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THE PROPERTIES OF THORIUM ALLOYS

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September 15, 1951

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BATTELLE MEMORIAL INSTITUTE

THE PROPERTIES OF THORIUM ALLOYS

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INTRODUCTION

A preliminary survey of the technology of thorium was reported as BMI-76. The present report is a more comprehensive treatment covering only the properties of thorium alloys. Similar reports will follow on other phases of thorium technology.

While there may be a few unintentional omissions in this report, it is intended to contain all of the pertinent information on thorium alloys available at the time of its preparation. This results in the presentation of considerable discordant data. However, in this early state of the "art", it is impossible to select single or best data. For example, in many instances in the report, a phase diagram is presented, and then contractory evidences are pointed out in the text. This does not necessarily mean that the diagram is to be preferred.

In some few cases, where data have been proved indisputably to be erroneous, they have been eliminated from the report to avoid confusion.

It is hoped that collection of existing knowledge in reports such as these will be an aid to various laboratories planning future work. The scanty and discordant information on thorium alloys shows the need for additional investigations. This additional work will be especially necessary as new higher purity thorium becomes available.

Information on the alloy systems listed in Table 1 is presented in this report. The table also indicates the laboratories studying the particular alloy systems at present. In addition to these systems, it is to be noted that work has commenced on alloys containing Cd, P, Pd, Pt, Se, Sr, and Te, although no data are yet available. (71)

TABLE 1. THORIUM-ALLOY SYSTEMS INCLUDED IN THIS REPORT

Aluminum (1,2,3)	Mercury
Barium (1,2)	Molybdenum (1)
Beryllium (2,3)	Nickel (1,2)
Bismuth (2)	Niobium (1,2,3)
Boron	Nitrogen (2)
Carbon (2)	Oxygen
Cerium (1,2,3)	Silicon (1,3)
Chromium (1,2)	Silver (1)
Cobalt (1,2)	Sodium
Copper (1,2)	Sulfur (2)
Gold	Tantalum (1,2)
Hydrogen	Thallium
Indium (3)	Titanium (2,3)
Iron (2)	Tin (1,2)
Lanthanum (1)	Tungsten (1,2)
Lead (1,2)	Uranium (1,2)
Lithium (2)	Vanadium (2)
Magnesium (2,3)	Zinc
Manganese (1,2,3)	Zirconium (1,2,3)

Post-letters indicate laboratories currently studying on thorium alloys containing small percentages of these elements:

1 = Iowa State College.

2 = Battelle Memorial Institute.

3 = Oak Ridge National Laboratory.

THORIUM-ALUMINUM SYSTEM

Figure 1 is the aluminum end of the thorium-aluminum constitution diagram as determined by Grube and Botzenhardt⁽⁷⁾. They report solid solubility of thorium in aluminum to be 2.3 weight per cent at 630 C (1165 F) and 0.1 per cent at 300 C (570 F). Their placing of the compound at ThAl_7 does not agree with earlier or later investigators. Hansen⁽¹⁶⁾ reports an eutectic at 25.6 weight per cent thorium and 650 C (1200 F), which is in good agreement with Figure 1. Hansen lists the compound as ThAl_3 , which decomposes by peritectic reaction at 880 C and 44 weight per cent thorium. He also reports an unknown phase "X" with higher thorium content. The report of Greninger, et al⁽¹⁷⁾ is somewhat confusing. They report the compound ThAl_3 and also an unknown phase "X" between 70 and 80 weight per cent thorium. However, this is the composition corresponding to ThAl_3 . For several alloys, they report the following:

<u>Weight Per Cent Th</u>	<u>Constituents</u>
8	Primary Al + eutectic
31	Primary ThAl_3 + eutectic
49	Primary ThAl_3 + eutectic
68	Primary ThAl_3 + remnants of eutectic
79	"X" + ThAl_3 from peritectic

Rough and Saller^(18, 19, 20, 21, 22), in some more recent work, report the following:

FIGURE 1. THORIUM - ALUMINUM SYSTEM^(2,7)

a. An eutectic at 24.5 weight per cent thorium and 625 C (1155 F) between aluminum and ThAl_3 . ThAl_3 is a hexagonal compound.

b. A second compound in the neighborhood of 95 per cent thorium, melting at about 1575 C (2870 F). This compound forms eutectics on both sides.

c. In alloys between 52 and 71 weight per cent thorium, a second thermal effect at 1130 C (2065 F).

d. Maximum solubility of thorium in aluminum as 0.8 weight per cent.

e. Maximum solubility of aluminum in thorium as less than 1 weight per cent. High-thorium alloys, up to at least 10 weight per cent aluminum, are unstable in air, decomposing to a fine powder^(17, 23).

Aluminum forms brittle intermetallic compounds with thorium. Therefore, the high-thorium alloys can not be cold worked⁽¹³⁾. Aluminum alloys containing up to at least 25 weight per cent thorium can be readily hot rolled, with a minimum of edge cracking⁽²⁹⁾.

Dip coatings of aluminum on thorium can easily be formed at 700 C (1290 F) and above with or without fluxes⁽²⁴⁾. The best temperature for dip coating is 800 C (1470 F)⁽²⁵⁾. A thick ThAl_3 layer is formed⁽¹⁷⁾.

Aluminum was roll clad to thorium at 1100 F (590 C)^(26, 27, 28). Low rates of reduction, 0.010 to 0.020 inch per pass, were used and total thorium reduction kept less than 40 per cent. On the other hand, ORNL roll clad aluminum to thorium with as high as 50 per cent reduction per pass⁽⁷⁶⁾.

The effect of small amounts of aluminum on the hardness of vacuum arc-melted thorium is as follows⁽²³⁾:

<u>Material</u>	<u>Hardness, R_p</u>
Unalloyed Th	62
2 weight % Al	94
4 weight % Al	96

Small amounts of residual aluminum, by itself or in addition to small amounts of beryllium, may be responsible for the poor fabricating and welding characteristics of some Ames thorium ingots⁽⁷⁵⁾.

Thorium, coupled with aluminum, increased the corrosion rate of aluminum in boiling water, but the corrosion rate of thorium did not change⁽³⁵⁾.

THORIUM-BARIUM SYSTEM

Work on this alloy system on the higher thorium end has recently been started at Iowa State College ⁽¹²⁾. An arc-melted, 5 weight per cent barium alloy had an as-cast Brinell hardness (500-kg load) of 70. The specimen broke after 37 per cent cold reduction⁽⁷²⁾.

THORIUM-BERYLLIUM SYSTEM

Figure 2 is the diagram of the beryllium-thorium alloy system (3, 5, 6). Details of the high-beryllium end are not known, although a primary compound is found in 2.5, 5, and 10 weight per cent thorium

FIGURE 2 . THORIUM-BERYLLIUM SYSTEM^(2,5,6)

An alloy containing 1.6 weight per cent beryllium, 22 weight per cent cerium, balance thorium was not forgeable at room temperature nor at 604 C (1120 F)⁽¹⁷⁾. A 2.11 per cent Be, 0.12 per cent C alloy was successfully rolled at 980 C (1800 F) but not at 870 C (1600 F) or 760 C (1400 F).

Alloys containing one and two weight per cent beryllium oxidized and scaled badly on standing in air⁽¹⁷⁾. Air-corrosion rates of beryllium alloys at various temperatures are as follows⁽³⁴⁾:

Exposure Time, Hr	Weight Gain, mg per cm ²				
	<u>400 C</u>	<u>425 C</u>	<u>437 C</u>	<u>450 C</u>	<u>500 C</u>
1	0.19	0.98	0.82	1.41	3.28
2	0.76	1.74	2.06	3.12	5.97
3	1.29	2.58	3.10	4.37	7.61
4	2.53	3.43	4.22	5.82	9.43

Iowa State College data⁽³⁵⁾ on corrosion of beryllium-thorium alloys in water are as follows:

Weight Per Cent Be	Weight Change, mg /cm ² /hrs		
	<u>100 C</u>	<u>140 C</u>	<u>180 C</u>
0	-22.3 x 10 ⁻³	-48.9 x 10 ⁻³	-68.7 x 10 ⁻³
2	-56.8 x 10 ⁻³	-66.0 x 10 ⁻³	-415 x 10 ⁻³

Corrosion data obtained by Chicago in boiling distilled water, pH = 5.6 to 5.8, are as follows (17, 36),

<u>Material</u>	<u>Time, hr</u>	<u>Weight Change, mg/cm²/hr</u>
Ames Billet	842	-0.0006
Westinghouse extrusion	842	-0.003
0.42% Be, as cast	112 592	+0.005 -0.00015
0.94% Be, as cast	112 592	+0.008 +0.0007
1.6% Be, as cast	112 592	+0.0023 +0.00022
1.6% Be, as cast*	112 592	+0.0018 +0.00028
2.46% Be, as cast	112 592	+0.003 +0.00017
1.11% Be + 0.62% Si, as cast	112 --	+0.001 -0.0085

*Melted in graphite, all others in BeO.

