti	0.5, 0.5	3/8	18.59	-	-	+0.19* +7.68*	Rough, one end cupped*
B-105	Nb, V	0.5, 0.5	3/8	18.68	-	-	+2.68 -0.24	Rough, one end cupped

*400 cycles

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Plate No. 4014

Fig. 2 Uranium-niobium alloys after cycling 500 times between the alpha-beta phases.
From left to right:

- E-54 Cold pressed and sintered 1.6 w/o Nb
- E-56 Arc-melted 1.6 w/o Nb
- E-61 Cold pressed and sintered 6 w/o Nb
- E-62 Arc-melted 6 w/o Nb
- E-71 Cold pressed and sintered 10 w/o Nb
- E-73 Arc-melted 10 w/o Nb

Initial diameters of E-56 and E-62 were smaller than those of other samples shown.

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c. Other Alloys

Several other binary and ternary systems were studied by means of thermal cycling tests. Most promising of these were the U-Cr, and U-Cr-X alloys. These showed very little distortion, in view of the small percentages of alloy element added. Alloys based on the U-Zr and U-W systems proved to be unsatisfactory. Erratic behavior was encountered in thermal cycling tests of U-Si alloys. Some specimens were barely affected by the cycling while others of the same composition and method of fabrication demonstrated large amounts of distortion. A small number of specimens containing vanadium as a binary or ternary addition were also thermal cycled and appeared to be relatively stable. Difficulties encountered in obtaining vanadium powder of satisfactory mesh size and purity limited investigation of this system. Typical results obtained by alpha-beta thermal cycling of the above mentioned alloys are reported in Tables XII and XIII and in Fig. 3.

B. Tensile Test Data

The tensile strength and hardness of several cold-pressed and sintered binary uranium alloys were determined at various times during the investigation. Typical values of these properties are reported in Tables XIV and XV. Data for slow-cooled alloys (i.e., those cooled to room temperature more than two hours after sintering) represent an average of values determined on four specimens, while the data for fast-cooled alloys are an average of at least eight determinations.

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TABLE XII

TYPICAL RESULTS OF ALPHA-BETA THERMAL CYCLING OF BINARY URANIUM ALLOYS

Specimen Number	Alloy Additions	Preparation	Initial Diameter, inches	Density, Calculated	gm/cm ³		% Change/500 Cycles		Appearance after cycling
					before cycling	after cycling	Length	Diameter	
E-1	0.5 w/o Cr	CPS	1/5	18.85	18.04	18.31	-4.7	+3.1	Slightly rough, slight warp
E-5	1.0 w/o Cr	CPS	1/5	18.69	18.09	18.07	-2.9	+6.6	Smooth, slight warp
B-7	1.0 w/o Cr	CPS	3/8	18.69	17.99	17.65	+1.00	+3.87	Rough
B-66	0.5 w/o Si	As cast	3/8	18.34	18.00	18.16	-2.39	+2.90	Slightly rough, rounded ends
B-73	0.5 w/o Si	CPS	3/8	18.34	17.96	17.74	-3.54	+2.79	Smooth, slight flare one end
B-72	0.5 w/o Si	CPS	3/8	18.34	18.07	11.44	+22.61	+16.71	
B-78	1.0 w/o Si	As cast	3/8	17.73	17.51	17.66	-1.81	+1.86	Slightly rough, rounded ends
B-79	1.0 w/o Si	As cast	3/8	17.73	17.55	17.37	+6.40	+10.03	Rough, flared ends
B-83	1.0 w/o Si	Cast and Wrought	3/8	17.73	18.11	17.90	+5.73	+0.57	Slightly wrinkled, slightly flared ends
B-82	1.0 w/o Si	Cast and wrought	3/8	17.73	18.10	17.57	+18.19	+14.02	Rough, flared ends
B-89	0.5 w/o V	CPS	3/8	18.80	16.40	17.75	-2.40	+1.94	Smooth, tapered at one end
B-91	2.0 w/o W	CPS	3/8	19.01	18.31	13.92	+24.5	+10.21	
E-85	0.5 w/o Zr	CPS	1/5	18.82	17.81	11.74	+4.5	+32.8	Rough, warped, vertical cracks
E-87	1.0 w/o Zr	CPS	1/5	18.64	17.70	7.34	+30.4	+48.5	Rough, swollen
B-94	2.0 w/o Zr	CPS	3/8	18.30	17.26	14.02	+14.51	+12.57	Rough, flared ends

CPS = cold pressed and sintered

TABLE XIII

TYPICAL RESULTS OF ALPHA-BETA THERMAL CYCLING OF COLD-PRESSED
AND SINTERED TERNARY URANIUM ALLOYS

Specimen Number	Alloy Additions	w/o	Initial Diameter, inches	Density, gm/cm^3			% Change/500 Cycles		Appearance after cycling
				Calculated	before cycling	after cycling	Length	Diameter	
E-8	Cr, Al	1.0, 0.5	1/5	18.15	17.35	16.88	-1.4	+6.2	Slightly rough, slight warp
E-9	Cr, C	0.5, 0.1	1/5	18.70	17.92	18.20	-3.5	+2.5	Smooth, slight warp, cupped ends
E-12	Cr, C	1.0, 0.1	1/5	18.55	17.91	17.91	-1.7	+1.5	Smooth, slight warp
E-14	Cr, Si	0.5, 0.25	1/5	18.51	18.04	13.45	+15.9	+17.8	Rough, swollen
E-16	Cr, Si	1.0, 0.25	1/5	18.37	18.00	9.56	+24.4	+19.5	Rough, swollen
E-89	Zr, Al	0.5, 0.5	1/5	18.27	17.43	12.51	+5.2	+26.3	Cracked, ends appear "melted over"
E-91	Zr, Al	1.0, 0.5	1/5	18.10	17.26	10.13	+15.2	+41	Cracked, ends appear "melted over"
E-93	Zr, C	0.5, 0.1	1/5	18.68	17.90	12.32	+15.4	+30	Cracked, rough, one end "melted over"
E-95	Zr, C	1.0, 0.1	1/5	18.50	17.97	12.53	+3.1	+17.2	Cracked, rough, one end "melted over"
E-97	Zr, Si	0.5, 0.25	1/5	18.49	17.33	9.65	+20.2	+24.6	Rough, swollen
E-100	Zr, Si	1.0, 0.25	1/5	18.32	17.49	11.22	+12.4	+41.2	Rough, swollen, cracked, warped
B-106	Cr, V	1.0, 0.5	3/8	18.50	-	-	+1.57	+5.21	Slightly rough, barrel shaped
B-107	V, Si	0.5, 0.5	3/8	18.15	-	-	+3.36	+3.35	Rough

