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ORNL-3557
UC-25 – Metals, Ceramics, and Materials
TID-4500 (26th ed.)

MECHANICAL PROPERTIES OF X8001 AND 6061 ALUMINUM ALLOYS AND ALUMINUM-BASE FUEL DISPERSION AT ELEVATED TEMPERATURES

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OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

Printed in USA. Price: $0.75 Available from the
Office of Technical Services
U. S. Department of Commerce
Washington 25, D. C.

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ORNL-3557

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION

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ABSTRACT

The mechanical properties of two aluminum alloys and a fuel dispersion have been investigated for the purpose of selecting a cladding material and supplying data for design evaluation of the Advanced Test Reactor fuel plates.

The properties of the X8001, 6061, and the U_3O_8-Al dispersion were investigated. The creep properties of these materials in uniaxial tension were measured in the temperature range of 400 to 600°F for maximum strains of 1.0% and times of 450 hr. The tensile properties were measured from 70 to 600°F.

The 6061-0 is stronger in short-time tension and creep than the X8001-0 material. The tensile strength of X8001 can be increased by cold working. Recovery of the cold-worked X8001 and 6061 alloys was investigated and compared with the kinetics of the overaging of the 6061 alloy in the T6 condition. The fuel dispersion is stronger in creep than the X8001-0 matrix material. The tensile strength of the fuel dispersion is approximately twice that of X8001-0.

INTRODUCTION

The ATR is a high-flux water-moderated and light water-cooled reactor. Circular segment fuel elements consist of 19 curved fuel plates. The fuel plates are Al-U_3O_8 fuel dispersion clad with an aluminum alloy.

Several aluminum alloys were considered in the final conceptual design[1] as cladding materials. The materials most feasible for the fuel element are the 6061 and X8001 alloys based on the mechanical properties, corrosion resistance, and fabricability data. The purpose of the ATR

[1]D. R. deBoisblanc, The Advanced Test Reactor – ATR Final Conceptual Design, IDO-16667 (Nov. 1, 1960).

basic material testing program completed at the Oak Ridge National Laboratory was to supply the necessary material property data to facilitate selection of the type of aluminum best suited as the cladding for the fuel plates. A complete program was jointly agreed upon by the designer, Babcock and Wilcox Company, and ORNL at the inception of the program. The program included tensile and creep tests at temperatures up to 600°F for the two basic aluminum alloys, 6061 and X8001, in addition to limited mechanical property data of the fuel dispersion and fuel plate. The data of X8001 and 6061 alloys are reported in this report.

Mechanical Property Determinations Useful to Fuel Element Design

The mechanical property data needed to evaluate fuel element materials and design can be innumerable. One can evaluate the relative strengths of fuel element materials by yield strength in tension and, if one is designing in the plastic-strain range, minimum creep rate data. Normally, these data are not satisfactory in the evaluation of a particular fuel element design. A designer is interested in the relationship of stress and strain. The relationship for various stress states at a particular temperature and for a given environment is desirable. Experimental duplication of all these conditions can be costly and at times impossible. Therefore, one must rely on both theory and experimentally proven mathematical relationships of simple mechanical property data. Judicious selection of the type of mechanical property tests and material conditions will result in meaningful material property data.

The stress-strain curves for a material tested in tension at various strain rates are useful. Tangent, Young's, and other moduli can be obtained from these short-time tensile curves. An example of direct application of the stress-strain curve is the determination of elastic and plastic deflection in bending of thin plates such as the ATR fuel plates.

At elevated temperatures, strains or stresses far below the short-time yield stress or strain can result in time-dependent plastic deformation. Creep data can be generated and presented in many ways. More is understood about the experimental determination of and the

application of uniaxial tension data than any other type stress state. These type tests represent the most feasible time-dependent deformation tests. However, the stress state for the ATR fuel plate is bending and not uniaxial tension. The prediction of plastic deflection for rectangular cross sections, such as the ATR fuel plate, in bending from uniaxial tension data has been demonstrated.[2–4]

Creep data can be presented in many ways. The simplest, most voluminous method is the plot of strain vs time as obtained directly from test data. Each curve satisfies a given material at a particular temperature, stress, and environment. Details of several methods of correlating creep data for design have been reviewed by Aarnes and Tuttle.[5] However, no particular method of creep data presentation is both applicable and most convenient to all design evaluations. It is believed that the use of isochronous stress-strain curves is a clear and concise method of creep data presentation which is applicable[2] to many design studies.

One must also decide the type of heat treatment to be applied to the material prior to the generation of mechanical property data. Metallurgical instabilities of an alloy can significantly alter the mechanical properties. For some alloys, these structural changes can be predicted[6] from the thermal history. However, the combined effect of thermal and irradiation history on structural changes is not well known at this time. Several experiments[7] indicate that thermal annealing

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[2]N. A. Weil, "Isochronous Creep Curves for Strain Determinations Under Complex Loading Cycles," paper presented at the ASME Design Engineering Conference, Chicago, Illinois, April 30–May 3, 1962.

[3]W. H. Hill et al., Am. Soc. Testing Mater. Proc. 61, 890 (1961).

[4]J. Marin and J. Sauer, Strength of Materials, 2nd ed., MacMillan, New York, 1948.

[5]M. N. Aarnes and M. M. Tuttle, Presentation of Creep Data for Design Purposes, ASD-TR-61-216 (June 1961).

[6]R. E. Fortney and C. H. Avery, Effects of Temperature-Time Stress Histories on the Mechanical Properties of Aircraft Structural Metallic Materials. Part I. Temperature-Time Studies of 2024-T3 and 7075-T6 Alclad Sheet, WADC Tech. Rept. 56-585 (December 1956).

[7]A. M. Adair, R. E. Hook, and J. Garrett, Radiation Induced Over-Aging of a 2024-T3 Aluminum Alloy, ARL-132 (September 1961).

is enhanced in irradiation fields. Therefore, the properties of the fully annealed alloy is recommended at this time to ensure a dependable design and material evaluation.

Material and Experimental Procedure

The chemical composition of the cladding alloy tested is given in Table 1. The fuel dispersion is a 33% by weight dispersion of U_3O_8 in X8001 aluminum. The particle size of U_3O_8 before fabrication varied from −100 to +325 mesh. The fuel plate tested is 0.015-in. X8001 clad on an 0.020-in. fuel dispersion. The resulting 0.050-in.-thick fuel plate was fabricated using the technique described elsewhere.[8]

Table 1. Composition of Aluminum Alloys Under Investigation

Element	Percent Weight for Alloy X8001	MX8001	6061
Ni	1.19	0.93	
Si	0.06	0.003	0.60
Ti		0.11	
Fe	0.48	0.53	
Mg			1.00
Cu	260 ppm		0.25
Cr			0.25
Al	Bal	Bal	Bal

All specimens designated by a suffix, 0, were annealed 2 hr at 775°F in air and furnace cooled prior to testing to ensure removal of prior cold working.

The short-time tensile properties were obtained using a 10,000-lb-capacity Baldwin Universal testing machine. The cross-head speed was 0.05 in./min. The load-elongation curves were autographically recorded utilizing an extensometer arrangement on the specimens.

[8] R. L. Heestand et al., "Fabrication Development of the Advanced Test Reactor Fuel Element," pp 315–36 in Research Fuel Element Conference September 17–19, 1962, Gatlinburg, Tennessee, TID-7642, Book I (1963).

The time-dependent deformation data were obtained using constant load tests and an extensometer arrangement.

RESULTS AND DISCUSSION

Moduli

Elastic moduli were obtained from dynamic and static determinations. "Dynamic" moduli so determined[3] represent those moduli to be used in calculations of deformation at high rates of load application. These moduli for X8001 aluminum are given in Fig. 1 and 6061 in Fig. 2. Significant differences in moduli begin in the temperature range for which the temperature exceeds 0.5 of the absolute melting point. The dynamic moduli values presented here are slightly greater than the values presented earlier by Hill *et al.*[3] for 1100 aluminum.

Dynamic moduli of the fuel dispersion are given in Table 2. These moduli were calculated using the cross-sectional area of the fuel dispersion. If the modulus of the fuel dispersion is calculated using the cross-sectional area of the metallic matrix, the modulus is equivalent to the modulus of the matrix material. These data are shown in Table 2. Therefore, the modulus of fuel dispersion fabricated in a like manner can be predicted from the modulus of the matrix material and the volume fraction of dispersion. Venard and Swindeman[9] demonstrated the same relationship for the modulus of a dispersion of UO_2 in type 347 stainless steel.

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[9]J. T. Venard and R. W. Swindeman, Metals and Ceramics Div. Ann. Progr. Rept., May 31, 1962, ORNL-3313, p 33.

