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DMIC Report 183
February 7, 1963

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BINARY AND TERNARY PHASE DIAGRAMS OF COLUMBIUM, MOLYBDENUM, TANTALUM, AND TUNGSTEN

(Supplement to DMIC Report 152)

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

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2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

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Project No. 2(8-8975)

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DMIC Report 183
February 7, 1963

BINARY AND TERNARY PHASE DIAGRAMS OF COLUMBIUM, MOLYBDENUM, TANTALUM, AND TUNGSTEN

(Supplement to DMIC Report 152)

by

J. J. English

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

ACKNOWLEDGMENT

The Defense Metals Information Center expresses its appreciation to Dr. E. J. Rapperport of Nuclear Metals, Inc., who furnished the phase diagrams recently determined under Air Force Contract 33(616)-7157. Westinghouse Research Laboratories and the Massachusetts Institute of Technology participated with Nuclear Metals in this work.

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BINARY PHASE DIAGRAMS

Identification Code	
(5)-63	Columbium-Aluminum System
(5-1)-63	Columbium-Bismuth System
(7)-63	Columbium-Carbon System
(10)-63	Columbium-Cobalt System
(10-1)-63	Columbium-Copper System
(10-2)-63	Columbium-Gold System
(14-1)-63	Columbium-Manganese System
(16)-63	Columbium-Nickel System
(17)-63	Columbium-Nitrogen System
(18-1)-63	Columbium-Palladium System
(18-2)-63	Columbium-Platinum System
(22-1)-63	Columbium-Tellurium System
(24)-63	Columbium-Tin System
(28-1)-63	Columbium-Yttrium System
(37)-63	Molybdenum-Hafnium System
(43)-63	Molybdenum-Osmium System
(49)-63	Molybdenum-Rhodium System
(49-1)-63	Molybdenum-Ruthenium System
(55)-63	Molybdenum-Vanadium System
(55-1)-63	Molybdenum-Yttrium System
(57-1)-63	Tantalum-Aluminum System
(60)-63	Tantalum-Chromium System
(61)-63	Tantalum-Cobalt System
(61-1)-63	Tantalum-Gold System
(63-1)-63	Tantalum-Iridium System
(64-1)-63	Tantalum-Manganese System
(66)-63	Tantalum-Nitrogen System
(68-1)-63	Tantalum-Platinum System
(70-1)-63	Tantalum-Rhodium System
(73-1)-63	Tantalum-Thorium System
(77-1)-63	Tantalum-Yttrium System
(78)-63	Tantalum-Zirconium System
(80)-63	Tungsten-Boron System
(81)-63	Tungsten-Carbon System
(84-1)-63	Tungsten-Iridium System
(85-1)-63	Tungsten-Lead System
(89)-63	Tungsten-Oxygen System
(89-1)-63	Tungsten-Palladium System
(92-1)-63	Tungsten-Rhodium System
(98-1)-63	Tungsten-Yttrium System

TERNARY PHASE DIAGRAMS

(99-1)-63	Columbium-Aluminum-Nickel System (Ni_3Al-Ni_3Cb System)
(99-2)-63	Columbium-Aluminum-Silicon System (1400 C)
(99-3)-63	Columbium-Aluminum-Titanium System (20 C)

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Identification Code	
(99-4)-63	Columbium-Aluminum-Titanium System (1200 C)
(99-5)-63	Columbium-Boron-Silicon System (1600 C)
(99-6)-63	Columbium Carbide-Hafnium Carbide-Uranium Carbide System (2050 C)
(99-7)-63	Columbium Carbide-Hafnium Carbide-Vanadium Carbide System (2050 C)
(99-8)-63	Columbium-Carbon-Uranium System (1700 C)
(99-9)-63	Columbium-Chromium-Nickel System (1100 C)
(99-10)-63	Columbium-Chromium-Silicon System (1000 C)
(99-11)-63	Columbium-Chromium-Silicon System (Melting Temperatures, C)
(99-12)-63	Columbium-Chromium-Vanadium System (1450 C)
(99-13)-63	Columbium-Iron-Phosphorus System (Room Temperature)
(102-1)-63	Columbium-Molybdenum-Carbon System (1900 C)
(102-2)-63	Columbium-Molybdenum-Chromium System (1000 C)
(102-3)-63	Columbium-Molybdenum-Chromium System (1200 C)
(102-4)-63	Columbium-Molybdenum-Chromium System (Liquidus Isotherms)
(105-1)-63	Columbium-Molybdenum-Uranium System (700 C, 800 C, 900 C)
(105-2)-63	Columbium-Molybdenum-Uranium System (1100 C)
(105-3)-63	Columbium-Molybdenum-Uranium System (1200 C)
(105-4)-63	Columbium-Molybdenum-Uranium System (1300 C)
(107-1)-63	Columbium-Nitrogen-Oxygen System (1500 C)
(107-2)-63	Columbium-Oxygen-Titanium System (1500 C)
(107-3)-63	Columbium-Oxygen-Zirconium System (1500 C)
(107-4)-63	Columbium-Silicon-Vanadium System (Schematic)
(116-1)-63	Columbium-Titanium-Zirconium System (Melting Temperatures, C)
(118-1)-63	Columbium-Uranium-Zirconium System (1000 C)
(122-1)-63	Columbium-Tungsten-Silicon System (Room Temperature)
(123-1)-63	Columbium-Tungsten-Zirconium System (1100 C)
(123-2)-63	Columbium-Tungsten-Zirconium System (1600 C)
(123-3)-63	Columbium-Tungsten-Zirconium System (1800 C)
(123-4)-63	Columbium-Tungsten-Zirconium System (2000 C)
(123-5)-63	Molybdenum-Aluminum-Nickel System (1175 C)
(123-6)-63	Molybdenum-Aluminum-Silicon System (1600 C)
(129-1)-63	Molybdenum-Boron-Nickel System (1000 C)
(130-1)-63	Molybdenum-Boron-Titanium System (1200 C)
(130-2)-63	Molybdenum-Boron-Titanium System (1700 C)
(148-1)-63	Molybdenum-Hafnium-Rhenium System (1600 C)
(148-2)-63	Molybdenum-Hafnium-Rhenium System (2000 C)
(148-3)-63	Molybdenum-Hafnium-Rhenium System (2400 C)
(149-1)-63	Molybdenum-Iron-Phosphorus System (Room Temperature)
(149-2)-63	Molybdenum-Iron-Silicon System (20 C)
(155-1)-63	Molybdenum-Nickel-Silicon System (1100 C)
(155-2)-63	Molybdenum-Nickel-Titanium System (1175 C)
(157-1)-63	Molybdenum-Oxygen-Titanium System (1500 C)
(157-2)-63	Molybdenum-Oxygen-Zirconium System (1500 C)
(157-3)-63	Molybdenum-Silicon-Vanadium System (800 C)
(162-1)-63	Molybdenum-Titanium-Vanadium System (Room Temperature)
(162-2)-63	Molybdenum-Titanium-Zirconium System (1500 C)
(164-1)-63	Molybdenum-Tungsten-Chromium System (1800 C)
(167-1)-63	Molybdenum-Tungsten-Silicon System (1900 C)
(167-2)-63	Molybdenum-Uranium-Vanadium System (500 C)
(167-3)-63	Molybdenum-Uranium-Vanadium System (600 C)
(167-4)-63	Molybdenum-Uranium-Vanadium System (1000 C)
(167-5)-63	Molybdenum-Uranium-Zirconium System (1000 C)
(167-6)-63	Tantalum-Aluminum-Silicon System (1400 C)
(167-7)-63	Tantalum-Boron-Nickel System (TaB_2-Ni)
(168-1)-63	Tantalum Carbide-Hafnium Carbide-Uranium Carbide System (2050 C)

