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**AN EXAMINATION OF TEMPERATURE-INDUCED
SHAPE MEMORY OF URANIUM-5.3-TO-6.9
WEIGHT PERCENT NIOBIUM ALLOYS**

V. C. Hemperly

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**OAK RIDGE Y-12 PLANT
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OF URANIUM-5.3-TO-6.9 WEIGHT PERCENT
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ABSTRACT

The uranium-niobium alloy system was examined in the range of 5.3-to-6.9 weight percent niobium with respect to shape memory, mechanical properties, metallography, coefficient of linear thermal expansion, and differential thermal analysis. Shape memory increased with increasing niobium levels in the study range. There were no useful correlations found between shape memory and the other tests. Coefficient of linear thermal expansion tests of as-quenched 5.8 and 6.2 weight percent niobium specimens, but not 5.3 and 6.9 weight percent niobium specimens, had a contraction component on heating, but the phenomenon was not a contributor to shape memory.

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SUMMARY

The uranium-niobium alloy system was examined at four alloy levels (5.3, 5.8, 6.2, and 6.9 wt % Nb) with respect to temperature-induced shape memory, mechanical properties, metallography, linear coefficient of thermal expansion, and differential thermal analysis. The irreversible component of shape memory of coupons, cold bent after water quenching (800° C) and heat cycled to 240° C, increased with increasing niobium content. The magnitude of the reversible component was controlled by the strain remaining after irreversible set rather than by niobium level, *per se*. There were no useful correlations between shape memory and the other test results.

Coefficient of linear thermal expansion tests of as-quenched specimens showed an unusual contraction component at about 200° C with the 5.8 and 6.2 weight percent niobium alloys, but not with the 5.3 and 6.9 weight percent niobium alloys. This phenomenon was not a contributor to shape memory.

Differential thermal analysis showed unexplained, low-temperature heating exotherms at about 200° C that were not related to the other test results.

INTRODUCTION

The mechanical properties of uranium can be improved markedly by alloying, followed by heat treatment. In general, low-level alloys of gamma-miscible elements in uranium can be solution treated, water quenched, and age hardened to obtain a relatively high strength with good ductility for engineering applications. The uranium-niobium and uranium-molybdenum alloy systems are two that are quite useful for this purpose. However, both of these alloy systems, as well as uranium-rhenium alloys, develop a phenomenon referred to as "temperature-induced shape memory".⁽¹⁻³⁾ That is, when the alloys are reheated after solution treating, water quenching, and cold shaping, they return, in part, toward their preworked shape. Because such behavior does not occur after hardening, shape memory is not detrimental to the usefulness of these alloys in engineering systems where they are used in their high-strength condition. However, shape memory does preclude the use of cold-working techniques in metallurgical processing.

Interest in the present study, conducted at the Oak Ridge Y-12 Plant,^(a) is limited to temperature-induced shape memory of the uranium-6 weight percent niobium (U-6 Nb) alloy in that niobium range which might reasonably be encountered in alloy-preparation variability. Metallography, tensile tests, coefficient of linear thermal expansion tests, and differential thermal analyses were made to further evaluate shape memory as related to metallurgical processing.

Jackson and Johns⁽⁴⁾ have studied the phenomenon of heat-sensitive shape memory in the uranium-niobium system and have demonstrated that shape memory: (1) occurs in samples stressed by bending, tension, or compression; (2) is found at niobium levels between 4 and 8 weight percent niobium; (3) is a maximum at about 6 weight percent niobium; (4) has both reversible and irreversible components, but (5) has only a reversible component below the temperature at which it was cold worked.

Somewhat comparable shape-memory behavior has been reported for some nonuranium alloys, namely: indium-tellurium,^(5,6) gold-cadmium,^(7,8) and titanium-nickel.^(9,10) The Brook-Illes patents of shape memory also cover manganese-copper alloys. The shape memory in all of these nonuranium alloy systems has been ascribed to martensitic transformation.

The fact that U-6 Nb alloy readily age hardens at the temperature and times used in demonstrating shape memory introduces the question of how shape memory and age hardening relate to each other. Koger^(b) has demonstrated, in unreported work, that irreversible shape memory in this alloy was unaffected by heating times up to 24 hours at

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Energy Research and Development Administration.

(b) J. W. Koger, Union Carbide Corporation, Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee.