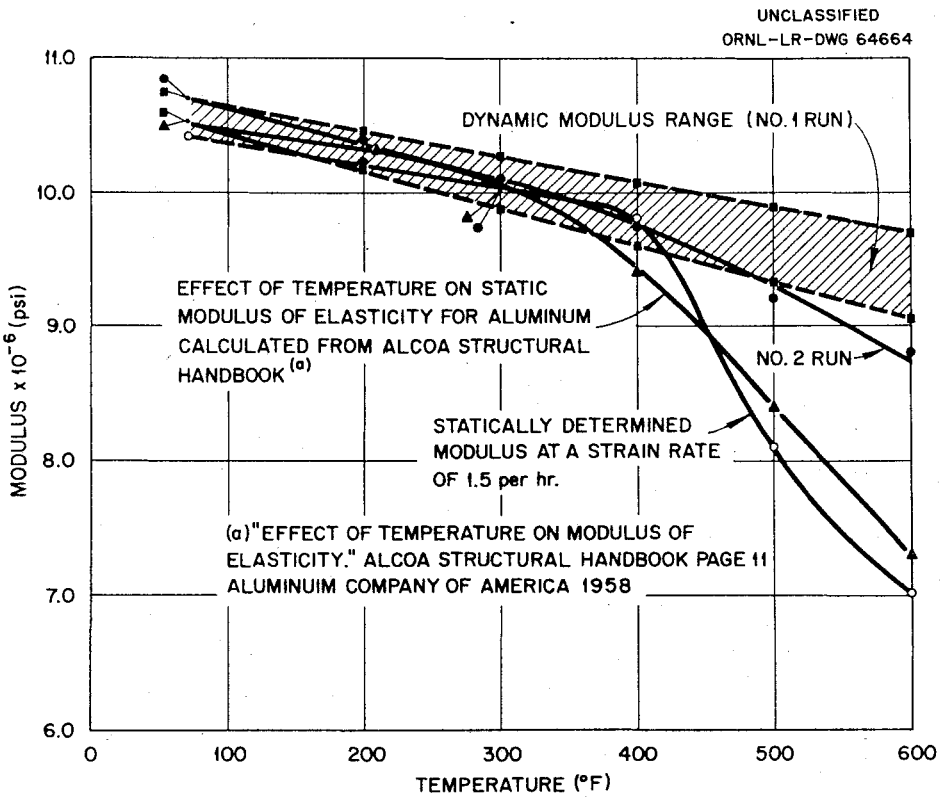

Fig. 1. Young's Modulus for X8001-O Aluminum as a Function of Temperature.

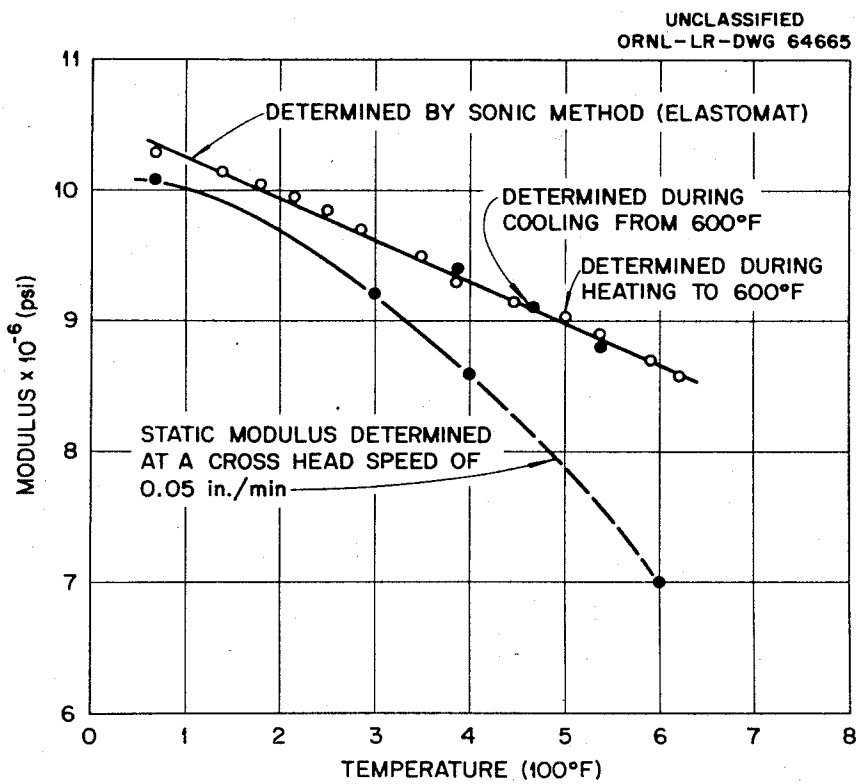

Fig. 2. Effect of Temperature on Modulus of Elasticity of 6061 Aluminum.

Table 2. Dynamic Moduli of 33 wt % Dispersion of U_3O_8 in X8001 Aluminum

Test Temperature (°F)	Dynamic Moduli of Dispersion (psi)	Dynamic Moduli of X8001 (psi)	Calculated[a] Dispersion Moduli (psi)
70	9.3×10^6	10.5×10^6	9.1×10^6
200	8.9×10^6	10.3×10^6	8.9×10^6
300	8.5×10^6	10.1×10^6	8.7×10^6
400	8.1×10^6	9.7×10^6	8.4×10^6
500		9.2×10^6	8.0×10^6
600	7.6×10^6	8.8×10^6	7.6×10^6

[a]Note: Calculation of fuel dispersion modulus:

$$\text{Modulus of Fuel Dispersion} = \left(1 - \text{Volume Fraction of Dispersion}\right)\left(\text{Modulus of Matrix Material}\right)$$

Yield Strength and Ultimate Tensile Strength

The yield strength and ultimate tensile strength of these alloys are given in Figs. 3 and 4, respectively. The tensile properties of the fuel matrix and dispersion are compared in Table 3. These properties of the X8001 alloy are very similar to those of 1100 aluminum. The strength of the 6061 alloy is significantly greater than the X8001 alloy. The yield strength of the fuel dispersion is higher than that of the X8001 alloy. The stress-strain curves for the 6061 and X8001 alloys are given in Figs. 5 and 6, respectively.

Table 3. Comparison of the Mechanical Properties of Fuel Dispersion and Matrix Material

Test Temperature (°F)	Fuel Dispersion		
	Yield Strength (psi)	Ultimate Tensile Strength (psi)	Percent Elongation at Rupture
70	19,000	22,000	6.8
300	9,800	10,215	8.6
400	8,795	8,845	5.0
500	7,140	7,300	6.8
600			

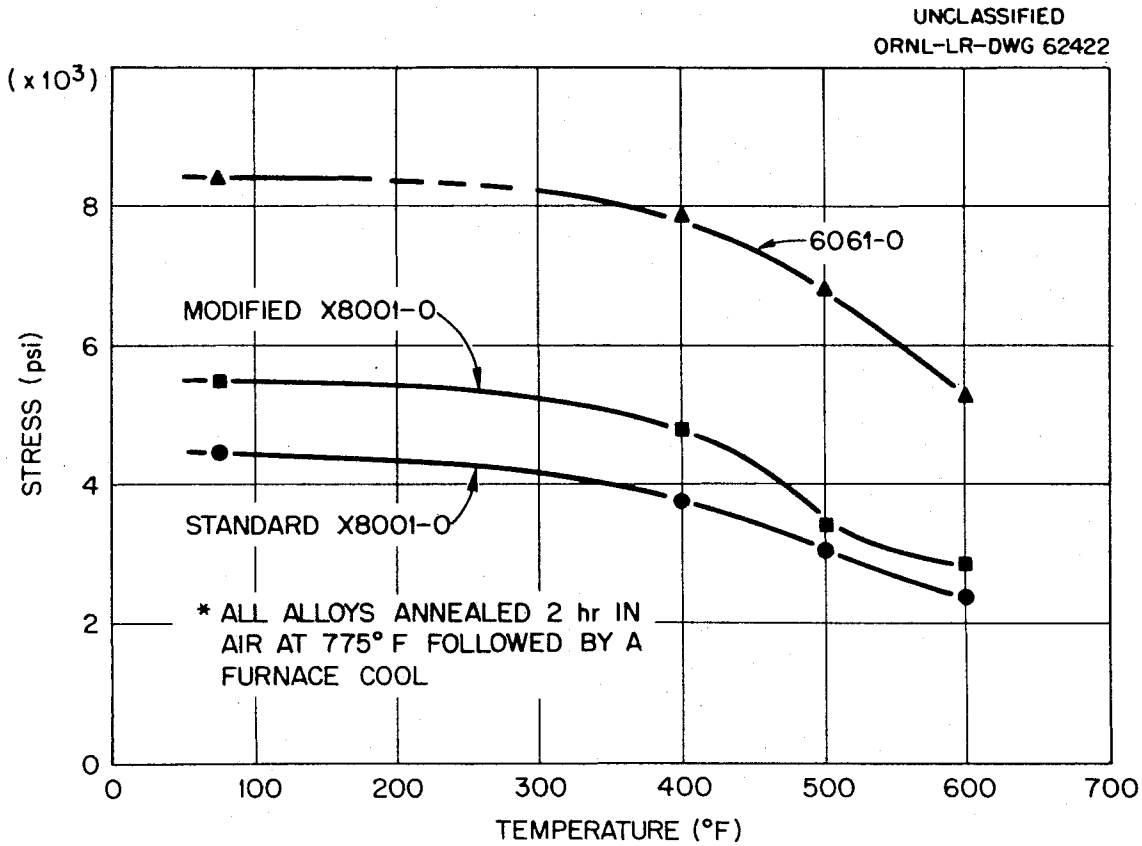

Fig. 3. Yield Strength of Alloys as a Function of Test Temperature.

