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THE MECHANICAL PROPERTIES OF DEPLETED URANIUM— 2 w/o MOLYBDENUM ALLOY

Prepared for
U.S. DEPARTMENT OF ENERGY
ASSISTANT SECRETARY FOR ENVIRONMENT
ENVIRONMENTAL CONTROL TECHNOLOGY DIVISION

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TOPICAL REPORT

on

THE MECHANICAL PROPERTIES OF
DEPLETED URANIUM-2 w/o MOLYBDENUM ALLOY

Prepared for

U.S. DEPARTMENT OF ENERGY
ASSISTANT SECRETARY FOR ENVIRONMENT
ENVIRONMENTAL CONTROL TECHNOLOGY DIVISION

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by

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EXECUTIVE SUMMARY

An excellent record has been established for safety and environmental control during the shipment of radioactive materials. This record can be attributed in part to good engineering in the design and fabrication of shipping-container systems. Strict design criteria are used and safety evaluations are conducted to assess the acceptability of the systems with respect to safety and environmental control during normal and accident conditions. The dynamic impact response of a container system is a complex structural problem that usually cannot be treated adequately by simple but conservative (worst-case) analyses. Further, the cost of conducting tests with full-scale shipping containers to determine system response characteristics is often prohibitive. The alternative is to test scale models of shipping containers. Scale-model testing can be an economical method that yields practical results.

The primary objective of this ongoing program for DOE/ECT is to develop data and techniques for determining the dynamic impact response of radioactive-material shipping-container systems for environmental control and safety overview and assessment. One phase of this program is the dynamic testing of 1/8-, 1/4- and 1/2-scale models of uranium-shielded truck casks. These linearly scaled models are fabricated from the same materials typically used in full-size prototype casks.

In order to analytically evaluate the results of dynamic tests, it is necessary to know the mechanical properties of the materials of construction. Since the properties of cast uranium-molybdenum alloys vary significantly with casting and heat-treating techniques, it is necessary to fully characterize the mechanical properties of the uranium used in the model tests. This report presents the results of these studies. The uranium alloy exhibited a tensile strength equal to or greater than that reported by others. As indicated by the percentage of elongation and reduction in area, the ductility was lower. Comparative data for the other mechanical properties measured were not found in the literature.

INTRODUCTION

Spent nuclear fuel and high-level radioactive waste have been shipped for over two decades in carefully engineered and constructed shipping containers or casks. The technical aspects that must be evaluated for safety assessment are the structural integrity, criticality control, shielding capability, and thermal control. Analytical methods for safety assessment of the criticality, shielding, and thermal considerations are relatively well established and verified by experimental data. However, methods for assessing the structural integrity of the shipping containers are less well developed, especially when considering the dynamic forces that might be experienced during certain types of hypothetical accidents. The United States Department of Energy/Environmental Control Technology Division (DOE/ECT) is funding a continuing program at Battelle's Columbus Laboratories to investigate, through modeling techniques, the response of lead- and uranium-shielded shipping containers to various types of impact conditions.

The objectives of the program are to:

- Determine the validity of classical scaling methods to predict the dynamic structural response of lead/stainless steel and depleted uranium/stainless steel shipping containers.
- Establish a scientific data base for assessing the safety and environmental control provided by DOE nuclear shipping containers under dynamic impact conditions
- Provide experimental data for verification and correlation with dynamic-structural-analysis computer codes being developed by The Los Alamos Scientific Laboratory for DOE/ECT.

To meet these program objectives it is necessary to know all laboratory test conditions and the mechanical properties of the materials of construction of the cask models. The structural properties of the Type 304 stainless steel components are well defined and available in the literature. However, a survey of the literature⁽¹⁾ indicated that the structural properties of the shielding materials are less well known, especially for dynamic load conditions. Consequently shield-material characterization studies were performed

as part of the program. The results of the characterization studies of the depleted uranium are presented in this report. The results of the lead characterization are given in an earlier report describing the results of impact studies of lead-shielded model shipping containers.⁽²⁾

TESTS PERFORMED AND SPECIMEN CONFIGURATIONS

Eleven types of static and dynamic tests were performed on the depleted uranium-2 w/o molybdenum (U-2Mo) alloy material. The test matrix for this evaluation is shown in Table 1. The test specimens were removed from a single billet of U-2Mo, cast, and heat treated in the same manner as the uranium-shield components used in the depleted uranium/stainless steel cask models.