100 and 250° C. At 350° C, shape memory was affected after heating for 24 hours, but not after 8 hours. Jackson and Johns⁽⁴⁾ demonstrated a loss in reversible shape memory in their cold-bend memory tests at 375° C, but not in test specimens cycled at 250° C or below. Therefore, at the low temperatures of interest, such data demonstrate that the age-hardening response of the alloy is unrelated to temperature-induced shape memory. Consequently, any low-temperature test measurements which do correlate with the hardening response are not measurements which correlate with shape memory and can be discarded from consideration. This conclusion simplifies designing the experiment.

Warner, et al,⁽¹¹⁾ and Vandermeer⁽¹²⁾ have found and evaluated a reverse shape memory in a uranium-niobium-zirconium alloy. In their work, quenched specimens aged under an external bend stress for some period of time freely assumed the stressed shape; and, on further age hardening under no external stress, continued to bend further in the same direction. This particular effect is indeed related to age hardening of the alloy, but with a shape-change direction opposite to, and unrelated to, shape memory of the present study.

Caution: Alloys of niobium with uranium may produce explosions on pickling with nitric acid. However, a hydrofluoric acid addition to the pickling bath eliminates the problem.

EXAMINING TEMPERATURE-INDUCED SHAPE MEMORY

PRESENTATION OF EXPERIMENTAL WORK

Alloy Preparation

The U-6 Nb alloy is prone to segregation of the alloying element on both a macro and a micro scale. In order to minimize the effects of segregation variability among the test specimens in the niobium range of interest, the ingots poured were small (40 x 140 x 180 mm) and the test blanks were cut from those sections of the rolled plates which had been the bottom of the ingots. The chemical analyses samples were also taken from the bottom of the ingots. Because solidification is a factor in segregation, slower cooling inherent with large ingots would provide greater alloy element segregation. Consequently, material from large ingots can be compared only qualitatively with the study materials.

Plate scrap of the U-6 Nb alloy, and the required proportion of Derby-grade uranium or U-10 Nb master alloy, were comelted and poured (1450° C) in a vacuum-induction furnace. The graphite crucibles were plasma sprayed with zirconia to minimize carbon contamination of the melts, and the graphite ingot molds were washed with Zirconite A. Carbon in the ingots ranged between 76 and 100 ppm. The niobium content of the prepared melts came out to be 5.3, 5.8, 6.2, and 6.9 weight percent.

All of the ingots were homogenized *in vacuo* at 1000° C for four hours and then gamma rolled from a salt bath (800° C) to 13-mm plates. Longitudinal test blanks were cut from the plates, solution treated (*in vacuo*) for one hour in the gamma range (800° C), then water quenched. Salt-bath heating for rolling adds hydrogen to uranium and uranium alloys, and high hydrogen levels degrade the mechanical properties. However, hydrogen is readily removed by heating at elevated temperatures, so vacuum heating was used for the solutioning treatment prior to water quenching.

Cold-Bend Shape-Memory Tests

For the cold bend shape-memory tests, water-quenched blanks from each of the four niobium levels were machined to 3 by 13 by 100-mm specimens. These specimens were bent at room temperature around a 13-mm-diameter pin to 90 degrees under load, and the springback angle was measured. The bent specimens were then heat cycled in an oil bath three times between room temperature and 240° C. Heating time per cycle was about 10 minutes and the samples were water quenched to room temperature. The leg spread of each specimen was measured at room temperature and at 240° C on each heat cycle. The included angle of the bend was determined after the final cycle. In addition, the specimens were reheated in an argon-atmosphere muffle oven to 300° C for 1/2 hour. The included angles were measured after the specimen returned to room temperature.

Table 1 reports the measurements taken from the cold-bend shape-memory tests at each of the four niobium levels. The irreversible component of shape memory, as measured by the change in leg spread, increased with increasing niobium level (2.44 to 7.76 mm). There was no shape-memory maximum within the range of 5.3 to 6.9 wt % niobium. The same table

