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PHYSICAL, MECHANICAL, AND IRRADIATION PROPERTIES OF THORIUM AND THORIUM ALLOYS

Joseph P. Hammond

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
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APRIL 1968

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ABSTRACT

Physical and mechanical property data on thorium and thorium alloys were reviewed, and information pertinent to nuclear reactor application is compiled.

INTRODUCTION

Information on physical and mechanical properties of thorium and its alloys was reviewed, and an up-to-date compilation was prepared for use in the forthcoming revision of the Reactor Handbook. We are publishing this compilation now for prompt availability, in view of the interest in thorium-matrix fuels for desalination reactors.

PHYSICAL PROPERTIES OF THORIUM METAL

Radioactive and Decay Process

Natural thorium is practically pure ^{232}Th. This isotope is radioactive with a half-life of 1.39×10^{10} years and is the first naturally occurring member of the radioactive series that decays to ^{208}Pb. The decay scheme,[1] listing particle emissions and half-lives in the radioisotopes, is summarized in Table 1.

Physical Properties [2—10]

The physical constants of thorium are given in Tables 2 and 3. Table 4 lists thermodynamic functions.

Table 1. Thorium Disintegration Series[a]

Isotope	Emission	Energy (Mev)	Half-Life	Daughter
Thorium (^{232}Th)	Alpha	4.01 3.95	1.39×10^{10} y	Mesothorium I
Mesothorium I (^{228}Ra)	Beta	0.055	5.7 y	Mesothorium II
Mesothorium II (^{228}Ac)	Beta Gamma	1.11 0.058 10 91	6.13 hr	Radiothorium
Radiothorium (^{228}Th)	Alpha Gamma	5.43 5.35 0.08 21 14 17	1.91 y	Thorium X
Thorium X (^{224}Ra)	Alpha Gamma	5.68 5.44 0.24	3.64 days	Thoron
Thoron (^{220}Rn)	Alpha Gamma	6.29 5.74 0.54	56 sec	Thorium A
Thorium A (^{216}Po)	Alpha	6.78	0.15 sec	Thorium B
Thorium B (^{212}Pb)	Beta Gamma	0.34 0.58 0.239 0.30 0.11–0.41	10.64 hr	Thorium C
Thorium C (^{212}Bi)	Alpha Gamma Beta Gamma	6.05 6.09 (9.5–10.5)[b] 0.040 2.25 2.20	60 min	Thorium C″ (alpha) Thorium C′ (beta)
Thorium C′ (^{212}Po)	Alpha	8.87	0.30×10^{-6} sec	Lead (stable ^{208}Pb)
Thorium C″ (^{208}Tl)	Beta Gamma	1.80 1.0–2.38 2.61 0.58 0.51 0.23–1.09	3.1 min	Lead (stable ^{208}Pb)

[a]Data taken from D. T. Goldman and J. R. Roesser (eds.), Chart of Nuclides, 9th ed., revised to July 1966, General Electric Company, Schenectady, New York, 1966.

[b]Radiations from short-lived daughter.

Table 2. Physical Properties of Thorium

Property	Values	Reference
Crystallography		
Crystal structure ≤1375°C	Face-centered cubic	2
Lattice parameter, A	a_0 (25°C) = 5.0843 ± 0.002	2
Crystal structure >1375°C	Body-centered cubic	3
Lattice parameter, A	a_0 (1450°C) = 4.11 ± 0.01	3
Density, g/cm^3		
Theoretical	11.72	
Calcium-reduced (as cast)	11.5 to 11.6	
Arc-melted iodide	11.66	
Elastic constants, 25°C		
Modulus of elasticity, psi	10.3×10^6	3
Shear modulus, psi	4.1×10^6	
Poisson's ratio	0.27	
Compressibility, $cm^2/dyne$	16.4×10^{-13}	3
Melting point, °C	1570	4
Boiling point, °C	3300–4500	3
Heat of fusion, kcal/mole	<4.6	3
Heat of sublimation, kcal/mole	131	5
Heat of vaporization, kcal/mole	<170	6
Vapor pressure 1757 to 1956°K	$\log P\ (\text{atm}) = -\frac{28780}{T\ (°K)} + 5.991$	5
Superconducting temperature, °K	1.3 to 1.4	4
Magnetic susceptibility of iodide grade, cgs units		7
20°C	0.54×10^{-6}	
−183°C	0.64×10^{-6}	
Work function, ev	3.39[a]	4
Hall coefficient, cm^3/coulomb	-8.8×10^{-5} (b)	4
Emissivity		8
1025–1425°C (λ = 6670A)	0.38	
Molten (λ = 6500A)	0.40	

[a]Represents an average of best values.

[b]This value corresponds to a density of conduction electrons of 7.1×10^{22} electrons/cm^3 or 2.4 electrons/atom.

Table 3. Properties of Thorium at Various Temperatures

Temperature (°C)	Thermal Conductivity[a] (cal sec^{-1} cm^{-1} $°C^{-1}$)	Electrical Resistivity (μohm-cm)	Mean Coefficient of Thermal Expansion[a] ($10^{-6}/°C$)
25		16.95	
100	0.090	21.45	
200	0.093	27.35	
300	0.096	33.20	
400	0.100	38.85	
500	0.102	44.20	
600	0.106	49.20	
650	0.108		
700		53.80	
800		58.04	
900		62.00	
20–100			11.55
30–300			11.65
30–500			11.9
30–700			12.5
30–900			12.5
30–1000			12.65

[a]O. N. Carlso *et al.*, "The Metallurgy of Thorium and Its Alloys," *Proc. Intern. Conf. Peaceful Use At. Energy, Geneva, 1955* **9**, 74–106 (1956).

[b]Ames Laboratory, *Semi-Annual Summary Research Report in Physics for January–June 1959*, IS-14 (October 1959).

Table 4. Thermodynamic Functions of Thorium[a]

Temperature		Value of Function, cal $mole^{-1}$ $°C^{-1}$				
°C	°K	C_p	C_v	S°	$(H° - H_0°)/T$	$-(F° - H_0°)/T$
−253	20	1.106	1.106	0.410	0.304	0.106
−223	50	4.048	4.042	2.770	1.801	0.969
−173	100	5.482	5.460	6.135	3.369	2.766
−123	150	5.965	5.927	8.460	4.164	4.296
−73	200	6.217	6.161	10.215	4.648	5.567
−23	250	6.392	6.318	11.623	4.980	6.643
25.00	298.16	6.532	6.441	12.760	5.220	7.540
27	300	6.538	6.446	12.799	5.228	7.571

[a]M. Griffel and R. E. Skochdopole, "The Heat Capacity and Entropy of Thorium from 18 to 300°K," *J. Am. Chem. Soc.* **75**, 5250–5251 (1953).

Effects of Irradiation on Physical Properties

Unlike uranium metal, face-centered cubic thorium has excellent resistance to damage by irradiation exposure. It is not subject to the anisotropy-induced growth produced in orthorombic uranium by thermal cycling or irradiation, and its shape and surface quality remain essentially unaltered.

When ^{232}Th is irradiated, it captures a neutron and decays to form ^{233}U with emission of two betas. The latter isotope fissions and produces a small volume increase resulting from the buildup of fission product atoms within the thorium lattice. This volume increase occurs approximately linearly with the amount of fissioning and at a rate of less than 1% per atomic percent burnup. When thorium is exposed to high levels of burnup at temperatures exceeding approximately 670°C, rapid and nonlinear swelling occurs and is attributed to the precipitation and expansion of fission gases.

Figure 1 shows the density and dimensional changes of right-cylindrical slugs of thorium and Th—5% ^{235}U alloy that were irradiated unrestrained in sodium-potassium at central metal temperatures of 50 to 200°C. All changes, even after heavy burnups, were small and independent of initial uranium concentration and fabrication and heat-treatment history.[11]

Thermal conductivity after irradiation has been estimated by Bowman and co-workers[12] from electrical resistivity measurements made on cyclotron-bombarded thorium wires. The results, given in Table 5, show thermal conductivity to decrease by about 5 to 8% at irradiation saturation.

Linear thermal expansion was measured[13] on two irradiated and one unirradiated specimens of Th—11% U alloy. Thermal expansion coefficients of over $25 \times 10^{-6}/°C$ were observed for the irradiated samples; this is twice the value ordinarily obtained on unirradiated material. This effect was attributed to expansion and contraction of internal pockets of fission gas.

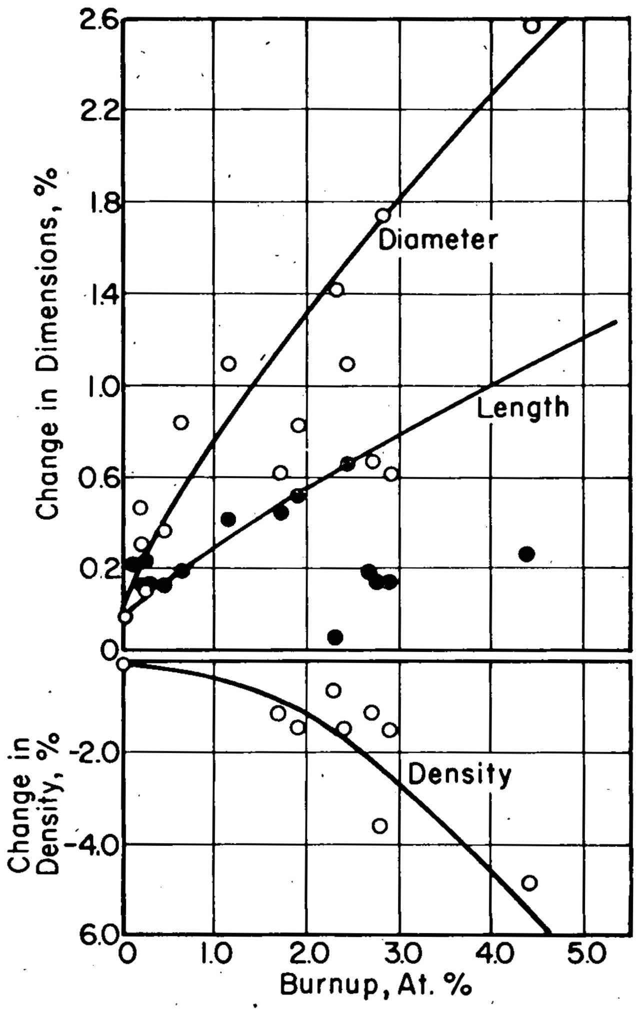

Fig. 1. Chnages in Dimensions and Density of Thorium and Thorium-Uranium Cylinders as a Result of Irradiation. [Reprinted from F. G. Foote and J. H. Kittel, "Effects of Radiation upon Thorium," The Metal Thorium, Proc. Conf., Cleveland, 1956, 278 (1958).]

Table 5. Effect of 38-Mev Alpha-Particle Bombardment on the Thermal Conductivity of Thorium Wires[a]

Temperature (°C)	Conductivity, w cm^{-1} $°C^{-1}$		Decrease at Saturation (%)
	Unirradiated	Irradiated[b]	
300	0.402	0.372	7.5
500	0.431	0.406	5.8

[a]Computed from the Wiedemann-Franz ratio and electrical-resistivity data. F. E. Bowman et al., Cyclotron Irradiation Damage of Thorium, Stainless Steel, and Zirconium, NAA-SR-287 (April 1, 1954).

[b]Saturation value, assuming no back annealing.

MECHANICAL PROPERTIES OF THORIUM METAL

Hardness

The hardness of the different grades of thorium for various conditions at room temperature[14] is indicated by representative values in Table 6. The change in hardness of worked Ames thorium as a function of temperature[15] is illustrated in Fig. 2.

Table 6. Hardness of Thorium at Room Temperature[a]

Method of Production	Hardness of Thorium, VHN		
	As Cast	Cold Worked 80%	Cold Worked and Annealed
Iodide	40	75	35
Ames	75	110	65
Pressed and sintered		140	110

[a]T. C. Runion, B. A. Rogers, and S. H. Paine, "Thorium," pp. 211–226 in Reactor Handbook, (ed. by C. R. Tipton, Jr.) 2nd ed., Vol. I, Interscience, New York, 1960.

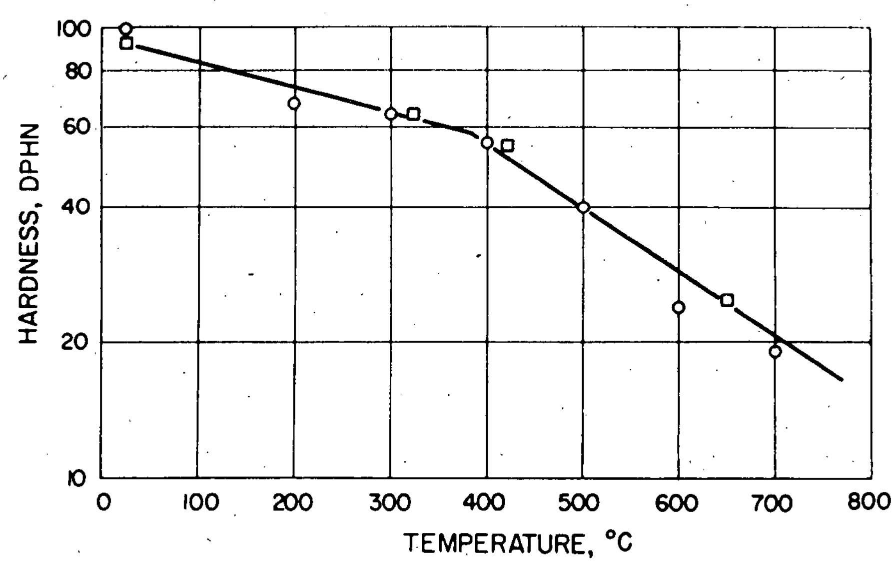

Fig. 2. Change in Hardness of Ames Thorium with Temperature.* [Reprinted from p. 222 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.]

*A. D. Schwope, G. T. Muehlenkamp, and L. L. Marsh, Mechanical and Metallurgical Properties of Thorium, BMI-784 (Nov. 18, 1952).

Recrystallization Temperature

The recrystallization characteristics of thorium were established by examining hardness and microstructure while varying the amount of reduction by cold rolling and temperature of annealing. The recrystallization temperatures of Ames and iodide thorium[16] are given in Table 7. Carbon, the principal contaminant in Ames thorium, does not appear to have a very significant effect on the recrystallization temperature range.

Table 7. Effect of Cold Work on Recrystallization of Throium[a]

Reduction in Area (%)	Recrystallization Temperature, °C			
	Start		Complete	
	Ames Thorium	Iodide Thorium	Ames Thorium	Iodide Thorium
80	520	500	625	575
60	520	510–520	625	600
40	540–550	520	650	600
20	550–575	550–575	650	700

[a]E. J. Boyle, "Recrystallization of Thorium," The Metal Thorium, Proc. Conf., Cleveland, 1956, 217–224, 1958.

Preferred Crystallographic Orientations

The preferred orientations formed in thorium by both extrusion to rod and rolling to plate have been determined. Table 8 shows the principal textures in Ames thorium fabricated under various conditions.[17]

The tensile properties in rolled sheet changed very little with orientation of specimens within the rolling plane, which is not unexpected for relatively isotropic thorium. For example, yield strength varied only 7.5% with specimen orientation for the cold-rolled condition. Recrystallization, which produces an entirely new texture (Table 8), diminished the yield strength to about one-third the value for cold-rolled material; however, variation of yield strength with specimen orientation remained small, about 6%.

Table 8. Preferred Crystallographic Textures in Ames Thorium[a]

Material Condition	Orientation Components
Fiber textures	
Cold extruded	⟨111⟩
Recrystallized during extrusion	⟨001⟩ or ⟨114⟩
Recrystallized after extrusion	⟨115⟩ – ⟨236⟩ or ⟨013⟩ – ⟨4,10,13⟩
Sheet textures	
Cold rolled to 75% reduction	$\{148\}\langle\bar{4}\bar{1}1\rangle$, $\{011\}\langle\bar{3}22\rangle$, and $\{034\}\langle\bar{1}00\rangle$
Cold rolled to 95% reduction	near $\{113\}\langle\bar{2}\bar{1}1\rangle$, near $\{011\}\langle\bar{2}\bar{1}1\rangle$, and $\{011\}\langle\bar{1}00\rangle$
Cold rolled to 75% reduction and recrystallized	$\{017\}\langle\bar{1}00\rangle$
Cold rolled to 95% reduction and recrystallized	{001}⟨100⟩ (the "cube" texture)

[a]L. K. Jetter and C. J. McHargue, "Preferred Orientation in Thorium," The Metal Thorium, Proc. Conf., Cleveland, 1956, 161–184 (1958).