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Identification Code	
(168-2)-63	Tantalum Carbide-Hafnium Carbide-Vanadium Carbide System (2050 C)
(169-1)-63	Tantalum-Carbon-Uranium System (1700 C)
(169-2)-63	Tantalum-Chromium-Nickel System (Solidus Temperature)
(173-1)-63	Tantalum-Cobalt-Iron System (20 C)
(173-2)-63	Tantalum-Cobalt-Iron System (1390 C)
(178-1)-63	Tantalum-Silicon-Titanium System ($TaSi_2$-$TiSi_2$)
(178-2)-63	Tantalum-Silicon-Vanadium System (Schematic)
(186-1)-63	Tantalum-Tungsten-Silicon System ($TaSi_2$-WSi_2)
(187-1)-63	Tungsten-Aluminum-Nickel System (800 C)
(187-2)-63	Tungsten-Aluminum-Nickel System (1200 C)
(187-3)-63	Tungsten-Aluminum-Silicon System (1500 C)
(188-1)-63	Tungsten-Boron-Thorium System (1800 C)
(194-1)-63	Tungsten-Carbon-Thorium System (1500 C)
(195-1)-63	Tungsten-Carbon-Uranium System (1000 and 1500 C)
(195-2)-63	Tungsten-Carbon-Vanadium System (1500 and 1800 C)
(195-3)-63	Tungsten-Chromium-Cobalt System (Room Temperature)
(202-1)-63	Tungsten-Chromium-Silicon System (1500 C)
(203-1)-63	Tungsten-Cobalt-Iron System (20 C)
(203-2)-63	Tungsten-Cobalt-Iron System (1400 C)
(203-3)-63	Tungsten-Germanium-Silicon System (1000 C)
(206-1)-63	Tungsten-Iron-Sulfur System (Room Temperature)
(209-1)-63	Tungsten-Silicon-Titanium System ($TiSi_2$-WSi_2 Schematic)

BIBLIOGRAPHY

BINARY AND TERNARY PHASE DIAGRAMS OF COLUMBIUM, MOLYBDENUM, TANTALUM, AND TUNGSTEN

SUMMARY

This report supplements DMIC Report 152 which is a compilation of binary and ternary phase diagrams of columbium, molybdenum, tantalum, and tungsten. Forty new binary and 80 new ternary diagrams are included, some of these being revised versions of the previously published diagrams. Included with each binary diagram and with some ternary diagrams is a short discussion listing terminal solubilities and crystal structures of intermediate phases. Many of the diagrams are tentative and are subject to revision as additional data become available.

INTRODUCTION

Increased interest in the refractory metals columbium, molybdenum, tantalum, and tungsten is reflected in the growing number of phase diagrams that are being determined for alloys of these metals. In DMIC Report 152, phase diagrams of alloy systems based on the four metals were assembled. Occasional supplements to DMIC Report 152 have been planned in order that up-to-date information on phase relationships in the refractory-metal-alloy systems will be available to those who need it. Data on approximately 70 additional systems have been collected by DMIC since the publication of Report 152. They are presented here along with new data on systems already reported on in DMIC 152.

It is hoped that the users of this report will supply the Defense Metals Information Center with additional phase-diagram information as it becomes available and also with any literature references that might have been inadvertently overlooked.

ORGANIZATION OF THE REPORT

The phase diagrams in this report are presented in two sections – one on binary and the other for ternary phase diagrams. Within each section, the diagrams are subdivided into four groups according to base-metal system – columbium, molybdenum, tantalum, and tungsten. The systems are then arranged in alphabetical order in these groups according to the spelling of the second element in the system. When two refractory metals occur in the same ternary system, they are listed first. For example, the columbium-molybdenum-carbon system is not listed as the columbium-carbon-molybdenum system.