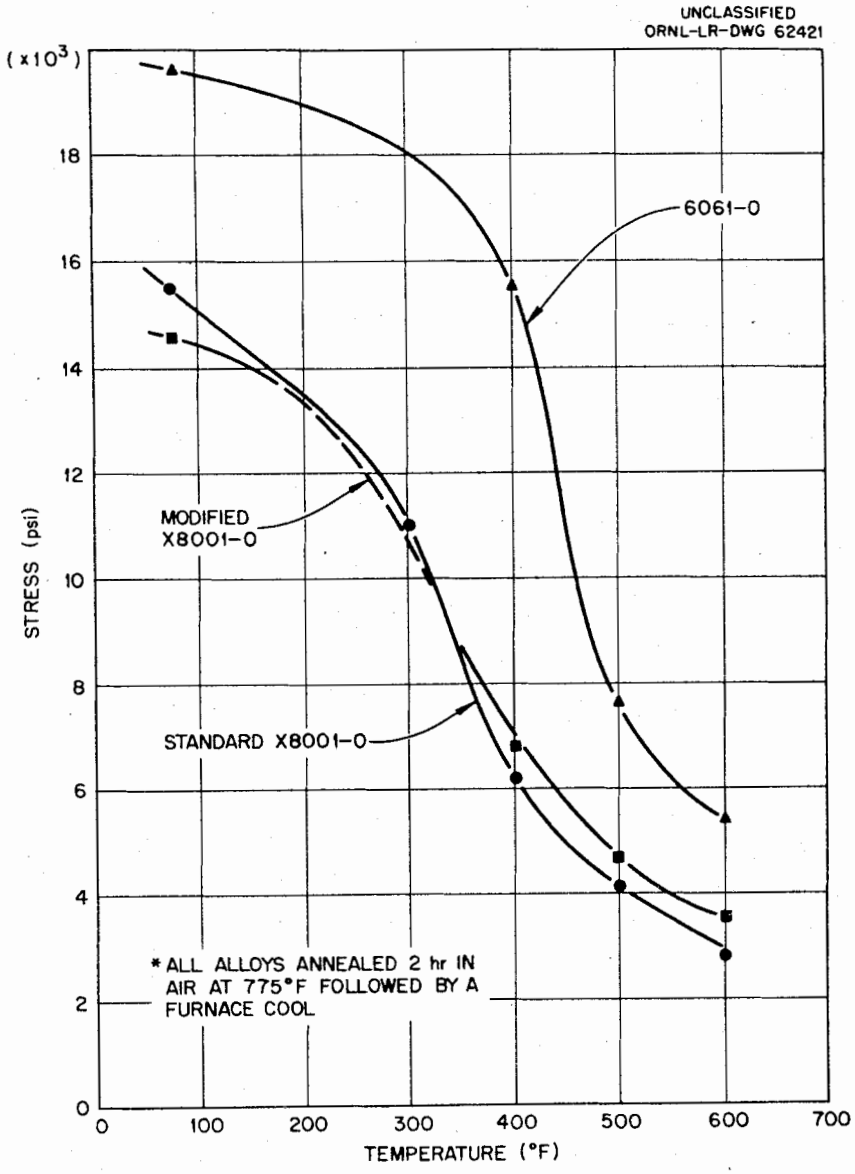

Fig. 4. Ultimate Tensile Strength as a Function of Temperature for Several Aluminum Alloys.

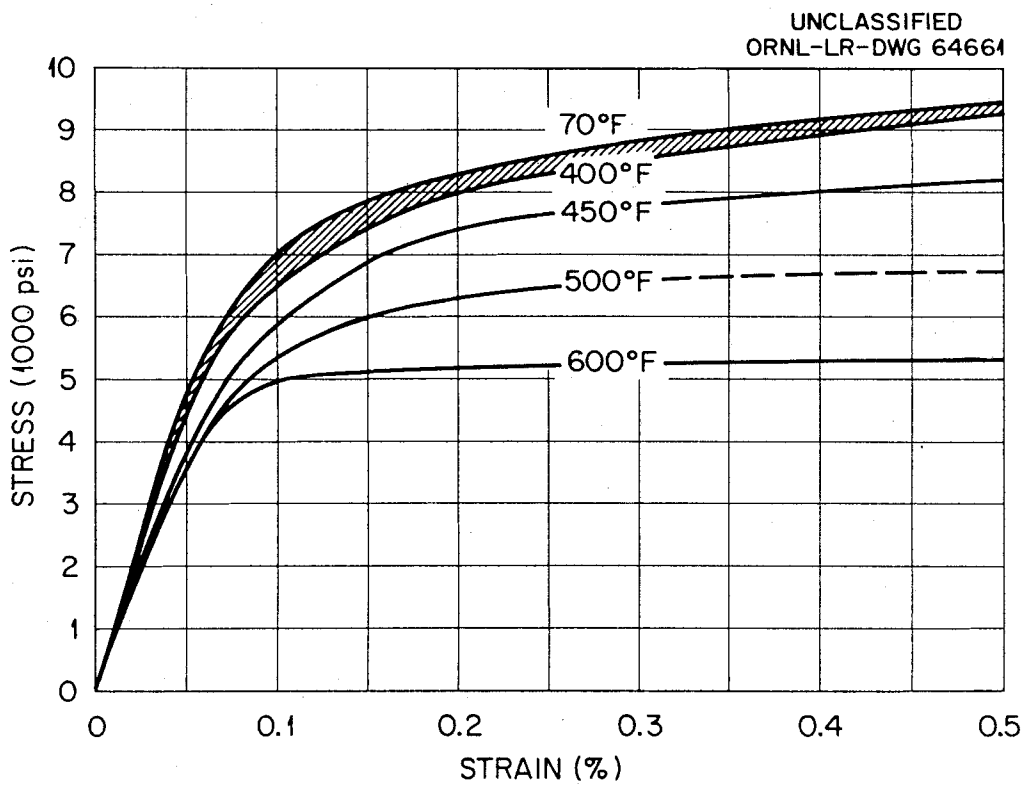

Fig. 5. Stress-Strain Tensile Curve for Aluminum Alloy 6061-0.

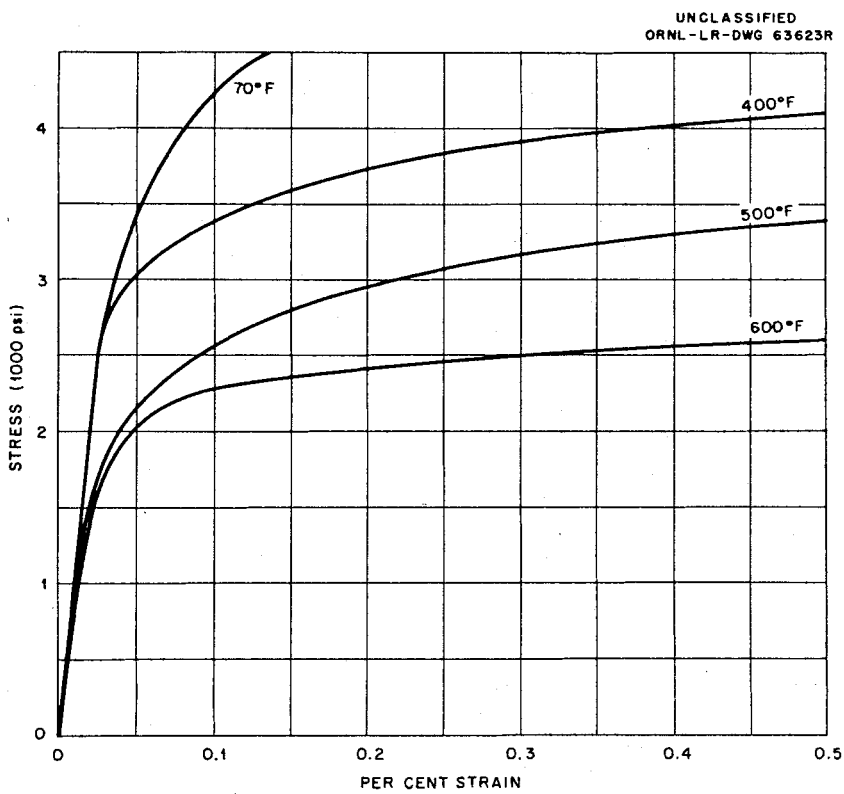

Fig. 6. Stress-Strain Tensile Curves for Aluminum Alloy X8001-O at Elevated Temperature.

The ductility of the fuel dispersion is low compared to the cladding material. The rupture elongation of the fuel plates at the temperatures investigated varies from 7 to 10% without apparent trend.