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Plate No. 4013

Fig. 3 Cold pressed and sintered uranium alloys after cycling 500 times between alpha-beta phases. From left to right:

E-5	1 w/o Cr
E-12	1 w/o Cr - 0.1 w/o C
E-89	0.5 w/o Zr - 0.5 w/o Al
E-100	1.0 w/o Zr - 0.25 w/o Si
E-43	2.0 w/o Mo - 0.5 w/o Zr

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TABLE XIV

TENSILE STRENGTH AND HARDNESS OF SLOW-COOLED
COLD-PRESSED AND SINTERED URANIUM ALLOYS

<u>Alloy Addition</u>	<u>Calculated Density, gm/cm³</u>	<u>Actual Density, gm/cm³</u>	<u>Hardness, DPH</u>	<u>Elongation, %</u>	<u>Yield Strength, psi</u>	<u>Tensile Strength, psi</u>
0.5 w/o Cr	18.85	18.06	217	4	48,000	83,000
1.0 w/o Cr	18.69	17.84	-	4	44,000	74,000
1.5 w/o Cr	18.54	17.69	216	4	47,000	75,000
2.0 w/o Cr	18.40	17.49	203	3	52,000	70,000
0.5 w/o Mo	18.92	18.02	246	3	70,000	103,000
1.0 w/o Mo	18.84	18.06	250	3	75,000	110,000
1.5 w/o Mo	18.76	18.21	285	2	93,000	122,000
2.0 w/o Mo	18.68	18.07	290	2	77,000	107,000
0.5 w/o Nb	18.88	17.89	211	5	46,000	86,000
1.0 w/o Nb	18.77	17.84	212	6	47,000	91,000
1.5 w/o Nb	18.66	17.19	196	3	51,000	84,000
2.0 w/o Nb	18.55	17.55	235	3	63,000	88,000
0.5 w/o Zr	18.82	17.63	184	3	43,000	60,000
1.0 w/o Zr	18.64	17.34	166	3	39,000	48,000
1.5 w/o Zr	18.47	17.15	174	5	38,000	55,000
2.0 w/o Zr	18.30	17.04	-	3	38,000	66,000

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TABLE XV

TENSILE STRENGTH AND HARDNESS OF FAST-COOLED
COLD-PRESSED AND SINTERED URANIUM ALLOYS

<u>Alloy Addition</u>	<u>Calculated Density, gm/cm³</u>	<u>Actual Density, gm/cm³</u>	<u>Hardness, DPH</u>	<u>Elongation, %</u>	<u>Yield Strength, psi</u>	<u>Tensile Strength, psi</u>
0.8 w/o Mo	18.87	18.44	279	6	69,000	122,000
*1.0 w/o Mo	18.84	18.19	279	4	89,000	119,000
1.0 w/o Mo	18.84	18.35	275	6	63,000	125,000
*1.4 w/o Mo	18.77	18.41	296	5.5	100,000	136,500
2.0 w/o Mo	18.68	18.20	306	4	87,000	135,000
3.0 w/o Mo	18.52	18.04	335	1.5	101,000	145,000
*3.5 w/o Mo	18.44	17.96	367	-	-	147,000
4.0 w/o Mo	18.37	17.94	392	1	136,000	160,000
*2.0 w/o Zr	18.30	18.08	278	9	81,000	122,000
0.5 w/o V	18.80	18.23	260	4.5	58,000	111,000
1.0 w/o V	18.60	18.17	277	4.5	55,000	110,000
0.75 w/o Si	18.03	17.80	250	3	46,000	80,000
3.0 w/o Nb	18.33	17.53	338	1.5	100,000	145,000

*Early determination

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All the addition elements tested appear to enhance the strength of uranium. Molybdenum alloys in particular had uniformly high tensile strength. For comparison, the yield strength of unalloyed cast uranium is given as 28,000 psi and the tensile strength as 56,000 psi⁽⁵⁾. Elongation in two inches is 4%.

Results of the test depended upon the rate at which the alloy was cooled from the sintering temperature. Fast-cooled alloys were stronger than slow-cooled ones of the same composition.

Carbon content was not determined in these specimens, but the uranium powder used was prepared from wrought stock which normally analyzed 500 to 600 ppm carbon.

C. Irradiation Effects

Several specimens of unalloyed and alloyed uranium prepared by powder metallurgical techniques at the Sylvania-Corning Nuclear Corporation were irradiated in the MTR and the results were reported by Kittel⁽¹⁾ and Paine of ANL. The compositions studied included binary alloys of uranium containing 1.0, 1.4, 2.0 and 2.5 w/o Mo; 1.6 w/o Nb; and 0.42 w/o Si.

The conclusion reached with regard to unalloyed uranium compacts was that little improvement in dimensional stability is shown by powder metallurgical specimens over beta-treated wrought material. The values of G_1 , rate of growth, were -23 micro-in/in/ppm burnup for the compacts and 25 micro-in/in/ppm burnup for beta-quenched rolled uranium. However, the surface smoothness of the powder compacts was considerably better than that shown by the wrought material.

The effects of irradiation on uranium alloys are recorded in Table XVI which is reproduced from the above-mentioned paper⁽¹⁾. The 1 w/o Mo alloy showed an average growth coefficient of 10 micro-in/in/ppm burnup, but a large amount of surface roughening occurred. Increasing the molybdenum content resulted in an improvement in surface smoothness, but also caused an increase in the lengthwise growth rate.