Each diagram is printed on a separate page and has a code number at the lower left corner of the page to assist in relating this report with DMIC Report 152, which it supplements. As an example of the use of this code, the revised columbium-aluminum system has been given the designation (5)-63. The (5) refers to the number in the lower corner of the now out-dated columbium-aluminum system found in DMIC Report 152. The columbium-manganese system, coded (14-1)-63 is a completely new system and follows the columbium-lanthanum system, coded (14) in DMIC Report 152.

Reference numbers in this report are a continuation of the references in the bibliography of DMIC Report 152. Thus any reference of lower number than 234 (the first reference in this report) will be found in the bibliography section of DMIC Report 152.

NOTES ON DIAGRAMS IN DEFENSE METALS INFORMATION CENTER REPORT 152

The following notes refer to the phase diagrams which appeared in DMIC Report 152, April, 1961; there are no new diagrams to accompany them in this report.

Molybdenum-Aluminum System:

The compound Al_7Mo has been identified by Claire[322]. Al_7Mo has a monoclinic structure with a = 5.12A, b = 13.0A, c = 13.5A, and β = 95 degrees. A peritectic reaction occurs at 706 ± 3 C where Al_7Mo reacts with liquid to form $Al_{12}Mo$.

Tantalum-Chromium System:

The solubility of tantalum in chromium was reported to increase from 1.5 weight per cent at 1200 C to 8 weight per cent at 1600 C.[323]

Tantalum-Ruthenium System:

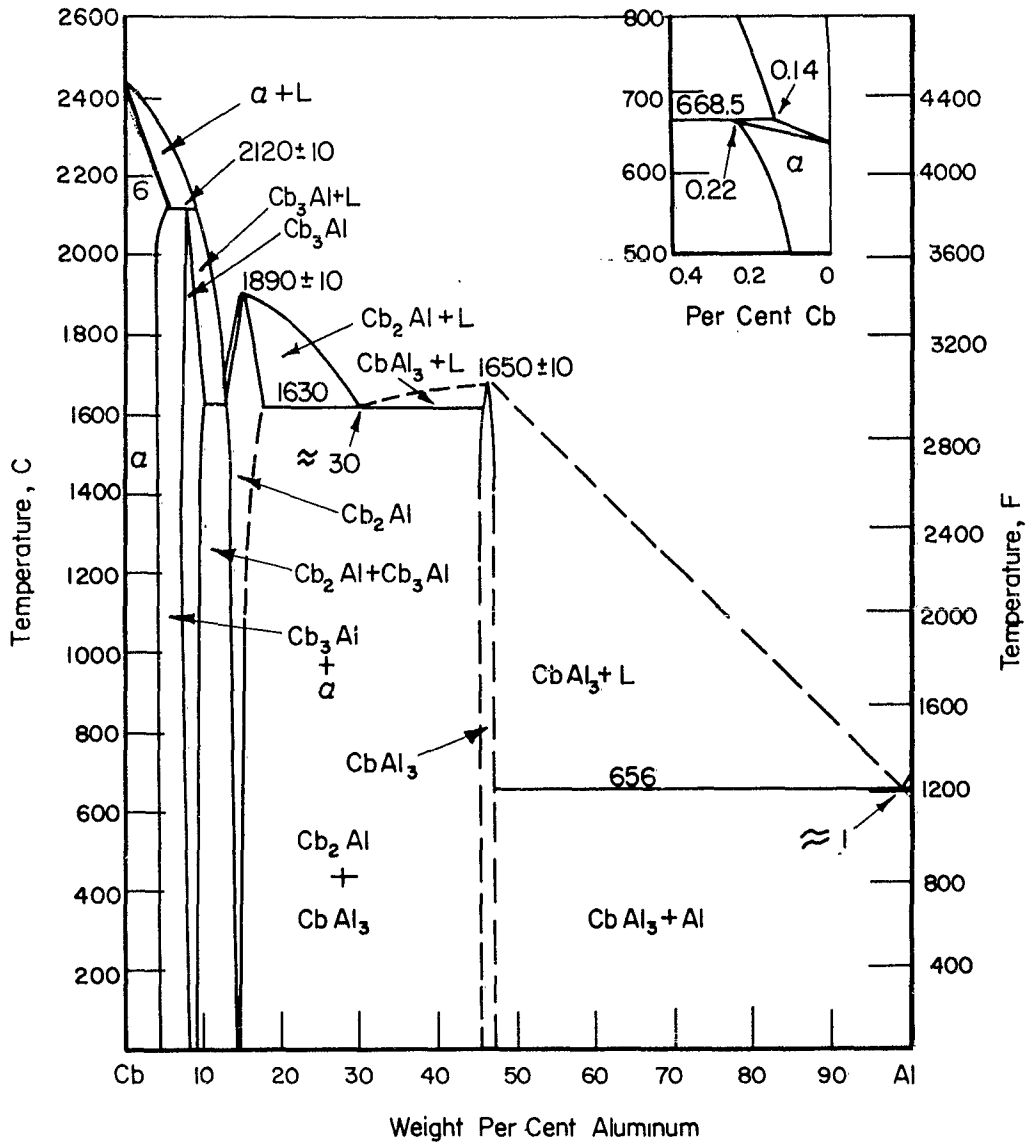
The μ phase is based on a CsCl B-2 type structure at 30 atomic per cent ruthenium, transforming to a distorted CsCl structure at 40 and 45 atomic per cent ruthenium.[324]

Tungsten-Hafnium System:

The previously reported value for the transformation of hafnium of 1875 ± 20 C has been observed to occur at 1750 ± 20 C by Deardorf[325]. Giessen[32] has verified the new value in more recent studies.