Creep Properties

The isochronous stress-strain curves for the X8001 alloy at 400, 500, and 600°F compared to the tensile curves at this temperatures are shown in Figs. 7, 8, and 9. The isochronous stress-strain curve for the 6061-0 at 350, 400, 500, and 600°F is given in Figs. 10 through 13. The isochronous stress-strain curves for the fuel dispersion at 400 and 500°F are given in Figs. 14 and 15.

These data show the creep strength of the fuel dispersion to be greater than that of the X8001 material but less than the 6061-0 alloy. The isochronous stress-strain curves for 6061-T6, data courtesy of Alcoa Research Laboratory, are presented in Figs. 16 through 19 for comparison with the strength of the annealed alloy. These data are, in the main, compatible with other data[10] to be found in the literature. At 400°F, the annealed alloy is weaker than the alloy in T6 condition for exposures of at least 1000 hr. However, at 500°F the creep strength of the alloys is similar after exposure of 100 to 1000 hr.

Effect of Cold Work on Tensile and Creep Properties of X8001 Aluminum

Previous investigations[11] demonstrated that cold work effectively increases the tensile yield strength of the X8001. Kemper and Powell[12] examined the recovery of these cold-worked alloys as a function of heat treatment, temperature and time, by the reduction of room-temperature yield strength after thermal treatment. From these data, one would expect the longest benefit of increased yield strength from a 10%

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[10] H. R. Voorhees and J. W. Freeman, Am. Soc. Testing Mater., Spec. Tech. Publ. 291, 131 (1960).

[11] D. E. Johnson and W. H. Ellis, A Preliminary Study of the Mechanical Properties of M-388, An Aluminum 1% Nickel Alloy, HW-41859 (March 1956).

[12] R. S. Kemper and K. F. Powell, Mechanical Properties of Aluminum Alloy M-388: Effect of Fabrication Variables, HW-54364 (January 1958).

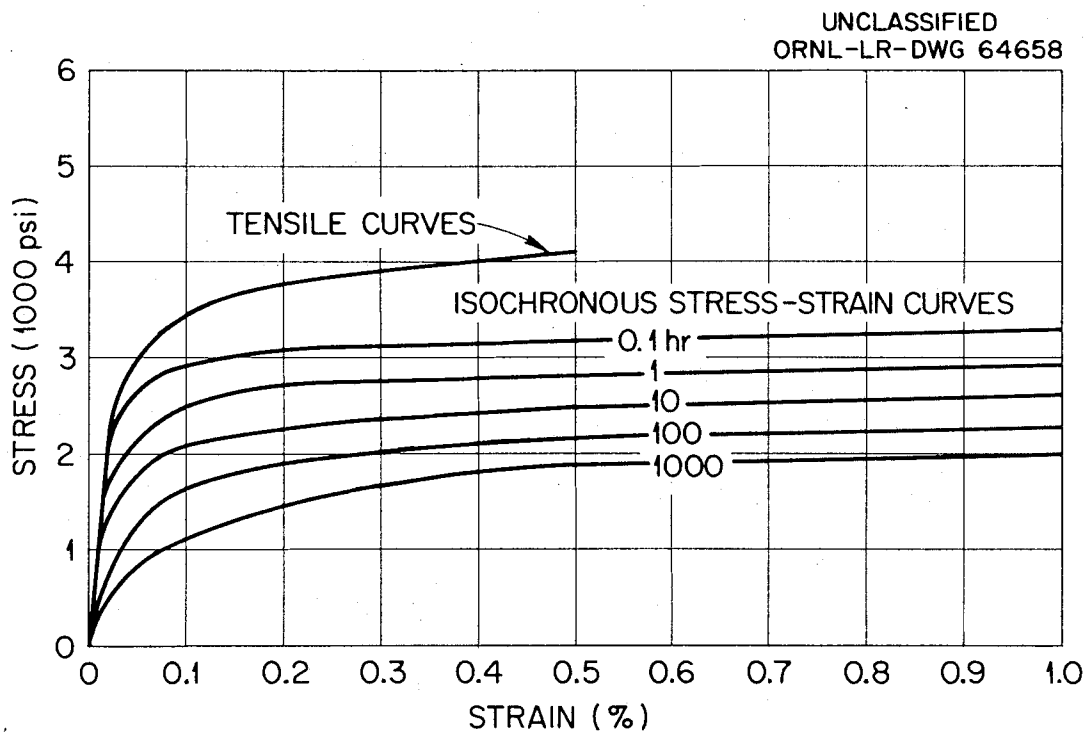

Fig. 7. Stress-Strain Curves for Aluminum Alloy X8001-0 Tested at 400°F in Air.

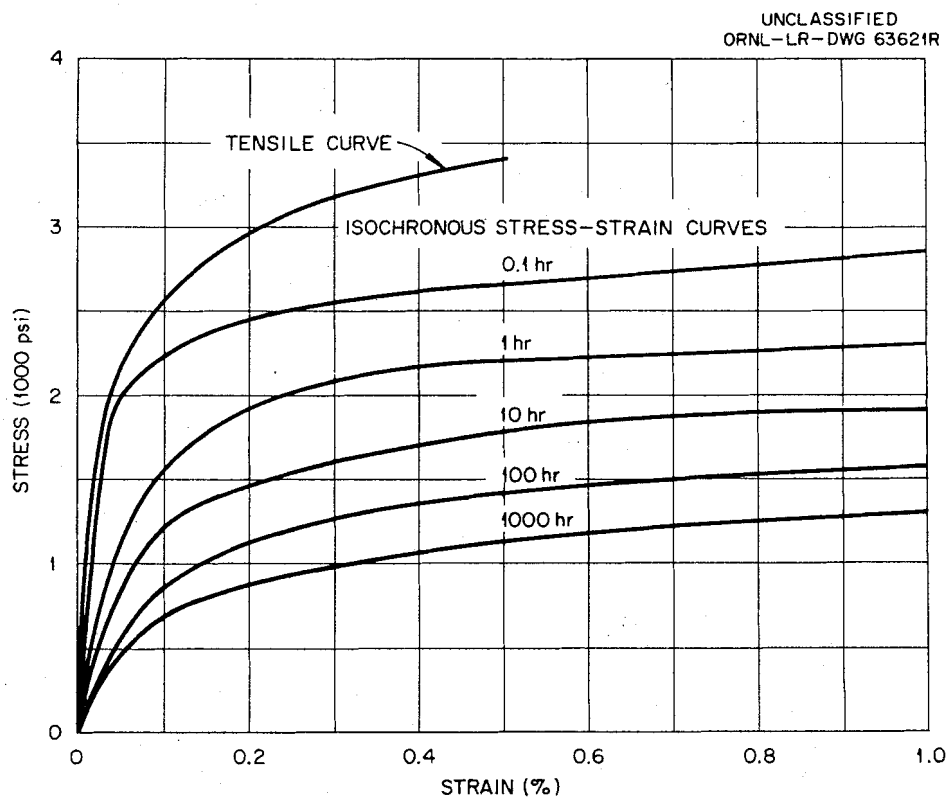

Fig. 8. Stress-Strain Curves for Aluminum Alloy X8001-0 Tested at 500°F in Air.

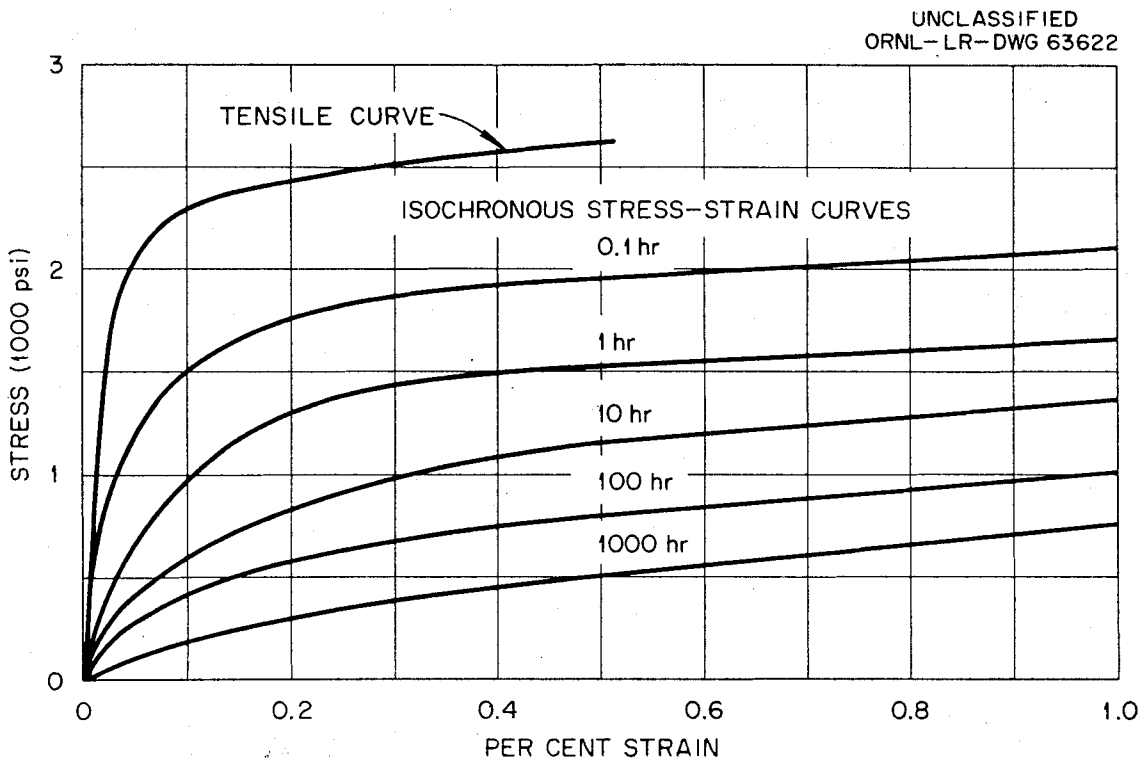

Fig. 9. Stress-Strain Curves for Aluminum Alloy X8001-0 Tested at 600°F in Air.