The yield strength of rapidly extruded thorium rod was approximately one-half that of slowly extruded rod. This large decrease in strength probably resulted from softening effects accompanying recrystallization rather than from the appearance of entirely different textures.

Tensile Properties

Considerable useful information in addition to tensile properties is afforded by plotting tensile stress against strain. Some differences in the character of the diagrams obtained on three types of thorium have been noted. Diagrams for iodide thorium do not have a yield point. Diagrams for cast Ames thorium occasionally show a yield point, and those for Ames thorium completely annealed after cold working usually do.

Diagrams for compacted metal powder also are likely to show a yield point. Figure 3 is a stress-strain diagram for cold-worked and annealed Ames thorium.[18]

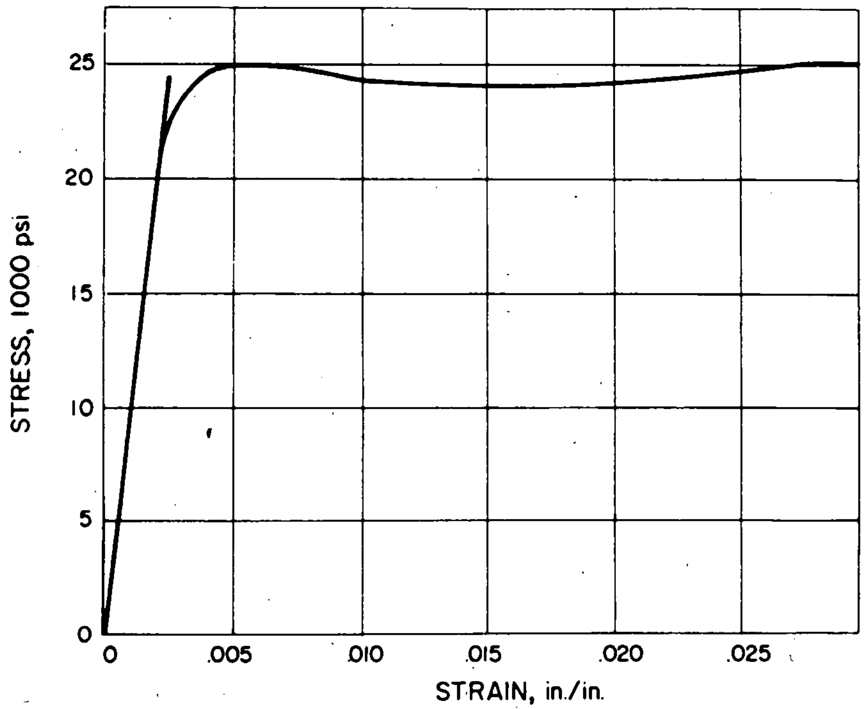

Fig. 3. Stress-Strain Graph for Cold-Rolled and Annealed Ames Thorium. Metal was cold rolled 35% and annealed at 750°C for 1 hr.* [Reprinted from p. 219 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed., Vol. I, Interscience, New York, 1960.]

*D. E. Hamby (ed.), Metallurgy of Thorium and Thorium Alloys, ORNL-1090, p. 16 (Dec. 7, 1951).

Rate of straining also affects the values obtained in tensile tests. For relatively low rates a 100% increase in the rate of strain changes the properties by only a few percent. Such an increase at a higher rate produces a much stronger effect. Low rates of straining were used in obtaining the data in Table 9. Values for Ames thorium are representative of metal that contains 0.025 and 0.03% C.[14]

The measured values of modulus of elasticity vary widely; a reasonable value is 10.5×10^6 psi. The effect of temperature on tensile properties, including the modulus of elasticity,[3] is shown in Fig. 4.

Table 9. Tensile Properties of Thorium[a]

Method of Preparation	Strength, psi		Ductility, %	
	Ultimate Tensile	2% Offset Yield	Elongation in 2 in.	Reduction of Area
		Annealed		
Iodide	18,000	6,000	40[b]	c
Ames[d]	25,000	15,000	60	75
Pressed and sintered	35,000	25,000[e]	35[f]	25[f]
		80% Cold Reduced		
Ames[d]	45,000	35,000	5	2–3[e]
Pressed and sintered	80,000		3	2–3[e]

[a]T. C. Runion, B. A. Rogers, and S. H. Paine, "Thorium," pp. 211–226 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.

[b]Local necking allows fracture at low elongations for 2-in. gage length.

[c]Large reduction in area but difficult to measure.

[d]For content of about 0.3% C.

[e]Estimated.

[f]Values vary through wide limits.

Properties in Compression

Very few measurements have been made on the strength of thorium in compression. Figure 5 is an incomplete stress-strain diagram[18] made on a test piece of Ames thorium that had been annealed at 750°C for 30 min.

Behavior in Creep

Thorium must be stressed to an unusually high fraction of its ultimate strength to promote continuing creep. To attain appreciable creep in Ames thorium at 300°C, the stress must be within 2000 psi of the ultimate strength. Calcium-reduced thorium tested as sheet or bar[19] creeps at a lower rate at 204°C than at 93 or 316°C. A similar phenomenon found in steels in the test range 100 to 300°C is termed

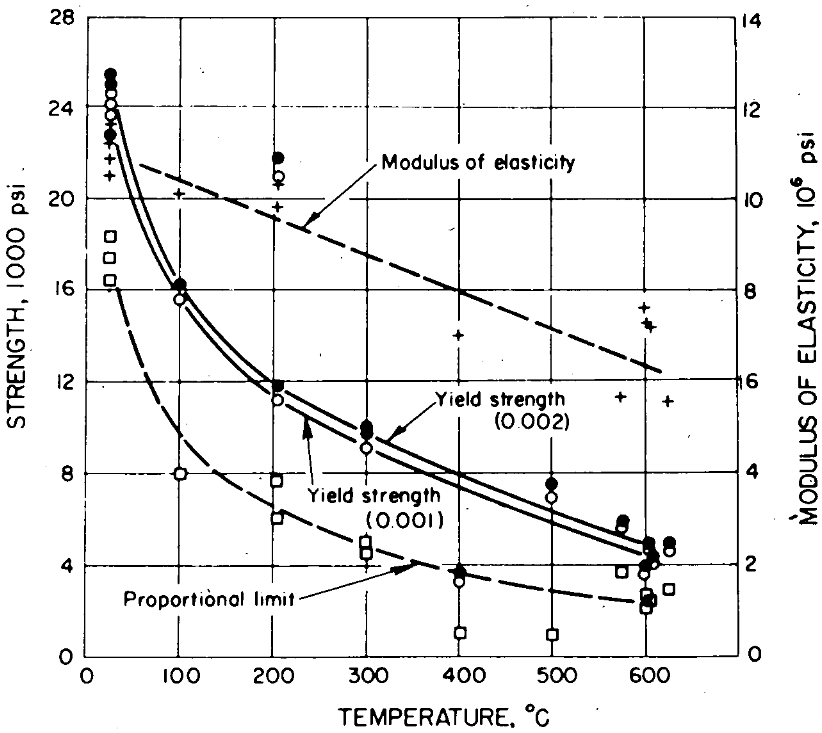

Fig. 4. Changes in Some Tensile Properties of Thorium with Temperature of Testing.* [Reprinted from p. 221 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed., Vol. I, Interscience, New York, 1960.]

*O. N. Carlson et al., "The Metallurgy of Thorium and Its Alloys," Proc. Intern. Conf. Peaceful Uses At. Energy, Geneva, 1955 9, 74–106 (1956).

"blue brittleness" and is associated with strain aging. The faster the rate of straining thorium at a fixed temperature, the less is the effect of strain aging. The results[20] of some creep tests on cast Ames thorium at room temperature and 300°C are given in Table 10.

The stress-rupture behavior of extruded calcium-reduced thorium bar containing 0.4% C depended on the extrusion rate.[21] This effect is illustrated in Fig. 6 for material tested at 300°C. The higher the speed of extrusion used, the lower the rupture stress for a given time under stress. The materials extruded at the higher rates probably were elevated in temperature relative to the slowly extruded thorium and had different crystallographic textures.

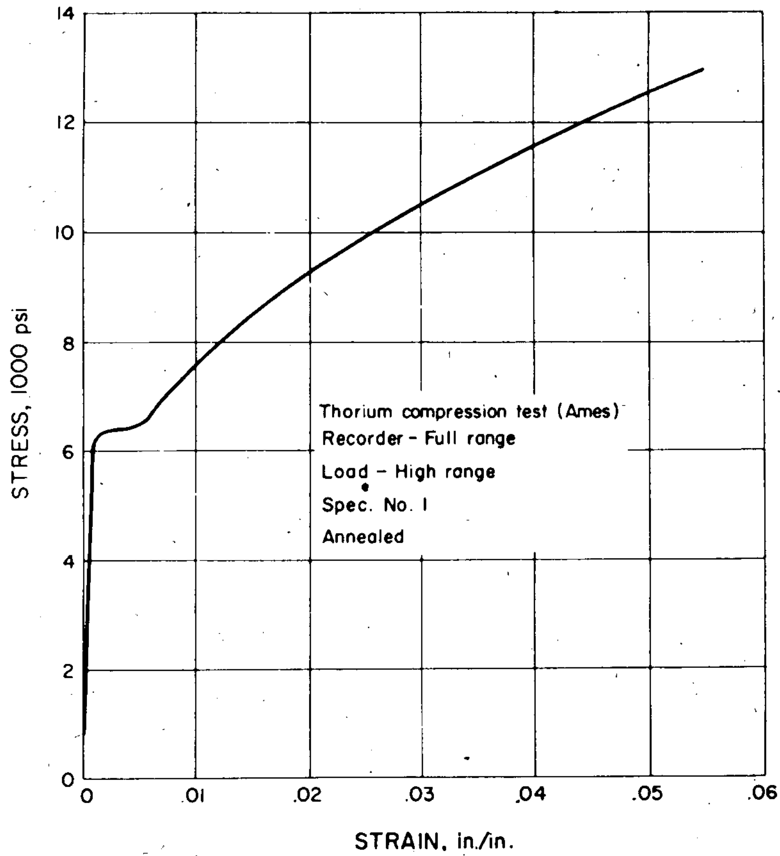

Fig. 5. Stress-Strain Graph for Ames Thorium in Compression.* [Reprinted from p. 221 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.]

*D. E. Hamby (ed.), Metallurgy of Thorium and Thorium Alloys, ORNL-1090, p. 16 (Dec. 7, 1951).

Table 10. Results of Creep Tests on Ames Thorium[a]

Temperature (°C)	Stress, psi		t_1[b] (hr)	Creep Rate (hr^{-1})	t_2[c] (hr)
	Preliminary	During Test			
				$\times 10^{-6}$	
25	20,000	25,000	4500	3.24	3930
25		15,000	600	0.82	2200
	15,000	19,000	700	1.53	1200
300		15,000		30.7	2000

[a]G. C. Danielson et al., Terminal Report of an Investigation of the Properties of Thorium and Some of Its Alloys, ISC-297 (Oct. 1, 1952).

[b]t_1, time required for the creep rate to become approximately constant.

[c]t_2, interval over which the indicated creep rate was maintained.

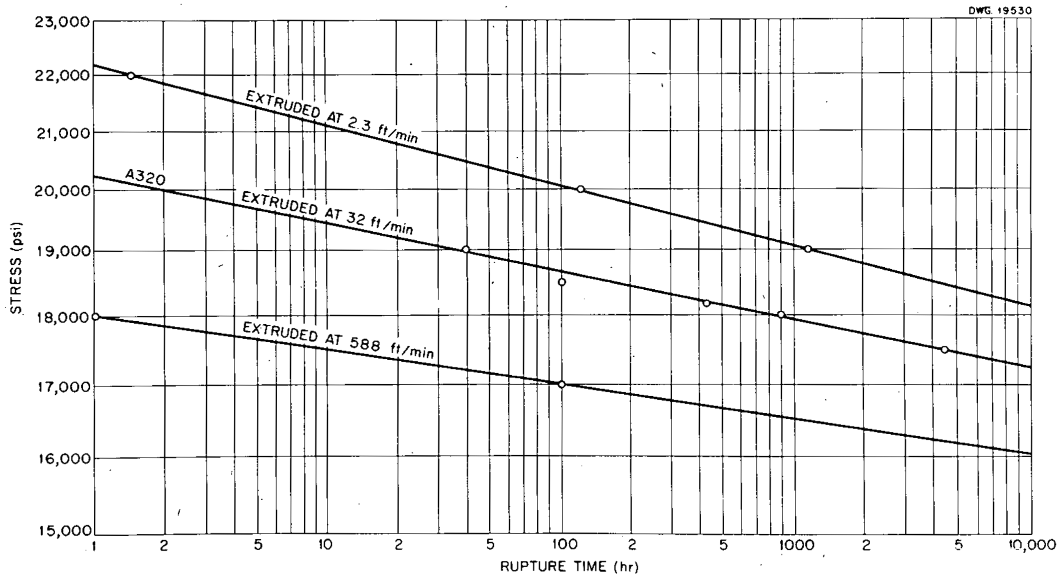

Fig. 6. Stress-Rupture Curves for Extruded Ames Thorium. Nominal carbon content, 0.040%, 0.505-in. round bar tested at 300°C and 4×10^{-4} torr.*

*R. B. Oliver, Metallurgy Div. Semiann. Progr. Rept. April 10, 1953, ORNL-1551, p. 6.

Fatigue

Reported values on endurance limit are higher for Ames thorium in sheet form than in rod. Differences again probably stem from differences in texture and degree to which recrystallization or softening had occurred.

The endurance limits[3] for rotating beam tests conducted on Ames thorium rod at room temperature were 12,000 to 12,500 psi for cast specimens, 15,000 psi for cold-rolled specimens, and 13,000 psi for specimens forged at 600°C.

Stress-cycle curves[15] for cold-rolled and annealed Ames thorium tested as sheet by cantilever bending are shown in Fig. 7. At an endurance limit of 10^7 cycles, the fatigue strengths were 22,500 and 17,500 psi for unnotched and notched specimens, respectively. Thorium appears to be moderately notch sensitive; that is, once a crack is formed, it is likely to propagate.[4]

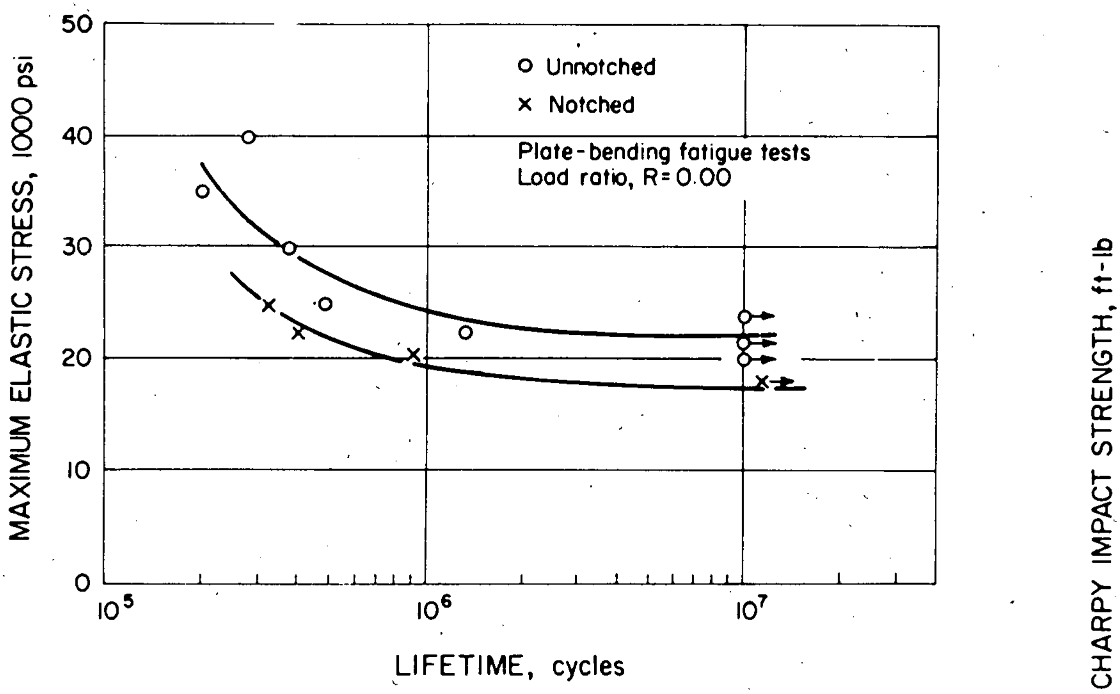

Fig. 7. Fatigue Behavior of Unnotched and Notched Thorium Sheet Specimens. Tests were made at room temperature on calcium-reduced thorium forged and hot rolled at 790°C, cold reduced 50%, and annealed 3 hr at 735°C.* [Reprinted from p. 223 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed., Vol. I, Interscience, New York, 1960.]