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TABLE XVI

EFFECT OF IRRADIATION ON COLD-PRESSED AND SINTERED URANIUM
ALLOY POWDER COMPACTS

Specimen Number	Composition, w/o	Grain Size, μ	Burnup, a/o	Calculated Temp., °C		Length Change, %	G ₁ , micro- in/in/ppm burnup	Diameter Change, %	Weight Change, mg	Density Change, %	Hardness Change, RA
				Surface	Center						
BD-6-2	1.0 Mo	50	0.17	75	90	2.76	16	5.41	-4.1	-3.42	(a)
BD-5-2	1.0 Mo	50	0.26	95	120	3.41	13	5.72	0.6	-5.17	(a)
BD-1-3	1.0 Mo	50	0.32	100	130	2.84	8.8	6.75	1.9	-2.31	(a)
BD-2-3	1.0 Mo	50	0.33	110	140	3.36	10	5.95	-18.5	-4.34	(a)
BD-7-2	1.0 Mo	50	0.36	120	150	2.56	7.0	5.06	-1.0	-2.08	(a)
BD-8-2	1.0 Mo	50	0.38	120	150	2.63	6.8	5.83	0.3	-2.37	(a)
CD-2-2	1.4 Mo	-	0.106	-	(b)	1.46	14	0.046	1.2	-	9.1
CD-1-2	1.4 Mo	-	0.110	-	(b)	1.80	16	0.50	3.0	-	9.6
CD-5-2	2.0 Mo	-	0.072	-	(b)	1.47	20	0.14	2.6	-	8.8
CP-4-2	2.0 Mo	-	0.085	-	(b)	0.75	8.7	0.47	5.9	-	9.7
CD-3-2	2.0 Mo	-	0.095	-	(b)	1.89	20	0.37	6.6	-	7.2
CD-6-2	2.5 Mo	-	0.055	-	(b)	1.21	22	0.091	1.9	-	7.4
BD-6-3	1.6 Nb	20	0.19	85	95	1.82	9.5	0.96	0.5	-1.88	6.2
BD-5-3	1.6 Nb	20	0.26	95	120	2.46	9.4	2.20	0.7	-3.22	4.3
BD-4-3	1.6 Nb	20	0.32	110	130	2.43	7.5	3.22	0.9	-4.00	4.9
BD-3-3	1.6 Nb	20	0.35	120	150	3.59	10	3.34	1.7	-5.30	0.5
BD-7-3	1.6 Nb	20	0.37	120	150	2.49	6.6	1.16	1.0	-1.68	(c)
BD-8-3	1.6 Nb	20	0.37	120	150	1.78	4.8	1.00	1.0	-1.25	11.3
BD-1-2	0.42 Si	300	0.30	100	130	16.2	50	(d)	(d)	(d)	(d)
BD-4-2	0.42 Si	300	0.32	110	130	19.8	56	(d)	(d)	(d)	(d)
BD-2-2	0.42 Si	300	0.33	110	140	17.3	48	(d)	(d)	(d)	(d)
BD-7-1	0.42 Si	300	0.35	120	150	35.2	86	(d)	(d)	(d)	(d)
BD-3-2	0.42 Si	300	0.35	120	150	29.4	74	(d)	(d)	(d)	(d)
BD-8-1	0.42 Si	300	0.37	120	150	22.2	54	(d)	(d)	(d)	(d)

(a) Specimen surface was too rough for measurement.

(b) Estimated to have been between 10° and 150°C.

(c) Specimen fractured when load was applied to indenter.

(d) Measurements could not be made because specimen was stuck in irradiation holder.

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The 1.6 w/o niobium specimens were the best of those studied. G_1 for this alloy was 8.0 micro-in/in/ppm burnup. Good surface smoothness was also obtained.

Specimens containing 0.42 w/o Si, after 0.3 a/o burnup, were so distorted and roughened that they could not be removed from the holders in which they were irradiated. Growth rate on these specimens was determined to be 61 micro-in/in/ppm burnup.

A correlation was obtained between grain size and surface roughening during irradiation in cold-pressed and sintered alloys. The finest grain size, 20 microns, was found in the 1.6 w/o niobium alloy and the coarsest, 300 microns, in the 0.42 w/o silicon alloy. These were the most satisfactory and least satisfactory, respectively, with regard to surface roughening.

IV. SUMMARY AND CONCLUSIONS

Sound homogeneous specimens of uranium and its alloys can be easily produced by powder metallurgical techniques. Both hot-pressing, and cold-pressing and sintering can be used for preparing unalloyed uranium and those alloys containing only relatively low melting additions. The more satisfactory alloys, those containing high-melting point additions such as molybdenum, niobium, and chromium, are best prepared by cold pressing followed by sintering at a temperature approaching the melting point of the alloy.

Slow alpha-beta thermal cycling on unalloyed uranium showed the amount of deformation in powder metallurgical specimens to be similar to that obtained with cast or wrought material. In all cases, the total distortion was undesirably large.

Alpha range thermal cycling of uranium alloys was found to be insufficiently discriminating. Slow alpha-beta cycling, from 200° to 720°C, was chosen as a standard test for alloys. Thermal cycling indicated the superiority of cold pressed and sintered alloys, as compared to hot pressed alloys of the same composition. Cold pressed and sintered alloys were

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found to deform as little or less than arc-melted, cast, or wrought alloys of the same composition. This behavior is attributed to the superior homogeneity of the powder metallurgical product.

The most stable alloys tested by alpha-beta thermal cycling were those containing 4 to 11 w/o molybdenum and 4.6 to 14 w/o niobium. A 2 w/o Mo + 0.5 w/o Zr alloy also displayed excellent stability. Other promising systems included U-Mo-Nb, U-Mo-V, U-Mo-C, U-Nb-V and U-Cr. A more complete investigation is necessary to determine the most satisfactory compositions in these systems.

Tests of mechanical properties of several binary uranium alloys indicated that such elements as Mo, Cr, Nb, Zr and V significantly increase the yield strength and tensile strength of uranium. Molybdenum is particularly effective in this respect.

Irradiation of several cold-pressed and sintered uranium alloys in the MTR indicated that fine grain size material (about 20 microns) was necessary to reduce surface roughening. Specimens containing 1.6 w/o Nb appeared to be most satisfactory of those tested from the point of view of surface texture and growth. Uranium-molybdenum alloys were somewhat less stable and alloys containing 0.42 w/o silicon were completely unsatisfactory. Only alloys with the above mentioned small additions were irradiated.

It is suggested that effort in the future be concentrated on determining the optimum amount of alloy elements which must be added to uranium to produce materials stable in alpha-beta thermal cycling. These materials should then be radiation tested to determine their behavior under actual reactor operating conditions.