Table 1
COMPARISON OF SHAPE MEMORY OF FOUR URANIUM-NIOBIUM
ALLOY COLD-BENT STRIPS

	U-5.3 wt % Nb			U-5.8 wt % Nb			U-6.2 wt % Nb			U-6.9 wt % Nb		
	Leg Spread (mm)	Change (mm)	Included Angle (deg)	Leg Spread (mm)	Change (mm)	Included Angle (deg)	Leg Spread (mm)	Change (mm)	Included Angle (deg)	Leg Spread (mm)	Change (mm)	Included Angle (deg)
Room Temperature	94.23		125	93.65		123	93.73		123	92.89		124
240° C	99.29	+ 5.66		101.39	+ 7.74		101.37	+ 7.64		101.41	+ 8.52	
Room Temperature	96.32	- 3.57		99.37	- 1.52		100.63	- 0.74		100.56	- 0.85	
240° C	99.59	+ 3.57		101.40	+ 1.43		101.17	+ 0.54		101.56	+ 1.00	
Room Temperature	96.57	- 3.22		100.30	- 1.40		100.76	- 0.41		100.64	- 0.92	
240° C	99.59	+ 3.02		101.50	+ 1.50		101.47	+ 0.71		101.45	+ 0.81	
Room Temperature	96.57	- 3.02	135	100.20	- 1.30	153	100.81	- 0.34	159	100.65	- 0.80	159
Irreversible	+ 2.44		10	+ 6.55		30	+ 7.08		36	+ 7.76		35
Reversible		+ 3.21			+ 1.43			+ 0.50			+ 0.88	
After 300° C			11			32			38			35

also shows the component of reversible shape memory in this range of niobium. Reversible shape memory, as a function of leg spread, was a function of the bend angle remaining after irreversible memory (see Figure 1) rather than a function of the niobium level. The strain level in the specimens was the controlling force and it overrode any influence that there might have been from the level of niobium in the alloys. On reheating to 300° C, there was an additional increase in bend angle of irreversible shape memory, as would be expected.

Two attempts were made to obtain the alloy with less niobium segregation for cold-bend shape-memory testing, but both attempts failed. In one case, a specimen was vacuum homogenized at 1000° C for 4 days. This treatment was not successful, although later work indicated that 1100° C for 6 hr did succeed. A second effort was to try to obtain less segregation by rapidly cooling the metal from the melt. A piece of a U-6.1 Nb ingot was placed in an electron-beam welder. A series of side-by-side bead welds were made on one side to obtain a 13 by 13 by 100-mm section that had been rapidly cooled from the melt. This section was cut out, along with an unwelded section on the opposite side of the ingot. Both sections were gamma rolled from a salt bath to 7-mm thickness and then vacuum-water quenched from 800° C. A 3 by 3 by 100-mm blank was machined from each, cold bent 90 degrees under load, and heat cycled three times to 240° C.

Changes in the leg spread and included angle are recorded in Table 2. There was some small difference between the two, but both showed the usual segregation on metallographic

Figure 1. COMPARISON OF THE BEND ANGLE WITH REVERSIBLE MEMORY FOR FOUR URANIUM-NIOBIUM ALLOYS.

Table 2
SHAPE-MEMORY TESTS OF URANIUM-NIOBIUM ALLOY
COLD-BEND SPECIMENS
(U-5.9 wt % Nb)

	Standard Preparation			Weld-Bead Metal		
	Leg Spread (mm)	Change (mm)	Included Angle (deg)	Leg Spread (mm)	Change (mm)	Included Angle (deg)
Room Temperature	89.58		114	89.81		114
240° C	100.46	+ 10.88		100.81	+ 11.00	
Room Temperature	96.77	- 3.69		97.74	- 3.07	
240° C	100.08	+ 3.31		100.51	+ 2.77	
Room Temperature	96.75	- 3.33		97.79	- 2.82	
240° C	99.92	+ 3.17		100.38	+ 2.59	
Room Temperature	96.82	- 3.10	143	97.84	- 2.54	141
Change	+ 7.24	+ 3.23	+ 29	+ 8.03	± 2.68	+ 27

examination. The pertinent point here is that the shape-memory results are not strictly comparable to the results from the study series. The springback on cold bending was only 114 degrees for the included angle rather than the 124 degrees on the test series. This difference, in itself, would leave a greater strain in the specimen and an increased shape memory. There are factors that were normalized among the test-series specimens that are of significance in shape memory.

Metallography

The metallographic specimens were prepared by Syntron polishing with Linde A and water followed by Linde B with a 5% chromic acid solution for attack polishing. The specimens were then etched electrolytically in a 5% oxalic acid solution.