*A. D. Schwope, G. T. Muehlenkamp, and L. L. Marsh, Mechanical and Metallurgical Properties of Thorium, BMI-784 (Nov. 18, 1952).

Strength Under Impact

Ability to resist impact, which reveals the notch sensitivity of a metal, is important in such fabrication operations as rolling and forging and in certain service applications. The resistance to impact of Ames thorium appears to be sensitive to carbon content, according to the results given in Fig. 8 for specimens cut from ingots.[20]

Temperature also has a considerable effect on the impact strength of thorium.[20] Cast Ames thorium, when tested as Charpy-type specimens, exhibits a transition from brittle to ductile failure between 100 and 500°C, as illustrated in Fig. 9.

The results of impact tests on Izod-type specimens of Ames thorium, shown in Fig. 10, display a narrower transition range centering at 50°C; interestingly enough, iodide thorium failed to reveal a transition and

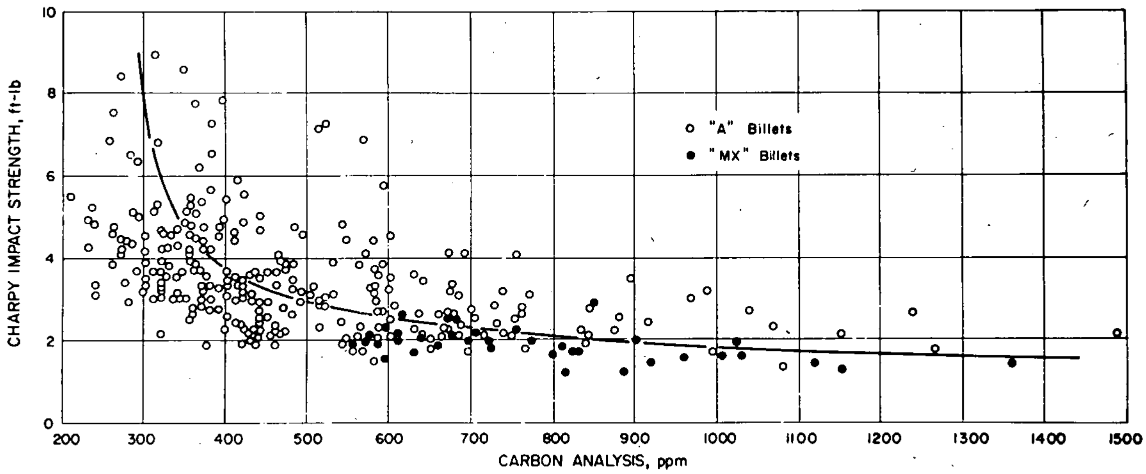

Fig. 8. Effect of Carbon Content on Impact Strength of Cast Ames Thorium. Specimens represented by the open circles were cut from ingots that were cast from scrap thorium (i.e., turnings, cropped ends of ingots, and the like).* [Reprinted from p. 223 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.]

*G. C. Danielson et al., Terminal Report of an Investigation of the Properties of Thorium and Some of Its Alloys, ISC-297 (Oct. 1, 1952).

showed increasing energy with lowering of temperature.[22] Iodide thorium with as little as 0.05% C shows a transition temperature, which increases with carbon content.

Damping Capacity

The damping capacity (ability to absorb energy under vibration) of thorium specimens subjected to transverse bending is shown in Fig. 11. This property is constant to 300°C and rises rapidly at higher temperatures.

Effect of Irradiation on Mechanical Properties

The results of tensile tests after two series of low-temperature irradiations on unalloyed thorium are reported by Bement.[23,24] One series of specimens was irradiated at about 150°C to fission burnups of ^{233}U ranging from 0.01 to 0.04 at. % of the thorium. Another series was irradiated at about 300°C to fission burnups of ^{233}U ranging from

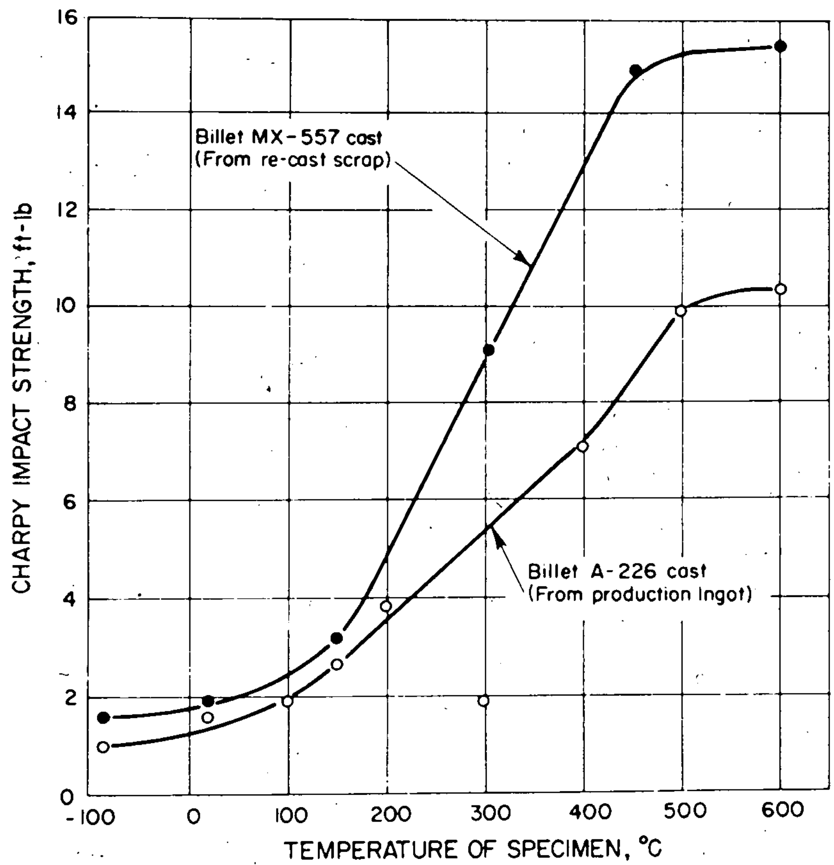

Fig. 9. Effect of Temperature on Impact Strength of Cast Ames Thorium. Charpy keyhole specimens were used.* [Reprinted from p. 223 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.]

*G. C. Danielson et al., Terminal Report of an Investigation of the Properties of Thorium and Some of Its Alloys, ISC-297 (Oct. 1, 1952).

0.1 to 2 at. % of the thorium. The results of room-temperature tensile tests on unirradiated and irradiated specimens are summarized in Table 11 and Figs. 12 and 13.

The data show that unirradiated annealed thorium yields plastically at about 15,000 psi and then work-hardens to an ultimate strength of about 25,000 psi (Table 11). The same material after a very slight neutron irradiation yields at a stress well above the former ultimate strength of 25,000 psi; then as shown in Fig. 12, it "work softens" to failure at a much lower stress than that at which plastic yielding first commenced. Figure 13 shows that the yield point increases and the total elongation of thorium decreases progressively with increasing dose.

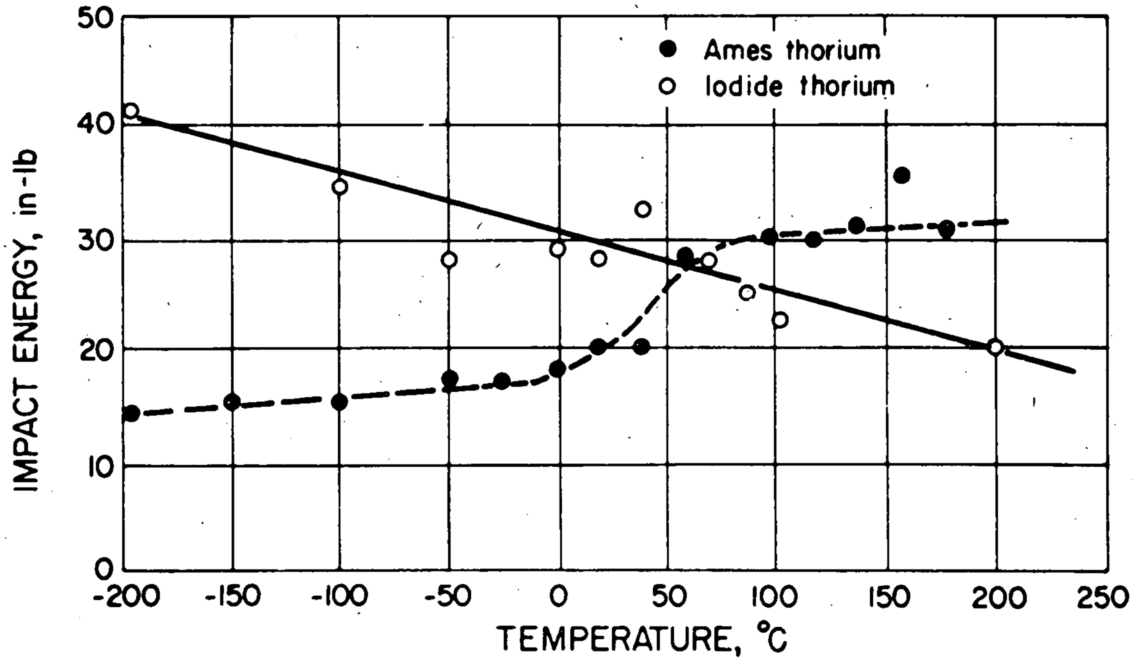

Fig. 10. Effect of Temperature on Impact Strength of Thorium Showing the Ductile-to-Brittle Transition.* [Reprinted from p. 223 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.]

*J. A. Milko, Metallurgy Div. Semiann. Progr. Rept. Oct. 10, 1953, ORNL-1625, p. 7.

The effects of neutron irradiation on mechanical properties of unalloyed thorium at room temperature, 590 and 815°C are shown in Table 12.[25] Although the room-temperature tensile values confirm the results in Table 11, the high-temperature results show a small increase in the ultimate strength and a large increase in the yield strength.

The hardness of thorium has been shown by various investigators[12,26] to increase with irradiation.

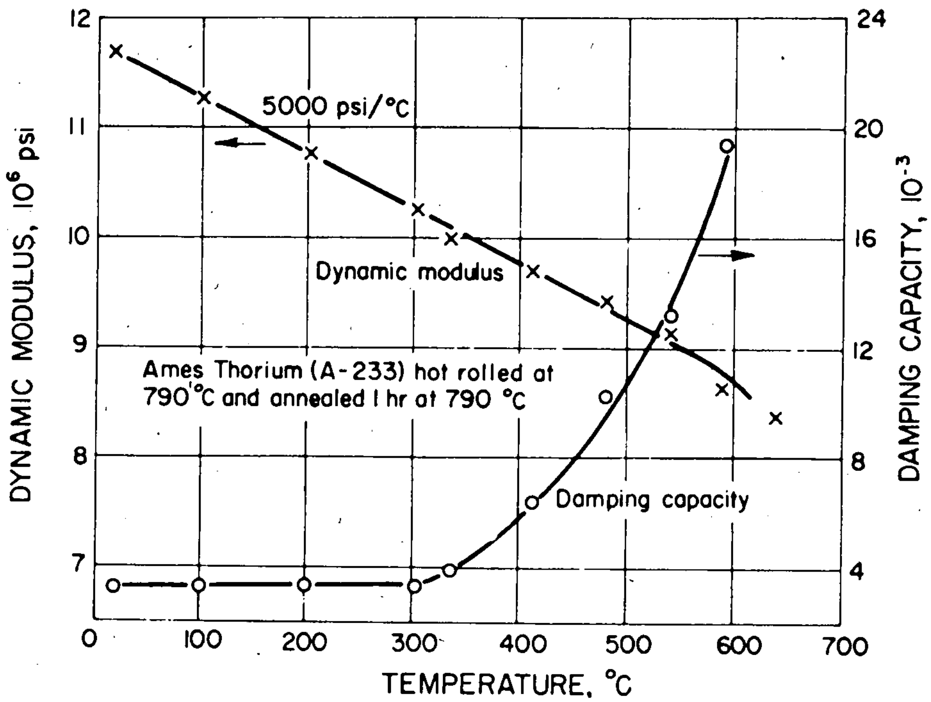

Fig. 11. Increase in the Damping Capacity of Thorium with Rising Temperature. Decrease in modulus of rigidity is also shown.* [Reprinted from p. 224 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.]

*A. D. Schwope, G. T. Muehlenkamp, and L. L. Marsh, Mechanical and Metallurgical Properties of Thorium, BMI-784 (Nov. 18, 1952).

Table 11. Tensile Data for Irradiated and Unirradiated Thorium[a]

Specimen	Specimen Origin[b]	Irradiation Data			Strength, psi		Total Elongation (%)	Modulus of Elasticity (psi)
		Dose (neutrons/cm^2)	Burnup (at. %)	Burnup (fissions/cm^3)	0.2% Offset Yield	Tensile		
		$\times 10^{20}$		$\times 10^{18}$	$\times 10^3$	$\times 10^3$		$\times 10^6$
B-1	Battelle				15.7	25.1	47	11.3
B-2	Battelle				15.4	24.2	37	12.1
H-1	Hanford				15.9	24.9	36.5	10.2
H-2	Hanford				20.7	28.6	39	8.2
EZ	Battelle	3.4	0.011	3.2	37.2	37.3	44.2	7.2
GZ	Battelle	3.5	0.012	3.5	37.6	37.8	34.6	8.7
DZ	Hanford	3.4	0.011	3.2	40.3	40.3	3.6[c]	9.7
FZ	Hanford	3.5	0.012	3.5	39.8	39.8	31.7	9.1
EW	Battelle	5.7	0.035	11.0	42.1	42.7	8.4	8.3
GW	Battelle	5.8	0.035	11.0	43.9	44.4	21.0[c]	8.9
DW	Hanford	5.7	0.035	11.0	43.9	43.8	15.6	8.6
FW	Hanford	5.8	0.035	11.0	53.1	52.9	7.4[c]	9.1
28	Battelle	9.9	0.12	35	49.8	50.8	17.8	12.2
27	Hanford	11.6	0.16	47	53.9	56.5	13.2	10.7
30	Battelle	31.2	0.95	300	69.1	74.9	2.4	11.2
26	Battelle	34.7	1.15	340		48.8[d]	0.8[c]	8.1
25	Hanford	44.6	1.65	480		55.9[d]	0.7[c]	9.6
29	Hanford	49.9	1.90	560	69.1	75.6	3.2	8.6

[a] Hanford Atomic Products Operation Quarterly Progress Report on Fuels Development Operation, October, November, December 1959, HW-64863 (January 15, 1960). CLASSIFIED.

[b] Grain size at 100×: Hanford, 150 grains/in.^{2}; Battelle, 50 grains/in.^{2}.

[c] Sample broke outside of gage length.

[d] Breaking strength.

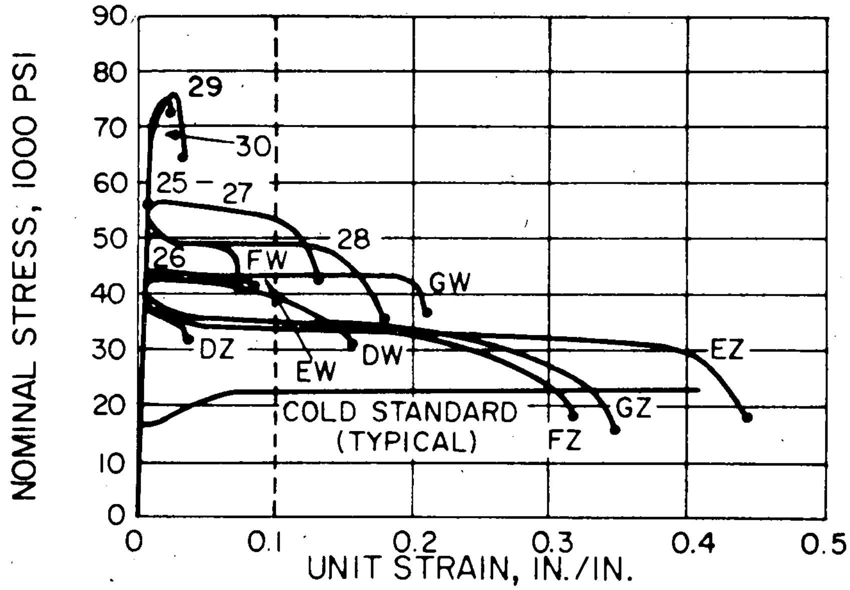

Fig. 12. Stress-Strain Curves for Irradiated Thorium. See Table 11 for specimen exposures.* [Reprinted from Reactor Mater. 5(1), 9 (February 1962).]