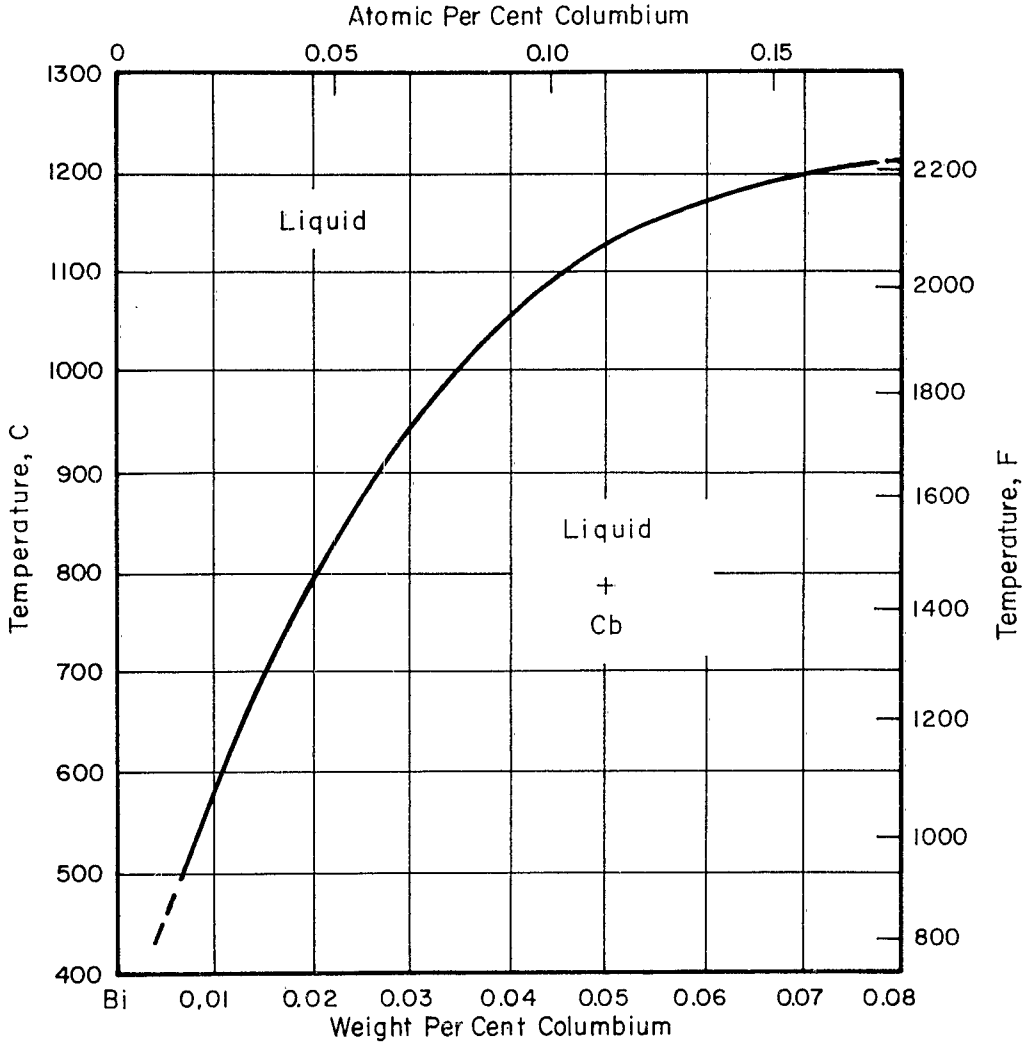
BINARY PHASE DIAGRAMS

COLUMBIUM-ALUMINUM SYSTEM



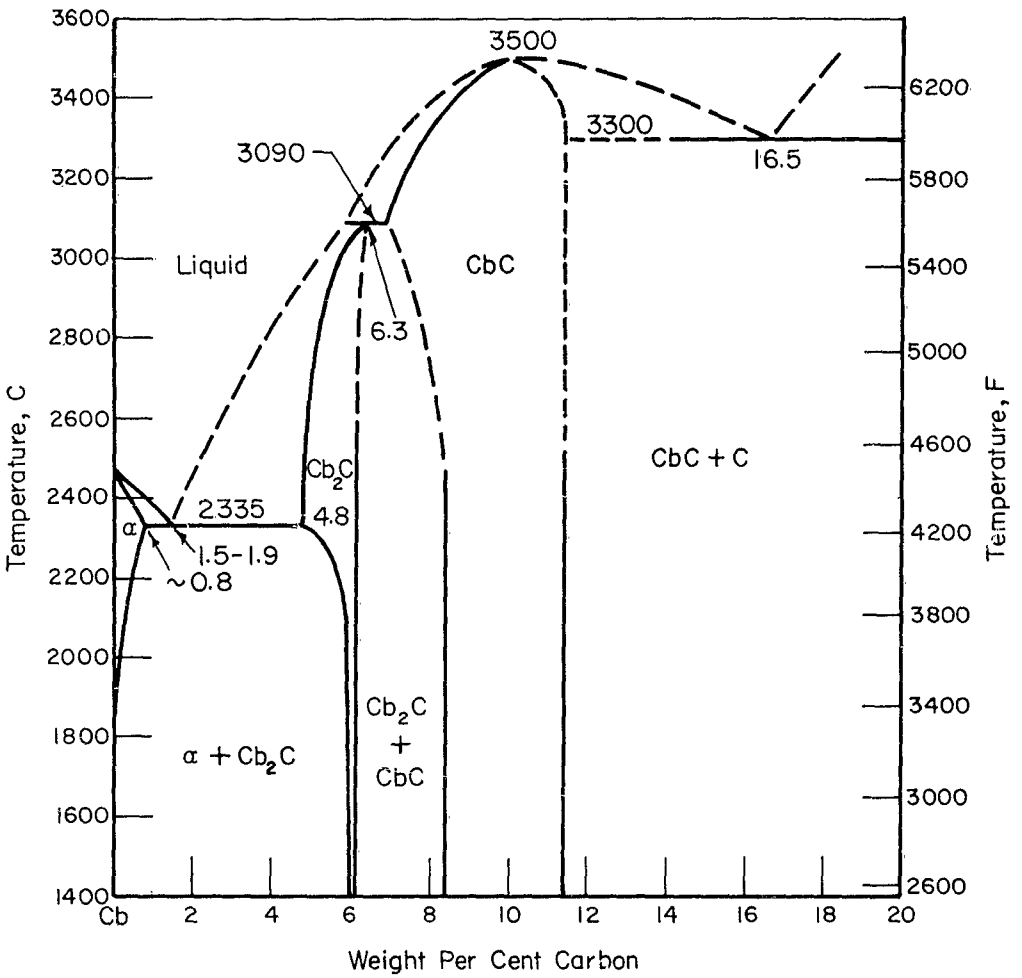
Cb_3Al has a cubic, β-tungsten type structure with a = 5.187 A.[1] Cb_2Al is tetragonal (σ-phase) with a = 5.438 A, c = 8.601 A, and c/a = 1.582.[3] Cb_2Al has been reported to form by a peritectic reaction at 1890 C[234] instead of melting congruently, as shown above.[235] The columbium-rich boundary of the Cb_2Al region was reported to be near 16 weight per cent aluminum (41 atomic per cent) at 1250 C.[236] Aluminum is soluble in columbium up to 6 weight per cent at 2120 C, decreasing to 4.5 per cent at room temperature.[234]