Weight changes in 178 C, 125-psi distilled water are as follows:

<u>Material</u>	<u>Weight Change, mg/cm²</u>				
	<u>0.8 Day</u>	<u>1.7 Days</u>	<u>4 Days</u>	<u>8 Days</u>	<u>16 Days</u>
Unalloyed Th	+0.47	0.0	-0.4	-12.3	-94.3
0.4 wt % Be	+0.46	+1.7	+1.65	+5.0	+7.0
0.94 wt % Be	+0.32	-0.13	Spec. corroded away		
1.6* wt % Be	-0.02	-0.62	-0.72	-1.0	-0.9
1.6 wt % Be	-0.36	-0.73	+34	Spec. corroded away	

<u>Material</u>	<u>Weight Change, mg/cm²</u>				
	<u>0.8 Day</u>	<u>1.7 Days</u>	<u>4 Days</u>	<u>8 Days</u>	<u>16 Days</u>
2.46 wt % Be	-0.55	-1.2	-1.1	-0.97	-0.6
1.11 wt % Be + 0.62 wt % Si	-0.58	-1.0	-0.96	-0.83	-3.8

*Melted in graphite, all others in BeO.

The alloy containing 2.11 wt per cent beryllium and 0.11 wt per cent carbon resisted corrosion eight days in 178 C, 175-psi distilled water, then pitted and lost weight at ^{the} same rate as unalloyed thorium.

Corrosion rates of a 0.5 weight per cent beryllium alloy in other liquid media were as follows ⁽³⁵⁾:

<u>Medium</u>	<u>Temp, C</u>	<u>Weight Change, mg/cm²/hr</u>
0.3 M in uranyl nitrate + 0.1 M in HNO ₃	100	-65.5 x 10 ⁻³
0.3 M in thorium nitrate	100	-41.4 x 10 ⁻³
0.5 M in HNO ₃	98	-48.3 x 10 ⁻³
15.4 M in HNO ₃ (conc)	96	-1235 x 10 ⁻³

THORIUM-BISMUTH SYSTEM

Figure 4 is a tentative diagram of the thorium-bismuth system ⁽⁹⁾. The alloys were made by co-reduction of the fluorides with calcium in a dolomite-lined steel bomb.

Solubilities of thorium in molten bismuth are ⁽⁹⁾:

700 C (1290 F)	15 wt %
1100 C (2010 F)	2.2 wt %

FIGURE 4. THORIUM-BISMUTH SYSTEM ⁽⁹⁾

The compounds are heavier than the molten bismuth and can be removed by centrifuging⁽⁹⁾.

As-cast hardness and fabricating characteristics of some Battelle arc-melted bismuth alloys are as follows⁽⁷¹⁾:

<u>Weight Per Cent Bi</u>	<u>Atomic Per Cent Bi</u>	<u>As-Cast VHN</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>
0.90	1	120	Fair	Fair
2.25	2.5	105	Poor	Poor
4.5	5	--	Chipped	Broke, first pass

Edge-cracking tests during cold rolling showed the following⁽⁷¹⁾:

<u>Weight Per Cent Bi</u>	<u>Atomic Per Cent Bi</u>	<u>VHN, Annealed 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Cracking</u>
0.90	1	111	144	--
2.25	2.5	97	121	74

Tensile properties of these alloys after hot rolling at 700 C to 0.080-inch sheet are shown in Table 2^(13, 71).

Aging tests of these bismuth alloys showed the following⁽⁷¹⁾:

<u>Weight Per Cent Bi</u>	<u>Atomic Per Cent Bi</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.9	1	111	122	117
2.25	2.5	97	102	107

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TABLE 2. TENSILE PROPERTIES OF BISMUTH ALLOYS

Weight Per Cent Bi	Atomic Per Cent Bi	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.90	1	32,000	48,000	23	24	80,000	0.18
2.25	2.5	24,800	44,200	19	32	96,000	0.28

THORIUM-BORON SYSTEM

Two compounds are formed in the thorium-boron system, ThB_4 and ThB_6 ⁽³⁷⁾. The homogeneity range of ThB_4 is narrow. It has a tetragonal crystal structure with $a_0 = 7.256 \pm 0.005 \text{ \AA}$ and $c_0 = 4.113 \pm 0.002 \text{ \AA}$. Density is 8.45 g/cm^3 ⁽³⁸⁾. ThB_4 has a melting point well above 2500 C (4530 F) ⁽³⁷⁾. The Th-ThB_4 eutectic temperature is about 1550 C (2820 F). ThB_6 has a simple cubic structure with $a_0 = 4.32 \text{ \AA}$. It is unstable at 1550 C (2730 F). Density is 6.4 g/cm^3 .

ThO_2 seems to form extensive solid solutions with ThB_4 ⁽³⁷⁾.

THORIUM-CARBON SYSTEM

Figure 5 is a tentative thorium-carbon equilibrium diagram ⁽³⁾. The actual system is probably much more complex ⁽³⁾. Two compounds, ThC and ThC_2 , are definitely established. ThC_2 has been shown to have monoclinic crystal structure with constants $a_0 = 6.53 \text{ \AA}$, $b_0 = 4.24 \text{ \AA}$, $c_0 = 6.56 \text{ \AA}$, and $\beta = 104^\circ$ ⁽⁵⁰⁾. This is a slight change from the previously reported tetragonal lattice. ThC has a face-centered cubic NaCl structure with $a_0 = 5.29 \text{ \AA}$.

Solubilities of carbon in thorium are as follows:

<u>Temperature</u>	<u>Weight Per Cent C</u>
900 C (1650 F)	<0.1 (39, 40)
1050 C (1920 F)	>0.3 <0.5 (39, 40)
1100 C (2010 F)	>0.5 <0.7 (39, 40)
1950 C (3540 F)	0.7 (approx.) (3)

FIGURE 5. TENTATIVE PHASE DIAGRAM OF THORIUM-CARBON SYSTEM ⁽³⁾

Small amounts of carbon harden thorium considerably and strengthen it⁽¹³⁾.

The effect of cold rolling on the hardness of two carbon-thorium alloys is as follows⁽⁷¹⁾:

<u>Weight Per Cent Carbon</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>
0.12	175	206
0.25	175	205

Tensile properties of these same two alloys after hot rolling at 700 C are shown in Table 3⁽⁷¹⁾.

Aging tests on these two alloys showed⁽⁷¹⁾:

<u>Weight Per Cent C</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.12	175	164	188
0.25	175	164	180

Carbon in solid solution in thorium increases its corrosion resistance to 178 C, 125-psi water⁽³³⁾. However, carbon as carbide materially decreases the corrosion resistance of thorium.

Corrosion rates in boiling distilled water, were as follows⁽³⁶⁾:

<u>Weight Per Cent C</u>	<u>Hours</u>	<u>Weight Change, mg/cm²/hr</u>
0.3, as-cast	490	-0.00055
1.24, as-cast	490	-0.098

TABLE 3. TENSILE PROPERTIES OF CARBON ALLOYS

Wt Per Cent C	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	29,000	39,000	32	46	66,000	0.18
0.12	57,600	58,600	—	19	87,000	0.16
0.25	52,100	57,700	—	27	86,000	0.16

For the same alloys in 178 C, 125-psi distilled water, weight changes were as follows⁽³⁶⁾:

Weight Per Cent C	Weight Change, mg/cm ²				
	<u>0.8 Day</u>	<u>1.7 Days</u>	<u>4 Days</u>	<u>8 Days</u>	<u>16 Days</u>
0.3	-0.09	-0.4	-0.16	-0.69	-0.4
1.24	-2.0	Spec. corroded away			

As little as 0.2 weight per cent carbon eliminated the sharp increase in electrical resistance of thorium near 1400 (2550 F)⁽³⁾. An electrical resistivity versus temperature curve for the dicarbide showed a sharp change in slope at about 1350 to 1650 C (2462 F to 3002 F). For the monocarbide, a rather large hysteresis effect was shown at 700 (1292 F) to 900 C (1652 F). Interpretation of the curves was not possible. The dicarbide is a particularly good electrical conductor at room temperature⁽³⁾. In comparison, the monocarbide has only one-fifth the conductivity⁽³⁾. No absolute values are given.

THORIUM-CERIUM SYSTEM

The thorium-cerium system is characterized by complete solubility in the liquid and solid states⁽³⁵⁾. There is quite a large gap between the liquidus and solidus, so that non-homogeneous material results from normal cooling. Homogenization for six days at 725 C (1335 F) eliminated the coring⁽³⁶⁾.

Fabrication of cerium-thorium alloys is difficult because of easy oxidation.

The effect of cerium on hardness of vacuum arc-melted thorium is as follows^(15, 23),

<u>Alloy</u>	<u>Hardness, R_B</u>
Unalloyed Th	62
0.25 weight % Ce	62
2 weight % Ce	60
4 weight % Ce	57
6 weight % Ce	52
8 weight % Ce	60

As-cast hardnesses and fabricating characteristics of some arc-melted cerium-thorium alloys are as follows⁽⁷¹⁾,

<u>Weight Per Cent Ce</u>	<u>Atomic Per Cent Ce</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>
0.61	1	115	Good	Good
3.04	5	112	Good	Good

The effect of cold work on the hardness is shown below⁽⁷¹⁾,

<u>Weight Per Cent Ce</u>	<u>Atomic Per Cent Ce</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>
0.61	1	115	143
3.04	5	118	142

Tensile properties of these alloys, as hot rolled at 700 C, are shown in Table 4.