Tensile-test specimens of a U-6 wt % Nb alloy were used in the metallographic study. In this case, the alloy had been prepared by consumable electrode-arc melting of elemental niobium and uranium strips. Longitudinal sections were taken from the threaded end (Figure 2) and from near the fracture end (Figure 3). X-ray diffraction analysis of the sample showed the expected alpha-double-prime structure of the as-quenched alloy. This condition is a supersaturated, alpha-like transition phase with an increase in angle between the a and b parameters that results in a monoclinic structure.

K291-1

Figure 2. THREADED-END URANIUM-6 WT % NIOBIUM ALLOY SPECIMEN. (As Quenched; Bright Field Illumination; 200X)

K291-2

Figure 3. FRACTURE-END SPECIMEN OF URANIUM-6 WT % NIOBIUM ALLOY. (As Quenched; Bright Field Illumination; 200X)

Figure 2 shows twinning within the original gamma grains, and such twinned grains are in alternate twinned and twin-free bands. In the material that was cold worked during tensile testing (Figure 3), there were no twins. In like manner, the edges of the threaded section were also twin free where a thin layer had been cold worked during specimen machining.

These two specimens were examined with a microprobe and a difference was found in the niobium content between the twinned and twin-free bands. The niobium level was 4.98 ± 0.22 wt % in the twinned-band areas; and, in the twin-free areas, it was 5.87 ± 0.35 wt %. Such variation in band compositions continued through the cold-worked fracture-end specimen which was totally twin free.

Metallographic specimens were taken from the cold-bend area of the 6.9 wt % niobium shape-memory test. Figure 4 is a view of the structure as bent; Figure 5 is a view of the structure after shape-memory testing. The twin-free areas were on both the tension and compression sides of the bends, as could be expected from a metallographic examination of the tensile-test specimen.

In the metallographic specimens, the twins are formed by the slight cold working that occurs in the polishing technique. Areas of higher hardness by virtue of chemical composition or by virtue of work hardening prior to polishing do not form twins, while the

L254.3

Figure 4. BEND AREA OF THE URANIUM-6.9 WT % NIOBIUM ALLOY PRIOR TO SHAPE-MEMORY TESTING. (Bright Field Illumination; 100X)

softer areas do twin. Thus, the metallographic twinning is associated with specimen hardness and cannot be associated directly with a shape-memory mechanism.

Standard tensile tests, in the as-quenched condition of the alloy, were made on each niobium level to determine whether or not there would be a useful correlation between mechanical properties and shape memory as determined by cold-bend heat-cycle tests. The results (average of two tests) are reported in Figure 6. Yield strength (0.2%) was about the same through the series. The ultimate tensile strength decreased and the ductility values increased with increasing niobium content. Although there was no direct correlation between mechanical properties and shape memory, an increase in the reduction-in-area values was considerable—31 to 60%. Such a marked increase in work hardening may represent a factor of significance to shape memory. The usual metallurgical control tensile test, however, is not a satisfactory measure of potential for shape memory in the U-6 Nb alloy.

Coefficient of Linear Thermal Expansion

Coefficient-of-linear-thermal-expansion (CTE) tests were made on a U-5.9 Nb alloy that was not one of the ingots specially prepared for the study series. Specimens were vacuum-water quenched from 920° C (the gamma region) and from 680° C, a region

L259-A

Figure 5. BEND AREA OF THE URANIUM-6.9 WT % NIOBIUM ALLOY AFTER SHAPE-MEMORY TESTING AT 240° C. (Bright Field Illumination; 100X)

reported to be an ordered, body-centered-tetragonal structure. Photomicrographs of samples from the two quenching temperatures (Figures 7 and 8) reveal a similar metallographic structure. As would be expected, the original 920° C gamma grain size was much larger than the grain size after a 680° C quench. There were no metallographic differences that could be associated with the gamma versus the ordered tetragonal structures of the respective quenching temperatures.

Coefficient-of-linear-thermal-expansion tests were made on each to 300° C, cooled to room temperature, and retested to 400° C. The heating rate was about 5° C/min. Figure 9 shows significant sections from the curves redrawn for ease of visual comparison. The curves were all distorted by an independent specimen contraction at low temperature. Much of the capacity for curve distortion was removed during the first run. The balance was completely removed on the second run, as evidenced by third runs (not shown) that had no curve distortions. Vacuum-water quenching from the ordered, body-centered-tetragonal region (680° C) did produce less curve distortion than quenching from the gamma region (920° C). However, the difference was small, so the effect of the quenching temperature was not evaluated any further.