*Hanford Atomic Products Operation Quarterly Progress Report on Fuels Development Operations, October, November, December 1959, HW-64863 (Jan. 15, 1960). CLASSIFIED.

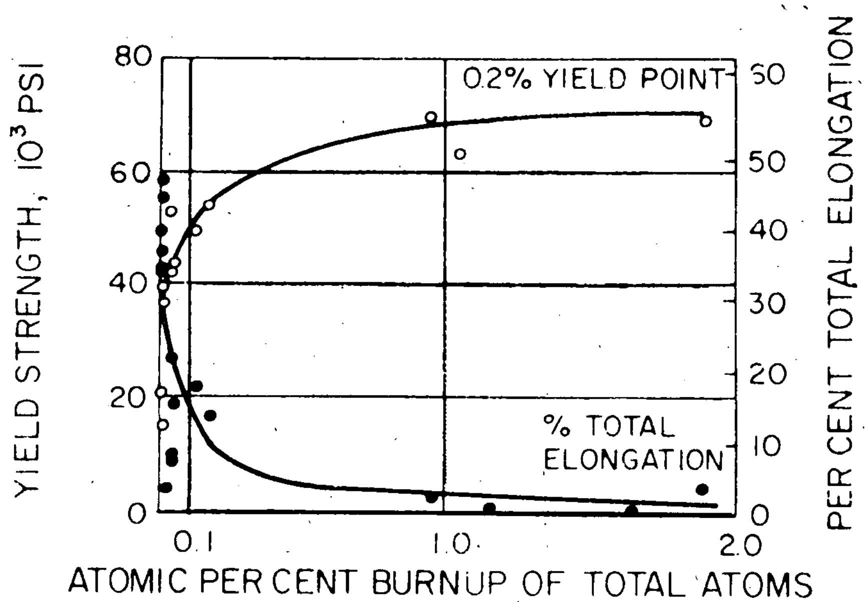

Fig. 13. Variation of Yield Strength and Elongation of Thorium with Burnup.* [Reprinted from Reactor Mater. 5(1), 9 (February 1962).]

*Hanford Atomic Products Operation Quarterly Progress Report on Fuels Development Operation, October, November, December 1959, HW-64863 (Jan. 15, 1960). CLASSIFIED.

Table 12. Room- and Elevated-Temperature Tensile Properties of Irradiated Thorium[a]

Test Temperature (°C)	Thermal Dose (neutrons/cm^2)	Burnup (at. %)	Strength, psi		Total Elongation in 1 in. (%)
			0.2% Yield	Ultimate	
	$\times 10^{20}$		$\times 10^3$	$\times 10^3$	
		Battelle Material[b]			
25	0		16.7	24.4	41
25	0		16.4	24.6	50
25	0		17.5	26.5	57
815	0		~7	~17	~43
25	8.1	0.077	44.2	44.6	24
25	7.1	0.058	44.5	44.9	29
590	7.3	0.060	~24	~27	~22
815	7.6	0.065	~20	~21	~9
		Hanford Material[c]			
25	0		21.0	31.7	55
25	0		22.3	29.9	d
590	0		~9	~20	~92
815	0		~8	~16	~26
25	7.7	0.070	50.5[e]	51.1	d
25	8.4	0.085	48.6[e]	49.5	d
590	7.3	0.060	~22	~23	~24
815	7.5	0.065	~19	~19	~16

[a]Hanford Atomic Products Operation Quarterly Progress Report on Fuels Development Operation, October, November, December 1960, HW-70355 (Jan. 13, 1961). CLASSIFIED.

[b]Grain size of 3 grains/cm^2 at 100×; contains 70 ppm Fe, 370 ppm C, and 1125 ppm O.

[c]Grain size of 23 grains/cm^2 at 100×; contains 155 to 315 ppm Fe, 295 to 730 ppm C, and 850 ppm O.

[d]Sample broke outside of 1 in. gage length.

[e]Lower yield strength.

MECHANICAL PROPERTIES OF THORIUM ALLOYS

Considerable research has been done on alloying thorium to improve its mechanical properties for use in reactor fuel elements. Many potential hardeners were found, some of the most effective being C, Zr, Mo, U, and Al. More recent studies on thorium have been directed toward improvement of elevated-temperature properties. In this connection, solid-solution strengthening, precipitation hardening, and hard-particle dispersion hardening have figured prominently.

For exploratory studies directed to high-temperature alloys, hot hardness has frequently been used as a preliminary test. Elevated-temperature tensile and creep tests have been conducted on the more promising alloys. The results of separate studies are not always comparable because of differing impurity levels in the thorium base and differing fabricating or testing techniques.

In discussing the properties of thorium alloys, hot-hardness results are first reviewed. Subsequently, the individual alloy systems are treated in order of their merit from the point of view of nuclear and high-temperature properties.

Survey of Hot Hardness of Arc-Melted Thorium Alloys

Oak Ridge National Laboratory[27] has studied the effects of binary and ternary additions to arc-melted thorium and evaluated the results by hot-hardness traverses on hot-rolled plate. Battelle[28] has conducted similar studies on thorium-uranium and thorium-uranium-base alloys. The hot-hardness results stemming from these investigations are listed in Table 13 in order of hardness at 600, 750, and 800°C.

The elements C, In, U, and Zr all have significant solid solubility in thorium. Of these elements, carbon was principally effective below 500°C, although carbon in combination with Cr, Mo, U, and Be appeared to enhance hardness at 600°C. As single additions, indium and zirconium had the strongest effect on hardness at 600°C and higher. They also had the greatest effect in raising the recrystallization temperature.[27] As seen in Table 13, 10% U—thorium-base alloys containing small or moderate

Table 13. Thorium-Base Alloys in Order of Decreasing Hardness

Alloy[a]	Composition (wt %)	Hardness (kg/mm^2)
	600°C	
ORNL[b]	4 In	91
BMI[c]	10 U—0.5 Al	75.7
BMI[d]	10 U—10 Zr—2 Nb	73.2
BMI[c]	10 U—0.1 Be	69.1
BMI[c]	10 U—0.2 C	67.3
BMI[c]	10 U—10 Y	66.1
BMI[c]	10 U—1.5 Mo—0.2 C	64.7
ORNL[b]	2 In	63
BMI[c]	10 U—0.2 Be	62.3
ORNL[b]	10 Zr	59
ORNL[b]	5 Zr	59
BMI[c]	10 U—2 Nb—0.2 C	58
BMI[c]	10 U—4 Nb	56.6
BMI[d]	10 U—10 Zr	54.5
ORNL[b]	5 Zr—0.2 C	54
ORNL[b]	20 Zr	54
ORNL[b]	5 V—0.2 C	50
BMI[c]	10 U—2 Mo	49.3
ORNL[b]	4 In—5 Zr	49
ORNL[b]	2 In—0.2 C	49
ORNL[b]	2 Cr—0.2 C	47
BMI[e]	20 U	46.2
BMI[e]	5 U	45.4
BMI[e]	10 U	45.4
ORNL[b]	2 Mo—0.2 C	44
ORNL[b]	5 U—0.2 C	44
ORNL[b]	0.2 Al—0.2 C	43
ORNL[b]	8 Nb	43
BMI[d]	10 U—2 Nb	42.7
BMI[d]	10 U—20 Zr	42.4
BMI[d]	10 U—1.5 Mo	41.1
ORNL[b]	0.2 Be—0.2 C	40
ORNL[b]	5 Ti—0.2 C	40
BMI[e]	15 U	39.2
BMI[d]	10 U—25 Zr	39.2
ORNL[b]	0.2 C	38
ORNL[b]	5 Ti	37
ORNL[b]	20 U	36
ORNL[b]	0.4 Al	35
ORNL[b]	8 Cr	35
ORNL[b]	0.2 Al	32
ORNL[b]	5 V	32
ORNL[b]	5 U	30

Table 13. (continued)

Alloy[a]	Composition (wt %)	Hardness (kg/mm^2)
ORNL[b]	8 Mo	30
ORNL[b]	0.15 C	29
ORNL[b]	2 Nb—0.2 C	29
ORNL[b]	10 U	28
ORNL[b]	4 Mo	27
ORNL[b]	4 Cr	27
ORNL[b]	4 Nb	26
ORNL[b]	2 Nb	26
ORNL[b]	2 Mo	24
ORNL[b]	0.10 C	23
ORNL[b]	thorium	22
ORNL[b]	2 Cr	21
ORNL[b]	0.2 Be	21
	750°C	
ORNL[b]	4 In	55
ORNL[b]	5 Zr	37
ORNL[b]	4 In—5 Zr	34
ORNL[b]	5 V—0.2 C	33
ORNL[b]	2 In	31
ORNL[b]	5 Zr—0.2 C	31
ORNL[b]	5 U—0.2 C	26
ORNL[b]	20 Zr	25
ORNL[b]	10 Zr	25
ORNL[b]	8 Nb	25
ORNL[b]	5 Ti—0.2 C	24
ORNL[b]	5 Ti	23
ORNL[b]	2 In—0.2 C	23
ORNL[b]	0.2 Be—0.2 C	20
ORNL[b]	5 V	20
ORNL[b]	2 Cr—0.2 C	20
ORNL[b]	0.2 Al—0.2 C	20
ORNL[b]	0.4 Al	19
ORNL[b]	0.2 Al	19
ORNL[b]	20 U	18
ORNL[b]	8 Cr	18
ORNL[b]	5 U	18
ORNL[b]	8 Mo	17
ORNL[b]	2 Mo—0.2 C	17
ORNL[b]	4 Nb	17
ORNL[b]	10 U	15
ORNL[b]	4 Mo	15
ORNL[b]	2 Nb	14
ORNL[b]	0.2 Be	14
ORNL[b]	0.2 C	13

Table 13. (continued)

Alloy[a]	Composition (wt %)	Hardness (kg/mm^2)
ORNL[b]	4 Cr	13
ORNL[b]	2 Mo	13
ORNL[b]	0.15 C	11
ORNL[b]	thorium	11
ORNL[b]	2 Cr	11
ORNL[b]	2 Nb–0.2 C	11
ORNL[b]	0.10 C	9
	800°C	
BMI[c]	10 U–0.2 Be	29.6
BMI[c]	10 U–0.1 Be	27.3
BMI[c]	10 U–0.5 Al	26.9
BMI[c]	10 U–1.5 Mo–0.2 C	24.3
BMI[e]	5 U	24.0
BMI[c]	10 U–0.2 C	22.5
BMI[d]	10 U–1.5 Mo	22.4
BMI[c]	10 U–10 Y	22.4
BMI[d]	10 U–10 Zr	22.2
BMI[e]	10 U	22.1
BMI[c]	10 U–4 Nb	21.3
BMI[d]	10 U–2 Nb	20.3
BMI[c]	10 U–2 Nb–0.2 C	19.8
BMI[d]	10 U–10 Zr–2 Nb	17.2
BMI[e]	20 U	14.0
BMI[d]	10 U–25 Zr	11.8
BMI[d]	10 U–20 Zr	10.7
BMI[e]	15 U	10.6

[a]Nominal composition prepared by arc melting.

[b]Ames thorium, tested in hot-rolled condition. Ref: J. A. Burka and J. P. Hammond, Evaluation of Thorium-Base Alloys for High-Temperature Strength, ORNL-3777 (April 1965).

[c]Ames thorium, tested in as-cast condition. Ref: M. S. Farkas, A. A. Bauer, and R. J. Dickerson, "Development of Thorium-Uranium and Thorium-Uranium-Base Alloys for Breeder Applications," pp. 468–497 in Proceedings of the Thorium Fuel Cycle Symposium, Gatlinburg, Tennessee, December 5–7, 1962, TID-7650, Book 2 (July 1963).

[d]Iodide thorium, tested in as-cast condition. Ref: Ibid.

[e]Ames thorium, tested in hot-rolled condition. Ref: Ibid.

additions of Be, Al, Nb, Mo, Zr, or Y at 600 and 800°C gave high hardness.[28] Beryllium and aluminum form compounds with both the uranium and thorium and probably contribute to strength by dispersion hardening and, to some extent, by solid-solution hardening. Niobium, molybdenum, and, to a lesser extent, zirconium stabilize the body-centered cubic (γ) modification of the uranium in these alloys and possibly contribute to strength by stabilizing a finely dispersed gamma phase.

Thorium Strengthened by Dispersion Hardening

Investigators at ORNL have examined[29] a number of means for introducing stable fine dispersions in thorium; representative hot-hardness results are given in Table 14. Excellent dispersion structures were achieved in thorium derived from the fragile hydride ball-milled with ultrafine ThO_2. Extruded rod of this material displayed good hardness and strength at 800°C. However, carbon has a deleterious effect on properties, and restricting carbon pickup and controlling the final oxide content by this method proved difficult. That carbon has a harmful effect on hardness at 800°C is seen by comparing specimens 5 and 3 of Table 14 (and by inference 4 and 2).

A fine dispersion of intermetallic UBe_{13} in thorium, introduced by a special procedure of "splat cooling" atmoized particles of the alloy while still molten, also gave good hardness to 800°C (specimen 6, Table 14).

By far the best hot-hardness results were obtained by an internal boronation process devised to form a stable zirconium boride dispersion (specimens 7 and 8). In this process a small amount of separated ^{11}B isotope in the form of 200-A soot is blended into an ultrafine powder of thorium containing 4.65% (10 at. %) Zr in solid solution. As in the case of the ThO_2-hardened material, the thorium is rendered fine by ball-milling it as hydride. Boron is then introduced and the mixture consolidated and hot extruded to rod. The boronated alloys picked up substantial carbon (3/4 to 1%), as did two of the ThO_2-hardened specimens (specimen 5 and presumably 4), from the hydrocarbon grinding liquid used in milling. However, the boronated alloys showed the extraordinarily high hot hardness in spite of carbon contamination. That the boron in

Table 14. Hot Hardness of Dispersion Hardened Thorium Alloys[a]

Specimen	Method of Hardening[b]	Additives (wt %)	Chemical Analysis (wt %)			Hardness[c] (DPH) at Temperature (°C)				
			B	C	O	25	500	600	700	800
1	None	None				85	30	22	15	
2[d]	ThO_2 embedment	5 ThO_2				123	53	41	29	21
3[d]	ThO_2 embedment	10 ThO_2		0.14		220	91	63	43	31
4[e]	ThO_2 embedment	5 ThO_2				326	126.5	68.5	23	7
5[e]	ThO_2 embedment	10 ThO_2		1.05		296	91.5	60.5	21.5	5.5
6[f]	SLIS	1.3 Be				139	86	71	45	28
7[g]	Boronation	4.65 Zr—0.54 B	0.43			427	129.5	92	70.5	74.5
8[g]	Boronation	4.65 Zr—0.14 B	0.15	0.91	0.53	403	152	94	62	53
9[h]	Carburization	4.65 Zr		0.77		280	88	33	16	10

[a]J. P. Hammond, Metals and Ceramics Div. Ann. Progr. Rept. June 30, 1967, ORNL-4170, p. 106.

[b]Thorium used to prepare each alloy was from a calcium-reduced grade analyzing 99.8% Th, 340 ppm C, 2000 ppm O, and 180 ppm N.

[c]Each value is an average of two measurements.

[d]Fine dispersion was prepared by dry ball-milling 0.03-μ ThO_2 with hydrided thorium in ordinary mill, followed by vacuum hot pressing in graphite at 1000°C and extruding at 900°C.

[e]Fine dispersion was prepared by ball-milling 0.03-μ ThO_2 with hydrided thorium in a high-energy mill, followed by dehydriding, cold pressing, vacuum sintering at 800°C, and extruding at 750°C. The high carbon content was attributed to carbon picked up from a hydrocarbon grinding liquid used in ball-milling.

[f]Fine dispersion is based on the $ThBe_{13}$ intermetallic and was prepared from powder made by the SLIS technique. Powders were consolidated by hot-upset-extrusion at 600°C.