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TABLE 4. TENSILE PROPERTIES OF CERIUM ALLOYS

Weight Per Cent Ce	Atomic Per Cent Ce	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	33,000	32	46	66,000	0.18
0.61	1	33,000	47,000	26	32	80,000	0.17
3.04	5	31,000	46,000	36	41	70,000	0.18

Aging tests on cerium alloys showed⁽⁷¹⁾:

<u>Weight Per Cent Ce</u>	<u>Atomic Per Cent Ce</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.61	1	115	109	108
3.04	5	118	115	113

An arc-melted, four weight per cent cerium alloy having an as-cast Brinell hardness (500-kg load) of 73 was reduced 83 per cent by cold rolling with no cracking⁽⁷²⁾. The alloy had the following mechanical and electrical properties:

<u>Condition</u>	<u>Brinell Hardness (500-Kg Load)</u>	<u>0.2% Offset Yield Strength, psi</u>	<u>Ultimate Strength, psi</u>	<u>Elonga- tion, % in 1 inch</u>	<u>Resis- tivity, microhm-cm</u>
As cold rolled	102	56,000	58,100	1	28
Annealed 90 min, 975 C	57	22,600	33,100	9	25.65

THORIUM-CHROMIUM SYSTEM

Figure 6 is the thorium-chromium composition diagram⁽²⁾. The system is characterized by the absence of compounds and only minute solubility of chromium in thorium or thorium in chromium⁽⁴²⁾.

Alloys with small percentages of chromium are relatively soft, and can be cold rolled⁽¹²⁾. Four and six weight per cent vacuum arc-melted alloys were cold rolled^{to reduction}/75 per cent/with no cracking⁽⁵⁵⁾. Hardnesses of these two alloys were:

FIGURE 6. THORIUM-CHROMIUM SYSTEM⁽²⁾

<u>Alloy</u>	<u>Hardness, Rp</u>
4 weight % Cr	76
6 weight % Cr	73

As-cast hardness and fabricating characteristics of some arc-melted chromium-thorium alloys were as follows⁽⁷¹⁾;

<u>Weight Per Cent Cr</u>	<u>Atomic Per Cent Cr</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>	<u>Cold Rolling</u>
0.2	1	108	Good	Good	Good
1.2	5	110	Good	Good	Good

Edge-cracking tests during cold rolling showed⁽⁷¹⁾;

<u>Weight Per Cent Cr</u>	<u>Atomic Per Cent Cr</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Cracking</u>
0.2	1	107	137	71
1.2	5	105	136	57

Tensile properties of these alloys are shown in Table 5⁽⁷¹⁾.

Aging tests on one of these alloys showed⁽⁷¹⁾;

<u>Weight Per Cent Cr</u>	<u>Atomic Per Cent Cr</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.2	1	107	96	99

Arc-melted chromium alloys of two and ten weight per cent, with respective as-cast hardnesses of 78 and 120 Brinell (500-kg load), were

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TABLE 5. TENSILE PROPERTIES OF CHROMIUM ALLOYS

Weight Per Cent Cr	Atomic Per Cent Cr	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.2	1	30,900	43,800	32	56	67,000	0.15

cold rolled successfully; the former to 50 per cent and the latter to 85 per cent reduction with no cracking⁽⁷²⁾. Mechanical and electrical properties were as follows:

<u>Condition</u>	<u>Brinell Hardness (500-Kg Load)</u>	<u>0.2% Offset Yield Strength, psi</u>	<u>Ultimate Strength, psi</u>	<u>Elonga- tion, % in 1 Inch</u>	<u>Electrical Resis- tivity, microhm-cm</u>
2% Cr, as cold rolled	106	40,300	68,100	1	21.8
10% Cr, as cold rolled	--	--	--	--	--
2% Cr, annealed 90 min, 875 C	64	27,000	42,800	17	20.2
10% Cr, annealed 90 min, 875 C	99	38,300	57,400	13	21.25

THORIUM-COBALT SYSTEM

The phase diagram for the thorium-cobalt system has not been completely worked out. However, the following phases have been identified:

<u>Phase</u>	<u>Crystal Structure</u>	<u>Lattice Constants</u>	<u>Reference</u>
Th ₇ Co ₃	Hexagonal, space group 4, C _{6v}	$a_0 = 9.81 \text{ \AA}$ $c_0 = 6.16 \text{ \AA}$	(44)
ThCo ₄ → ThCo ₅		$a_0 = 5.01 \rightarrow 5.01 \text{ \AA}$ $c_0 = 3.97 \rightarrow 3.97 \text{ \AA}$	(42, 45)
ThCo	Complex		(42)
ThCo ₂			(42)
ThCo ₉			(42)

As-cast hardness and fabricating characteristics of some arc-melted cobalt alloys were as follows⁽⁷¹⁾:

<u>Weight Per Cent Co</u>	<u>Atomic Per Cent Co</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>	<u>Cold Rolling</u>
0.25	1	116	Good	Good	Poor
0.6	2.5	108	Cracked	Not rolled	
1.3	5	146	Cracked	Not rolled	

A two weight per cent arc-melted cobalt alloy having an as-cast Brinell hardness (500-kg load) of 109 broke after 20 per cent cold reduction⁽⁷²⁾.

Tensile properties of the 0.25 weight per cent cobalt alloy after hot rolling are shown in Table 6.

Aging tests showed⁽⁷¹⁾:

<u>Weight Per Cent Co</u>	<u>Atomic Per Cent Co</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.25	1.0	115	112	118

THORIUM-COPPER SYSTEM

Figure 7 is a composition diagram for the thorium-copper system^(2, 7, 8). It is not in complete agreement with Raub and Engel⁽⁴³⁾, who report the following compounds and eutectics:

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TABLE 6. TENSILE PROPERTIES OF COBALT ALLOYS

Weight Per Cent Co	Atomic Per Cent Co	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.25	1.0	28,800	23,000	3	10	—	—

FIGURE 7. THORIUM - COPPER SYSTEM (2,7,8)

$\text{Cu} - \text{Cu}_6\text{Th}$ eutectic, 946 C, 25 weight % Th

Cu_6Th compound, mpt-1060 C, 38 weight % Th

$\text{Cu}_6\text{Th} - \text{Cu}_3\text{Th}$ eutectic, 1020 C, 47 weight % Th

Cu_3Th compound, mpt-1060 C, 55 weight % Th

$\text{Cu}_3\text{Th} - \text{Cu}_5\text{Th}_3$ eutectic, 920 C, 60 weight % Th

Cu_5Th_3 compound, mpt-1015 C, 69 weight % Th

$\text{Cu}_5\text{Th} - \text{Th}$ (?) eutectic, 583 C, 79 weight % Th

Rundle reports Th_2Cu to be body-centered tetragonal with $a_0 = 7.28 \text{ kx}$ and $c_0 = 5.74 \text{ kx}$ ⁽⁴⁶⁾ and ThCu_2 to be hexagonal with $a_0 = 4.35 \text{ kx}$ and $c_0 = 3.47 \text{ kx}$ ⁽³¹⁾.

The copper compounds are brittle and may be pyrophoric ^(23, 47, 48). Complete reaction takes place between thorium and copper at 950 C. This can be prevented by an intervening film of chromium 0.0002 inch thick ⁽⁴⁷⁾. In some cases, fires were caused by these pyrophoric compounds during shipment after extrusion of thorium in copper jackets ⁽⁴⁸⁾.

Alloys containing 5 and 10 weight per cent copper decomposed on standing in air ⁽⁷²⁾.

THORIUM-GOLD SYSTEM

Figure 8 is the gold end of the thorium-gold system ⁽⁴³⁾. The solubility of thorium in gold is < 0.05 weight per cent. The compound Au_5Th_3 is pyrophoric under some conditions.

FIGURE 8. THORIUM-GOLD SYSTEM⁽⁴³⁾

THORIUM-HYDROGEN SYSTEM

Chiotti and Rodgers⁽⁵¹⁾ report a method of producing thorium powder by passing through the hydride stage. First, a hydride, ThH_2 , is formed by passing purified hydrogen over thorium chips or solid thorium at 600 - 650 C (1100 - 1200 F). The dihydride is then converted by further hydrogen treatment to a higher hydride, ThH_x , at temperatures not over 320 C (610 F). Grinding can be done in this stage if necessary. The ThH_x is then decomposed at temperatures up to 500 C (930 F), and the resulting ThH_2 decomposed at 700 C (1290 F) and low pressure.

ThH_2 has an X-ray density of 9.20 g/cm³. It is body-centered tetragonal with two molecules per unit cell. Space group is D_{46}^{16} -. Lattice constants are $a_0 = 4.09$ kx, $c_0 = 5.02$ kx (31). Heat of formation is -35,000 cal/mole. Decomposition pressure can be expressed by:

$$\log P_{\text{mm}} = \frac{-7700}{T} + 9.54$$

ThH_x varies in composition from $\text{ThH}_{3.75}$ to ThH_4 . Its X-ray density is 8.33 g/cc. It has a simple cubic structure with 16 molecules per unit cell. Space group is $T_d^6 - 143d$. Heat of formation is -19,000 cal/mole. Decomposition pressure can be expressed by:

$$\log_{10} P_{\text{mm}} = \frac{-4220}{T} + 9.50$$

Mallett and Campbell⁽⁵³⁾ report the following equilibrium data for dissociation of thorium hydrides:

Atom Ratio, H:Th	$\text{Log}_{10} P_{\text{mm}}$	ΔH_{1073} - kcal/mole	ΔS_{1073} - cal/mole/K	ΔF_{1073} - kcal/mole
0.05	$\frac{-4720}{T} + 5.71$	+21.6	+12.9	+7.72
0.10	$\frac{-4760}{T} + 6.26$	+21.8	+15.5	+5.18
0.30	$\frac{-7220}{T} + 8.99$	+33.0	+27.9	+3.11
0.50	$\frac{-7550}{T} + 9.34$	+34.5	+29.4	+2.93
0.90	$\frac{-7550}{T} + 9.36$	+34.5	+29.5	+2.85
1.30	$\frac{-7460}{T} + 9.33$	+34.1	+29.4	+2.55
1.50	$\frac{-7480}{T} + 9.36$	+34.2	+29.6	+2.39
1.65	$\frac{-7480}{T} + 9.44$	+34.2	+29.9	+2.11
1.85	$\frac{-8060}{T} + 10.47$	+36.9	+34.4	-3.37

THORIUM-INDIUM SYSTEM

Oak Ridge National Laboratory reports the following effect of indium on the hardness of vacuum arc-melted thorium⁽²³⁾:

<u>Alloy</u>	<u>Hardness, RB</u>
Unalloyed Th	62
2 weight % In	80
4 weight % In	85
6 weight % In	86
8 weight % In	80

Cold rolling of the 2 weight per cent alloy was not possible⁽²³⁾.