Coefficient-of-linear-thermal-expansion tests of the four alloy levels of the study series are portrayed in Figure 10. The specimens were water quenched from 800° C, and each one was

Figure 6. TENSILE TESTS OF FOUR URANIUM-NIOBIUM ALLOYS. (As Quenched; Average of 2 Specimens)

Differential Thermal Analysis

One test method, differential thermal analysis (DTA), was included in the experiment design to examine the shape-memory behavior of the uranium-niobium alloy series from a thermodynamic viewpoint rather than a mechanical one.

Eight-gram samples were heated at a rate of $6^{\circ}\text{C}/\text{min}$ in a flowing argon atmosphere ($4.55\text{ dm}^3/\text{hr}$) in alumina crucibles. Tungsten was used as the equivalent mass for the second thermocouple. The results from tests of the four alloy levels are summarized in Figure 11.

In this study, an effort was made to keep the alloy segregation uniform through the series by using small ingots, cooled at about the same rate, with tests taken from the same ingot location for each alloy level. However, there is one contributor to alloy segregation which is inherent in the alloy level for which no compensation could be made (ie, solidification

tested twice to 300°C . The middle specimens (5.8 and 6.2 wt % Nb) also showed the severe curve distortion from specimen contraction near 200°C . There was no comparable curve distortion in the 5.3 and 6.9 wt % Nb alloys. In these two, however, there was a slight change in the CTE between the first and second runs. There was no correlation between curve distortion of the CTE and shape memory measured on the cold-bend specimens.

The specimen contraction in these thermal expansion tests is not heat-induced shape memory. Although such a low-temperature contraction in these tests was, no doubt, also present in the cold-bend shape-memory tests, its presence could not affect either the leg spread or the angle measurements. Such a small contraction in leg length could not be measured by the technique used to measure leg spread. In addition, contraction in leg length could not affect the bend angle in this or in Koger's experiment.

The linear expansion curve data suggest, but do not demonstrate, that it would be advisable to use the alloy in the aged condition to provide greater certainty of dimensional stability.

K522-2

Figure 7. URANIUM-5.8 WT % NIOBIUM ALLOY THAT WAS WATER QUENCHED FROM 920° C. (Bright Field Illumination; 400X)

K522-1

Figure 8. URANIUM-5.8 WT % NIOBIUM ALLOY THAT WAS WATER QUENCHED FROM 680° C. (Bright Field Illumination; 400X)

Figure 9. SIGNIFICANT SEGMENTS FROM COEFFICIENT OF THERMAL EXPANSION CURVES OF THE URANIUM-6.0 WT % NIOBIUM ALLOY.

Figure 10. SIGNIFICANT SEGMENTS FROM COEFFICIENT OF THERMAL EXPANSION CURVES OF THE URANIUM-NIOBIUM ALLOYS.

Figure 11. DIFFERENTIAL THERMAL ANALYSIS RESULTS OF THE URANIUM-NIOBIUM ALLOY SERIES. (Water-Quenched Samples)

segregation due to the temperature range between the solidus and liquidus temperatures). There was no apparent relationship between cold-bend shape memory and the temperature ranges of the mushy stages. Therefore, it was concluded that the segregation from this variable was not a significant contributor to shape memory.

On the other hand, there was a positive correlation between the solidus-liquidus range and distortion of the CTE curves. The comparison suggests that specimen contraction of the as-quenched alloys in the thermal expansion tests is related to alloy segregation.

The phase-change temperatures are also given in Figure 11. The solid dots are not true measures under equilibrium conditions, a situation that probably arises from a very sluggish

gamma one-to-gamma three transformation. No conclusions concerning shape memory were evident in these measurements of phase-change temperatures.

The low-temperature points in Figure 11 are heating exotherms at each alloy level. There was no correlation between the cold-bend shape-memory test results and the low-temperature heating exotherms. The temperatures were near those at which specimen contraction occurred in the thermal expansion tests. However, all four alloy levels showed the heating exotherms, but only the two middle alloys showed the curve distortion. From this result it can be concluded that the heating exotherms in DTA are also unrelated to distortion of the thermal expansion curves, and so represent an entirely different metallurgical mechanism.