The typical microstructure of the U-2Mo material evaluated is shown in Figure 1. The structure contains a considerable amount of impurity phase, most of which appears to be carbide. Oxide also is seen occasionally and is particularly evident around the edges of casting voids. Some evidence of microsegregation can also be seen.

The cast billet was divided into two sections approximately at its midlength and the test specimens were removed from both halves. The location from which the specimens were removed is shown in Figure 2. The specimens were tested as described below using standardized testing procedures wherever possible.

Tension

The configuration of the tensile test specimen is shown in Figure 3. Procedures used for tension testing are those recommended in ASTM Methods E8 and E21. Specimens were tested at each temperature to determine ultimate tensile strength, 0.2 percent offset yield strength, elongation, and reduction in area. The modulus of elasticity was obtained from load-strain curves plotted by an autographic recorder during each test.

TABLE 1. CHARACTERIZATION TEST MATRIX FOR U-2Mo CASTING

Test Type	Tests at Indicated Temperature, F							Total Tests
	-40	-20	0	32	70	200	400	
Tensile	3			3	3	2	3	14
Dynamic Tensile Strain Rate, 10 in./in./sec					3			3
Compression	3				3	1	2	9
Shear					3		2	5
Charpy Impact	2	3	3	2	4	2		16
Poisson's Ratio					2			2
Fatigue, Axial					10			10
$K_{Ic}^{(a)}$	3			3	3	1	2	12
$da/dN^{(b)}$					4			4
$K_{th}^{(c)}$					5	2	3	10
Cyclic Stress-Strain					1			1
Thermal Expansion RT to 400 F								<u>2</u> 88

(a) Plane-strain fracture toughness.

(b) Crack growth rate versus cycles.

(c) Stress intensity at crack initiation (K threshold).

250X

250X

FIGURE 1. TYPICAL MICROSTRUCTURE OF
THE U-2Mo CASTING

FIGURE 2. LOCATION OF SPECIMEN REMOVAL FROM U-2Mo CASTING

All tensile tests were carried out in Baldwin Universal testing machines equipped with integral automatic strain pacers and autographic strain recorders. These machines are calibrated at regular intervals in accordance with ASTM Method E4 to assure loading accuracy within 0.2 percent.

Dynamic tensile tests were performed in an MTS electrohydraulic-servocontrolled machine. Conducting the tests using a "slack" grip with chain for the slack portion assured that the loading ram had sufficient time to achieve proper velocity to impart a strain rate of 10 in./in./sec to the specimen gage length.

Compression

The configuration of the compression specimens is shown in Figure 4. Procedures used for compression testing are those recommended in ASTM Method E9.

Shear

The configuration of the double-shear-pin-type specimens is shown in Figure 5. There is no published method for this type of shear-property determination; however, the test is a standard, accepted procedure (ARTC-13).

Impact

Impact tests were performed using the standard Charpy V-notch specimen shown in Figure 6. The test procedure was ASTM Method E23.

Poisson's Ratio

Poisson's Ratio was measured on three specimens (Figure 7) using a BCL-developed extensometer. The apparatus consists of a 1/2-in.-gage-length extensometer to measure longitudinal strain and a diametral extensometer to measure diametral strain.

FIGURE 3. TENSILE SPECIMEN

Note: End to be flat and parallel to within 0.0002" of ϕ .

FIGURE 4. COMPRESSION SPECIMEN

FIGURE 5. PIN SHEAR SPECIMEN

Fatigue

The configuration of the fatigue specimen is shown in Figure 8. Fatigue tests* were conducted using MTS electrohydraulic-servocontrolled testing machines. The frequency of cycling of these machines is variable to beyond 2,000 cpm depending on specimen rigidity. These machines operate with closed-loop deflection, strain or load control. Under load control used in this program, cyclic loads were automatically maintained (regardless of the required amount of ram travel) by load-cell feedback signals. The calibration and alignment of each machine are checked periodically. In each case, the dynamic load-control accuracy was within ± 3 percent of the test load.

Fracture Toughness and Crack Propagation

Specimen configurations are shown in Figures 9 and 10. Test procedures were those recommended by ASTM Method E399. The specimens shown in Figure 10 were also used for crack-initiation threshold tests.

Cyclic Stress-Strain

Cyclic tests were conducted to determine the strain hardening or softening characteristics of the U-2Mo. The approach followed is described by Landgraf, Marrow and Endo.⁽³⁾ In this test, a tensile specimen is subjected to repeated cyclic loading in increments of increasing strain to a predetermined maximum, usually about 1 percent. The cyclic loading is then continued in decreasing increments to zero strain. This procedure is repeated many times until a stable response condition is achieved. The accuracy of the stable cyclic loading stress-strain curve is verified by a continuous cycling test at a strain amplitude approximately 0.1 percent offset from the static modulus curve.