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APPENDIX

Results of Slow Alpha-Beta Thermal
Cycling of Uranium and Uranium Alloys
Performed at Sylvania-Corning Nuclear
Corporation (500 Cycles).

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Specimen Number	Alloy Addition	w/c	Preparation	Initial Diameter inches	Density, gm/cm ³			Hardness, DPH		% Change/500 Cycles			Appearance After Cycling
					Calculated	Before Cycling	After Cycling	Before Cycling	After Cycling	Length	Diameter		
U-1	None	-	Beta-treated	3/8	19.0	18.80	17.42	224	-				Broke capsule, oxidized badly
	None	-	wrought										
U-2	None	-	" " "	3/8	19.0	18.85	18.54	241	-	+31.6	+13.16		Growth in all directions
U-3	None	-	" " "	3/8	19.0	18.82	17.95	238	-	+56.7	-		Spiny, cactus-like
U-4	None	-	" " "	3/8	19.0	18.82	18.70	225	-	+ 9.09	+18.40		Completely distorted
U-5	None	-	CPS	3/8	19.0	18.49	13.34	-	-	+12.98	+16.76		Mushroomed severely one end, rough
B-1	Cr	1.0	CPS	3/8	18.69	17.31	15.65	221	351	+ 6.60	+ 6.13		Rough, badly warped
B-2	Cr	1.0	CPS	3/8		18.30	17.72	-	-	- 0.99	+13.10		Twisted and wrinkled
B-3	Cr	1.0	CPS	3/8		18.22	18.03	250	-	+ 0.66	+ 0.93		Smooth
B-4	Cr	1.0	CPS	3/8		18.31	16.92	231	-	+ 4.57	+ 0.83		
B-5	Cr	1.0	CPS	3/8		18.29	17.16	227	-	+ 3.64	+ 6.97		
B-6	Cr	1.0	CPS	3/8		17.89	10.31	-	-	+25.20	+21.33		
B-7	Cr	1.0	CPS	3/8		17.99	17.65	-	-	+ 1.00	+ 3.87		Rough
B-8	Cr	1.0	CPS	3/8		17.97	16.86	-	-	+ 9.15	- 1.87		Very rough
B-9	Mo	1.2	CPS	3/8	18.81	18.43	18.23	-	-	+ 0.40	+ 4.80		Badly wrinkled
B-10	Mo	1.2	CPS	3/8		18.22	18.22	-	-	- 1.53	+ 1.95		Smooth, two indentations
B-11	Mo	1.2	CPS	3/8		18.51	18.50	287	290	+ 1.18	+ 0.54		Rough, slightly oxidized
B-12	Mo	1.2	CPS	3/8		18.41	18.47	300	-	- 0.40	+ 1.99		Rough, oval shape, slight oxidation
B-13	Mo	1.2	CPS	3/8		18.48	18.36	310	-	0	+ 2.47		Rough, slightly wrinkled, slightly oval, slight oxidation
B-14	Mo	1.2	CPS	3/8		18.52	18.30	-	-	+ 0.60	+ 1.19		
B-15	Mo	1.2	CPS	3/8		18.53	18.41	-	-	+ 0.67	+ 0.89		
B-16	Mo	1.2	CPS	3/8		18.68	18.40	-	-	+ 2.93	+ 1.06		
B-17	Mo	1.2	CPS	3/8		18.50	18.54	-	-	+ 0.007	- 0.45		Smooth, slight bulge in center
B-18	Mo	1.2	CPS	3/8		18.56	18.49	-	-	- 1.33	+ 1.72		
B-19	Mo	1.2	CPS	3/8		18.50	18.48	-	-	- 0.07	+ 1.86		
B-20	Mo	1.4	cast, hot rolled	3/8	18.77	18.45	-	395	-	- 3.67	+ 8.48		Rough, bent and warped, oval shape
B-21	Mo	1.4	as cast	3/8		18.53	-	286	-	- 3.86	+ 6.63		Rough, bent, warped, oval shape
B-22	Mo	1.4	as cast	3/8		18.45	-	303	-	- 2.49	+ 4.60		Rough, bent, warped, oval top, round bottom
B-23	Mo	1.4	as cast	3/8		18.47	-	322	-	- 2.17	+ 5.48		Rough, bent, warped, oval shape
B-24	Mo	1.4	as cast	3/8		18.44	18.11	297	-	- 2.29	+ 7.60		Rough, bent, warped, wrinkled, oxidized
B-25	Mo	1.4	as cast	3/8		18.47	18.50	303	-	- 1.00	+ 2.78		Slightly rough, oval, one lump