COLUMBIUM-BISMUTH SYSTEM



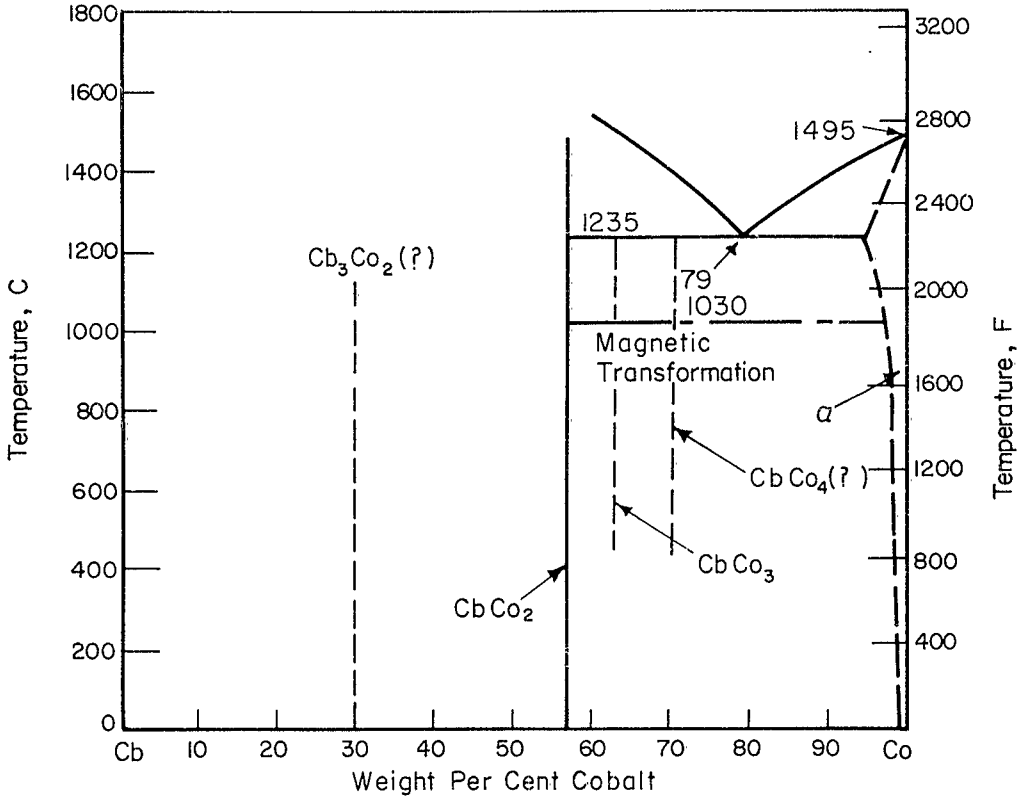
The solubility of columbium in liquid bismuth (mp = 271 C) is shown above.[237] There was no indication of the formation of intermetallic compounds in the system.