Thermal Expansion

Linear-thermal-expansion measurements were performed in a recording dilatometer with specimens protected by a vacuum of about 2×10^{-5} mm of mercury. In this apparatus, a sheet-type specimen is supported between two

*Axial tension and relaxation to a lower tensile stress.

FIGURE 6. CHARPY IMPACT SPECIMEN

FIGURE 7. POISSON'S RATIO SPECIMEN

FIGURE 8. UNNOTCHED FATIGUE SPECIMEN

FIGURE 9. COMPACT-TENSION-TYPE FRACTURE-TOUGHNESS SPECIMEN

FIGURE 10. CRACK PROPAGATION AND CRACK-INITIATION THRESHOLD SPECIMEN

graphite structures inside a tantalum-tube heater element. The differential movement of the two structures caused by specimen expansion during heating produces a displacement of the core of a linear-variable differential transformer. The output of the transformer is recorded continuously as a function of specimen temperature. The furnace is controlled to heat the specimen at the desired rate. In these studies the rate was 5 F per minute. Errors associated with thermal expansion measurements in this apparatus are estimated to be less than ± 2 percent. This is based on calibration with materials of known thermal-expansion characteristics.

TEST RESULTS AND DISCUSSION

Results

Tension

Results of static tests at -40 F, 32 F, room temperature, 200 F, and 400 F are given in Table 2. The effect of temperature is indicated by the curves in Figure 11. Typical stress-strain curves at each temperature are presented in Appendix Figure A-1.

Three specimens were tested at a strain rate of 10 in./in./sec. Results of these tests are given in Table 3. A typical dynamic stress-strain curve is presented in Appendix Figure A-2.

Compression

Results of compression tests at -40 F, room temperature, 200 F, and 400 F are given in Table 4. The effect of temperature on the compressive strength is shown by the curves in Figure 12. Typical compressive stress-strain curves at each temperature are presented in Appendix Figure A-3, and typical compressive tangent-modulus curves are presented in Appendix Figure A-4.

Shear

Double-shear pin-type specimens were tested at room temperature and 400 F. The results are shown in Table 5.

TABLE 2. TENSILE TEST RESULTS FOR U-2Mo CASTING

	TUS, ksi	TYS, ksi	e, percent	RA, percent	E, 10 ³ ksi
<u>-40 F</u>					
	147.5	72.5	5.5	6.4	22.1
	146.4	70.2	5.0	4.5	22.1
	154.0	74.1	8.5	8.2	20.3
Average	149.3	72.3	6.3	6.4	21.5
<u>32 F</u>					
	145.7	69.4	14.0	15.9	23.5
	139.4	67.8	8.5	9.9	23.1
	136.4	69.7	6.0	7.4	22.6
Average	140.5	69.0	9.5	11.1	23.1
<u>Room Temperature</u>					
	131.2	65.4	10.0	12.7	21.6
	133.4	66.2	11.0	12.0	21.7
	131.4	69.6	8.0	10.6	21.1
Average	132.0	67.1	9.7	11.8	21.5
<u>200 F</u>					
	108.3	60.6	10.0	12.9	18.4
	109.7	63.2	7.5	12.8	20.3
Average	109.0	61.9	8.7	12.9	19.4
<u>400 F</u>					
	80.4	49.0	21.5	34.0	19.5
	77.8	49.1	19.5	38.6	19.3
	79.8	50.8	23.0	32.6	18.7
Average	79.3	49.6	21.3	35.1	19.2

FIGURE 11. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF A U-2Mo CASTING

FIGURE 12. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF A U-2Mo CASTING

TABLE 3. DYNAMIC TENSILE TEST RESULTS^(a)
 (ROOM TEMPERATURE ONLY) FOR
 U-2Mo CASTING

	TUS, ksi	e, percent	RA, percent
	130.8	7.7	19.2
	139.8	9.4	30.2
	139.5	7.8	20.4
Average	136.7	8.3	23.3

(a) Strain rate of 10 in./in./sec.