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Specimen Number	Alloy Addition	w/o	Preparation	Initial Diameter, inches	Density, gm/cm ³			Hardness, DPH		% Change/500 Cycles		Appearance After Cycling
					Calculated	Before Cycling	After Cycling	Before Cycling	After Cycling	Length	Diameter	
B-26	Mo	1.4	as cast	3/8	18.77	18.49	18.45	337	-	-5.07	+3.89	
B-27	Mo	1.4	as cast	3/8		18.48	18.55	316	-	-2.60	+5.33	Slightly rough, egged at one end
B-28	Mo	1.4	as cast	3/8		18.48	18.55	295	-	-6.42	+8.81	
B-29	Mo	1.4	CPS	3/8		18.54	18.53	283	320	+0.26	+1.61	Slightly oxidized, warped, graininess
B-30	Mo	1.4	CPS	3/8		18.25	-	261	-	+0.78	-2.19	
B-31	Mo	1.4	CPS	3/8		18.44	18.29	302	-	-2.06	0	
B-32	Mo	1.4	CPS	3/8		18.30	18.35	291	-	+0.07	+0.61	Slightly wrinkled
B-33	Mo	1.4	CPS	3/8		18.47	18.36	-	-	+1.73	+0.72	Slightly rough, tapered one end
B-34	Mo	1.4	CPS	3/8		18.52	18.30	-	-	+0.66	+2.00	Rounded at both ends
B-35	Mo	1.4	CPS	3/8		18.53	18.28	-	-	+0.53	+1.60	Smooth, slightly oval
B-36	Mo	1.4	CPS	3/8		18.30	18.33	-	-	+0.13	+1.59	Slightly rough, bumpy
B-37	Mo	1.4	CPS	3/8		18.52	18.45	-	-	+0.13	+1.33	Smooth, slightly rounded one end
B-38	Mo	1.4	CPS	3/8		18.52	18.43	-	-	+0.80	+1.07	Smooth, slightly rounded one end
B-39	Mo	1.75	CPS	3/8	18.72	18.38	18.37	-	-	+1.33	+1.60	Smooth, one wrinkle
B-40	Mo	1.75	CPS	3/8		17.87	17.65	-	-	+0.07	+0.66	
B-41	Mo	1.75	CPS	3/8		17.99	17.59	-	-	+1.73	+1.85	Slightly wrinkled
B-42	Mo	1.75	CPS	3/8		17.97	17.73	-	-	+0.66	+0.87	Smooth
B-43	Mo	1.75	CPS	3/8		17.86	17.63	-	-	+0.33	+0.80	
B-44	Mo	2.0	CPS	3/8	18.68	18.09	17.62	-	-	+9.51	+5.44	Slight melting caused by temp. over-shoot
B-45	Mo	2.0	CPS	3/8		18.52	18.36	-	-	-0.93	-1.33	
B-46	Mo	2.5	CPS	3/8	18.60	18.24	17.97	-	-	+1.86	+1.32	Slightly rough
B-47	Mo	2.5	CPS	3/8		18.30	18.13	-	-	-0.13	+0.88	Smooth, shiny
B-48	Mo	2.5	CPS	3/8		18.22	18.08	-	-	+2.19	+1.06	Slightly rough
B-49	Mo	2.5	CPS	3/8		18.18	17.46	-	-	+0.07	+4.52	Rough, slightly oval, slight melting
B-50	Mo	2.5	CPS	3/8		18.31	18.20	-	-	-0.46	+0.31	
B-51	Mo	2.5	CPS	3/8		18.21	17.84	-	-	+2.00	+1.86	Slightly wrinkled
B-52	Mo	2.5	CPS	3/8		18.37	18.26	-	-	-0.13	+0.35	
B-53	Mo	2.5	CPS	3/8		18.15	17.88	-	-	+2.80	+2.26	Slightly wrinkled
B-54	Mo	3.0	CPS	3/8	18.52	18.09	18.03	375	-	+2.66	+0.96	Rough, slightly oval, slightly oxidized
B-55	Mo	3.5	CPS	3/8	18.44	18.12	17.98	374	259	+0.26	-0.54	Smooth, slightly oxidized
B-56	Mo	3.75	CPS	3/8	18.40	17.80	17.91	-	-	-0.53	+0.40	

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Specimen Number	Alloy Addition	w/o	Preparation	Initial Diameter, inches	Density, gm/cm ³			Hardness, DPH		% Change/500 Cycles		Appearance After Cycling
					Calculated	Before Cycling	After Cycling	Before Cycling	After Cycling	Length	Diameter	
B-57	Mo	3.75	CPS	3/8	18.40	17.62	17.73	-	-	-1.07	+0.35	
B-58	Mo	3.75	CPS	3/8		17.85	17.69	-	-	+2.46	+2.21	Wrinkled
B-59	Mo	4.0	CPS	3/8	18.37	16.78	16.77	248	-	+0.67	+0.61	Slightly wrinkled, slightly oxidized
B-60	Mo	4.0	CPS	3/8		17.13	17.05	349	-	+0.13	+0.95	Slightly wrinkled, slightly oxidized
B-61	Mo	4.5	CPS	3/8	18.29	17.46	17.44	-	-	+0.40	-0.18	
B-62	Mo	4.5	CPS	3/8		17.57	17.48	-	-	+0.60	0	Smooth
B-63	Mo	4.5	CPS	3/8		17.70	17.60	-	-	+0.27	+0.80	
B-64	Mo	4.5	CPS	3/8		17.50	17.48	-	-	0	-0.22	Smooth
B-65	Si	0.5	as cast	3/8	18.34	17.96	18.02	-	-	-0.60	+2.77	Smooth
B-66	Si	0.5	as cast	3/8		18.00	18.16	-	-	-2.39	+2.90	Slightly rough, rounded ends
B-67	Si	0.5	as cast	3/8		17.96	18.13	-	-	+0.13	+3.43	Smooth, rounded ends, bow in middle
B-68	Si	0.5	as cast	3/8		17.97	18.03	-	-	+1.33	+7.12	Rough, slightly tapered both ends
B-69	Si	0.5	CPS	3/8		17.39	18.36	236	290	-5.94	+1.87	Slightly rough, bad warp
B-70	Si	0.5	CPS	3/8		18.21	-	300	-	+4.73	+3.60	
B-71	Si	0.5	CPS	3/8		18.16	-	274	-	+5.74	+6.32	
B-72	Si	0.5	CPS	3/8		18.07	11.44	-	-	+22.61	+16.71	
B-73	Si	0.5	CPS	3/8		17.96	17.74	-	-	-3.54	+2.79	Smooth, slight flare one end
B-74	Si	0.5	CPS	3/8		17.76	10.21	-	-	+22.30	+22.02	Rough, bloated
B-75	Si	0.5	CPS	3/8		18.07	9.68	-	-	+29.73	+25.93	
B-76	Si	0.5	CPS	3/8		18.06	9.66	-	-	+46.34	+11.79	
B-77	Si	0.5	CPS	3/8		18.05	9.93	-	-	+20.40	+17.07	
B-78	Si	1.0	as cast	3/8	17.73	17.51	17.66	-	-	-1.81	+1.86	Slightly rough, rounded ends
B-79	Si	1.0	as cast	3/8		17.55	17.37	-	-	+6.40	+10.03	Rough, flared ends
B-80	Si	1.0	as cast	3/8		17.51	sample was pyrophoric and burned when capsule was cut open					
B-81	Si	1.0	cast and wrought	3/8		18.08	18.05	-	-	-2.27	+6.38	Smooth, rounded ends, bow in middle
B-82	Si	1.0	cast and wrought	3/8		18.10	17.57	-	-	+18.19	+14.02	Rough, flared ends
B-83	Si	1.0	cast and wrought	3/8		18.11	17.90	-	-	+5.73	+0.57	Slightly wrinkled, slightly flared ends
B-84	Si	1.0	cast and wrought	3/8		18.11	17.88	-	-	+10.49	-2.39	Slightly rough
B-85	Si	1.0	cast and wrought	3/8		18.15	17.43	-	-	+18.18	-3.20	Medium wrinkling
B-86	Si	1.0	cast and wrought	3/8		18.38	17.93	-	-	+15.22	-3.19	Medium wrinkling
B-87	Si	1.0	cast and wrought	3/8		17.89	17.40	-	-	+11.07	+0.72	Slightly wrinkled, slightly flared ends