THORIUM-IRON SYSTEM

Thorium-iron diagram data are scarce. Two horizontals are reported between Th and the first compound⁽²⁾. One is at 911 C (1672 F)

the other at 856 C (1573 F). An eutectic is reported at 46 atomic per cent iron and 860 C (1580 F). Some solubility of thorium in iron is reported⁽⁶⁴⁾. The following compounds have been identified at Iowa State College^(45, 46).

1. The Th_7Fe_3 - hexagonal, $a_0 = 9.83 \text{ \AA}$, $c_0 = 614 \text{ \AA}$

Space group = C_{6v}^4

2. ThFe - complex

3. ThFe_9 - ThFe_{19} - complex

As-cast hardnesses of two iron alloys are as follows⁽¹⁾:

<u>Alloy</u>	<u>Hardness, R_p</u>
2.57 weight % Fe	79
5.43 weight % Fe	103

As-cast-hardnesses and fabricating characteristics of some arc-melted iron-thorium alloys are as follows⁽⁷¹⁾:

<u>Weight Per Cent Fe</u>	<u>Atomic Per Cent Fe</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>	<u>Cold Rolling</u>
0.2	1	112	Good	Good	Fair
0.6	2.5	95	Fair	Fair	
1.2	5	130	Cracked	Not rolled	

Edge-cracking tests during cold rolling showed⁽⁷¹⁾:

<u>Weight Per Cent Fe</u>	<u>Atomic Per Cent Fe</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Cracking</u>
0.2	1	108	141	79
0.6	2.5	85	125	54

A two weight per cent arc-melted iron alloy broke on cold rolling⁽¹²⁾.

Physical properties of these as hot rolled at 700 C (1290 F) are shown in Table 7.

Aging tests showed⁽⁷¹⁾:

<u>Weight Per Cent Fe</u>	<u>Atomic Per Cent Fe</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.2	1	108	112	107
0.6	2.5	85	91	92

Corrosion data for tests in boiling distilled water are as follows⁽³⁵⁾:

<u>Weight Per Cent Fe</u>	<u>Weight Loss, mg/cm²/hr</u>
0	22.3×10^{-3}
1.32	12.2×10^{-3}
2.60	430.0×10^{-3}

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TABLE 7. TENSILE PROPERTIES OF IRON ALLOYS

Weight Per Cent Fe	Atomic Per Cent Fe	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.2	1.0	32,700	44,400	31	41	70,000	0.15
0.6	2.5	23,800	36,600	—	37	57,000	0.14

THORIUM-LANTHANUM SYSTEM

Work has recently started on this binary system at Iowa State College⁽¹²⁾. A 5 weight per cent lanthanum alloy, having an as-cast Brinell hardness (500-kg load) of 99, was cold rolled to 82 per cent reduction with no cracking⁽⁷²⁾. Mechanical and electrical properties of this alloy are as follows:

<u>Condition</u>	<u>Brinell Hardness (500-Kg Load)</u>	<u>0.2% Offset Yield Strength, psi</u>	<u>Ultimate Strength, psi</u>	<u>Elonga- tion, % in 1 Inch</u>	<u>Resis- tivity, microhm-cm</u>
As cold rolled	109	23,800	58,800	1	28.4
Annealed 90 min at 875 C	53	20,000	31,500	8	24.6

THORIUM-LEAD SYSTEM

Thorium is only slightly oxidized by molten lead at 900 C (1650 F)⁽⁵⁶⁾. Thorium disintegrated in lead containing 2 per cent U at 1000 C (1830 F)⁽⁵⁵⁾.

As-cast hardness and fabricating characteristics of some arc-melted lead-thorium alloys are as follows⁽⁷¹⁾:

<u>Weight Per Cent Pb</u>	<u>Atomic Per Cent Pb</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>
0.89	1	109	Good	Good
2.20	2.5	104	Good	Good
2.45	5	--	Cracked badly	Not rolled

Edge-cracking tests during cold rolling showed⁽⁷¹⁾:

<u>Weight Per Cent Pb</u>	<u>Atomic Per Cent Pb</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Cracking</u>
0.89	1	118	146	--
2.20	2.5	91	126	74

Five, ten, and fifteen weight per cent lead alloys having respective as-cast Brinell hardnesses (500-Kg load) of 83, 103, and 109 were cold rolled⁽⁷²⁾. The five per cent alloy was reduced 90 per cent with no cracking. The ten and fifteen per cent alloys cracked at 25 and 26 per cent reduction, respectively.

Physical properties of some lead alloys as hot rolled at 700 C are shown in Table 8^(13, 71).

Mechanical and electrical properties of some other arc-melted cold-rolled lead alloys follow⁽⁷²⁾:

<u>Alloy Weight Per Cent Pb</u>	<u>Per Cent Reduction</u>	<u>Brinell Hardness (500-Kg Load)</u>	<u>Ultimate Tensile Strength, psi</u>	<u>Elonga- tion, % in 1 Inch</u>	<u>Resis- tivity, microhm-cm</u>
5	94	92	61,100	1	42.5
10	25	122	--	--	--
15	26	110	--	--	--

Aging tests on lead alloys showed⁽⁷¹⁾:

<u>Weight Per Cent Pb</u>	<u>Atomic Per Cent Fe</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.89	1	118	111	110
2.20	2.5	91	92	94

TABLE 8. TENSILE PROPERTIES OF LEAD ALLOYS

Weight Per Cent Pb	Atomic Per Cent Pb	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.89	1	32,000	46,000	32	42	78,000	0.19
2.20	2.5	24,000	42,700	19	42	75,000	0.19

THORIUM-LITHIUM SYSTEM

In lithium at 600 C (1110 F), thorium was not significantly attacked, but was decarburized to a depth of 2 mils⁽⁵⁷⁾.

At 1000 C (1830 F), lithium does not attack thorium in up to 40 hours^(55, 58). This lack of reaction is probably caused by an adherent, protective, nitride film.

THORIUM-MAGNESIUM SYSTEM

Oak Ridge National Laboratory is considering the thorium-magnesium alloy system because of the possibility of appreciable solid solubility⁽¹⁴⁾.

THORIUM-MANGANESE SYSTEM

There is an eutectic in the thorium-manganese system at 911 C (1670 F) beyond 20 atomic per cent manganese⁽²⁾.

The following compounds have been identified⁽⁴⁶⁾:

1. ThMn_2 , hexagonal, $a_0 = 5.47 \text{ kx}$, $c_0 = 8.93 \text{ kx}$.
2. $\text{Th}_{24}\text{Mn}_{92}$ (formerly called ThMn_4) - face-centered cubic, space group O_h^5 - F M s m, $a_0 = 12.50 \text{ kx}$.
3. ThMn_{12} , complex.

One atomic per cent Mn added to Ames thorium greatly improves cold-rolling properties and lowers its lattice constant. This suggests a scavenging action⁽²⁾.

As-cast hardness and fabricating characteristics of some arc-melted manganese-thorium alloys follow⁽⁷¹⁾:

<u>Weight Per Cent Mn</u>	<u>Atomic Per Cent Mn</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>	<u>Cold Rolling</u>
0.2	1	111	Good	Good	Good
1.2	5	118	Good	Good	Fair

Edge-cracking tests during cold rolling showed:

<u>Weight Per Cent Mn</u>	<u>Atomic Per Cent Mn</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Cracking</u>
0.2	1	104	141	79
1.2	5	107	--	--

Three and five weight per cent arc-melted manganese alloys had as-cast hardnesses (500-kg load) of 74 and 171 BHN, respectively⁽⁷²⁾. On cold rolling, one end of the three per cent alloy cracked at 70 per cent reduction. Its Brinell hardness (500-kg load) was 110. The five per cent alloy cracked on the first pass.

Tensile properties of some of the manganese alloys are shown in Table 9⁽⁷¹⁾.

Aging tests showed⁽⁷¹⁾:

TABLE 9. TENSILE PROPERTIES OF MANGANESE ALLOYS

Weight Per Cent Mn	Atomic Per Cent Mn	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.2	1	30,800	41,500	—	—	66,000	0.14
1.2	5	30,800	44,400	31	41	70,000	0.15

<u>Weight Per Cent Mn</u>	<u>Atomic Per Cent Fe</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.2	1	104	104	105
1.2	5	107	96	111

THORIUM-MERCURY SYSTEM

Thorium reacts with mercury at 350 C (660 F) to form the compounds ThHg_3 and Th_3Hg_4 (2).

The solubility of thorium in mercury is 0.0154 weight per cent at 25 C (77 F) (60).

ThHg_3 has an X-ray density of 14.2 g/cm³. It is close-packed hexagonal with $a_0 = 3.38 \text{ \AA}$ and $c_0 = 4.72 \text{ \AA}$ (44).