[g]Fine dispersion was prepared by boronating a finely ground thorium alloy powder containing 4.65% Zr in solid solution. The alloy was hydrided, ball-milled in a high-energy mill, and then dehydrided, and a 200-A boron soot was introduced by dry blending. Consolidation was by vacuum sintering at 800°C and extruding at 750°C. The high carbon content was attributed to carbon gained from a hydrocarbon grinding liquid used in ball-milling.

[h]Processed the same as specimens 7 and 8 except that no boron was added.

conjunction with zirconium and not carbon accounts for the high hot hardness was proven by a supplemental experiment conducted to introduce carbon while excluding boron from the thorium-zirconium alloy (specimen 9). Without boron, these alloys showed very low hot hardness. Further work is warranted on boronated thorium-zirconium alloys to eliminate carbon contamination and determine mechanical properties.

Effects of Interstitial Solutes on Thorium[30,31]

The effects of the interstitial atoms normally found in bomb-reduced thorium (carbon, nitrogen, and oxygen) on the tensile strength, yield strength, hardness, and ductility of iodide thorium that has been worked and annealed are presented in Fig. 14. For ready reference, the normal composition ranges of carbon, nitrogen, and oxygen in calcium-reduced metal are indicated in the graph. Carbon, with a room-temperature solubility of 0.35%, has a marked solid-solution hardening effect on thorium, whereas oxygen, with a very low room-temperature solubility, has a negligible effect. The effect of the 0.009 to 0.016% N normally present in calcium-reduced material is not known. Larger amounts of nitrogen raise moderately the tensile strength, yield strength, and hardness of thorium.

Thorium-Uranium Alloys

Uranium is an essential ingredient in thorium fuel alloys because it is added to provide a fissionable isotope and it forms as a product of neutron irradiation. Uranium is moderately soluble in thorium,[32] the solubility being around 1.1% at 600°C and about 1.8% at 1100°C. Uranium in excess of the solubility limit exists as free uranium, which at levels in excess of about 15% is present as a grain-boundary network regardless of fabricating procedure used.[28] Below 15% U, the composition of the alloy and metallurgical treatment will govern the size and distribution of the uranium phase, which, in turn, affects the physical properties and irradiation performance. Heating to high temperature tends to agglomerate free uranium and decrease strength.[33] Thorium-uranium alloys are

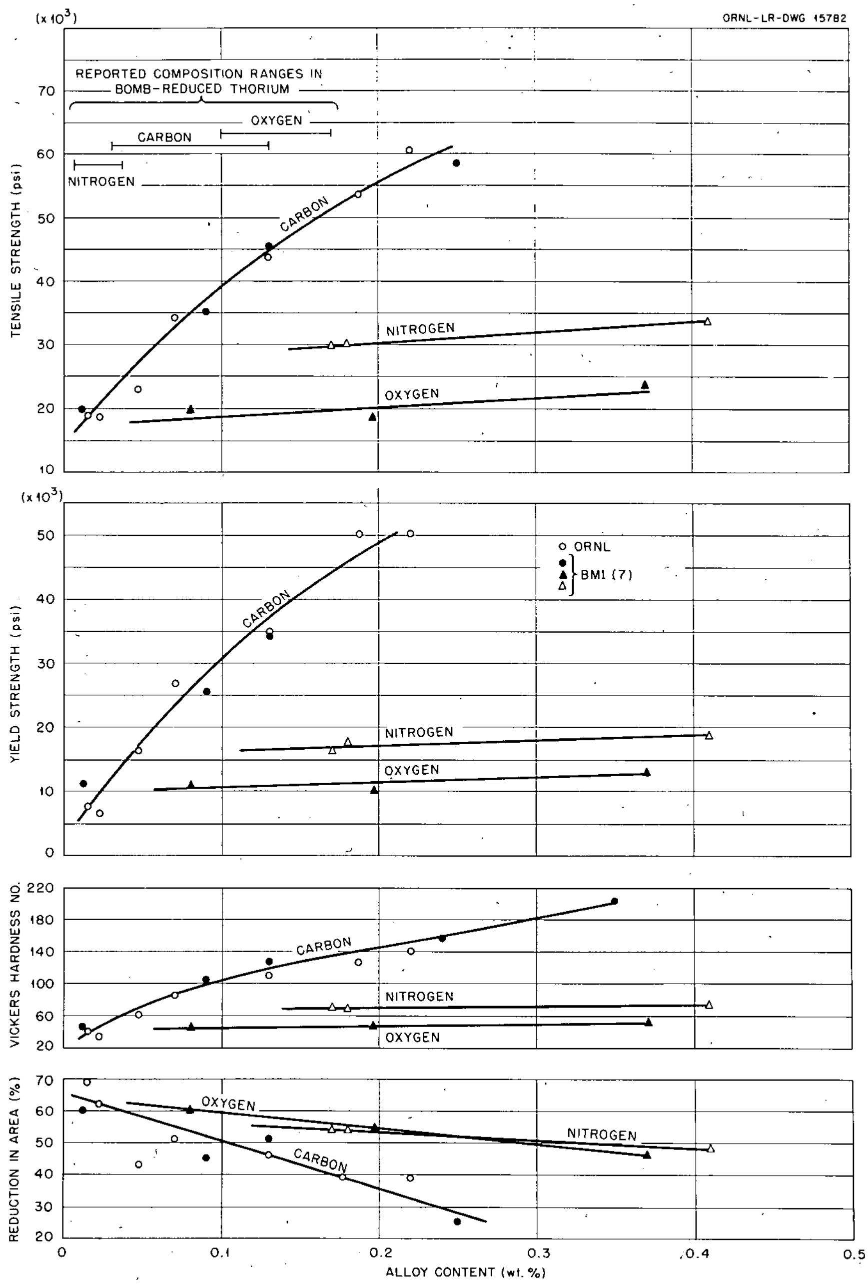

Fig. 14. Effect of Some Interstitial Solutes Normally Found in Bomb-Reduced Thorium on the Room-Temperature Tensile Properties and Hardness of Iodide Thorium. Base metal compositions and metallurgical treatments: BMI — 0.012% C, 0.080% O; forged and hot rolled at 700°C, cold reduced 50%, annealed in argon 2 hr at 850°C.* ORNL — 0.015% C, 0.080% O; arc-melted, cold reduced 85%, vacuum annealed 0.5 hr at 650°C.**

*R. M. Goldhoff et al., A Study of the Strengthening of Thorium by Alloying, Cold Work, and Aging, BMI-776 (Nov. 1, 1952).

**J. A. Milko, R. E. Adams, and W. O. Harms, "The Mechanical Properties of Thorium and High-Thorium Alloys," The Metal Thorium, Proc. Conf. Cleveland, 1956, 186–216 (1958).

readily melted and fabricated to uranium contents of 50%; Table 15 shows that the room-temperature strength of alloys based on bomb-reduced thorium increases with the uranium content.[34,35]

Battelle[28] finds that Th—5% U has greater creep strength at 600 and 700°C than alloys of greater amounts of uranium, as shown in Fig. 15. Data of Atomics International[5] show that a Th—9% U alloy has considerable creep strength at 600°C and that mechanical work further increases the creep strength. Kittel et al.[36] found somewhat superior irradiation performance in alloys containing 15% U and less, although thorium with uranium to 25% gives good resistance to swelling.

Thorium-Uranium-Containing Alloys

Battelle Memorial Institute[28] also investigated the room- and high-temperature mechanical properties of fabricated ternary alloys containing 10% U, shown in Table 16 along with results for thorium and Th—10% U alloy for comparison. Observe that the addition of 1.5% Mo or 2% Nb to Th—10% U has little effect on the tensile properties of the base alloy at room or elevated temperature, whereas the incorporation of 10% Zr or 10% Zr and 2% Nb has a very substantial effect. This effect is dramatically reversed in creep at 600 and 700°C, as shown in Fig. 16. The addition of 1.5% Mo, 2% Nb, or 0.1% Be to Th—10% U increases its creep strength by 50 to 75%.

This reversal in mechanical properties between short- and long-time tests is attributed to the properties of the grain-boundary network of uranium found in these alloys and to the relative effects of the alloying additions in stabilizing the gamma modification of this constituent and thus conferring thermal stability to the network.[28] The contribution of zirconium to strength in short-time tests stems primarily from solid-solution strengthening of the thorium matrix.

Advanced Technology Laboratories[33] studied ternary additions to thorium containing 5 and 10% U. Tensile and stress-rupture strengths of the base alloys at 600 and 800°C could be essentially doubled by alloying. The most noticeable improvements were obtained with 2 and 5% Zr additions

Table 15. Mechanical Properties of Bomb-Reduced-Thorium-Uranium Alloys[a]

Analyzed Composition (wt % U)	Strength, psi		Elongation in 1 in. (%)	Reduction of Area (%)	Hardness (VHN)	Reference
	0.2% Offset Yield	Tensile				
Unalloyed	19,400	31,700	46	50	79	34
1.00	25,600	38,400	37	51	104	34
5.08	27,400	42,300	38	44	105	34
10.2	30,000	45,000	35	50		34
20.6	30,800	47,600	38	41	122	35
30.9	36,100	55,800	24	34	131	35
40.6	38,500	62,400	28	35	143	35
51.2	40,100			23	146	35
49.1	43,500	66,500	10	26	146	35

[a]Annealed 2 hr at 850°C.

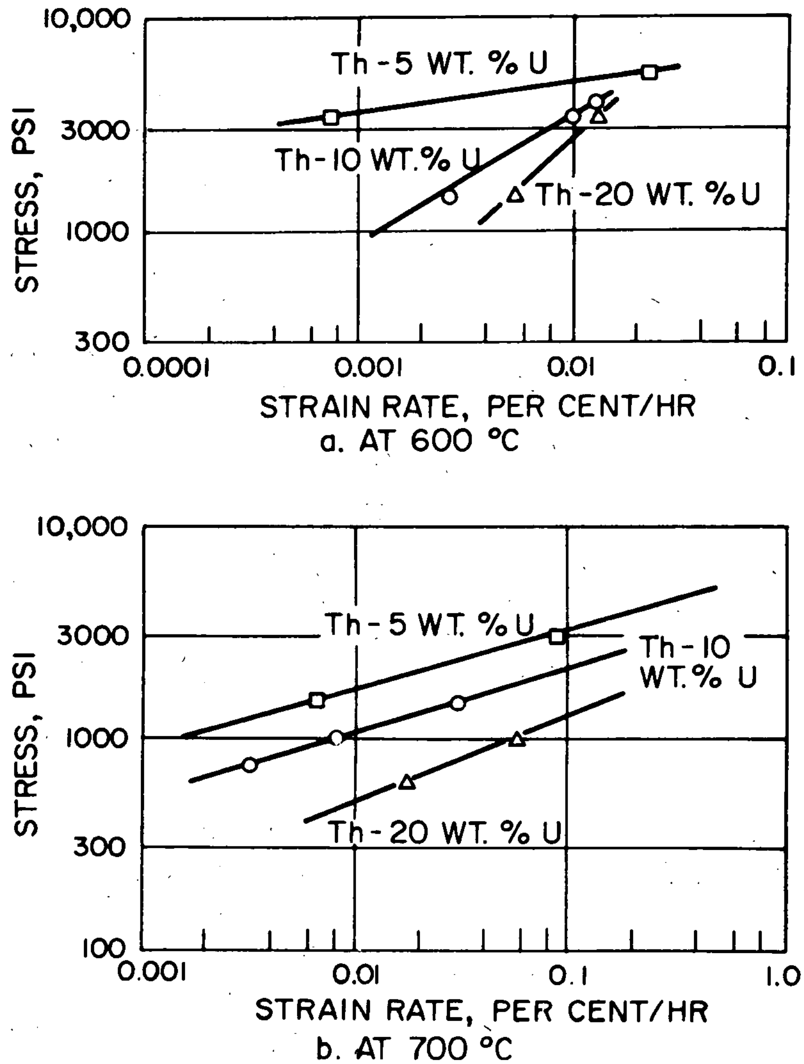

Fig. 15. Creep Strength of Thorium-Uranium Alloys.* [Reprinted from Reactor Mater. 6(4), 20 (Winter 1963–1964).]

*M. S. Farkas, A. A. Bauer, and R. J. Dickerson, "Development of Thorium-Uranium and Thorium-Uranium-Base Alloys for Breeder Applications," pp. 468–497 in Proceedings of the Thorium Fuel Cycle Symposium, Gatlinburg, Tennessee, December 5–7, 1962, TID-7650, Book 2 (July 1963).

Table 16. Tensile Properties of Thorium-Base Alloys[a]

Composition (bal Th) (wt %)	Test Temperature (°C)	Strength, psi		Elongation in 1 in. (%)
		0.2% Offset Yield	Tensile	
Ames thorium	25–29	34,900	37,700	13
10 U	25–29	26,900	37,700	13.5
10 U–1.5 Mo	25–29	26,400	41,000	15
10 U–2 Nb	25–29	22,900	35,400	22
10 U–10 Zr	25–29	35,200	53,200	12
10 U–10 Zr–2 Nb	25–29	39,200	60,400	14
Ames thorium	600	13,800	15,700	26
10 U	600	13,800	17,970	41
10 U–1.5 Mo	600	11,220	17,700	43
10 U–2 Nb	600	12,550	18,000	37
10 U–10 Zr	600	19,600	28,400	44
10 U–10 Zr–2 Nb	600	19,200	25,640	48
Ames thorium	700	4,280	8,090	58
10 U	700	8,800	10,300	44
10 U–2 Nb	700	8,400	10,800	66
10 U–10 Zr	700	15,400	20,000	39
10 U–10 Zr–2 Nb	700	12,100	13,910	77
10 U–0.1 Be	700	8,610	11,200	47

[a]M. S. Farkas, A. A. Bauer, and R. J. Dickerson, "Development of Thorium-Uranium and Thorium-Uranium-Base Alloys for Breeder Applications," pp. 468–497 in Proceedings of the Thorium Fuel Cycle Symposium, Gatlinburg, Tennessee, December 5–7, 1962, TID-7650, Book 2 (July 1963).

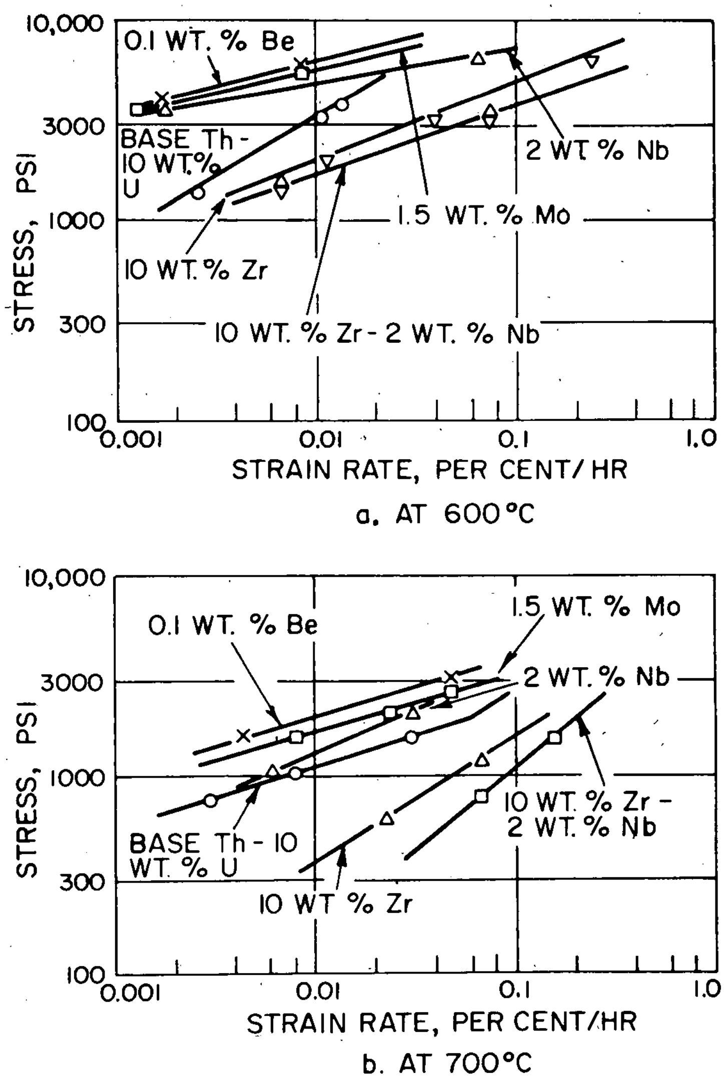

Fig. 16. Creep Strength of Th–10% U Alloys Containing Indicated Additions.* [Reprinted from Reactor Mater. 6(4), 21 (Winter 1963–1964).]