COLUMBIUM-CARBON SYSTEM



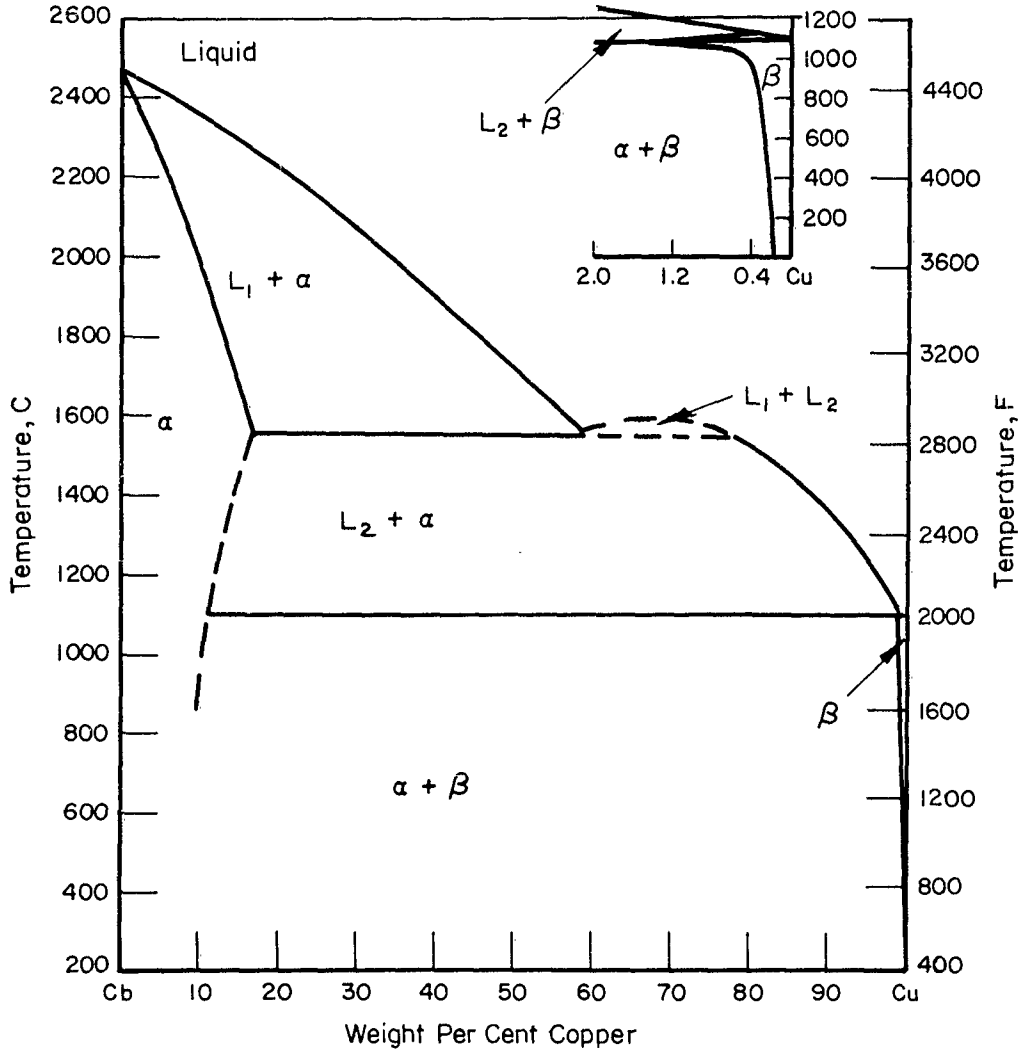
Cb_2C has a hexagonal structure with the single-phase region ranging from $CbC_{0.39}$ at the eutectic temperature to a maximum of $CbC_{0.52}$ at the peritectic temperature.[238] CbC is face-centered cubic with a = 4.470 at 25 C.[8, 9, 238] The maximum melting point of CbC occurs at a composition of $CbC_{0.86}$. Beyond the maximum melting point, the solidus drops to meet the CbC-C eutectic at 3300 C and 60.5 atomic per cent carbon.[239] The maximum solubility of carbon in columbium is 0.7 to 0.8 weight per cent.[10, 239]

COLUMBIUM-COBALT SYSTEM



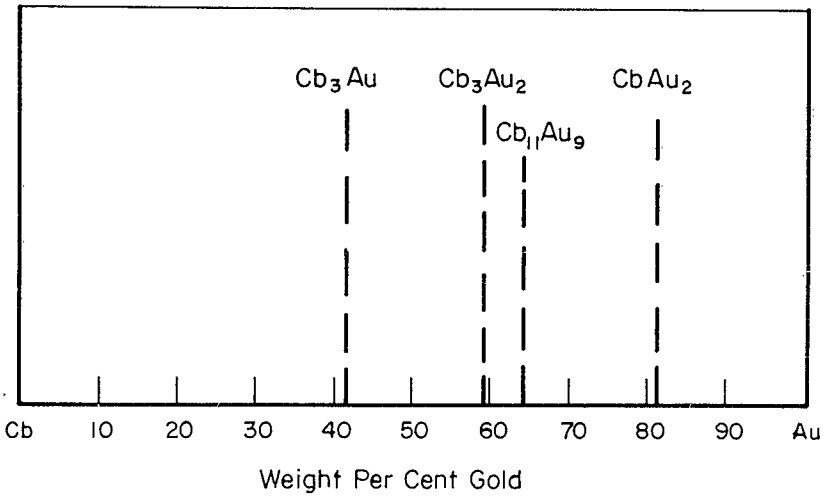
$CbCo_2$ is believed to exist in two modifications. One is at 33.3 atomic per cent columbium, and has a cubic $MgCu_2$ (C15) type of structure with a = 6.758 A; the second structure exists around 27 atomic per cent columbium and has the $MgNi_2$ (C36) type of structure with a = 4.738 A, c = 15.46 A, and c/2a = 1.631.[14, 15, 16] Two additional phases were reported to exist at 1100 C, Cb_3Co_2 and $CbCo_4$.[241] The solubility of columbium in cobalt is about 5 weight per cent at 1100 C.[240]