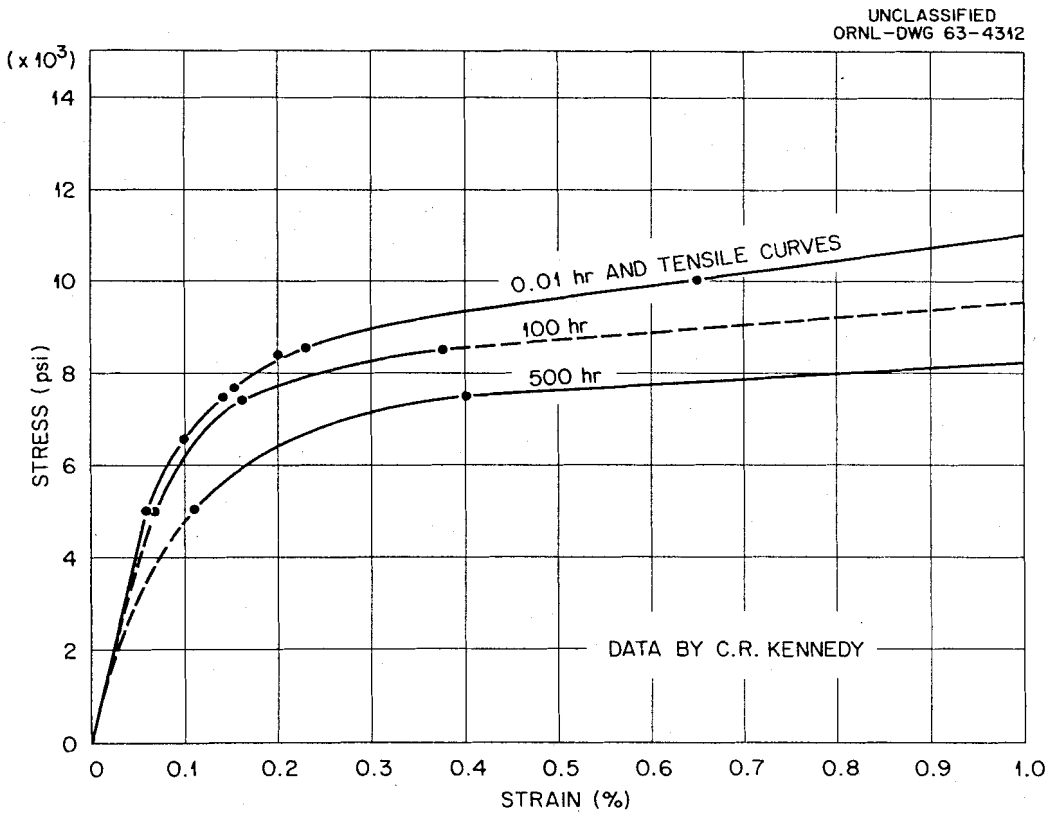

Fig. 10. Stress-Strain Curves of 6061-0 Aluminum at 350°F.

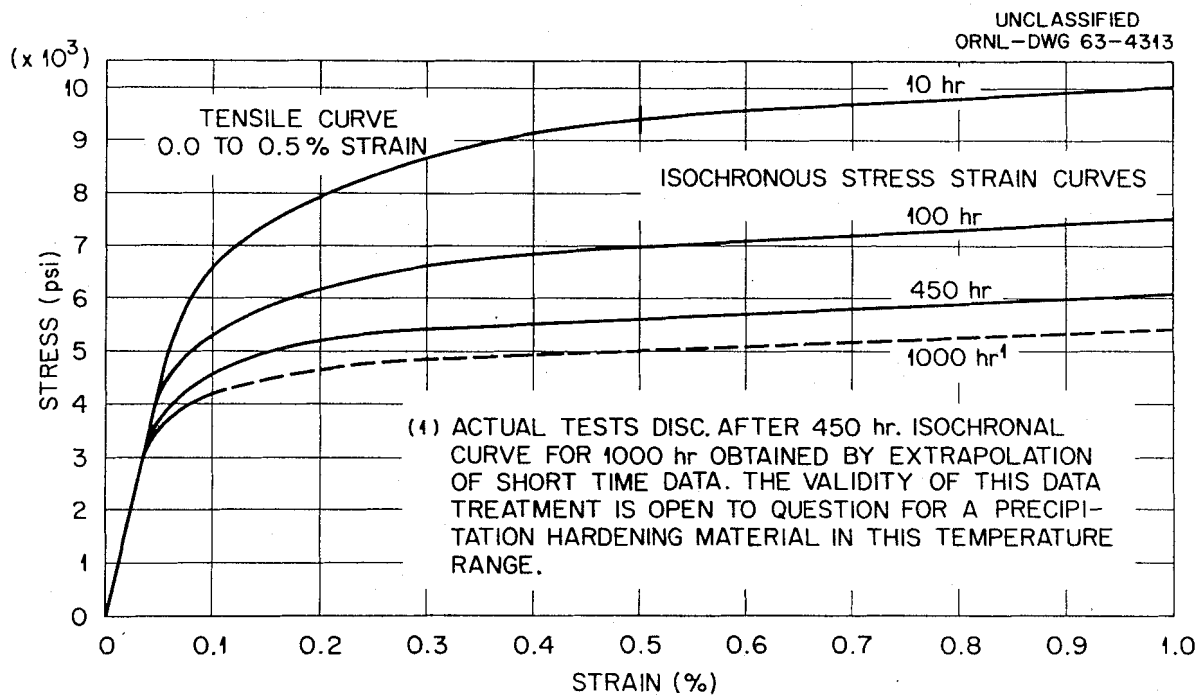

Fig. 11. Stress-Strain Curves for Aluminum Alloy 6061-0 Tested at 400°F in Air.

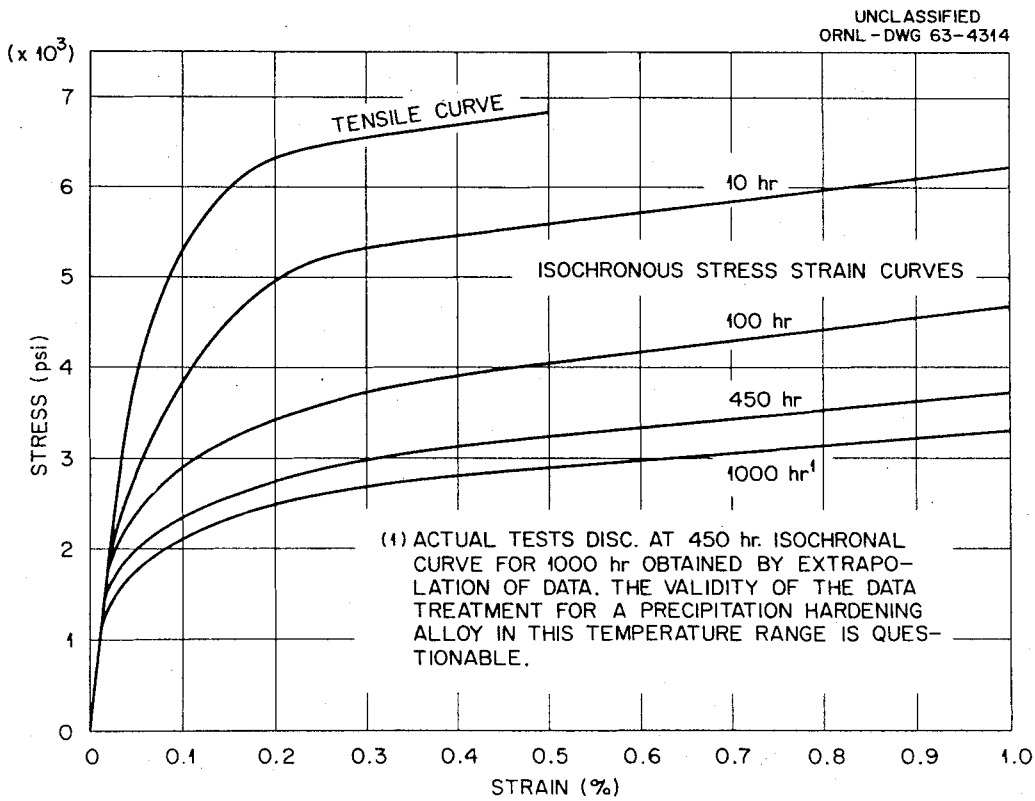

Fig. 12. Stress-Strain Curves for Aluminum Alloy 6061-0 Tested at 500°F in Air.