THORIUM-MOLYBDENUM SYSTEM

Data for the thorium-molybdenum constitution diagram are not available. Presumably, it is similar to the chromium-thorium diagram, with no compounds and limited solid solubilities.

As-cast hardnesses and fabricating characteristics of some arc-melted molybdenum-thorium alloys are as follows (71):

<u>Weight Per Cent Mo</u>	<u>Atomic Per Cent Mo</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>
0.4	1	80	Good	Good
2.0	5	87	Good	Good

Edge-cracking tests during cold rolling showed⁽⁷¹⁾:

<u>Weight Per Cent Mo</u>	<u>Atomic Per Cent Mo</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Cracking</u>
0.4	1	77	114	54
2.0	5	81	124	71

Cold-rolling characteristics of some other arc-melted molybdenum alloys were as follows⁽⁷²⁾:

<u>Weight Per Cent Mo</u>	<u>BHN, As Cast (500-Kg Load)</u>	<u>Per Cent Cold Reduction</u>	<u>BHN, As Rolled (500-Kg Load)</u>	<u>Remarks</u>
2	70	94	82	No cracking.
5	91	94	137	End split.
10	86	82	135	No cracking.
20	84	81	128	No cracking.

Mechanical and electrical properties of these four alloys are shown in Table 10⁽⁷²⁾.

Tensile properties of the Battelle alloys are shown in Table 11⁽⁷¹⁾.

Aging tests showed⁽⁷¹⁾:

<u>Weight Per Cent Mo</u>	<u>Atomic Per Cent Mo</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.4	1	77	81	78
2.0	5	81	88	86

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TABLE 10. TENSILE AND ELECTRICAL PROPERTIES OF MOLYBDENUM ALLOYS (72)

Wt Per Cent Mo	Condition	BHN (500-Kg Load)	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elonga- tion, Per Cent in 1 Inch	Resistivity, microhm- cm	20 C Temp Coef of Resist. Per °C
2	As cold rolled (94%)	82	51,100	60,600	1	21.4	—
2	Annealed 90 min, 875 C	61	23,700	32,700	20	20.5	—
5	As cold rolled (94%)	137	37,900	57,500	1	25.0	—
10	As cold rolled (82%)	135	49,700	76,900	1	17.4	—
10	Annealed 90 min, 875 C	82	27,100	54,500	22	16.13	0.0031
20	As cold rolled (81%)	128	—	—	—	—	—

50

TABLE 11. TENSILE PROPERTIES OF MOLYBDENUM ALLOYS⁽⁷¹⁾

Weight Per Cent Mo	Atomic Per Cent Mo	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.4		20,100	32,400	29	53	54,000	0.19
2.0	5	23,000	37,600	31	50	61,000	0.17

The 0.4 and 2.0 weight per cent molybdenum alloys seemed to have superior welding properties, compared with unalloyed thorium⁽⁷¹⁾.

THORIUM-NICKEL SYSTEM

Figure 9 is the thorium-nickel constitution diagram according to Horn and Basserman⁽¹⁰⁾. This is in fair agreement with Iowa State College data, except for the compositions of the compounds^(45,46,74).

Iowa State College reports the following phases:

1. Variable Composition

ThNi ₉	ThNi ₁₉	complex	$a_0 = 8.348 \longrightarrow 8.335 \text{ kx}$
			$c_0 = 8.124 \longrightarrow 8.027 \text{ kx}$

2. Variable composition

ThNi ₄	ThNi ₅	hexagonal	$a_0 = 4.95 \longrightarrow 4.92 \text{ kx}$
			$c_0 = 3.98 \longrightarrow 3.98 \text{ kx}$

3. ThNi ₂	hexagonal, mpt, 1016 C	$a_0 = 3.955 \text{ kx}$
		$c_0 = 3.83 \text{ kx}$

4. ThNi	complex	mpt, abt 1180 C
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5. Th ₇ Ni ₃	hexagonal	mpt, abt 1015 C	$a_0 = 9.84 \text{ Å}$
			$c_0 = 6.22 \text{ Å}$

As-cast hardnesses and forging characteristics of some arc-melted nickel-thorium alloys are as follows⁽⁷¹⁾:

<u>Weight Per Cent Ni</u>	<u>Atomic Per Cent Ni</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>	<u>Cold Rolling</u>
0.24	1	108	Good	Good	Good
0.60	2.5	92	Good	Good	Good
1.30	5	132	Slight cracking	Slight cracking	poor

FIGURE 9. THORIUM-NICKEL ALLOY SYSTEM

Edge-cracking tests made during cold rolling showed⁽⁷¹⁾:

<u>Weight Per Cent Ni</u>	<u>Atomic Per Cent Ni</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Cracking</u>
0.24	1	110	142	79
0.60	2.5	85	127	65

A three weight per cent arc-melted nickel alloy, 133 BHN (500-kg load) as cast, cracked after 15 per cent cold reduction⁽⁷²⁾. Resulting hardness was 120 BHN (500-kg load). Tensile properties of these alloys are shown in Table 12.

Aging tests showed⁽⁷¹⁾:

<u>Weight Per Cent Ni</u>	<u>Atomic Per Cent Ni</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN , Quenched After 2 Hr at 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.24	1	110	113	107
0.60	2.5	85	90	90

THORIUM-NIOBIUM SYSTEM
(THORIUM-COLUMBIUM SYSTEM)

There is an eutectic on the thorium-rich side with a melting point of about 1315 C (2400 F)⁽⁵⁴⁾.

Small amounts of niobium are said to improve the cold workability of thorium^(2, 5).

Hardnesses of vacuum arc-melted thorium-niobium alloys are as follows⁽²³⁾:

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TABLE 12. TENSILE PROPERTIES OF NICKEL ALLOYS⁽⁷¹⁾

Weight Per Cent Ni	Atomic Per Cent Ni	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent psi in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.24	1	29,000	43,000	—	40	65,000	0.14
0.60	2.5	23,800	37,300	20	37	61,000	0.16

<u>Material</u>	<u>Hardness, R_B</u>
Unalloyed Th	62
2 weight % Nb	54
4 weight % Nb	46
6 weight % Nb	62
8 weight % Nb	--

As-cast hardnesses and fabricating characteristics of some arc-melted niobium alloys are as follows⁽⁷¹⁾:

<u>Weight Per Cent Nb</u>	<u>Atomic Per Cent Nb</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>
0.4	1	103	Good	Good
2.0	5	--	Good	Good
2.0	5	101	Good	Good

Edge-cracking tests during cold working showed⁽⁷¹⁾:

<u>Weight Per Cent Nb</u>	<u>Atomic Per Cent Nb</u>	<u>VHN, Annealed at 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Cracking</u>
0.4	1	121	141	--
2.0	5	78	106	--
2.0	5	61	97	85

A two weight per cent arc-melted niobium alloy with an as-cast BHN (500-kg load) of 66 was cold rolled 84 per cent without cracking⁽⁷²⁾.

Resulting mechanical and electrical properties were:

<u>BHN</u> <u>(500-Kg Load)</u>	<u>0.2%</u> <u>Offset</u> <u>Yield</u> <u>Strength,</u> <u>psi</u>	<u>Ultimate</u> <u>Tensile</u> <u>Strength,</u> <u>psi</u>	<u>Elonga-</u> <u>tion,</u> <u>% in</u> <u>1 Inch</u>	<u>Resis-</u> <u>tivity,</u> <u>microhm-cm</u>
95	52,500	55,000	1	19.0

Tensile properties of the Battelle alloys as hot rolled at 700 C (1290 F) are shown in Table 13⁽⁷¹⁾.

Aging tests showed the following⁽⁷¹⁾:

<u>Weight</u> <u>Per Cent</u> <u>Nb</u>	<u>Atomic</u> <u>Per Cent</u> <u>Nb</u>	<u>VHN,</u> <u>Annealed</u> <u>at 750 C</u>	<u>VHN,</u> <u>Quenched</u> <u>After 2 Hr</u> <u>at 850 C</u>	<u>VHN,</u> <u>Aged 2 Hr</u> <u>at 400 C</u>
0.4	1	121	103	101
2.0	5	78	79	78
2.0	5	61	69	69

Niobium alloys seemed to have superior welding characteristics compared with unalloyed thorium⁽⁷¹⁾.

THORIUM-NITROGEN SYSTEM

Nitrogen reacts readily with thorium at 750 to 850 C (1380 - 1560 F)⁽⁶²⁾. At 950 C (1740 F), equilibrium at 100 per cent Th₃N₄ is reached in three days.

Heat of formation (25 C) for Th₃N₄ is -283.6 kilocalories per mole⁽⁶³⁾, free energy of formation (25 C) is -310.4 kilocalories per mole, and entropy of formation is -89.6 cal/mole/degree K. Melting point is not known. Color of Th₃N₄ varies from maroon to black⁽⁴⁾.

TABLE 13. TENSILE PROPERTIES OF NIOBIUM ALLOYS

Weight Per Cent Nb	Atomic Per Cent Nb	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.4	1	30,000	45,000	36	54	82,000	0.21
2.0	5	14,700	29,000	—	31	59,000	0.15

Water reacts slowly with Th_3N_4 to give NH_3 ⁽⁶²⁾. At 750 to 950 C (1380 to 1740 F), Th_3N_4 is oxidized rapidly by water vapor⁽⁶⁴⁾.

The crystal structure of Th_3N_4 is face-centered cubic with $a_0 = 5.18 \text{ \AA}$ ⁽⁶⁵⁾. Another nitride, ThN , is reported with a NaCl-type structure ⁽⁶³⁾.