COLUMBIUM-COPPER SYSTEM



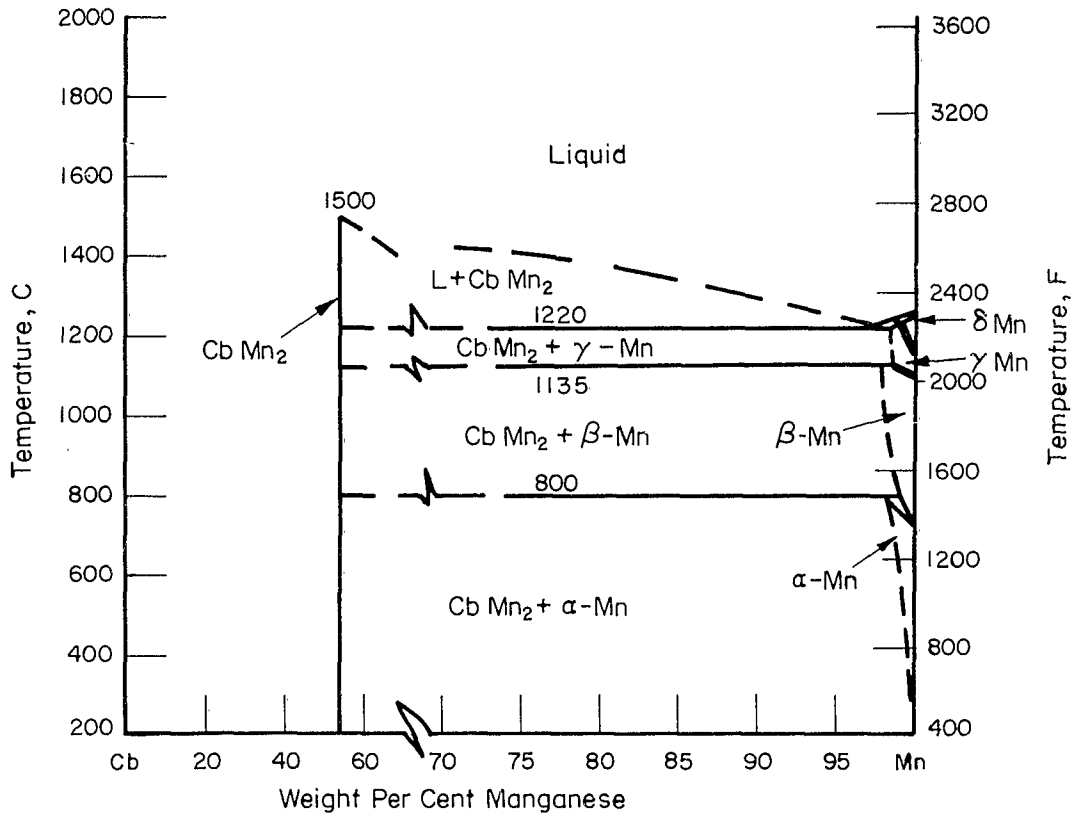
No intermetallic compounds are found in the columbium-copper system.[241]

COLUMBIUM-GOLD SYSTEM



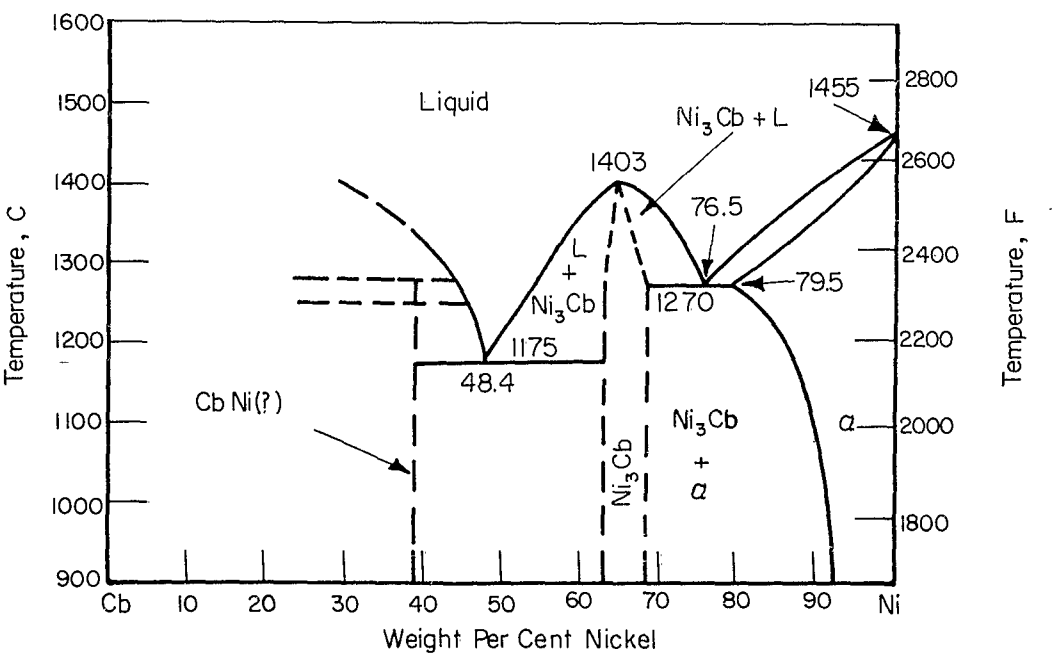
Cb_3Au is a cubic Cr_3O-type compound with a = 5.20 kX. Cb_3Au_2 has a D_{4h}^{17}-I4/mm structure with a = 3.37 kX and c = 5·3.03 kX. $Cb_{11}Au_9$ possesses a β-manganese structure with a = 7.04 kX. The structure of $CbAu_2$ is of the B_2Al type with a = 4.60 kX and c = 2.71 kX.[242]