*M. S. Farkas, A. A. Bauer, and R. J. Dickerson, "Development of Thorium-Uranium and Thorium-Uranium-Base Alloys for Breeder Applications," pp. 468–497 in Proceedings of the Thorium Fuel Cycle Symposium, Gatlinburg, Tennessee, December 5–7, 1962, TID-7650, Book 2 (July 1963).

to the Th–5% U and Th–10% U alloys, prepared by carefully controlled arc melting and heat treated by quenching and aging. Additions of Nb, Mo, C, Al, and Be also significantly improved strength.

Thorium-Zirconium Alloys

The solid solubility of zirconium in thorium is about 2.5% at 900°C; no intermetallics are present.[32]

Data from two laboratories[20,35] on room-temperature tensile properties of thorium-zirconium alloys containing up to 50% Zr are graphically presented[37] in Fig. 17. A 1% alloy shows a sharp increase in tensile and yield strengths, but a 2% alloy shows a drastic drop in strength values

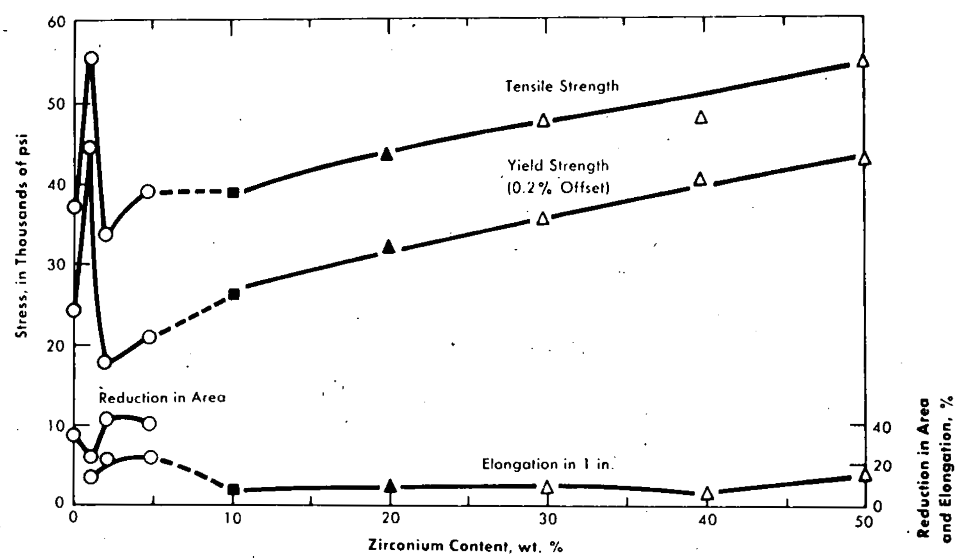

Fig. 17. Effect of Zirconium on Tensile Properties of Wrought Annealed Iodide Thorium. ○: forged, hot-rolled at 700°C, cold-reduced 50%, annealed 1 hr at 750°C;* Δ: cold-reduced 70 to 87%, annealed 2 hr at 850°C;** ■: cold-reduced 70 to 80%, annealed 20 hr at 825°C;** ▲: hot-rolled, annealed 20 hr at 825°C.** Lines connect data from two laboratories. [Reprinted from I. B. Roll, "Thorium and Its Alloys," p. 176 in Nuclear Reactor Fuel Elements, Metallurgy and Fabrication (ed. by A. R. Kaufmann), Interscience, New York, 1962.]

*R. M. Goldhoff et al., A Study of Thorium-Base Alloys, BMI-720 (Dec. 26, 1951).

**G. C. Danielson et al., Terminal Report of an Investigation of the Properties of Thorium and Some of Its Alloys, ISC-297 (Oct. 1, 1952).

below those of the base metal. Similar depreciation of tensile properties is observed in thorium when alloyed with other strong carbide formers and is attributed to removal of carbon from solid solution. Alloys with zirconium contents increasing from 5 to 50% show steady increase in strength.

The limited data available[38] on tensile properties of thorium-zirconium alloys at 800°C are given in Table 17. Strength appears to increase rather than decrease with zirconium content in the range 0 to 5% at high temperature. Since carbon in solid solution does not contribute appreciably to the strength of thorium above 500°C, softening should not be expected to accompany any scavenging of carbon by zirconium. The cause of unexpected low ductility displayed by the 5% Zr alloy was not determined but is believed characteristic of the alloy.

Table 17. Tensile Properties of Thorium-Zirconium Alloys at 800°C[a,b]

Intended Composition (wt % Zr)	Strength, psi		Elongation in 2 in. (%)
	0.2% Offset Yield	Tensile	
0	2140	2885	40.0
2	4245	5350	55
5[c]	No yield	4570	0.4

[a]J. A. Burka and J. P. Hammond, "High-Temperature Thorium-Base Alloys," Metals and Ceramics Div. Ann. Progr. Rept. June 30, 1964, ORNL-3670, pp. 249–250.

[b]Arc-melted, calcium-reduced base metal, homogenized at 1000°C and hot rolled to 25% reduction at 800°C.

[c]Average of two tests.

Thorium-Indium Alloys

Indium has restricted solubility in thorium at ordinary temperatures but is soluble to 0.8% at 800°C. It reacts with thorium to form at least one intermediate phase,[32] Th_2In. This suggests that indium may harden by both solid-solution strengthening and precipitation hardening.

Goldhoff _et al_.[30,35] got indications of excellent room-temperature strength in an arc-melted Th–2.5% In alloy prepared from bomb-reduced thorium. However, they did not analyze for indium, and since indium has such a high vapor pressure, it was not certain whether indium or carbon was the major contributor to strength.[39]

In exploratory hot-hardness studies on arc-melted binary alloys of thorium, ORNL found indium to be superior to all other elements as a high-temperature hardener.[27] An alloy analyzing 3.8% In gave a DPH value of 55 kg/cm^2 at 750°C, which is five times as high as unalloyed thorium and substantially higher than all other binary alloys. To circumvent the problems imposed by the high vapor pressure of indium when alloys are prepared by induction or arc-melting, a powder metallurgy procedure for making thorium-indium alloys was devised. Ductile indium was ball-milled in alcohol to ultrafine powder, then blended with fine calcium-reduced thorium powder; the mixture was consolidated by hot pressing. Table 18

Table 18. Tensile Properties of Thorium-Indium Alloys at 800°C[a,b]

Indium Content (wt %)		Strength (psi)		Elongation (%)
Nominal	Actual	Ultimate Tensile	0.2% Offset Yield	
2	1.78	6475	5550	10.0
3	2.60	7315	6330	6.0
4	3.68	6940	6120	5.5
5	4.38	7810	7130	20.0

[a]J. A. Burka and J. P. Hammond, "High-Temperature Thorium-Base Alloys," _Metals and Ceramics Div. Ann. Progr. Rept. June 30, 1964_, ORNL-3670, pp. 249–250.

[b]Prepared by powder metallurgy, hot pressed under argon, homogenized at 1000°C, and extruded at 900°C.

gives the results[38] of tensile tests conducted at 800°C on alloys containing 2 to 5% In; Fig. 18 shows the results of hot hardness traverses made on these alloys.[38] The alloy that analyzed 4.38% In shows an exceptionally good combination of ductility, strength, and hardness at 800°C. While indium does not have a sufficiently low thermal-neutron absorption cross section for fuel application in thermal reactors, its absorption spectrum is favorable for use in fast reactors.

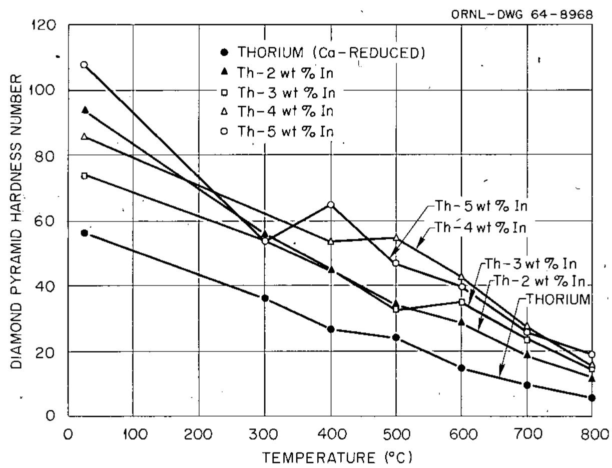

Fig. 18. Hardness (1-kg load) of Thorium and Thorium-Indium Alloys at Elevated Temperatures.*

*J. A. Burka and J. P. Hammond, "High-Temperature Thorium-Base Alloys," Metals and Ceramics Div. Ann. Progr. Rept. June 30, 1964, ORNL-3670, pp. 249–250.

Thorium-Carbon Alloys

The solubility of carbon in thorium is 0.2 to 0.35% at room temperature and increases with temperature. Several compounds exist.[32]

As shown in Fig. 14, p. 30, carbon is a potent strengthener of thorium. It strengthens by solid-solution strengthening and also by age hardening, as exemplified by bomb-reduced throium. Strength imparted by carbon persists to temperatures around 400°F; it drops off abruptly with further increase in temperature.

Carbon also had pronounced effect on the impact resistance of thorium,[22] illustrated in Fig. 19. Bomb-reduced and iodide thorium containing 0.16 and 0.21% C, respectively, show low impact resistance and a brittle fracture at temperatures near or below room temperature. As temperature is increased above a certain level, a higher energy is required to produce fracture. Above this transition temperature, the fracture is ductile. Iodide thorium containing about 0.02% C shows no transition temperature and fractures in a ductile manner even at −196°C.

Carbon and, to a lesser extent, nitrogen confer age-hardening characteristics to thorium.[30] Hardening develops on aging carbon-containing

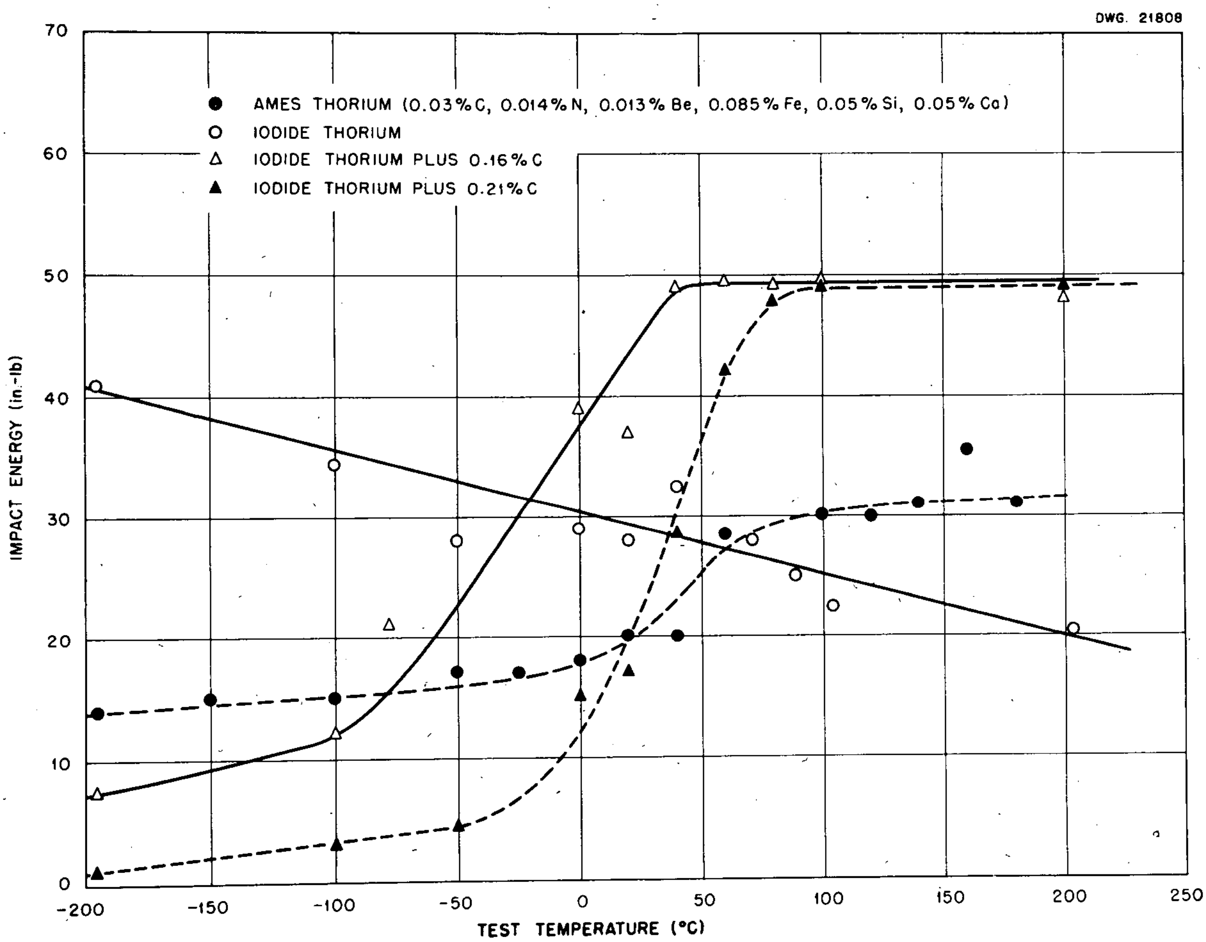

Fig. 19. Impact Behavior of Annealed Thorium Containing Carbon.*

*J. A. Milko, Metallurgy Div. Semiann. Progr. Rept. Oct. 10, 1953, ORNL-1625, p. 7.

thorium alloys that have been quenched from above approximately 800°C or have been cold rolled. The degree of hardening developed is time and temperature dependent and increases with the amount of carbon. Maximum hardness appears to develop after heating from 1 to 5 hr at temperatures between 250 and 350°C. Table 19 gives the mechanical properties of a 0.10% C alloy in various conditions of heat treatment.[40]

Certain alloying ingredients, when added to thorium containing carbon, apparently combine with carbon and result in softening. Titanium, molybdenum, niobium, and zirconium have shown this scavenging effect. Other elements, such as indium and uranium, appear to act independently of carbon and augment its strengthening effect.

Table 19. Mechanical Properties of an Induction-Melted Th–0.10% C Alloy in Various Conditions[a]

Condition	Strength, psi		Elongation in 1 in. (%)	Reduction of Area (%)	Hardness (VHN)
	0.2% Offset Yield	Tensile			
Annealed 2 hr at 850°C	29,200	40,100	26	48	110
Solution annealed 2 hr at 850°C and quenched	30,000	40,900	40	49	103
Aged 20 hr at 350°C after solution anneal	29,600	43,600	40	47	113
Cold rolled 20%	49,200	52,100	14	51	127
Cold rolled 20% and aged 20 hr at 350°C	46,000	59,400	20	37	153
Cold rolled 50%	50,400	55,800	10	37	133
Cold rolled 50% and aged 20 hr at 350°C	56,400	62,200	8	26	159

[a]R. M. Goldhoff, H. R. Ogden, and R. I. Jafee, Thorium-Carbon Alloys, AECD-3560 (June 19, 1953).