Thorium is embrittled by nitrogen of 0.3 weight per cent, as compared with the normal 0.02 weight per cent in Ames thorium⁽¹⁵⁾. The 0.3 weight per cent nitrogen material could not be cold rolled. A cast tensile specimen showed zero ductility.

THORIUM-OXYGEN SYSTEM

The only known oxide is ThO_2 , although it is possible that oxygen can substitute for carbon or nitrogen in ThC or ThN to give ThO ⁽²⁾. Melting point of ThO_2 is 2800 C (4400 F). ThO_2 has a fluorite-type structure.

At 1275 C (2325 F), there is agglomeration and solution of ThO_2 in thorium, both Ames and Westinghouse types⁽⁶⁶⁾. There is some reprecipitation of ThO_2 at 900 C (1650 F)⁽⁶⁶⁾. Solubility of oxygen in thorium is low. The oxide is present as angular gray constituents⁽⁶⁷⁾.

Thorium oxide is reported to be soluble in anhydrous alcohol saturated with anhydrous HCl ⁽⁶⁸⁾.

Thorium oxide dissolves readily in molten thorium just above the melting point⁽⁶⁹⁾.

THORIUM-SILICON SYSTEM

There is an eutectic in the thorium-silicon system at approximately 13 weight per cent silicon ⁽⁶⁸⁾. It melts above 1300 C (2370 F). There is at least one intermetallic compound, ThSi₂ ^(63, 68). Crystal structure of ThSi₂ is body-centered tetragonal ⁽⁶³⁾.

As-cast hardnesses of some silicon alloys made from vacuum arc-melted Ames thorium are as follows ^(15, 23):

Weight % Si	0	0.25	2	4	6	8
Hardness, R _p	62	41	92	98	102	80

Silicon forms a brittle intermetallic compound. Alloys with silicon cannot be cold rolled ⁽²³⁾. A five weight per cent arc-melted silicon alloy broke after 1 per cent cold reduction ⁽⁷¹⁾.

Hardnesses of some as-cast ternary alloys with zirconium are as follows ⁽¹⁵⁾:

Weight % Si	0	1	1	1	2	4
Weight % Zr	0	1	2	4	1	1
Hardness, R _p	62	80	57	41	71	75

Corrosion rates of some as-cast silicon alloys in boiling distilled water are as follows ⁽³⁶⁾:

Weight Per Cent Si	Corrosion Rate, <u>mg/cm²/hr</u>
0	-0.00060
1.08	+0.00033
2.0	+0.00034
4.3	+0.00018

The same alloys showed the following weight changes in 178 C, 125-psi water⁽³⁶⁾:

Weight Per Cent Si	Weight Change, mg/cm ²				
	0.8 Day	1.7 Days	4 Days	8 Days	16 Days
1.08	+0.51	+0.69	+1.0	-39.2	-171
2.0	+0.2	+0.26	+1.0	- 9.3	-106
4.3	+0.0	-0.28	+0.03	-12.3	- 74

THORIUM-SILVER SYSTEM

Figure 10 is a diagram of the silver-rich end of the thorium-silver system⁽¹¹⁾. Solid solubility of thorium in silver is less than 0.2 weight per cent⁽¹¹⁾. Small amounts of thorium have little effect on the hardness of silver⁽¹¹⁾. Higher thorium compounds are probable⁽¹¹⁾. The compound Ag₅Th₃ is pyrophoric

Two and ten weight per cent silver alloys were arc melted at Ames⁽⁷²⁾. The 10 per cent alloy (actual analysis 9.6) was pyrophoric. The two per cent alloy had an as-cast BHN (500-kg load) of 96. It was cold rolled to 85 per cent reduction without cracking. Resulting mechanical and electrical properties were as follows:

Condition	BHN (500-Kg Load)	0.2% Offset Yield Strength,	Ultimate Tensile Strength,	Elonga- tion, % in	Resis- tivity,
		psi	psi	1 Inch	microhm-cm
As cold rolled (85%)	126	58,500	73,200	1	25.5
Annealed 90 min at 865 C	60	23,700	24,600	9	21.9

FIGURE 10. THORIUM-SILVER SYSTEM⁽¹¹⁾

THORIUM-SODIUM SYSTEM

Figure 11 is a diagram of the sodium end of the thorium-sodium system⁽⁷⁾. Ames thorium immersed in sodium at 500 C (930 F) lost 458 mg/cm² in 5.6 days⁽³⁶⁾. Film formation probably prevented further dissolution. Sodium-potassium alloy of 50 per cent composition wets thorium at 150 C (300 F), but there is no dissolution⁽³³⁾. This same alloy, deoxidized, forms a thin tenacious film on thorium at 600 C (1110 F)⁽⁴⁸⁾. Further dissolution is prevented. Oxygen in the NaK, however, forms a brittle film that flakes off, allowing dissolution to continue.

THORIUM-PHOSPHORUS SYSTEM

There are two known thorium phosphides, ThP with a NaCl-type crystal structure, and Th₃P₄ with a D₃⁷ structure⁽⁶³⁾.

THORIUM-SULFUR SYSTEM

Thorium and hydrogen sulfide react at 400 C (750 F) to give ThS₂⁽⁷⁰⁾. The disulfide, held molten under vacuum at 2000 C (3630 F),
to
goes over/the monosulfide in the following steps:

Heats of formation and melting points of thorium sulfide are given by Brewer⁽⁶³⁾ as follows:

FIGURE II. SODIUM END OF SODIUM-THORIUM SYSTEM⁽⁷⁾

<u>Sulfide</u>	<u>Estimated Heat of Formation, Kilocalories per Atom of Contained Sulfur</u>	<u>Melting Point</u>	
		<u>C</u>	<u>F</u>
ThS	-120 $\pm$ 5	2200	4000
Th ₂ S ₃	103 $\pm$ 1	2000	3600
Th ₄ S ₇	- 95 $\pm$ 5	2000	3000
ThS ₂	- 85 $\pm$ 10	1930	3500

THORIUM-TANTALUM SYSTEM

Thorium and tantalum react slowly even at 2000 C (3630 F)⁽²⁾. There are no intermetallic compounds⁽²⁾. Solid solubility of tantalum in thorium is low⁽²⁾.

As-cast hardness data and fabricating properties of two arc-melted tantalum alloys are as follows⁽⁷¹⁾:

<u>Weight Per Cent Ta</u>	<u>Atomic Per Cent Ta</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>	<u>Cold Rolling</u>
0.7	1	107	Good	Good	Fair
3.8	5	102	Good	Good	Fair

Hot rolling was to 0.080-inch sheet. Cold rolling was from 0.080-inch sheet to first sign of edge cracking. Edge-cracking data are as follows⁽⁷¹⁾:

<u>Weight Per Cent Ta</u>	<u>Atomic Per Cent Ta</u>	<u>VHN, Annealed 1 hr 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Edge Cracking</u>
0.7	1	105	135	86 (no cracking to limit of mill)
3.8	5	106	134	67

Three, five, and ten weight per cent arc-melted tantalum alloys were cold rolled with the following results⁽⁷²⁾:

<u>Weight Per Cent Ta</u>	<u>BHN, As Cast (500-Kg Load)</u>	<u>Per Cent Cold Reduction</u>	<u>BHN, As Rolled (500-Kg Load)</u>	<u>Remarks</u>
3	55	84	84	No cracking.
5	67	81	98	No cracking.
10	62	82	90	No cracking.

Mechanical and electrical properties of these same alloys are shown in Table 14⁽⁷²⁾.

Tensile properties of the other alloys are shown in Table 15⁽⁷¹⁾.

Age-hardening tests showed the following⁽⁷¹⁾:

<u>Weight Per Cent Ta</u>	<u>Atomic Per Cent Ta</u>	<u>VHN, Annealed 1 Hr 750 C</u>	<u>VHN, Quenched After 1 Hr 850 C</u>	<u>VHN, After Aging 2 Hr 400 C</u>
0.7	1	105	105	107
3.8	5	106	101	99

THORIUM-THALLIUM SYSTEM

As-cast hardness data and fabricating characteristics of three Battelle arc-melted thallium alloys are given below⁽⁷¹⁾:

<u>Weight Per Cent Th</u>	<u>Atomic Per Cent Tl</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>
0.88	1	112	139	--
2.2	2.5	85	123	85

TABLE 14. TENSILE AND ELECTRICAL PROPERTIES OF TANTALUM ALLOYS

Alloy and Condition	BHN (500-Kg Load)	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elonga- tion, Per Cent in 1 Inch	Resistivity, microhm- cm	20 C Temp Coef. of Resist., Per °C
3%, cold rolled 84%	84	39,400	45,600	1	17.8	—
3%, annealed 90 min, 875 C	53	13,000	29,500	13	17.36	—
5%, cold rolled 81%	98	54,400	56,700	1	19.7	0.00335
5%, annealed 90 min, 875 C	53	15,800	34,300	22	17.40	—
10%, cold rolled 82%	90	55,700	57,800	1	18.1	0.00309
10%, annealed 90 min, 875 C	53	—	—	—	17.73	—

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TABLE 15. TENSILE PROPERTIES OF TANTALUM ALLOYS

Weight Per Cent Ta	Atomic Per Cent Ta	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "n"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.7	1	31,800	42,000	—	54	67,000	0.15
3.8	5	28,600	44,600	35	45	66,000	0.13

A two weight per cent arc-melted thallium alloy, having a BHN (500-kg load) of 75, was cold rolled at Ames to 81 per cent reduction with no cracking⁽⁷²⁾. Resulting mechanical and electrical properties were as follows:

<u>Alloy</u>	<u>Condition</u>	<u>BHN (500-Kg Load)</u>	<u>0.2% Offset Yield Strength, psi</u>	<u>Ultimate Tensile Strength, psi</u>	<u>Elonga- tion, % in 1 Inch</u>	<u>Resis- tivity, microhm-cu</u>
2.0% Tl	Cold rolled, 81%	102	53,800	56,800	1	23.4

Tensile properties of the Battelle alloys as annealed at 750 C are shown in Table 16.