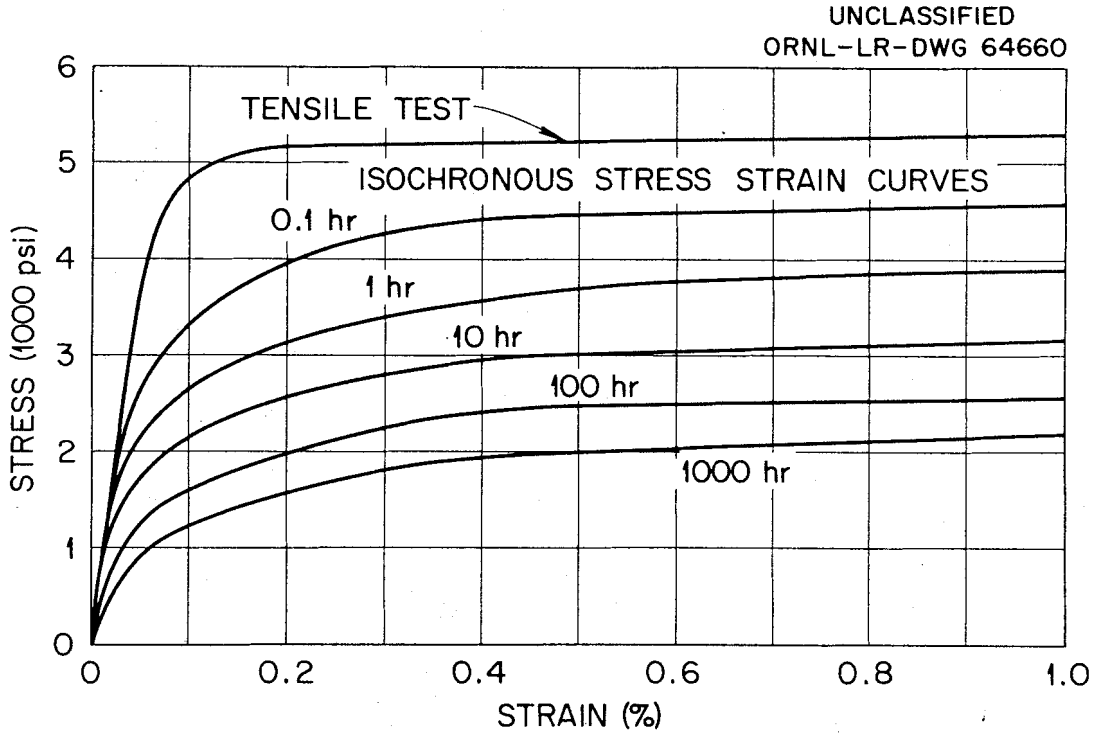

Fig. 13. Stress-Strain Curves for Aluminum Alloy 6061-0 Tested at 600°F in Air.

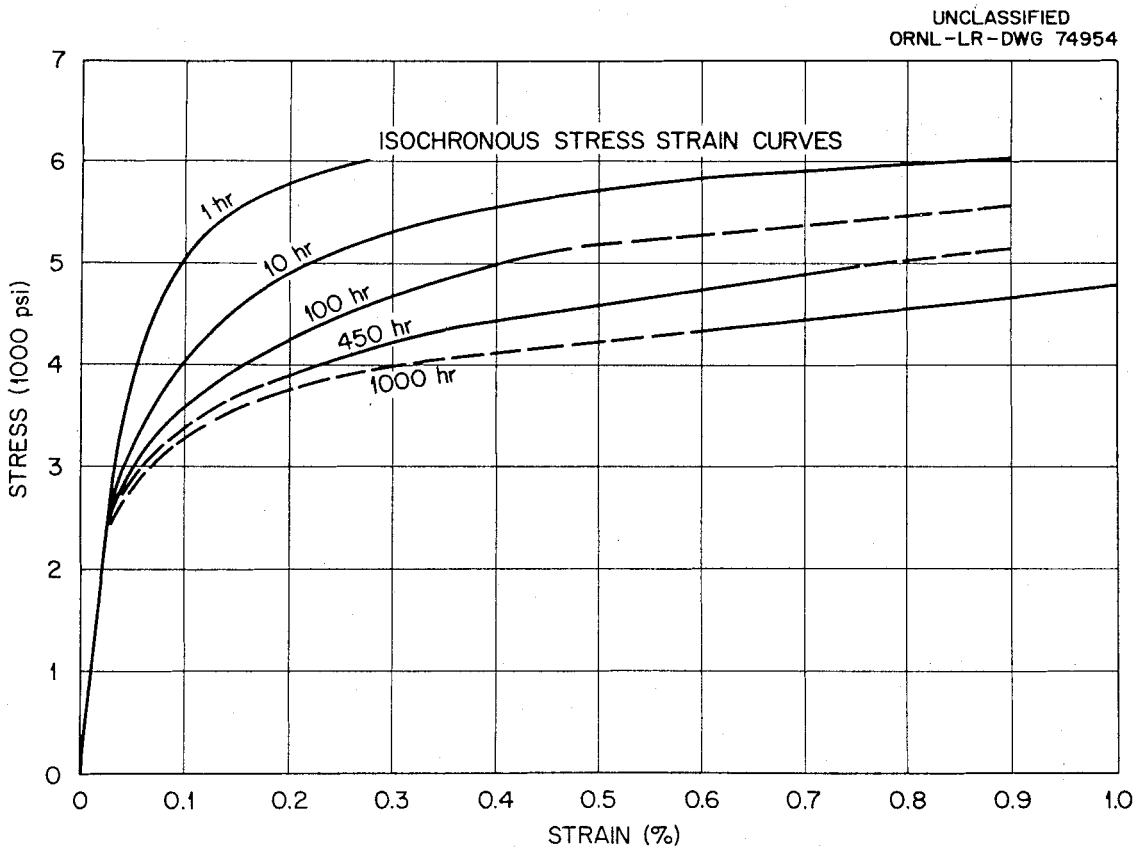

Fig. 14. Stress-Strain Curves for 35% by Weight U_3O_8 Dispersion in X8001 Aluminum Tested at 400°F in Air.

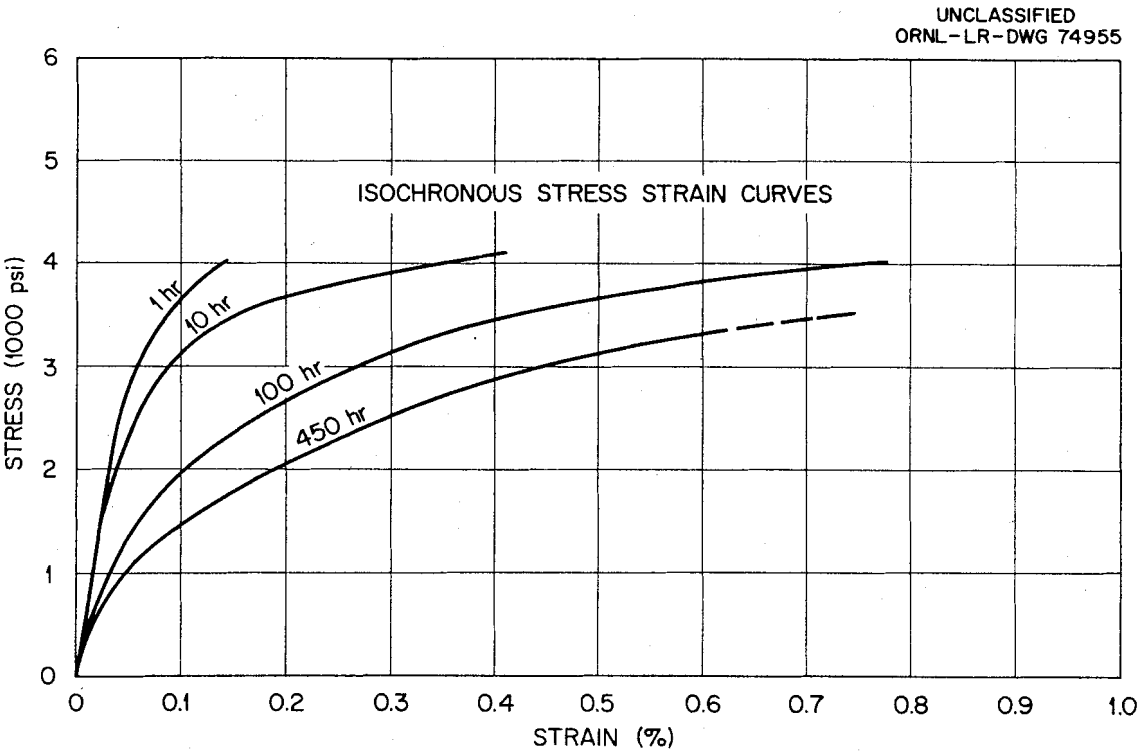

Fig. 15. Stress-Strain Curves for 35% by Weight U_3O_8 Dispersion in X8001 Aluminum at 500°F in Air.