TABLE 4. COMPRESSION TEST RESULTS
FOR U-2Mo CASTING

	CYS, ksi	E _c , 10 ³ ksi
	<u>-40 F</u>	
	85.9	20.4
	84.3	19.9
	<u> </u>	<u> </u>
Average	85.1	20.2
	<u>Room Temperature</u>	
	73.9	18.5
	78.5	19.5
	73.3	19.1
	<u> </u>	<u> </u>
Average	75.2	19.0
	<u>200 F</u>	
	72.9	19.4
	70.8	17.9
	<u> </u>	<u> </u>
Average	71.9	18.7
	<u>400 F</u>	
	51.8	17.6
	57.1	16.9
	<u> </u>	<u> </u>
Average	54.5	17.3

TABLE 5. SHEAR TEST RESULTS FOR U-2Mo CASTING

Specimen	Ultimate Shear Strength, ksi
<u>Room Temperature</u>	
1	97.6
2	96.6
3	<u>99.1</u>
Average	97.8
<u>400 F</u>	
4	59.2
5	<u>56.1</u>
Average	57.7

Impact

Charpy V-notch specimens were tested at -40 F, -20 F, 0 F, 32 F, room temperature, and 200 F. Test results are given in Table 6. The effect of the temperature on impact properties is indicated in Figure 13.

Poisson's Ratio

Tests were conducted on three specimens at room temperature. Test results are given in Table 7.

Fatigue

Axial load tests were performed on unnotched specimens at room temperature at a stress ratio of $R = 0.1$. Test results are given in Table 8. Figure 14 is an S-N (stress versus cycles) curve.

TABLE 6. IMPACT TEST RESULTS
FOR U-2Mo CASTING

Specimen	Impact Energy, ft/lb
<u>-40 F</u>	
15	4.5
16	4.5
Average	<u>4.5</u>
<u>-20 F</u>	
12	6.0
13	5.0
14	5.0
Average	<u>5.3</u>
<u>0 F</u>	
9	5.0
10	6.5
11	7.0
Average	<u>6.2</u>
<u>32 F</u>	
7	7.0
8	8.0
Average	<u>7.5</u>
<u>Room Temperature</u>	
3	9.5
4	8.5
5	8.5
6	8.5
Average	<u>8.8</u>
<u>200 F</u>	
1	14.5
2	13.5
Average	<u>14.0</u>

FIGURE 13. EFFECT OF TEMPERATURE ON THE IMPACT PROPERTIES OF A U-2Mo CASTING

TABLE 7. POISSON'S RATIO DETERMINATION FOR U-2Mo AT ROOM TEMPERATURE

	Poisson's Ratio	E, 10 ³ ksi
	0.353	24.2
	0.332	23.5
	0.321	23.1
Average	0.335	23.6

TABLE 8. AXIAL LOAD FATIGUE TEST RESULTS
FOR U-2Mo CASTING (R = 0.1)

Specimen	Maximum Stress, ksi	Cycles to Failure
1	100	4,229
2	80	13,987
3	70	27,530
7	60	47,590
4	50	118,730
8	47.5	62,110
9	45	134,550
6	45	10,007,480 ^(a)
5	35	11,129,730 ^(a)

(a) Did not fail.

FIGURE 14. AXIAL-LOAD FATIGUE BEHAVIOR OF A U-2Mo CASTING AT ROOM TEMPERATURE

Fracture Toughness

Compact-tension-type specimens were tested at -40 F, 32 F, room temperature, and 400 F. The results of these tests are given in Table 9. Figure 15 shows the effect of temperature on fracture toughness.

TABLE 9. FRACTURE-TOUGHNESS TEST RESULTS FOR U-2Mo CASTING

Specimen	Thickness, B, in.	Width, W, in.	Maximum Stress, ksi	Initial Precrack, in.	Apparent SIF, K_{IC} , ksi $\sqrt{\text{in.}}$
<u>-40 F</u>					
4	1.25	2.51	11.1	1.31	56.3
5	1.25	2.51	10.3	1.35	56.3
6	1.25	2.51	11.6	1.39	59.8
				Average	57.5
<u>32 F</u>					
7	1.25	2.50	11.4	1.35	58.3
8	1.25	2.51	13.3	1.31	57.1
9	1.25	2.51	12.3	1.32	58.2
				Average	57.9
<u>Room Temperature</u>					
10	1.25	2.51	13.4	1.31	57.3
11	1.25	2.51	11.8	1.37	49.6
12	1.25	2.51	12.9	1.38	56.7
				Average	54.3
<u>400 F</u>					
13	1.25	2.51	17.3	1.33	41.4
14	1.25	2.51	16.3	1.34	40.1
15	1.25	2.51	15.4	1.36	45.1
				Average	42.2

FIGURE 15. EFFECT OF TEMPERATURE ON FRACTURE TOUGHNESS OF A U-2Mo CASTING

Crack Propagation

Results of crack-propagation tests for four specimens at room temperature are presented in Figure 16. Tests were attempted at 400 F and 200 F in an air environment; however, because of surface discoloration and scaling, it was impossible to follow the propagation of the crack. Tests in an inert atmosphere or vacuum were not possible because the test equipment does not lend itself to such tests.