Specimen Number	Alloy Addition	w/o	Preparation	Initial Diameter, inches	Density, gm/cm ³			Hardness, DPH		% Change/500 Cycles			Appearance After Cycling
					Calculated	Before Cycling	After Cycling	Before Cycling	After Cycling	Length	Diameter		
B-88	V	0.5	CPS	3/8	18.80	17.58	16.47	-	-	+2.60	+5.59		Slightly rough
B-89	V	0.5	CPS	3/8		16.40	17.75	-	-	-2.40	+1.94		Smooth, tapered at one end
B-90	W	2.0	CPS	3/8	19.01	18.72	13.62	269	-	+38.2	+4.68		Very rough, oval, some points
B-91	W	2.0	CPS	3/8		18.31	13.92	236	-	+24.5	+10.21		
B-92	Zr	2.0	CPS	3/8	18.30	17.16	12.54	180	-	+15.7	+15.8		Rough, slightly flared ends, one indentation
B-93	Zr	2.0	CPS	3/8		16.82	14.54	-	-	+4.46	+13.10		Rough, flared and cracked one end
B-94	Zr	2.0	CPS	3/8		17.26	14.02	-	-	+14.51	+12.57		Rough, flared ends
B-95	Zr	2.0	CPS	3/8		17.92	10.44	-	-	+16.07	+25.87		Very rough, bloated
B-96	Zr	2.0	CPS	3/8		17.75	9.27	-	-	+30.13	+29.87		Bloated, many small points
B-97	Mo-Nb	0.5-0.5	CPS	3/8	18.80	18.40	18.31	297	323	+1.3	+3.4		Slightly rough
B-98	Mo-Nb	0.75-0.75	CPS	3/8	18.71	18.34	17.83	280	277	+8.5	+6.1		Slightly rough, ends cupped
B-99	Mo-Nb	0.75-0.75	CPS	3/8		18.27	18.31	312	366	+3.3	+0.9		Wrinkled surface
B-100	Mo-Si	0.5-0.5	CPS	3/8	18.27	-	-	-	-	+1.01	+0.09		Smooth, many small points on surface
B-101	Mo-Ti	0.5-0.5	CPS	3/8	18.62	-	-	-	-	+3.04	+2.84		Slightly rough
B-102	Mo-V	0.5-0.5	CPS	3/8	18.72	-	-	-	-	+1.29	+1.46		Slightly rough
B-103(1)	Mo-V	0.5-0.5	CPS	3/8		-	-	-	-	+1.80	-0.45		Smooth, ends cupped, slight warp
B-104(1)	Nb-Ti	0.5-0.5	CPS	3/8	18.59	-	-	-	-	+0.19	+7.68		Rough, one end cupped
B-105	Nb-V	0.5-0.5	CPS	3/8	18.68	-	-	-	-	+2.68	-0.24		Rough, one end cupped
B-106	Cr-V	1.0-0.5	CPS	3/8	18.50	-	-	-	-	+1.57	+5.21		Slightly rough, barrel shaped
B-107	V-Si	0.5-0.5	CPS	3/8	18.15	-	-	-	-	+3.36	+3.35		Rough
C-1	Mo	0.5	CPS	1/5	18.92	17.57	17.12	249	264	+11.3	+1.04		Rough, warped badly
C-2	Mo	1.0	CPS	1/5	18.84	17.88	17.42	268	288	+0.97	+1.60		Slightly rough, bulge in center
C-3	Mo	6.0	CPS	1/5	18.06	17.59	17.41	430	228	+0.27	+0.63		Unchanged
C-4	Mo	6.0	CPS	1/5		17.73	17.60	428	223	+0.21	+0.51		Unchanged
C-5	Mo	11.0	CPS	1/5	17.35	16.91	16.94	309	315	-0.03	0		Unchanged
C-6	Mo	11.0	CPS	1/5		16.90	16.97	309	315	0	+0.03		Unchanged
C-7	Mo-Al	1.0-0.5	CPS	1/4	18.29	17.25	17.54	301	333	-1.46	+1.36		
C-8	Mo-Al	0.5-0.5	CPS	1/5	18.37	17.62	14.40	338	√33	+7.47	+3.85		Slightly rough, ends cupped
C-9	Mo-C	0.5-0.1	CPS	1/5	18.78	18.00	17.56	272	310	+2.53	+6.19		
C-10	Mo-C	1.0-0.1	CPS	1/4	18.70	15.62	16.27	137	219	+3.4	+1.7		Badly warped, surface cracked
C-11	Mo-C	1.0-0.1	CPS	1/5		17.56	17.74	250	301	+0.13	+0.74		Smooth, ends cupped