Thorium-Nitrogen Alloys

The solubility of nitrogen in thorium[41] varies almost linearly from 0.05% at 850°C to about 0.35% at 1500°C. As indicated in Fig. 14, p. 30, nitrogen apparently gives moderate strengthening up to 0.17%, after which strengthening leveled off.[30] Both a solid-solution effect and age hardening may contribute to strengthening. Figure 20 shows the effect of

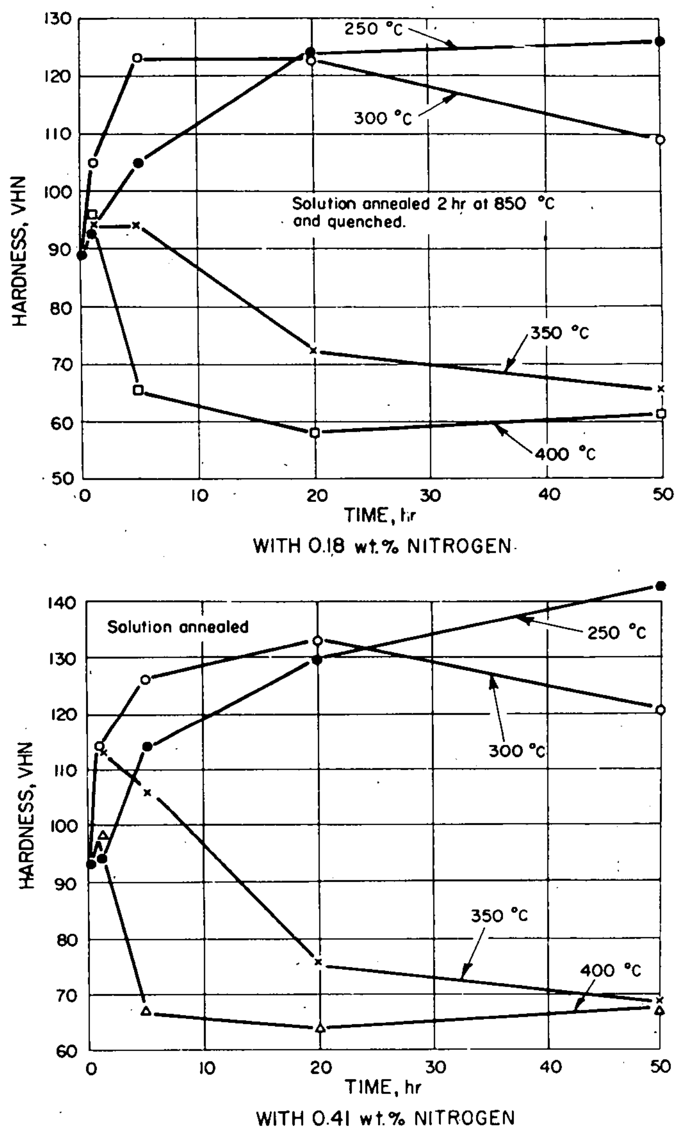

Fig. 20. Aging Curves for Iodide Thorium Alloyed with Nitrogen.* [Reprinted from Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol I, Interscience, New York, 1960.]

*R. M. Goldhoff et al., A Study of the Strengthening of Thorium by Alloying, Cold Work, and Aging, BMI-776 (Nov. 1, 1952).

age-hardening time and temperature on the hardness of iodide thorium containing 0.18 and 0.41% N.

Thorium-Oxygen Alloys

Investigations of alloying behavior of oxygen in thorium indicate little, if any, solubility of oxygen in the thorium.[32] Thorium and oxygen form the stable compound ThO_2. A preliminary examination of thorium-oxygen alloys[34] indicated that only a slight strengthening effect was achieved by adding oxygen to iodide or bomb-reduced thorium.

Thorium-Chromium Alloys

Chromium forms a simple eutectic phase diagram with thorium with no known solid solubility at either end.[32] Tests conducted at ORNL on alloys prepared from three separate lots of iodide thorium indicate that chromium improves strength and hardness.[42] Table 20 gives tensile and hardness data of representative alloys.[39] The general trend is one of increasing strength with increasing chromium, although several discrepancies appear, which are probably attributable to varying carbon content among the alloys.

In thorium-chromium alloys with carbon purposely added (Table 20), the strengthening effect on the iodide thorium by the combination of chromium and carbon is quite marked.[39] Relatively high strength and hardness values were obtained without a severe reduction in ductility.

The effects of chromium on the mechanical properties of bomb-reduced thorium are not well defined, since the data available represent alloys that had received different heat treatments. However, these data[35,43–45] indicate that chromium is a moderate strengthener and hardener of bomb-reduced thorium.

Thorium-Tin Alloys

A preliminary investigation showed tin to be only slightly soluble in thorium, and an observed embrittling effect suggested that intermetallic compound form.[39]

Table 20. Mechanical Properties of Thorium-Chromium Alloys With and Without Added Carbon[a,b]

Analysis, wt %		Proportional Limit (psi)	Strength, psi		Elongation in 2 in. (%)	Reduction of Area (%)	Hardness (R_H)
Chromium	Carbon		0.2% Offset Yield	Tensile			
			Thorium-Chromium Alloys				
0	0.062	3,800	7,900	17,700	29.0	62.0	66
0.25	0.016	3,400	5,500	17,800	38.0	63.0	62
0.42	0.011	4,000	6,600	20,400	23.0	34.0	64
0.86	0.017	10,100	15,100	30,700	29.0	41.0	90
1.81	0.009	5,300	10,600	27,700	24.0	46.0	82
2.77	0.038	11,200	18,000	35,500	24.5	46.0	95
3.29	0.019	7,900	14,800	31,700	19.0	36.0	90
4.95	0.015	11,100	23,700	44,100	18.0	30.0	100
4.63	0.055	15,600	23,600	42,400	25.0	40.0	100
5.39	0.065	14,900	28,100	45,300	5.0	11.0	105
7.01	0.058	20,900	36,000	53,500	9.0	25.0	110
			Thorium-Chromium-Carbon Alloys				
0.22	0.041	23,100	28,200	35,700	43.0	55.0	106
0.28	0.112	26,500	32,300	39,500	42.0	55.0	55
0.78	0.104	28,400	36,100	45,500	35.5	56.0	58
1.55	0.101	28,900	38,900	51,500	29.0	37.0	64
2.42	0.091	32,100	41,400	56,000	32.0	36.0	68
3.60	0.075	32,400	46,000	62,200	20.0	16.5	68

[a]R. E. Adams et al., "Thorium Alloys," pp. 227–247 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.

[b]Values given are averages of duplicate tests on material based on iodide thorium and arc melted, cold rolled about 85%, and annealed 30 min at 650°C.

A cursory investigation of the effect of tin on the mechanical properties of iodide thorium disclosed that even small additions tend to harden and strengthen thorium.[39] The data of Table 21, from specimens with approximately the same carbon level, indicate that tin is a potent alloying element for the given treatment. Ductility appears to be lowered appreciably even with the low tin additions.

The addition of tin to bomb-reduced thorium also indicates a hardening and strengthening effect[35] (Table 22). This effect is not as pronounced in the given treatment as it is in the iodide thorium with its particular treatment.

Alloys containing up to 2% Sn could be cold rolled to about 85% reduction without edge cracking, an indication of good fabricability.

Thorium-Molybdenum Alloys

Molybdenum is only very slightly soluble in thorium and forms a simple eutectic phase diagram with it.[32]

The effects of molybdenum on the tensile properties and hardness of iodide thorium[39] are given in Table 23. Molybdenum appears to have a moderate effect in strengthening and hardening thorium; the ductility drops off with strengthening. Similar results were obtained[35] when molybdenum was added to bomb-reduced thorium, as shown in Table 24. Little or no improvement in strength properties was obtained up to about 3% Mo; there is some evidence of softening, presumably because carbon scavenges molybdenum.

Thorium-Niobium Alloys

Niobium is soluble in thorium to only 0.1% or less and appears not to form intermetallic compounds.[32]

A preliminary study[39] showed that niobium moderately strengthens and hardens iodide thorium; results are in Table 25. A slight softening and an accompanying decrease in strength occur at 1 to 2.5% Nb. This again appears to be a carbon-scavening effect. Similar trends[46] are evidenced in the data presented in Table 26 for niobium-containing alloys prepared from bomb-reduced thorium.

Table 21. Mechanical Properties of Iodide Thorium-Tin Alloys[a,b]

Analysis, wt %		Proportional Limit (psi)	Strength, psi		Elongation in 2 in. (%)	Reduction of Area (%)	Hardness	
Tin	Carbon		0.2% Offset Yield	Tensile			Rockwell	Vickers[c]
0.32	0.019	23,000	29,000	31,000	9.0	45.0	102 R_H	81
0.33	0.017	20,100	27,000	31,700	9.0	44.0	102 R_H	83
0.52	0.015	23,700	31,700	36,000	9.0	49.0	105 R_H	94
0.79	0.017	24,200	38,100	43,000	10.5	50.0	109 R_H	106
0.97	0.006	28,700	38,000	43,000	9.0	39.0	52 R_B	112
1.57	0.012	31,600	46,500	54,000	10.0	40.0	71 R_B	133
2.00	0.017	39,200	53,000	60,000	8.0	22.0	75 R_B	146

[a]R. E. Adams et al., "Thorium Alloys," pp. 227–247 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.

[b]Cold rolled about 85% and annealed 1/2 hr at 650°C; all values are averages of two tests.

[c]10-kg load; 2/3-in. objective.

Table 22. Mechanical Properties of Alloys of Bomb-Reduced Thorium with Tin[a]

Tin Content (wt %)	Strength, psi: 0.2% Offset Yield	Strength, psi: Tensile	Elongation in 1 in. (%)	Reduction of Area (%)	Hardness (VHN)	Condition
Unalloyed	29,000	39,000	32.0	46.0	106	1 hr at 750°C after 50% cold rolling
0.47[b]	30,000	47,000	28.0	43.0	116	1 hr at 750°C after 50% cold rolling
Unalloyed	19,400	31,800	46.0	50.0	79	Cold rolled 50% and annealed 2 hr at 850°C
1.23[b]	23,000	41,000	18.0	35.0	88	Cold rolled 50% and annealed 2 hr at 850°C
1.32[c]	24,000	40,500	31.0	43.0	96	Cold rolled 50% and annealed 2 hr at 850°C

[a]R. M. Goldhoff et al., A Study of Thorium-Base Alloys, BMI-720 (Dec. 26, 1951).

[b]Analyzed value.

[c]Intended value.

Table 23. Mechanical Properties of Iodide Thorium-Molybdenum Alloys[a,b]

Analysis, wt %		Proportional Limit (psi)	Strength, psi		Elongation in 2 in. (%)	Reduction of Area (%)	Hardness (R_H)
Molybdenum	Carbon		0.2% Offset Yield	Tensile			
0.33	0.046	3,200	5,500	18,400	39.5	50.0	74
0.55	0.053	4,000	6,100	19,300	36.5	52.0	72
0.99	0.040	4,900	7,900	22,000	38.5	46.0	80
1.99	0.035	7,500	13,700	30,000	27.0	42.5	91
3.93	0.048	7,000	12,200	30,000	25.5	50.0	87
7.70	0.050	10,000	19,100	39,800	22.5	45.5	96

[a] R. E. Adams et al., "Thorium Alloys," p. 241 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.

[b] Specimens cold rolled about 85% and annealed 1/2 hr at 650°C. All values given are averages of duplicate tests.

Table 24. Mechanical Properties of Bomb-Reduced-Thorium-Molybdenum Alloys[a,b]

Molybdenum Analysis (wt %)	Strength, psi		Elongation in 1 in. (%)	Reduction of Area (%)	Hardness (VHN)
	0.2% Offset Yield	Tensile			
Unalloyed	22,800	35,200		45	82
0.50	20,100	32,400	29.0	53.0	77
0.72	25,400	36,900		46.0	101
2.20	23,000	37,600	31.0	50.0	81

[a]R. M. Goldhoff _et al._, _A Study of Thorium-Base Alloys_, BMI-720 (Dec. 26, 1951).

[b]Specimens cold rolled 50% and annealed 2 hr at 850°C. All values are averages of four tests.

Table 25. Mechanical Properties of Iodide Thorium-Niobium Alloys[a,b]

Analysis, wt %		Proportional Limit (psi)	Strength, psi		Elongation in 2 in. (%)	Reduction of Area (%)	Hardness (R_H)
Niobium	Carbon		0.2% Offset Yield	Tensile			
0.40	0.042	14,900	25,000	29,100	8.0	47.0	97
0.85	0.041	15,900	22,800	29,100	7.0	48.0	97
1.29	0.050	12,300	20,200	28,700	19.0	38.0	92
2.44	0.048	6,600	12,700	26,000	22.5	52.0	85
4.54	0.041	16,000	29,700	39,800	23.0	39.0	101
9.15	0.052	16,300	31,300	43,400	11.0	46.0	102

[a]R. E. Adams *et al.*, "Thorium Alloys," p. 235 in *Reactor Handbook* (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.

[b]Specimens arc melted, cold rolled about 85%, and annealed 1/2 hr at 650°C. All values given are averages of two tests.

Table 26. Mechanical Properties of Bomb-Reduced-Thorium-Niobium Alloys[a,b]

Analysis, wt %		Proportional Limit (psi)	Strength, psi		Elongation in 2 in. (%)	Reduction of Area (%)
Niobium	Carbon		0.2% Offset Yield	Tensile		
0.25	0.051	28,500	36,000	41,300	20	38[c]
0.69	0.055	18,300	27,200	35,400	23	46[d]
1.29	0.085	13,600	23,900	34,300	26	44[d]
2.28	0.047	5,700	9,500	24,900	40	60[d]
5.37	0.039	7,500	13,100	30,100	33	59[d]
9.30	0.036	6,600	13,400	33,200	29	50[d]

[a]J. A. Milko, Metallurgy Div. Quart. Progr. Rept. Oct. 31, 1952, ORNL-1437, pp. 3–4.

[b]Cast 1 1/4-in.-diam billet, swaged to 5/8-in. diameter, and annealed 1/2 hr at 750°C.

[c]Average of three test bars.

[d]Average of four test bars.

Thorium-Titanium Alloys

Titanium forms a simple eutectic phase diagram with thorium and has very little solid solubility in thorium — probably less than 0.1% at room temperature.[32]

Dilute additions and large amounts of titanium in low-carbon iodide thorium have a slight hardening and strengthening effect.[30] Dilute additions of titanium to carbon-containing iodide thorium alloys reduce their strength, as illustrated in Table 27. Also, up to about 1% Ti diminishes hardness and tensile properties in bomb-reduced thorium, whereas 10% Ti appears to have strengthened it[35,45] (Table 28). The observed softening probably results from titanium combining with carbon, a good interstitial solute strengthener.

Table 27. Properties of Annealed Iodide Thorium-Titanium Alloys[a]

Composition (bal iodide thorium) (wt %)	Hardness (VHN)	Strength, psi		Elongation in 1 in. (%)	Reduction of Area (%)
		0.2% Offset Yield	Tensile		
Unalloyed	45	11,200	19,700	45	60
0.15 C	116	27,300	38,800	46	49
0.15 C, 0.78 Ti	50	13,400	25,600	16	51
1.16 Ti	51	11,500	23,900	32	45

[a]R. M. Goldhoff *et al.*, *A Study of the Strengthening of Thorium by Alloying, Cold Work, and Aging*, BMI-776 (Nov. 1, 1952).

Table 28. Mechanical Properties of Annealed Bomb-Reduced Thorium-Titanium Alloys[a]

Titanium Content (bal bomb-reduced thorium) (wt %)	Hardness	Strength, psi		Elongation in 2 in. (%)	Reduction of Area (%)
		0.2% Offset Yield	Tensile		
		Annealed at 875°C			
Unalloyed		21,300	32,600	38	
1	F30 BHN[b]	9,900	28,000	19	
5	F55 BHN[b]	14,800	34,900	19	
10	F54 BHN[b]	25,100	42,300	13	
		Annealed 1 hr at 750°C			
Unalloyed	106 VHN	30,300	39,600		52
0.22	95 VHN	26,400	38,300	35	49
1.20	53 VHN	10,900	23,600	33	50

[a]R. M. Goldhoff *et al.*, *A Study of Thorium-Base Alloys*, BMI-720 (Dec. 26, 1951); and H. A. Wilhelm *et al.*, *Semiannual Progress Report in Metallurgy*, ISC-203 (March 31, 1952).

[b]500-oz load.

Thorium-Vanadium Alloys

As in the preceding three alloy systems, vanadium forms a simple eutectic phase diagram with thorium and has very little solid solubility in thorium.[32]

Table 29 shows the mechanical properties of thorium-vanadium alloys prepared with iodide thorium as a base and carbon maintained at an essentially constant level.[39] Vanadium shows a moderate strengthening and hardening effect in iodide thorium along with a corresponding decrease in ductility. A probable tendency toward carbon scavenging may be noted at 0.5 to 1% V.

A similar investigation[39,46] conducted with bomb-reduced thorium seemed to indicate a decrease in strength and ductility with additions of vanadium up to 3.5% and possibly higher (Table 30); this is probably associated with removal of carbon from solid solution.

Thorium-Aluminum Alloys

Aluminum forms one or more intermetallic compounds with thorium. Indications are that it has very low solid solubility in thorium, practically nil at room temperature.[32] Preliminary attempts to fabricate thorium-aluminum alloys for study of properties resulted in failure because of their inherent brittleness.[35,43,47] Mechanical property data[20,30,35] for alloys containing only small amounts of aluminum are presented in Table 31. In the alloys prepared from iodide thorium, the small additions of aluminum seem to strengthen and harden the thorium only slightly. A similar but somewhat inconsistent pattern is evident for the bomb-reduced alloys.

Thorium-Beryllium Alloys

Beryllium forms the intermetallic compound $ThBe_{13}$ with thorium; this intermetallic forms an eutectic with thorium.[32] Beryllium has only slight solubility in thorium; there is evidence of the brittle beryllide phase in iodide thorium containing only 0.07% Be.