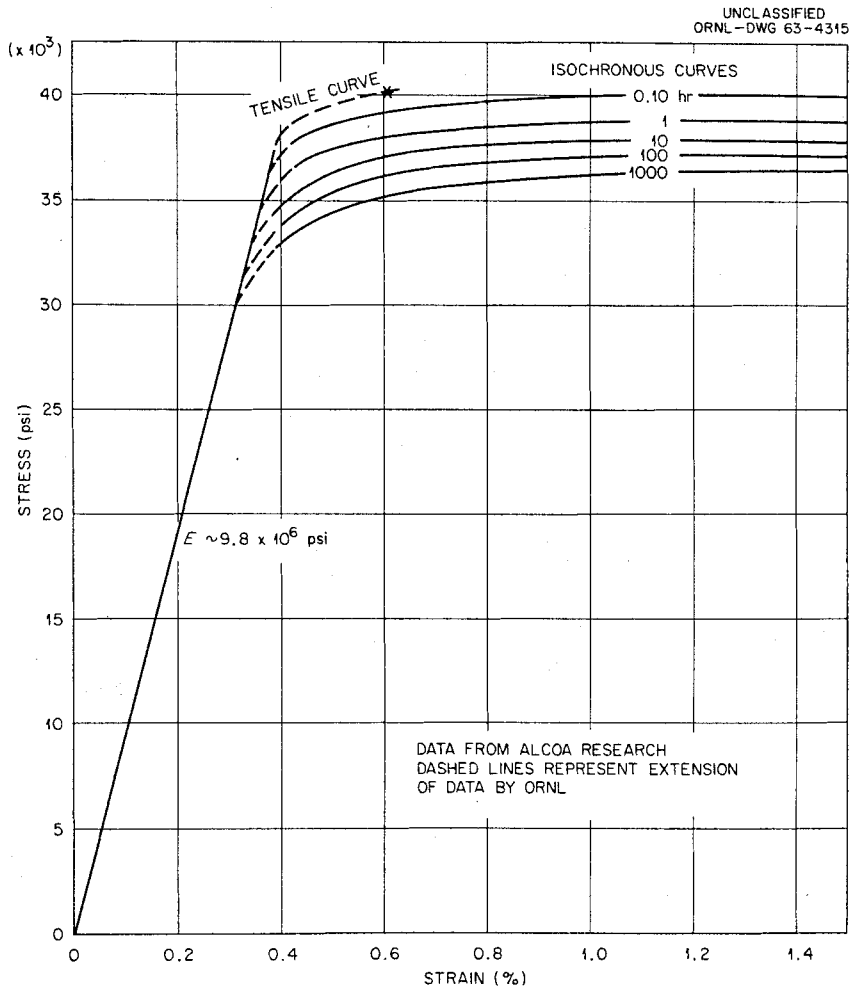

Fig. 16. Stress-Strain Curves for 6061-T6 Aluminum Tested at 212°F.

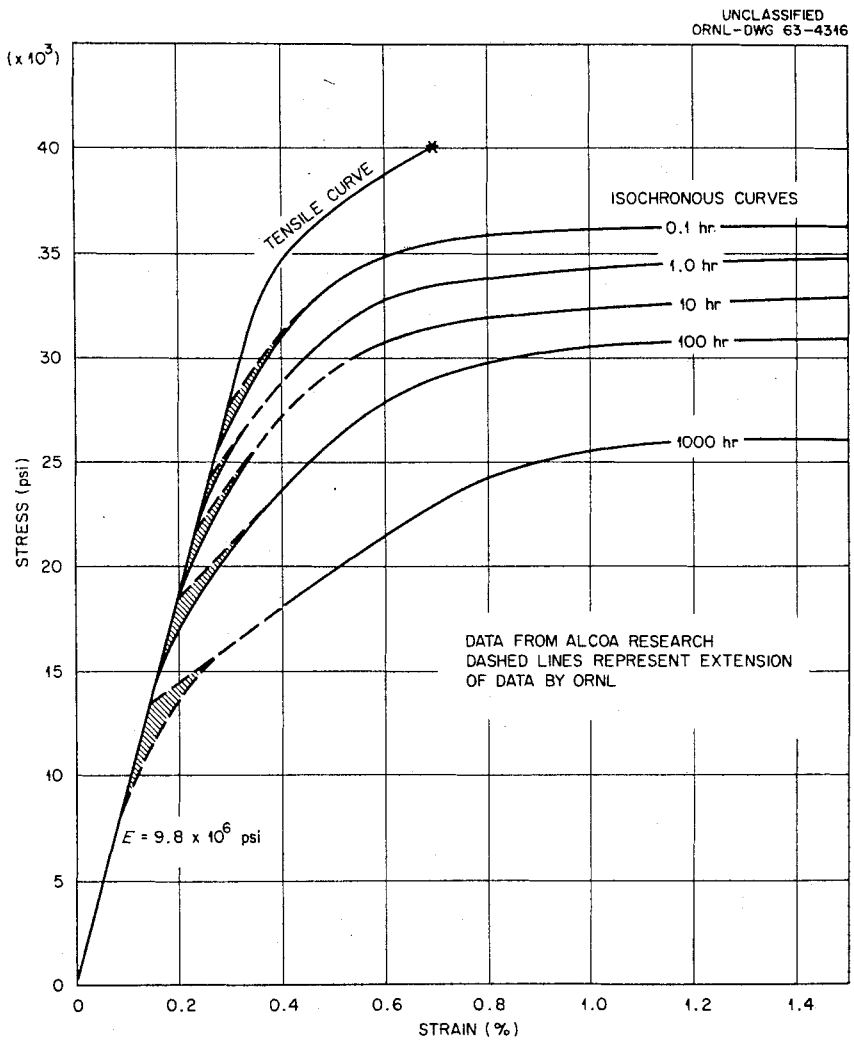

Fig. 17. Stress-Strain Curves for 6061-T6 Aluminum Tested at 300°F.

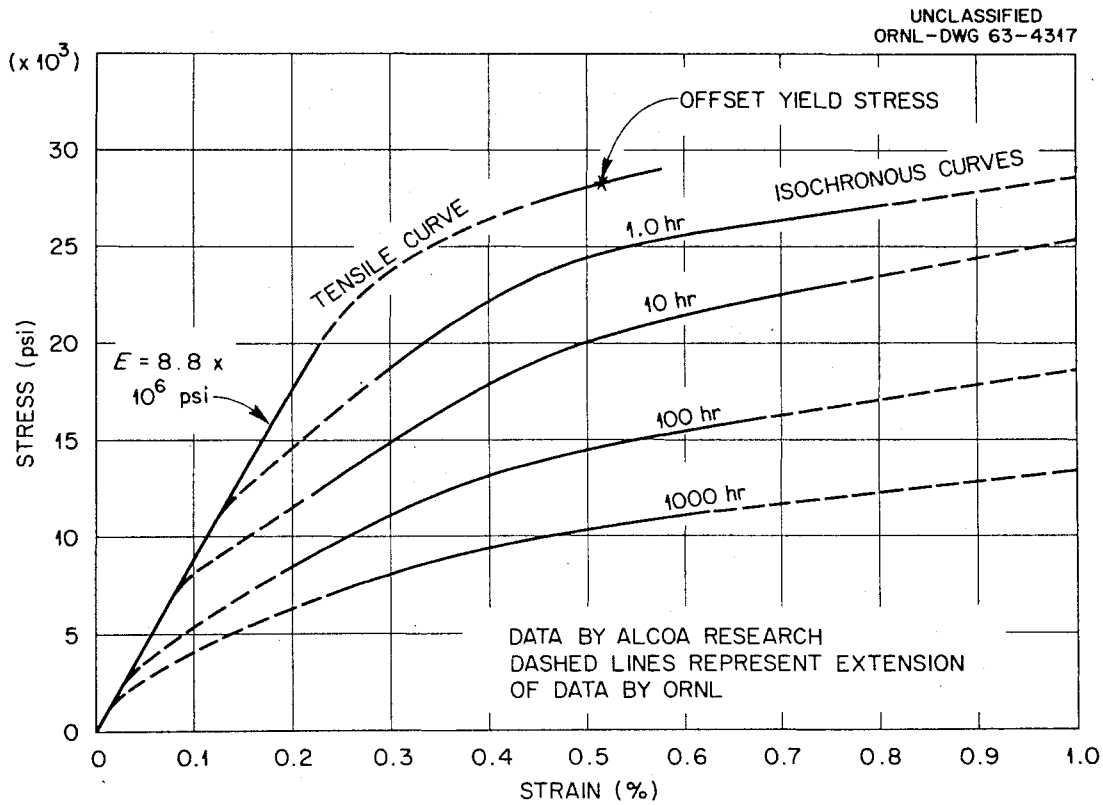

Fig. 18. Stress-Strain Curves for Aluminum Alloy 6061-T6 Tested at 400°F.