Specimen Number	Alloy Addition	w/o	Preparation	Initial Diameter, inches	Density, gm/cm ³			Hardness, DPH		% Change/500 Cycles		
					Calculated	Before Cycling	After Cycling	Before Cycling	After Cycling	Length	Diameter	Appearance After Cycling
C-12	Nb	1.0	CPS	1/4	18.77	17.82	15.73	262	165	+16.0	+5.70	Rough, cupped ends
C-13	Nb-Al	1.0-0.5	CPS	1/5	18.23	17.20	16.86	242	192	+2.67	+4.97	Rough, slight warp
C-14	Nb-C	0.5-0.1	CPS	1/4	18.74	14.95	12.61	~91	~45	+31.3	+3.27	
C-15	Nb-C	0.5-0.1	CPS	1/4		17.30	13.22	218	83	+13.7	+13.2	Smooth, surface cracked
C-16	Nb-C	1.0-0.1	CPS	1/4	18.63	17.05	13.84	216	60	+10.0	+13.6	Surface cracked, ends cupped
C-17	Nb-Si	0.5-0.25	CPS	1/4	18.56	17.61	13.09	200	-	+26.3	+13.0	Wrinkled, ends cupped
C-18	Nb-Si	1.0-0.25	CPS	1/4	18.45	15.95	15.81	197	229	+2.23	+0.17	Slightly rough, ends cupped
E-1	Cr	0.5	CPS	1/5	18.85	18.04	18.31	257	353	-4.7	+3.1	Slightly rough, slight warp
E-2	Cr	0.5	CPS	1/5		17.99	18.18	250	380	-2.0	+1.6	Smooth, slight warp
E-3	Cr	0.5	CPS	1/5		18.27	16.93	240	-	-0.8	+7.6	Slightly rough, slight warp
E-4	Cr	1.0	CPS	1/5	18.69	18.21	18.11	267	376	-1.6	+2.8	Fairly smooth, slight warp
E-5	Cr	1.0	CPS	1/5		18.09	18.07	265	369	-2.9	+6.6	Smooth, slight warp
E-6	Cr	1.0	CPS	1/5		18.50	17.77	269	-	-2.3	+8.3	Slightly rough, slight swelling in center
E-7	Cr-Al	1.0-0.5	CPS	1/5	18.15	17.24	14.41	301	-	+43.2	+28 to +54	Bottle shape, part of surface rough
E-8	Cr-Al	1.0-0.5	CPS	1/5		17.35	16.88	290	375	-1.4	+6.2	Slightly rough, slight warp
E-9	Cr-C	0.5-0.1	CPS	1/5	18.70	17.92	18.20	274	344	-3.5	+2.5	Fairly smooth, cupped ends, slight warp
E-10	Cr-C	0.5-0.1	CPS	1/5		17.95	18.01	262	387	-5.3	+2.6	Smooth, slightly warped, ends cupped
E-11	Cr-C	0.5-0.1	CPS	1/5		18.29	17.28	252	-	+1.3	+4.9	Slightly rough
E-12	Cr-C	1.0-0.1	CPS	1/5	18.55	17.91	17.91	261	374	-1.7	+1.5	Smooth, slight warp
E-13	Cr-C	1.0-0.1	CPS	1/5		17.87	17.87	268	339	-2.4	+2.5	Smooth, slight warp
E-14	Cr-Si	0.5-0.25	CPS	1/5	18.51	18.04	13.45	282	~75	+15.9	+17.8	Rough, swollen
E-15	Cr-Si	0.5-0.25	CPS	1/5		17.97	11.80	296	~83	+13.2	+18.6	Rough, swollen
E-16	Cr-Si	1.0-0.25	CPS	1/5	18.37	18.00	9.56	340	~66	+24.4	+19.5	Rough, swollen
E-17	Cr-Si	1.0-0.25	CPS	1/5		17.75	10.33	321	~60	+23.8	+16.8	Rough, swollen
E-18	Mo	1.2	CPS	1/5	18.81	18.41	18.83	293	-	-1.6	+1.7	Slightly rough, slight warp
E-19	Mo	1.2	CPS	1/5		18.19	18.22	303	358	-	-	Completely distorted as if melted
E-20	Mo	1.4	CPS	1/5	18.77	17.99	18.31	305	-	-	-	Completely distorted as if melted
E-21	Mo	1.4	CPS	1/5		18.39	18.86	308	-	-1.2	+1.75	Smooth
E-22	Mo	1.4	CPS	1/5		18.04	18.14	313	367	-	-	Completely distorted as if melted
E-23	Mo	1.75	CPS	1/5	18.72	17.99	17.71	300	330	+2.0	+4.6	Slightly rough
E-24	Mo	1.75	CPS	1/5		17.86	16.82	-	-	+0.3	+0.4	Rough, ends cupped

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Specimen Number	Alloy Addition	w/o	Preparation	Initial Diameter, inches	Density, gm/cm^3			Hardness, DPH		% Change/500 Cycles		
					Calculated	Before Cycling	After Cycling	Before Cycling	After Cycling	Length	Diameter	Appearance After Cycling
E-25	Mo	1.75	CPS	1/5	18.72	17.95	16.67	297	316	+2.0	+10.6	Rough, ends cupped
E-26	Mo	1.75	CPS	1/5		18.17	16.86	-	306	-0.5	+1.4	Rough, ends cupped
E-27	Mo	2.0	CPS	1/5	18.68	17.36	17.15	312	347	+2.1	+7.1	Rough
E-28	Mo	2.0	CPS	1/5		17.33	17.46	-	331	-2.1	-0.4	Slightly rough
E-29	Mo	2.0	CPS	1/5		17.82	17.44	317	374	+0.9	+5.4	Rough
E-30	Mo	2.0	CPS	1/5		17.68	17.41	-	316	-0.7	+0.5	Slightly rough
E-31	Mo	2.5	CPS	1/5	18.60	17.51	17.20	297	409	+1.0	+1.0	Smooth
E-32	Mo	2.5	CPS	1/5		17.31	17.12	-	351	+1.1	-0.4	Smooth
E-33	Mo	2.5	CPS	1/5		17.46	16.95	298	394	+1.0	+1.0	Smooth
E-34	Mo	2.5	CPS	1/5		17.32	17.01	296	396	+2.1	+1.6	Smooth
E-35	Mo	2.5 Hot powder rolled	1/4			17.72	17.63	224	-	+15.3	-2.2	Rough, elongated
E-36	Mo	6.0	CPS	1/5	18.06	16.75	16.71	-	171	+0.1	0	Unchanged
E-37	Mo	6.0	CPS	1/5		16.89	16.66	325	173	+0.1	0	Unchanged
E-38	Mo-C	0.5-0.1	CPS	1/5	18.78	18.23	9.77	315	(2)	-	-	Very rough, elongated
E-39	Mo-C	0.5-0.1	CPS	1/5		18.23	10.46	323	(2)	+32.1	+40.0	Swollen, many surface cracks
E-40	Mo-C	1.0-0.1	CPS	1/5	18.70	18.00	18.08	319	388	-	-	Completely distorted as if melted
E-41	Mo-C	1.0-0.1	CPS	1/5		18.46	18.21	320	-	0	+0.9	Slightly rough, slight warp
E-42	Mo-Si	0.5-0.25	CPS	1/5	18.59	17.89	12.29	350	81	-	-	Swollen and distorted
E-43	Mo-Zr	2.0-0.5	CPS	1/5	18.50	17.66	17.92	330	400	-0.7	+0.2	Slight graininess
E-44	Mo-Zr	2.0-0.5	CPS	1/5		17.79	17.99	300	389	-0.1	+0.7	Slight graininess
E-45	Mo-Zr	2.0-0.5	CPS	1/4		17.72	17.92	306	406	-0.2	+0.4	Slight graininess
E-46	Mo-Zr	2.0-0.5	CPS	1/4		17.70	17.97	310	380	-0.3	+0.5	Slight graininess
E-47	Mo-Zr	2.0-0.5	CPS	1/4		17.69	17.91	308	413	-0.5	+0.5	Slight graininess
E-48	Mo-Zr	2.0-0.5	CPS	1/4		17.65	17.92	299	379	-0.7	+0.5	Slight graininess
E-49	Nb	0.5	CPS	1/5	18.88	18.19	12.11	234	(2)	+25.1	+19.3	Rough, elongated
E-50	Nb	0.5	CPS	1/5		17.96	11.51	232	-	+20.2	+20.9	Swollen to diameter of containing tube
E-51	Nb	0.5	CPS	1/5		18.21	11.97	280	119	+25.4	+19.6	Very rough, one end cupped, swollen
E-52	Nb	1.6	CPS	1/5	18.64	17.73	16.20	284	202	+2.4	+7.1	Rough on part of surface
E-53	Nb	1.6	CPS	1/5		17.84	15.85	276	226	+5.2	+7.1	Rough, warped, one end cupped
E-54	Nb	1.6	CPS	1/5		17.75	15.95	290	200	+4.2	+8.9	Rough, warped, one end cupped
E-55	Nb	1.6	CPS	1/5		17.71	15.79	278	224	+3.6	+8.0	Rough, warped, one end cupped