Age-hardening tests showed the following⁽⁷¹⁾:

<u>Weight Per Cent Tl</u>	<u>Atomic Per Cent Tl</u>	<u>VHN, Annealed 750 C</u>	<u>VHN, Quenched From 850 C</u>	<u>VHN , Aged 2 Hr at 400 C</u>
0.88	1	112	108	104
2.2	2.5	85	96	91

THORIUM-TIN SYSTEM

As-cast hardness and fabricating properties of some Battelle arc-melted thorium-tin alloys are as follows⁽⁷¹⁾:

<u>Weight Per Cent Sn</u>	<u>Atomic Per Cent Sn</u>	<u>VHN , As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>
0.51	1	116	Good	Good
1.28	2.5	100	Fair	Poor
2.56	5	--	Cracked	Not rolled

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TABLE 16. TENSILE PROPERTIES OF THALLIUM ALLOYS⁽⁷¹⁾

Weight Per Cent Tl	Atomic Per Cent Tl	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.88	1	32,000	45,000	32	31	80,000	0.20
2.2	2.5	24,200	36,000	18	48	66,000	0.18

Cold-reduction data are as follows⁽⁷¹⁾:

<u>Weight Per Cent Sn</u>	<u>Atomic Per Cent Sn</u>	<u>VHN, Annealed at 700 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Edge Cracking</u>
0.51	1	116	153	--
1.28	2.5	88	126	74

One, two, and five weight per cent tin alloys were arc-melted at Ames⁽⁷²⁾. Cold-rolling data are as follows:

<u>Weight Per Cent Sn</u>	<u>BHN, As Cast (500-Kg Load)</u>	<u>Per Cent Cold Reduction</u>	<u>BHN, As Rolled (500-Kg Load)</u>	<u>Remarks</u>
1	74	80	110	No cracking.
2	106	25	--	Cracked.
5	102	--	--	Broke first pass.

Mechanical and electrical properties of the 1 weight per cent Ames alloy were as follows⁽⁷²⁾:

<u>BHN (500-Kg Load)</u>	<u>0.2% Offset Yield Strength, psi</u>	<u>Ultimate Tensile Strength, psi</u>	<u>Elonga- tion, % in 1 Inch</u>	<u>Resistivity, microhm-cm</u>
110	38,600	60,000	1	30.9

Tensile properties of the Battelle alloys are shown in Table 17⁽⁷¹⁾.

Age-hardening data are as follows⁽⁷¹⁾:

TABLE 17. TENSILE PROPERTIES OF TIN ALLOYS (71)

Weight Per Cent Sn	Atomic Per Cent Sn	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.51	1	30,000	47,000	28	43	81,000	0.19

<u>Weight Per Cent Sn</u>	<u>Atomic Per Cent Sn</u>	<u>VHN, Annealed 750 C</u>	<u>VHN, Quenched From 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.51	1	116	115	111
1.28	2.5	88	94	93

THORIUM-TITANIUM SYSTEM

There is an eutectic in the thorium-titanium system at about 2 weight per cent Ti, and at about 1175 C (2245 F)⁽²⁾.

Titanium decreases the hardness of thorium considerably, suggesting a possible scavenging action^(2, 15, 23, 71, 72).

Hardnesses of a series of arc-melted alloys were as follows^(15,23) (some ternary alloys are included as well as information on cold-rolling characteristics):

<u>Weight Per Cent</u>		<u>Hardness</u>		<u>Cold Rolling</u>
<u>Ti</u>	<u>Zr</u>	<u>R_B</u>	<u>R_H</u>	
0	0	62	--	--
2	0	2	--	--
4	0	8	95	Cold rolled 75%, no cracks.
6	0	4	93	Cold rolled 75%, no cracks.
8	0	37	--	--
1	1	--	91	Cold rolled 75%, no cracks.
1	2	--	96	Cold rolled 75%, no cracks.
1	4	--	110	Cracked
2	1	--	91	Cold rolled 75%, no cracks.
4	1	--	94	Cold rolled 75%, no cracks.

As-cast hardnesses and fabricating characteristics of two arc-melted titanium alloys were as follows⁽⁷¹⁾,

<u>Weight Per Cent Ti</u>	<u>Atomic Per Cent Ti</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>	<u>Cold Rolling</u>
4.3	1	96	Good	Good	Fair
20.0	5	70	Good	Good	Good

Edge-cracking limit tests in cold rolling showed the following⁽⁷¹⁾:

<u>Weight Per Cent Ti</u>	<u>Atomic Per Cent Ti</u>	<u>VHN, As Annealed</u>	<u>VHN, After 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Edge Cracking</u>
4.3	1	95	120	76
20	5	53	87	90 (no crack to limit of mill.)

Some Ames arc-melted titanium alloys were cold rolled, with the following results⁽⁷²⁾:

<u>Weight Per Cent Ti</u>	<u>BHN, As Cast (500-Kg Load)</u>	<u>Per Cent Cold Reduction</u>	<u>BHN, As Rolled (500-Kg Load)</u>	<u>Remarks</u>
1	63	80	95	No cracking.
5	80	83	114	Ditto
10	90	80	133	"
15	120	72	142	"
20	151	70	163	"
25	116	69	145	"
30	124	72	154	"

Mechanical and electrical properties of some of these alloys are shown in Table 18⁽⁷²⁾.

TABLE 18. TENSILE AND ELECTRICAL PROPERTIES OF TITANIUM ALLOYS

Wt Per Cent Ti	Condition	BHN (500-Kg Load)	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elonga- tion, Per Cent in 1 Inch	Resistivity, microhm-cm
1	Cold rolled 80%	95	47,100	51,000	1	21.05
1	Annealed 90 min, 875 C	53	9,900	28,200		17.65
5	Cold rolled 83%	114	48,000	70,800	1	23.2
5	Annealed 90 min, 875 C	53	14,800	34,900		18.93
10	Cold rolled 80%	133	42,800	81,000	1	24.75
10	Annealed 90 min, 875 C	54	25,100	42,300		20.95
15	Cold rolled 72%	142	—	—	—	—
20	Cold rolled 70%	163	—	—	—	—
25	Cold rolled 69%	145	—	—	—	—
30	Cold rolled 72%	154	—	—	—	—

Physical properties of the Battelle alloys are shown in Table 19⁽⁷¹⁾.

Age-hardening tests showed the following⁽⁷¹⁾:

<u>Weight Per Cent Ti</u>	<u>Atomic Per Cent Ti</u>	<u>VHN, Annealed 750 C</u>	<u>VHN, Quenched From 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
4.3	1	95	99	88
20	5	53	52	68

THORIUM-TUNGSTEN SYSTEM

There are no intermetallic compounds in the thorium-tungsten system⁽²¹⁾. The liquidus rises sharply from the thorium end. A solidus point has been measured at 1475 C (2685 F) on the thorium-rich side⁽²⁾.

As-cast hardnesses and fabricating characteristics of two arc-melted tungsten alloys are as follows⁽⁷¹⁾:

<u>Weight Per Cent W</u>	<u>Atomic Per Cent W</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>	<u>Cold Rolling</u>
0.7	1	108	Good	Good	Good
4.0	5	107	Good	Good	Fair

Edge-cracking tests showed the following⁽⁷¹⁾:

<u>Weight Per Cent W</u>	<u>Atomic Per Cent W</u>	<u>VHN, As Annealed</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Edge Cracking</u>
0.7	1	109	142	60
4.0	5	107	148	86 (no crack to limit of mill)

TABLE 19. TENSILE PROPERTIES OF TITANIUM ALLOYS⁽⁷¹⁾

Weight Per Cent Ti	Atomic Per Cent Ti	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
4.3	1	24,600	38,300	35	49	66,000	0.15
20	5	10,900	23,600	33	56	45,000	0.14

Three and five weight per cent tungsten alloys were arc melted at Ames⁽⁷²⁾. Cold-rolling data were as follows:

<u>Weight Per Cent W</u>	<u>BHN, As Cast (500-Kg Load)</u>	<u>Per Cent Cold Reduction</u>	<u>BHN, As Rolled (500-Kg Load)</u>	<u>Remarks</u>
3	77	84	109	No cracks.
5	33	77	109	No cracks.

Mechanical and electrical properties of these two alloys were as follows⁽⁷²⁾:

<u>Weight Per Cent W</u>	<u>BHN (500-Kg Load)</u>	<u>0.2% Offset Yield Strength, psi</u>	<u>Ultimate Tensile Strength, psi</u>	<u>Elonga- tion, % in 1 Inch</u>	<u>Resistivity, microhm-cm</u>
3	109	41,100	59,500	1	22.2
5	109	--	--	--	--

Physical properties of the two Battelle alloys are shown in Table 20⁽⁷¹⁾.

Aging tests showed the following⁽⁷¹⁾:

<u>Weight Per Cent W</u>	<u>Atomic Per Cent W</u>	<u>VHN, Annealed 750 C</u>	<u>VHN, Quenched From 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.7	1	109	104	106
4.0	5	107	107	107

Tungsten alloys seemed to have superior welding characteristics, as compared with unalloyed thorium⁽⁷¹⁾.