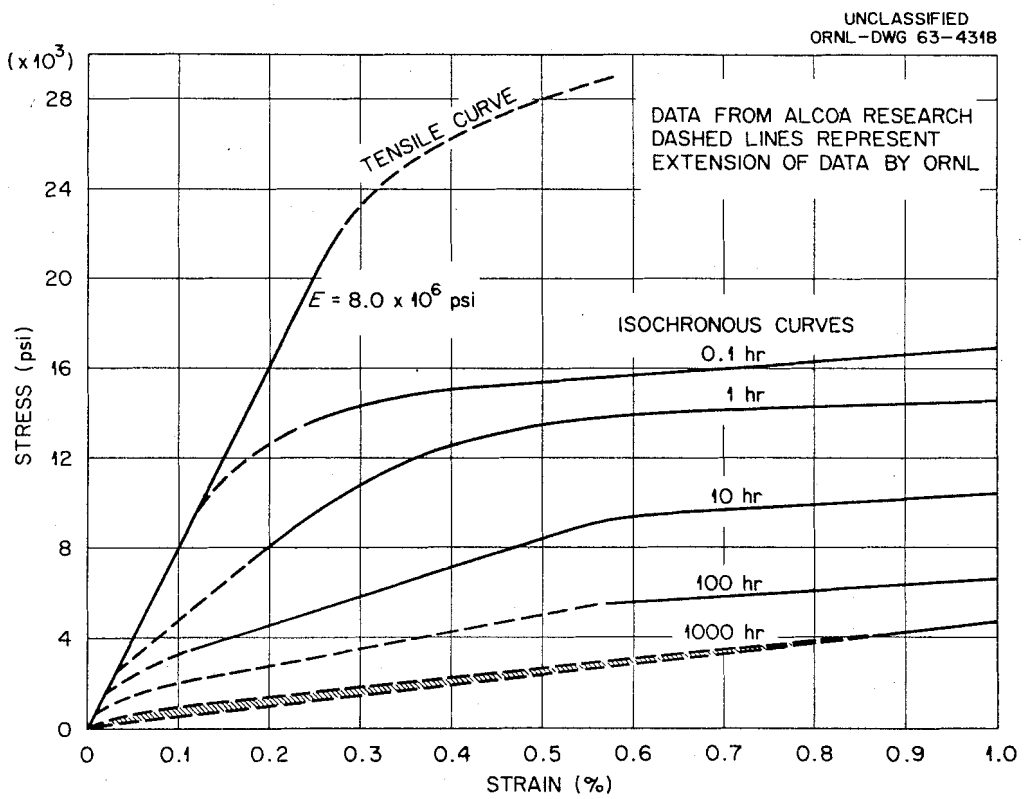

Fig. 19. Stress-Strain Curves for 6061-T6 Aluminum Tested at 500°F.

cold-worked X8001 material at temperatures in the range of 400 to 500°F. The tensile properties of a 10% cold-worked alloy are given in Table 4 as a function of test temperature. The creep strength of the 10% and a 15% cold-worked X8001 is compared to that of an annealed alloy at 400°F in Table 5. These data show that the advantage of increased strength due to cold working evidenced by tensile data is not indicated by creep data for exposure at temperatures of 400°F or above.

Table 4. Short-Time Tensile Strength of a 10% Cold-Worked and Annealed X8001 Aluminum Alloy

Test Temp (°F)	Yield Strength (psi)		Ultimate Tensile Strength (psi)		Total Elongation at Rupture	
	Annealed	Cold-Worked	Annealed	Cold-Worked	Annealed	Cold-Worked
70	5,025	15,550	15,635	17,085	37	26.0
400	3,810	8,620	6,165	9,010	46	25.0
500	3,100	6,530	4,220	6,685	61	16.5
600	2,430	4,410	2,735	4,740	73	16.0

Table 5. Comparison of Typical Isochronous Stress-Strain Data for Cold-Worked X8001 and Annealed Aluminum at Elevated Temperatures

Type of Material	Stress (psi) Necessary to Produce 0.1% Strain in a Given Time at Various Temperatures			
	400°F		500°F	
	100 hr	450 hr	100 hr	450 hr
X8001-1	1325	1050	750	620
X8001, 10% Cold-Worked	1650	1100	850	
X8001, 15% Cold-Worked	1650	1100	750	

It is evident that there is no advantage in using the cold-worked material for creep conditions because of the recovery phenomena. In terms of recovery, there are two types of processes — the dynamic recovery and static recovery. The process of dynamic recovery is assisted by an applied stress whereas the usual static recovery is not. Certainly at the temperatures of 400°F, both processes occur. The static recovery of the 6061 was investigated (see Appendix I) to obtain some information as to its significance at these temperatures.

CONCLUSIONS

Tensile and creep data of two aluminum alloys and a fuel dispersion have been investigated for application to fuel plate material selection and evaluation of fuel element design. The basic material property data can be summarized as follows:

1. The tensile and creep properties of annealed X8001 are similar to 1100 aluminum alloy but significantly less than the 6061 alloy. Heat treatment of the 6061 alloy to the T6 condition can increase the strength of the alloy for exposure at 400°F, but the increase in strength is not observed after exposure of 100 to 1000 hr at 500°F.

2. The degree of increased tensile strength due to cold working of X8001 is marginal for irradiation exposure at temperatures of 400°F and above. Cold working does not increase the creep strength of annealed X8001 alloy at temperatures of 400°F and strains up to 1%.

3. The dynamic modulus of a fuel dispersion can be calculated from the dynamic modulus of the matrix material and the volume fracture of dispersion.

4. The tensile and creep strength of the fuel dispersion is significantly greater than that of the matrix material X8001.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of E. Bolling, R. Waddell, V. G. Lane, B. McNabb, and C. W. Dollins who performed the mechanical properties tests. They also thank the Alcoa Research Laboratory for their permission to publish their tensile data on 6061-T6 alloy.

APPENDIX I

STATIC RECOVERY OF ALUMINUM ALLOYS

Recovery is normally studied by measuring at room temperature one of the properties, such as yield strength or hardness, prior to and after a given heat treatment at elevated temperatures. These data are then plotted as a function of time for a given heat treatment temperature. The shape of these curves then illustrates (1) the time at which recovery and recrystallization occurs for cold-worked material or (2) for an age-hardening alloy, the process of aging or overaging. But it is difficult from these data to correlate the recovery for any other time or temperature other than those investigated.

However, other experimenters[13] have investigated the response of cold-worked stainless steel and the age-hardenable 7075 aluminum alloy with heat treatment and correlated their data using the Larson-Miller parameter.

The correlation was good; therefore, an effort has been made to investigate the recovery of the 6061 alloy in both the cold-worked and age-hardened conditions. In these studies the hardness of the alloy was measured prior to and after heat treatment of 1, 10, 100, and 500 hr at 150, 200, 250, and 300°C.

The percent recovery (R) was defined as:

$$R = \frac{A - B}{A - C} 100 \quad ,$$

where

A = initial hardness of the material after the cold working or T6 condition,

B = hardness after exposure for time, t, at a given temperature, T, and

C = hardness of the alloy after complete annealing.

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[13]C. D. Brownfield and D. R. Apodaca, Effect of Severe Thermal and Stress Histories on Material Strength — Rate Process Theory Approach AISI 301 Extra Hard, PH 15-7 Mo RH, René 41, 7075-T6, ASD-TR-61-194 (January 1962).

The time-temperature correlations used were the Larson-Miller parameter, θ, and the relationship:

$\theta = T\ (D + \log t)$,

T = temperature of heat treatment in degrees Kelvin,

t = time of heat treatment in hours, and

D = material constant (17.7 for this alloy).

The correlated data giving the value of θ for a given percent recovery and a given alloy condition are shown in Table 6. This relationship does not predict the relative strength at room temperature of cold-worked and age-hardened alloys but merely the rate at which the increased strength due to cold working or aging decreases with exposure at elevated temperatures. These data should prove valuable in predicting the recovery of the alloy for times and temperatures not investigated. For example, in an actual yield strength test, 6061-T6 showed 9% recovery after 10 hr at 232°C. The data given in Table 6 would have predicted 10% recovery.

Table 6. Static Recovery of 6061 Aluminum

Alloy Condition	θ Necessary to Obtain a Given Percent Recovery for 6061 Aluminum (% Recovery)					
	10	20	30	40	50	60
6061-0						
5% Cold-Worked	10,700	11,500	11,700	11,800	11,950	12,100
10% Cold-Worked	11,200	11,700	11,900	12,050	12,200	12,300
25% Cold-Worked	10,500	10,850	11,150	11,400	11,600	11,800
50% Cold-Worked	9,150	9,800	10,100	10,300	10,350	10,450
6061-T6	9,450	9,900	10,250	10,450	10,600	

A similar type study could be performed on irradiated alloy and the data generated from postirradiation hardness tests correlated in a similar manner. A comparison of the data of unirradiated and irradiated alloy might substantiate the findings of Adair et al.[14] whose metallographic and hardness examination of 2024 aluminum alloy indicated that irradiation increased the rate of aging at a given exposure temperature.

[14]A. M. Adair, R. E. Hook, and J. Garrett, Radiation Induced Overaging of a 2024-T3 Aluminum Alloy, ARL-132 (September 1961).

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