On the hypothesis that the heating exotherms could be the release of energy from mechanical strains introduced in quenching, a separate U-5.9 wt % alloy was examined in three conditions with DTA. An as-quenched sample showed the heating exotherm at 209° C, while a specimen that had been quenched and then cold rolled 25% showed a quite comparable exotherm at 218° C. There was no evidence of the release of cold-work energy in the tests, so the hypothesis was in error. The specimen that was quenched and aged did not have a low-temperature heating exotherm, because the potential for such had been removed in the aging treatment.

CONCLUSIONS

The following conclusions are proposed as a result of this study:

1. Cold-bend shape-memory tests demonstrated that the irreversible component of shape memory increases with increasing niobium content between 5.3 and 6.9 wt % Nb. Also, it was demonstrated that the magnitude of the reversible component of shape memory is dependent upon the bend angle remaining after irreversible memory set.
2. Twinning in metallographic specimens of the alloy is related to material hardness and cannot be related directly to a shape-memory mechanism.
3. Mechanical properties of tensile tests are not a useful measure of the capacity for temperature-induced shape memory in the alloy range examined. However, a marked increase in reduction-in-area values with an increasing niobium level suggests that capacity for work hardening is a significant contributor to the shape-memory phenomenon.
4. Coefficient-of-linear-thermal-expansion curves at 5.8 and 6.2 wt % Nb levels were distorted by specimen contraction at about 200° C, while there was no distortion at higher or lower alloy levels. Such curve distortions are not a part of the shape-memory behavior and are caused by a separate metallurgical mechanism.
5. Differential thermal analysis made no contribution toward an understanding of shape memory. However, there is a correlation between distortion of the thermal expansion curves and the solidus-liquidus ranges of the study alloy series.

6. The material for this study was prepared to minimize alloy-segregation variations. However, there was sufficient evidence developed to justify an evaluation of temperature-induced shape memory as a function of alloy segregation on a micro scale.

REFERENCES

- (1) Jackson, R. J., Boland, J. F., and Frankeny, J. L.; *US Patent 3,567,523*; Dow Chemical Company; March 2, 1971.
- (2) Brook, G. B. and Iles, R. F.; *UK Patents 1,315,652 and 1,315,653*; Fulmer Research Institute, Ltd (1973).
- (3) Brook, G. B. and Iles, R. F.; *German Patent 2,021,348*; Fulmer Research Institute, Ltd (1973)
- (4) Jackson, R. J. and Johns, W. L.; *Temperature-Induced Shape Memory in Polycrystalline Uranium-Base Niobium Alloys: Characterization*, RFP-996; Dow Chemical Company, Golden, Colorado (1970).
- (5) Burkart, M. W. and Read, T. A.; "Diffusionless Phase Changes in the Indium-Thallium System", *Trans AIME, J Metals*, **197**, p 1516 (1953).
- (6) Basinski, Z. S. and Christian, J. W.; "Experiments on the Martensite Transformation in Single Crystals of Indium-Thallium Alloys", *Acta Met*, **2**, p 101 (1954).
- (7) Chang, L. C. and Read, T. A.; "Plastic Deformation and Diffusionless Phase Changes in Metals, The Gold-Cadmium Beta Phase", *Trans AIME, J Metals*, **189**, p 47 (1951).
- (8) Lieberman, D. S., Wechsler, M. S., and Read, T. A.; "Cubic to Orthorhombic Diffusionless Phase Change - Experimental and Theoretical Studies of AuCd", *J Appl Phy*, **26**, p 473 (1955).
- (9) Buehler, W. J., Gilfrich, J. V., and Wiley, R. C.; "Effect of Low-Temperature Phase Changes on the Mechanical Properties of Alloys Near Composition TiNi", *J Appl Phys*, **34**, p 1475 (1963).
- (10) DeLange, R. G. and Zijderveld, J. A.; "Shape-Memory Effect and the Martensitic Transformation of TiNi", *J Appl Phys*, **39**, p 2195 (1968).
- (11) Warner, T. D., et al; *Characterization of the Anelastic and Thermoplastic Properties of a Uranium-Niobium-Zirconium Alloy*, Y-1974; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; May 2, 1975.
- (12) Vandermeer, R. A., *Aging Induced Shape Instability in an Elastically Bent Uranium-7.5 wt % Niobium-2.5 wt % Zirconium Alloy*; Union Carbide Corporation-Nuclear Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee. (Journal Article accepted for publication in *Metallurgical Transactions*)

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