TABLE 20. TENSILE PROPERTIES OF TUNGSTEN ALLOYS⁽⁷¹⁾

Weight Per Cent W	Atomic Per Cent W	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction at Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.7	1	33,600	45,700	—	37	67,000	0.12
4.0	5	31,800	43,000	33	31	67,000	0.15

THORIUM-URANIUM SYSTEM

Figure 12 is a constitution diagram for the thorium-uranium system⁽⁴⁾. It shows a two-liquid region, instead of the simpler eutectic system previously reported^(2, 25). Battelle has made some preliminary measurements of the solubility of uranium in thorium⁽²⁰⁾. As-cast alloys contained five weight per cent or more of uranium in solution. At 815 C (1500 F), solubility is 3 to 4 weight per cent, while at 705 C (1300 F), opposite the beta-uranium-phase region, it seems to be about 5 weight per cent.

Physical properties of a 10 weight per cent uranium alloy are as follows⁽¹³⁾:

Weight % U	0	10
0.2 % offset yield strength, psi	29,000	36,000
Ultimate tensile strength, psi	39,000	52,000
Elongation, % in 1 inch	32	17
Reduction of Area, %	46	23
Strain coefficient, "B"	66,000	88,000
Strain exponent, "n"	0.18	0.17
VHN, quenched from 850 C	--	119
VHN, aged 2 hrs at 400 C after 850 C quench	--	80

Hardness of some impure thorium-uranium alloys are given as follows⁽²⁵⁾:

Weight % U	0	5	10	50	90	95	99
Hardness, R _B	77	70	75	90	95	93	91

FIGURE 12. THORIUM-URANIUM SYSTEM ⁽⁴⁾

A 0.6 weight per cent uranium alloy was readily hand forged at 1400 F⁽²⁵⁾. Only the skin was worked by hand forging at room temperature.

This 0.6 weight per cent uranium alloy seemed to corrode about the same as "pure" Ames thorium in 70 C, pH 6.5 water, containing 20 ppm Ca⁺⁺, 16 ppm Mg⁺⁺ ~ , 85 ppm SO₄⁻⁻, 1 ppm Cl⁻, and ~ 5 x 10⁻³ N in H₂O₂, circulating at 20 ft per sec⁽¹⁾. A smooth black protective film was formed. Average weight loss after 813 hours was 0.018 mg per cm² per hour.

THORIUM-VANADIUM SYSTEM

As-cast-hardnesses and fabricating characteristics of two arc-melted vanadium alloys were as follows⁽⁷¹⁾:

<u>Weight Per Cent V</u>	<u>Atomic Per Cent V</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>	<u>Cold Rolling</u>
0.2	1	106	Good	Good	Good
1.1	5	110	Good	Good	Good

Edge-cracking tests on cold rolling showed the following⁽⁷¹⁾:

<u>Weight Per Cent V</u>	<u>Atomic Per Cent V</u>	<u>VHN, As Annealed</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Edge Cracking</u>
0.2	1	100	134	57
1.1	5	80	116	88 (no crack to limit of mill)

A three weight per cent vanadium alloy with an as-cast BHN (500-kg load) of 80 was cold rolled at Ames. There was no cracking after

81 per cent cold reduction⁽⁷²⁾. Resulting BHN (500-kg load) was 10.4.

Tensile properties of the Battelle alloys are shown in Table 21 (71).

In age-hardening tests, the following was observed ⁽⁷¹⁾:

<u>Weight Per Cent V</u>	<u>Atomic Per Cent V</u>	<u>VHN, Annealed 750 C</u>	<u>VHN, Quenched From 850 C</u>	<u>VHN, Aged 2 Hr at 400 C</u>
0.2	1	100	107	104
1.1	5	80	81	79

THORIUM-ZINC SYSTEM

The thorium-zinc system is of importance because zinc is used to lower the melting point and improve the recovery in the Ames process for producing thorium. Alloys containing from 5 to 12 weight per cent zinc are produced in the bomb reduction process.

An intermetallic compound, probably Th_2Zn at 12.3 weight per cent zinc, decomposes at 1040 C (1900 F) to give thorium and zinc⁽²⁾. The compound is body-centered tetragonal with $a_0 = 7.60 \text{ \AA}$, $c_0 = 5.64 \text{ \AA}$, $Z = 4$ (45).

The melting point of the 6 to 7 per cent zinc alloy is about 1200 C (2190 F)⁽²⁾. At 1600 C, under vacuum, only 200 ppm of zinc remain⁽⁶⁹⁾.

The 8 per cent zinc alloy is silver white, brittle, and reactive to water and to moisture in the air ⁽⁷³⁾. It is stable in dry air.

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TABLE 21. TENSILE PROPERTIES OF VANADIUM ALLOYS⁽⁷¹⁾

Weight Per Cent V	Atomic Per Cent V	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.2	1	26,400	42,800	—	54	—	—
1.1	5	20,900	33,400	30	56	58,000	0.20

THORIUM-ZIRCONIUM SYSTEM

Figure 13 is a diagram of the thorium-zirconium alloy system⁽⁴⁾.

In general, this work has been checked by preliminary work at Battelle⁽²⁰⁾.

As-cast hardnesses and fabricating characteristics of some zirconium alloys were as follows⁽⁷¹⁾:

<u>Weight Per Cent Zr</u>	<u>Atomic Per Cent Zr</u>	<u>VHN, As Cast</u>	<u>Forging, 700 C</u>	<u>Rolling, 700 C</u>
0.39	1	93,110	Fair	Fair
1.96	5	71,110	Good	Good

Edge-cracking tests showed the following⁽⁷¹⁾:

<u>Weight Per Cent Zr</u>	<u>Atomic Per Cent Zr</u>	<u>VHN, Annealed 750 C</u>	<u>VHN, 50 Per Cent Cold Reduction</u>	<u>Per Cent Cold Reduction to First Edge Cracking</u>
0.39	1	121	131	--
0.39	1 (2nd ingot)	80	107	77
1.96	5	78	112	--
2.5	6	74	120	--
5.0	12	94	107	--

Arc-melted zirconium-thorium alloys, made at Ames, had the following cold-rolling characteristics⁽⁷²⁾:

FIGURE 13. THORIUM-ZIRCONIUM SYSTEM⁽⁴⁾

<u>Weight Per Cent Zr</u>	<u>BHN, As Cast (500-Kg Load)</u>	<u>Per Cent Cold Reduction</u>	<u>BHN, As Rolled (500-Kg Load)</u>	<u>Remarks</u>
2	80	82	99	No cracking.
5	82	86	114	No cracking.
10	128	71	151	No cracking.
15	245	23	--	Cracked.
20	276	10	--	Cracked.
25	297	--	--	Broke, first pass.
30	305	--	--	Broke, first pass.

Mechanical and electrical properties of the five weight per cent zirconium alloy were as follows⁽⁷²⁾:

<u>Condition</u>	<u>BHN, (500-Kg Load)</u>	<u>0.2% Offset Yield Strength, psi</u>	<u>Ultimate Tensile Strength, psi</u>	<u>Elonga- tion, % in 1 Inch</u>	<u>Resis- tivity, microhm-cm</u>
As cold rolled 86 % cold rolled	114	56,300	64,500	1	32.0
Annealed 90 min, 875 C	54	23,700	43,000	20	27.15

Tensile properties of the arc-melted Battelle zirconium alloys are shown in Table 22⁽⁷¹⁾.

Hardnesses and cold-rolling characteristics of some Oak Ridge arc-melted alloys were as follows^(23, 55):

TABLE 22. TENSILE PROPERTIES OF ZIRCONIUM ALLOYS⁽⁷¹⁾

Weight Per Cent Zr	Atomic Per Cent Zr	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, Per Cent in 1 Inch	Reduction of Area, Per Cent	Strain Coefficient, "B"	Strain Exponent, "n"
0	0	29,000	39,000	32	46	66,000	0.18
0.39	1	23,500	37,200	—	50	66,000	0.12
0.39	1	45,000	56,000	23	43	62,000	0.24
1.96	5	18,000	34,000	28	43	81,000	0.19
5.0	12	21,100	39,600	24	40	57,000	0.16

<u>Weight Per Cent Zr</u>	<u>R_B</u>	<u>R_H</u>	<u>Cold Rolling</u>
0	62	--	--
2	24	--	--
4	--	105	Cold rolled 75%, no cracks.
6	41	103	Cold rolled 75%, no cracks.
8	36	--	--
1 (+1% Si)	88	--	Cracked after 10% cold rolled.
2 (+1% Si)	57	--	Ditto
4 (+1% Si)	41	--	"
1 (+2% Si)	71	--	"
1 (+4% Si)	75	--	"
1 (+1% Ti)	--	91	Cold rolled 75%, no cracks.
2 (+1% Ti)	--	96	Cold rolled 75%, no cracks.
4 (+1% Ti)	--	110	Cracked, 10% cold rolled.
1 (+2% Ti)	--	91	Cold rolled 75%, no cracks.
1 (+4% Ti)	--	94	Cold rolled 75%, no cracks.

Aging tests showed the following⁽⁷¹⁾:

<u>Weight Per Cent Zr</u>	<u>Atomic Per Cent Zr</u>	<u>VHN, Annealed 750 C</u>	<u>VHN, Quenched 850 C</u>	<u>VHN, Aged 2 Hr 400 C</u>
0.39	1	121	119	113
0.39	1	80	85	83
1.96	5	61	67	69
2.5	6	74	75	76
5.0	12	94	90	90

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