Table 29. Mechanical Properties of Iodide Thorium-Vanadium Alloys[a,b]

Analysis, wt %		Proportional Limit (psi)	Strength, psi		Elongation (%)	Reduction of Area (%)	Hardness (R_H)
Vanadium	Carbon		Yield	Tensile			
0.22	0.036	7,300	11,900	23,400	44.0	63.0	78
0.50	0.038	5,600	7,000	20,800	44.0	62.0	65
0.95	0.042	6,200	9,400	23,800	40.0	61.5	75
1.85	0.041	7,100	10,500	26,400	36.5	59.0	81
3.86	0.045	10,400	17,000	36,100	24.5	48.0	93
7.81	0.038	13,600	25,800	41,400	21.0	52.0	100

[a]R. E. Adams *et al.*, "Thorium Alloys," p. 238 in *Reactor Handbook* (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.

[b]Specimens cold rolled about 85% and annealed 1/2 hr at 650°C.

Table 30. Mechanical Properties of Bomb-Reduced Thorium-Vanadium Alloys[a,b]

Analysis, wt %		Proportional Limit (psi)	Strength, psi		Elongation in 2 in. (%)	Reduction of Area (%)
Vanadium	Carbon		0.2% Offset Yield	Tensile		
0.39	0.038	16,200	20,000	30,900	47.0	57.0[c]
0.59	0.035	13,700	17,900	29,300	57.0	64.0[d]
1.17	0.033	13,700	16,600	27,400	51.0	62.0[d]
3.33	0.040	11,400	16,300	33,600	34.0	55.0[e]
6.30	0.087	12,100	20,400	39,500	26.0	40.0[c]
8.46	0.041	12,700	20,200	36,700	28.0	50.0[c]

[a]R. E. Adams et al., "Thorium Alloys," p. 239 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1950.

[b]Cast 1 1/4-in.-diam billet swaged to 5/8-in. diameter and annealed 1/2 hr at 750°C.

[c]Average of four test bars.

[d]Average of three test bars.

[e]Average of two test bars.

Table 31. Mechanical Properties of Thorium-Aluminum Alloys[a]

Aluminum Analysis (wt %)	Strength, psi		Elongation (%)	Reduction of Area (%)	Hardness	Reference	Condition
	0.2% Offset Yield	Tensile					
Iodide Thorium							
Unalloyed	11,200	19,700	44[b]	60	45 VHN	30	Cold rolled 50% and annealed 2 hr at 850°C.
0.015	11,900	20,700	46[b]	69	56 VHN	30	Cold rolled 50% and annealed 2 hr at 850°C.
0.17	13,000	26,600	c	71	60 VHN	30	Cold rolled 50% and annealed 2 hr at 850°C.
Bomb-Reduced Thorium							
Unalloyed	19,400	31,300	46[b]	50	79 VHN	35	Cold rolled 50% and annealed 2 hr at 850°C.
0.10	24,600	40,800	34[b]	43	90 VHN	35	Cold rolled 50% and annealed 2 hr at 850°C.
Unalloyed	21,500	33,400	54	60	71 R_E	20	Probably annealed at 835°C for 1/2 hr.
0.02	28,400	38,900	29		80 R_E	20	Probably annealed at 825°C for 1/2 hr.
0.05	21,600	34,600	43		76 R_E	20	Probably annealed at 825°C for 1/2 hr.
0.10	24,600	39,000	38		81 R_E	20	Probably annealed at 825°C for 1/2 hr.

[a]All values are averages of four tests.

[b]1-in. gage length.

[c]Fracture outside of gage length.

The fabricability of thorium-beryllium alloys is handicapped by their brittleness. Mechanical properties of some lean thorium-beryllium alloys prepared from iodide thorium[30,42] are presented in Table 32. Small amounts of beryllium, up to about 0.7%, appear to have a very small hardening and strengthening effect on thorium. Beryllium is present as an impurity in bomb-reduced thorium in amounts ranging between approximately 0.02 and 0.06% and may contribute slightly to its strength advantage over iodide thorium.

Table 32. Mechanical Properties of Annealed Iodide Thorium-Beryllium Alloys[a]

Beryllium Analysis (wt %)	Strength, psi		Elongation (%)	Reduction of Area (%)	Hardness (VHN)
	0.2% Offset Yield	Tensile			
Hot Rolled, Cold Rolled to 50% Reduction to 0.040 in. Thick, and Annealed 2 hr at 850°C					
0	11,200	19,700	44[b]	60	45
0.022	14,700	24,000	35[b]	73	53
0.066	14,400	22,900	30[b]	69	48
Cold Rolled to about 85% Reduction and Annealed 1/2 hr at 650°C					
0	7,600	18,000	27[c]	69	54
0.02	6,700	19,500	38[c]	71	44
0.03	7,000	18,600	41[c]	57	47
0.04	6,300	19,900	29[c]	76	46
0.11	7,800	21,700	38[c]	67	52
0.32	10,700	18,500	4[c]	13	62
0.50	12,200	24,100	29[c]	36	57
0.69	16,900	31,600	25[c]	34	72

[a]R. M. Goldhoff *et al.*, *A Study of the Strengthening of Thorium by Alloying, Cold Work, and Aging*, BMI-776 (Nov. 1, 1952); and E. J. Boyle *et al.*, *Metallurgy Div. Quart. Progr. Rept. April 30, 1952*, ORNL-1302, pp. 5–20.

[b]In 1 in.

[c]In 2 in.

Thorium-Tungsten Alloys

Tungsten forms a simple eutectic phase diagram with thorium. The solid solubility of tungsten in thorium is very small.[32] Alloys containing 0.7 and 4% W were readily rolled, and the addition of tungsten appeared to have a very slight strengthening effect.[35]

Thorium-Tantalum Alloys

The solubility of tantalum in thorium is not known, and information on the possible existence of an intermetallic compound appears to be contradictory. Small amounts of tantalum may scavenge carbon and reduce the hardness and strength of bomb-reduced thorium. Larger amounts (up to about 5%) have a slight strengthening effect.[35]

Thorium Alloys Containing Rare-Earth-Metal Additions

The effects of holmium, neodymium, and praseodymium on the mechanical properties of thorium were studied by the Bureau of Mines.[48] Holmium additions increased the tensile strength, yield strength, and elongation of thorium. A thorium alloy containing 50% Ho showed a tensile strength of 44,000 psi at 320°C and 28,000 psi at 540°C, compared to strengths of 31,500 and 22,500 psi at these temperatures for pure thorium. Elongation increased from 5% for thorium to 9% for Th—50% Ho at 320°C and from 8 to 16% at 540°C. Neodymium additions reduced the tensile strength and yield strength of thorium. At 320°C, a Th—50% Nd alloy showed a tensile strength of 23,400 psi and an elongation of 6%. Praseodymium showed effects similar to those of neodymium.

Effects of Irradiation on Mechanical Properties of Thorium Alloys

Little information is available on the effects of irradiation on the mechanical properties of thorium-base alloys except for thorium-uranium alloys. Table 33 illustrates the effects of neutron irradiation on the room-temperature mechanical properties of alloys containing 1, 4, and 5.4% U (93% ^{235}U). Central temperatures of the specimens during irradiation

Table 33. Mechanical Properties of Irradiated and Unirradiated Thorium-Uranium Alloys[a]

Uranium Content (wt %)	Accumulated Exposure		Elastic Modulus (psi)	Strength, psi		Total Elongation (%)
	neutrons/cm^2	Burnup (at. %)		0.2% Offset Yield	Ultimate Tensile	
	$\times 10^{20}$		$\times 10^6$	$\times 10^3$	$\times 10^3$	
1.0[b]	0		8.6	49.5	51.7	25.4
1.0	4.9	0.19	10.8	70.9	71.7	9.6
4.0[b]	0		10.1	51.8	55.7	24.6
4.0	0.4	0.08	10.3	68.7	68.7	15.6
4.0	0.7	0.15	10.5	70.7	72.2	15.0
5.4[c]	0		13.1	25.5	41.8	22.3
5.4	0.25	0.07	10.7	62.6	63.8	13.8

[a] Hanford Atomic Products Operation Quarterly Progress Report on Fuels Development Operation, October, November, December 1960, HW-70355. CLASSIFIED

[b] Tested as swaged.

[c] Annealed.

were less than 250°C. The data indicate that irradiation increases the yield strength substantially, increases the ultimate strength only moderately, and decreases the ductility.

REFERENCES

1. D. T. Goldman and J. R. Roesser (eds.), Chart of the Nuclides, 9th ed., revised to July 1966, General Electric Company, Schenectady, New York, 1966.

2. D. S. Evens and G. V. Raynor, "The Lattice Spacing of Thorium with Reference to Contamination," J. Nucl. Mater. 1, 281–288 (1959).

3. O. N. Carlson et al., "The Metallurgy of Thorium and Its Alloys," Proc. Intern. Conf. Peaceful Uses At. Energy, Geneva, 1955 9, 74–106 (1956).

4. L. K. Jetter, Metallurgy Div. Quart. Progr. Rept. Jan. 31, 1952, ORNL-1267, pp. 27–29.

5. Atomics International, Annual Technical Progress Report, AEC Unclassified Programs, Fiscal Year 1959, NAA-SR-3850 (Aug. 1, 1959).

6. J. J. Katz and G. T. Seaborg, The Chemistry of the Actinide Elements, p. 508, Methuen and Company, Ltd., London and Wiley, New York, 1957.

7. L. Klemm, "Magnetochemische Untersuchungen. XXXIII. Das magnetische Verhalten einiger Elemente," Z. Elektrochem. 45, 354 (1939).

8. H. A. Wilhelm and B. A. Rogers, "The Physical Metallurgy of Thorium," Nuclear Metallurgy, Am. Inst. Mining Met. Engrs. Inst. Metals Div. Spec. Publ. 1, 39–63 (1955).

9. Ames Laboratory, Semi-Annual Summary Research Report in Physics for January–June 1959, IS-14 (October 1959).

10. M. Griffel and R. E. Skochdopole, "The Heat Capacity and Entropy of Thorium from 18 to 300°K," J. Am. Chem. Soc. 75, 5250–5251 (1953).

11. F. G. Foote and J. H. Kittel, "Effects of Radiation upon Thorium," The Metal Thorium, Proc. Conf. Cleveland, 1956, 277–281 (1958).

12. F. E. Bowman et al., Cyclotron Irradiation Damage of Thorium, Stainless Steel, and Zirconium, NAA-SR-287 (April 1, 1954).

13. R. W. Dayton and C. R. Tipton, Jr., Progress Relating to Civilian Applications During February 1959, BMI-1324 (March 1, 1959).

14. T. C. Runion, B. A. Rogers, and S. H. Paine, "Thorium," pp. 211–226 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd ed. Vol. I, Interscience, New York, 1960.

15. A. D. Schwope, G. T. Muehlenkamp, and L. L. Marsh, Mechanical and Metallurgical Properties of Thorium, BMI-784 (Nov. 18, 1952).

16. E. J. Boyle, "Recrystallization of Thorium," The Metal Thorium, Proc. Conf. Cleveland, 1956, 217–224 (1958).

17. L. K. Jetter and C. J. McHargue, "Preferred Orientation in Thorium," The Metal Thorium, Proc. Conf. Cleveland, 1956, 161–184 (1958).

18. D. E. Hamby (ed.), Metallurgy of Thorium and Thorium Alloys, ORNL-1090, p. 16 (Dec. 7, 1951).

19. A. D. Schwope et al., The Creep Properties of Thorium, BMI-886 (Sept. 11, 1953).

20. G. C. Danielson et al., Terminal Report of an Investigation of the Properties of Thorium and Some of Its Alloys, ISC-297 (Oct. 1, 1952).

21. R. B. Oliver, Metallurgy Div. Semiann. Progr. Rept. April 10, 1953, ORNL-1551, pp. 4–6.

22. J. A. Milko, Metallurgy Div. Semiann. Progr. Rept. Oct. 10, 1953, ORNL-1625, pp. 6–7.

23. A. L. Bement, Jr., "Tensile Properties of Irradiated Thorium," J. Nucl. Mater. 6, 69–83 (1962).

24. Hanford Atomic Products Operation Quarterly Progress Report on Fuels Development Operation, October, November, December 1959, HW-64863 (Jan. 15, 1960). CLASSIFIED.

25. Hanford Atomic Products Operation Quarterly Progress Report on Fuels Development Operation, October, November, December 1960, HW-70355 (Jan. 13, 1961). CLASSIFIED.

26. Hanford Atomic Products Operation Quarterly Progress Report on Fuels Development Operation, July, August, September 1959, HW-62656 (Oct. 15, 1959). CLASSIFIED.

27. J. A. Burka and J. P. Hammond, Evaluation of Thorium-Base Alloys for High-Temperature Strength, ORNL-3777 (April 1965).

28. M. S. Farkas, A. A. Bauer, and R. J. Dickerson, "Development of Thorium-Uranium and Thorium-Uranium-Base Alloys for Breeder Applications," pp. 468–497 in Proceedings of the Thorium Fuel Cycle Symposium, Gatlinburg, Tennessee, December 5–7, 1962, TID-7650, Book 2 (July 1963).

29. J. P. Hammond, Metals and Ceramics Div. Ann. Progr. Rept. June 30, 1967, ORNL-4170, pp. 105–106.

30. R. M. Goldhoff et al., A Study of the Strengthening of Thorium by Alloying, Cold Work, and Aging, BMI-776 (Nov. 1, 1952).

31. J. A. Milko, R. E. Adams, and W. O. Harms, "The Mechanical Properties of Thorium and High-Thorium Alloys," The Metal Thorium, Proc. Conf. Cleveland, 1956, 186–216 (1958).

32. F. A. Rough and A. A. Bauer, Constitution of Uranium and Thorium Alloys, BMI-1300 (1958).

33. R. H. Cole and L. E. Wilkinson, Development of High-Strength Ternary and Quarternary Thorium-Uranium Base Fuels, ATL-A-128 (Nov. 1, 1961).

34. R. M. Goldhoff, H. R. Ogden, and R. I. Jaffee, "Thorium-Rich Alloys," pp. 484–494 in Proceedings of the Spring Metallurgy Conference, March 24–26, 1952, Ames, Iowa (March 1952). CLASSIFIED.

35. R. M. Goldhoff et al., A Study of Thorium-Base Alloys, BMI-720 (Dec. 26, 1951).

36. J. H. Kittel et al., Effects of Irradiation on Thorium and Thorium Uranium Alloys, ANL-5674 (April 1, 1963).

37. I. B. Roll, "Thorium and Its Alloys," pp. 146–193 in Nuclear Reactor Fuel Elements, Metallurgy and Fabrication (ed. by A. R. Kaufmann), Interscience, New York, 1962.

38. J. A. Burka and J. P. Hammond, "High-Temperature Thorium-Base Alloys," Metals and Ceramics Div. Ann. Progr. Rept. June 30, 1964, ORNL-3670, pp. 249–250.

39. R. E. Adams et al., "Thorium Alloys," pp. 227–247 in Reactor Handbook (ed. by C. R. Tipton, Jr.), 2nd. ed. Vol. I, Interscience, New York, 1960.

40. R. M. Goldhoff, H. R. Ogden, and R. I. Jaffee, Thorium-Carbon Alloys, AECD-3560 (June 19, 1953).

41. A. F. Gerds and M. W. Mallett, J. Electrochem. Soc. **101**, 175–180 (1954).

42. E. J. Boyle et al., Metallurgy Div. Quart. Progr. Rept. April 30, 1952, ORNL-1302, pp. 5–20. CLASSIFIED.

43. G. C. Danielson et al., Interim Report of an Investigation of the Properties of Thorium and Some of Its Alloys, ISC-200 (Jan. 18, 1952).

44. G. C. Danielson et al., Progress Report of an Investigation of the Properties of Thorium and Some of Its Alloys, ISC-213 (March 1, 1952).

45. H. A. Wilhelm et al., Semiannual Progress Report in Metallurgy, ISC-203 (March 31, 1952).

46. J. A. Milko, Metallurgy Div. Quart. Progr. Rept. Oct. 31, 1952, ORNL-1437, pp. 3–4.

47. D. E. Hamby, Interim Report on Metallurgy of Thorium and Thorium Alloys, ORNL-1090 (Dec. 7, 1951).

48. Bureau of Mines, Metallurgical Progress Report No. 16 for the Period July 1—Sept. 30, 1962, USBM-U-978.

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