Crack Initiation Threshold (K_{th})

K_{th} tests were conducted using the same specimen type as shown in Figure 10. Considerable difficulty was encountered with crack growth. From visual examination of the fracture surface, it appears that either impurities or voids (or both) in the casting interfered with crack growth. However, the limited data obtained appear reasonable; they are presented in Figure 17. The value of K_{th} is approximately $4.8 \text{ ksi } \sqrt{\text{in.}}$

Cyclic Stress-Strain

Cyclic tests were conducted primarily to see whether the material exhibited any strain hardening or softening behavior. In the incremental step

+ DATA SET 1
□ DATA SET 2
○ DATA SET 3
△ DATA SET 4

FIGURE 16. CRACK-PROPAGATION BEHAVIOR OF A U-2Mo CASTING

FIGURE 17. CRACK GROWTH (THRESHOLD) DATA FOR U-2Mo CASTING

test the stress response was essentially stable, as shown in Figure 18. The continuous cycling test exhibited a hardening characteristic; however, it was very slight as is also shown in Figure 18.

FIGURE 18. CYCLIC STRESS-STRAIN BEHAVIOR OF A U-2Mo CASTING

Thermal Expansion

The results of thermal-expansion measurements are shown in Figure 19. The expansion coefficient is constant up to a temperature of about 200 C. Its value over this range is 13.8×10^{-6} cm/cm/C (7.7×10^{-6} in./in./F). Above 200 C the expansion coefficient increases rapidly as shown in Figure 19. The curve of the measured expansion is presented in Appendix Figure A-5.

FIGURE 19. COEFFICIENT OF THERMAL EXPANSION OF U-2Mo CASTING IN AIR

Discussion

These studies accomplished their primary purpose -- to obtain data characterizing the uranium alloy used in the evaluation of drop tests of uranium-shielded models. The static tensile data exhibit the normally expected decrease in strength and an increase in ductility (as indicated by the elongation and reduction in area) with increasing temperature. The inflection in the elongation curve observed at 200 F is not abnormal for cast materials.

The possibility of anisotropy in the U-2Mo alloy was not investigated. However, cast materials normally do not exhibit anisotropic behavior. Reference to any previous observations of anisotropic properties of this alloy as-cast was not found in the literature.

The data are in very close agreement with the results presented by Zukas⁽⁴⁾ for this alloy in the as-cast condition. The data from these tests also indicate higher strengths and lower ductility than those reported by Blasch et al⁽⁵⁾ and Hemperly⁽⁶⁾. The static compression data exhibit the same pattern of strength with temperature as the static tensile data.

Dynamic tensile tests were conducted only at room temperature and at a strain rate of 10 in./in./sec. These data indicated only minor strain-rate effects from the static test condition, although the reduction in area is about double. The strain-rate insensitivity at this strain rate was expected since Robinson, et al⁽¹⁾ noted an increase in tensile strength of only 15 percent at strain rates 20 times those used here. The impact data are in good agreement with those of Zukas⁽⁴⁾.

The other data obtained in the tests indicate the normally expected trends with temperature for U-2Mo. However, comparable data were not found in the literature for this alloy.

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APPENDIX A

TYPICAL STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR
DEPLETED URANIUM-2 w/o MOLYBDENUM ALLOY

FIGURE A-1. TYPICAL STATIC TENSILE STRESS-STRAIN CURVES FOR U-2Mo AT SEVERAL TEMPERATURES

FIGURE A-2. TYPICAL STATIC AND DYNAMIC TENSILE STRESS-STRAIN CURVES FOR U-2Mo AT ROOM TEMPERATURE

FIGURE A-3. TYPICAL COMPRESSIVE STRESS-STRAIN CURVES FOR U-2Mo AT SEVERAL TEMPERATURES

FIGURE A-4. TYPICAL COMPRESSIVE TANGENT-MODULUS CURVES FOR U-2Mo AT SEVERAL TEMPERATURES

FIGURE A-5. THERMAL EXPANSION MEASURED FOR U-2Mo CASTING IN AIR