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Specimen Number	Alloy Addition	w/o	Preparation	Initial Diameter inches	Density, gm/cm ³			Hardness, DPH		% Change/500 Cycles		Appearance After Cycling
					Calculated	Before Cycling	After Cycling	Before Cycling	After Cycling	Length	Diameter	
E-56	Nb	1.6	arc melted	1/5	18.64	18.51	17.96	432	283	+7.0	+5.1	Rough, warped
E-57	Nb	4.6	CPS	1/5	17.99	16.46	13.30	315	Smooth, but crimped, ends deeply			cupped, appears to have collapsed around center
E-58	Nb	4.6	CPS	1/5		16.54	13.75	314	"	"	"	"
E-59	Nb	4.6	CPS	1/4		17.76	17.64	380	436	+0.13	+1.0	Slight graininess
E-60	Nb	6.0	CPS	1/4	17.71	16.76	16.86	352	323	+1.1	-0.07	Slight graininess
E-61	Nb	6.0	CPS (3)	1/4		16.85	16.97	362	359	-0.13	+0.48	Slight graininess
E-62	Nb	6.0	arc melted	1/6		17.45	17.43	326	328	+0.3	+0.8	Smooth, slight warp
E-63	Nb	6.0	arc melted	1/6		16.80	16.83	326	425	-0.4	+0.8	Smooth, slight warp
E-64	Nb	8.0	CPS	1/5	17.31	16.28	16.09	364	-	+0.4	+0.4	Unchanged
E-65	Nb	8.0	CPS	1/4		16.28	16.09	383	-	+0.5	+0.6	Unchanged
E-66	Nb	8.0	arc melted	1/6		16.86	16.86	303	219	0	+0.6	Unchanged
E-67	Nb	8.0	arc melted	1/6		16.16	16.17	279	275	-0.2	+1.2	Unchanged
E-68	Nb	8.0	arc melted	1/5		16.81	16.90	305	508	-0.3	+0.1	Unchanged
E-69	Nb	10.0	CPS	1/5	16.84	15.62	15.45	366	217	+0.3	+0.3	Unchanged
E-70	Nb	10.0	CPS	1/5		15.72	15.58	397	216	+0.3	+0.4	Unchanged
E-71	Nb	10.0	CPS	1/5		15.68	15.52	366	227	+0.3	+0.3	Unchanged
E-72	Nb	10.0	CPS	1/5		15.69	15.57	384	278	+0.3	+0.1	Unchanged
E-73	Nb	10.0	arc melted	1/5		16.17	16.12	273	233	0	+0.2	Unchanged
E-74	Nb	14	arc melted	1/5	16.23	14.69	14.67	237	285	+0.2	+0.2	Unchanged
E-75	Nb-Al	0.5-0.5	CPS	1/5	18.34	17.41	11.30	302	(2)	+9.3	+28.9	Network of five cracks, uneven diameter
E-76	Nb-Al	0.5-0.5	CPS	1/5		17.63	12.30	294	(2)	+7.4	+25.1	Several vertical cracks
E-77	Nb-Si	0.5-0.25	CPS	3/10	18.56	17.78	9.89	249	(2)	+26.2	+29.9	Swollen
E-78	Nb-Si	0.5-0.25	CPS	3/10		17.48	11.24	257	(2)	+15.3	+92.4	Swollen and cracked
E-79	Nb-Si	0.5-0.25	CPS	1/5		17.99	10.22	261	144	+33	+28.4	Swollen, cracked, one end cupped, other "melted over"
E-80	Nb-Si	0.5-0.25	CPS	1/5		17.73	9.75	254	(2)	+29.5	+27.8	Swollen
E-81	Nb-Si	1.0-0.25	CPS	3/10	18.45	16.90	11.32	237	(2)	+4/47	+28.4	Swollen to diameter of containing tube, one end cupped
E-82	Nb-Si	1.0-0.25	CPS	3/10		16.64	7.90	272	(2)	+28	+30.4	" " " " " " " "
E-83	Nb-Si	1.0-0.25	CPS	1/5		17.39	10.64	249	(2)	+41	+32.4	Swollen, warped, horizontal cracks, one end cupped
E-84	Nb-Si	1.0-0.25	CPS	1/5		17.47	10.64	270	(2)	+29.5	+42.2	Rough, swollen, several small cracks
E-85	Zr	0.5	CPS	1/5	18.82	17.81	11.74	280	87	+4.5	+32.8	Rough, warped, vertical cracks
E-86	Zr	0.5	CPS	1/5		17.88	11.22	287	65	+12.9	+21.5	Rough, badly warped, cupped ends

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