COLUMBIUM-MANGANESE SYSTEM



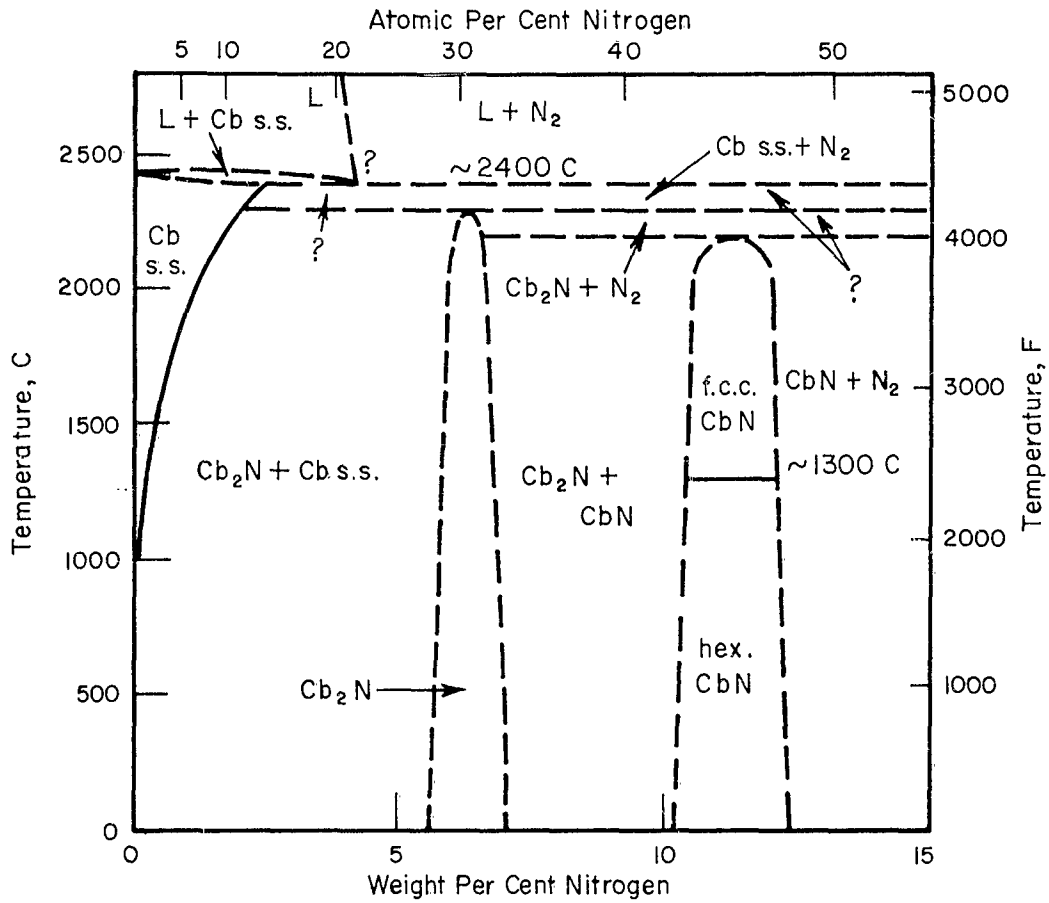
$CbMn_2$ has a hexagonal $MgZn_2$-type structure with a = 4.881 kX, c = 7.953 kX, and c/a = 1.629. Alloys containing less than 2 weight per cent columbium transform from γ-manganese to δ-manganese by a peritectic reaction near the melting point.[299]

COLUMBIUM-NICKEL SYSTEM



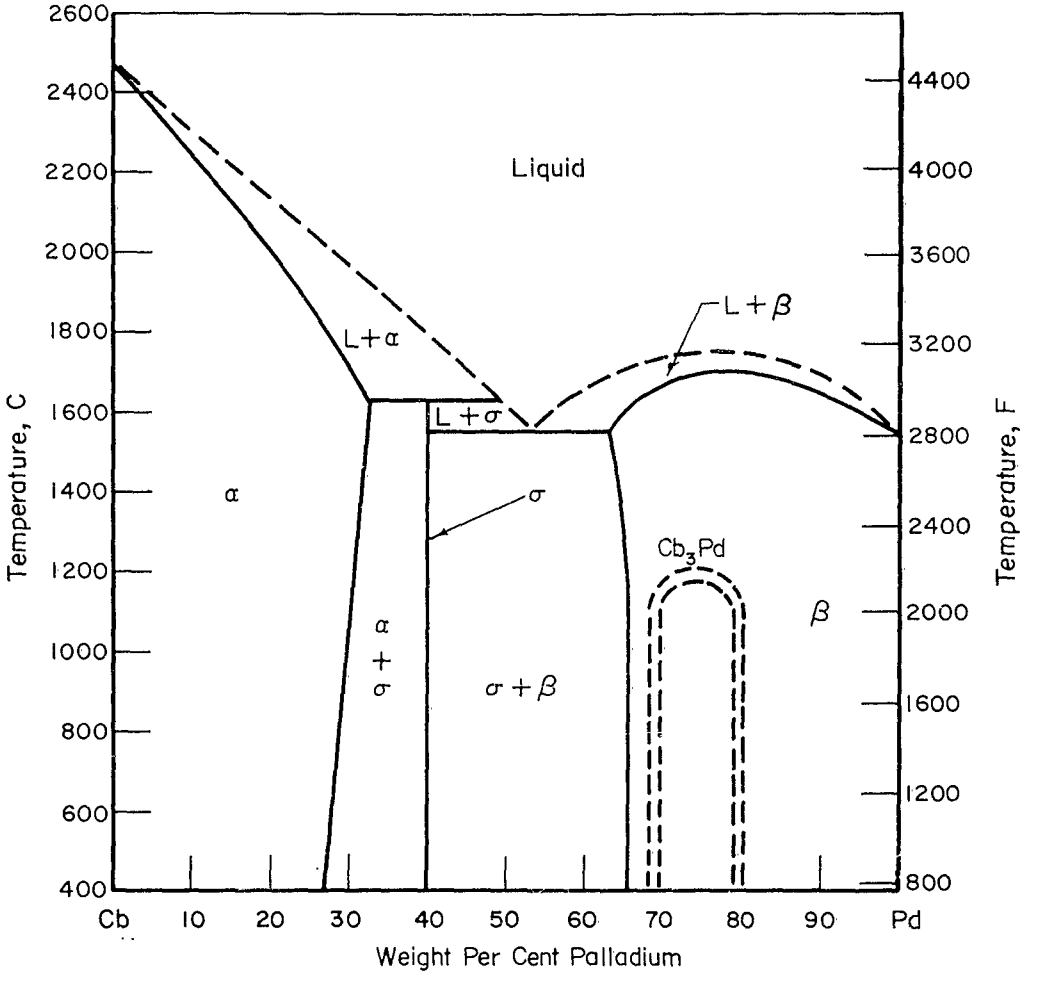
$CbNi_3$ has an orthorhombic $TiCu_3$-type structure with lattice parameters: a = 5.10 kX, b = 4.55 kX, and c = 4.25 kX.[23] The solubility of columbium in nickel is approximately 15 weight per cent at 1250 C. The solubility of nickel in columbium is less than 5 weight per cent.[24] The diagram was constructed from the data prepared by Pogodin and Selekmann.[25]

COLUMBIUM-NITROGEN SYSTEM



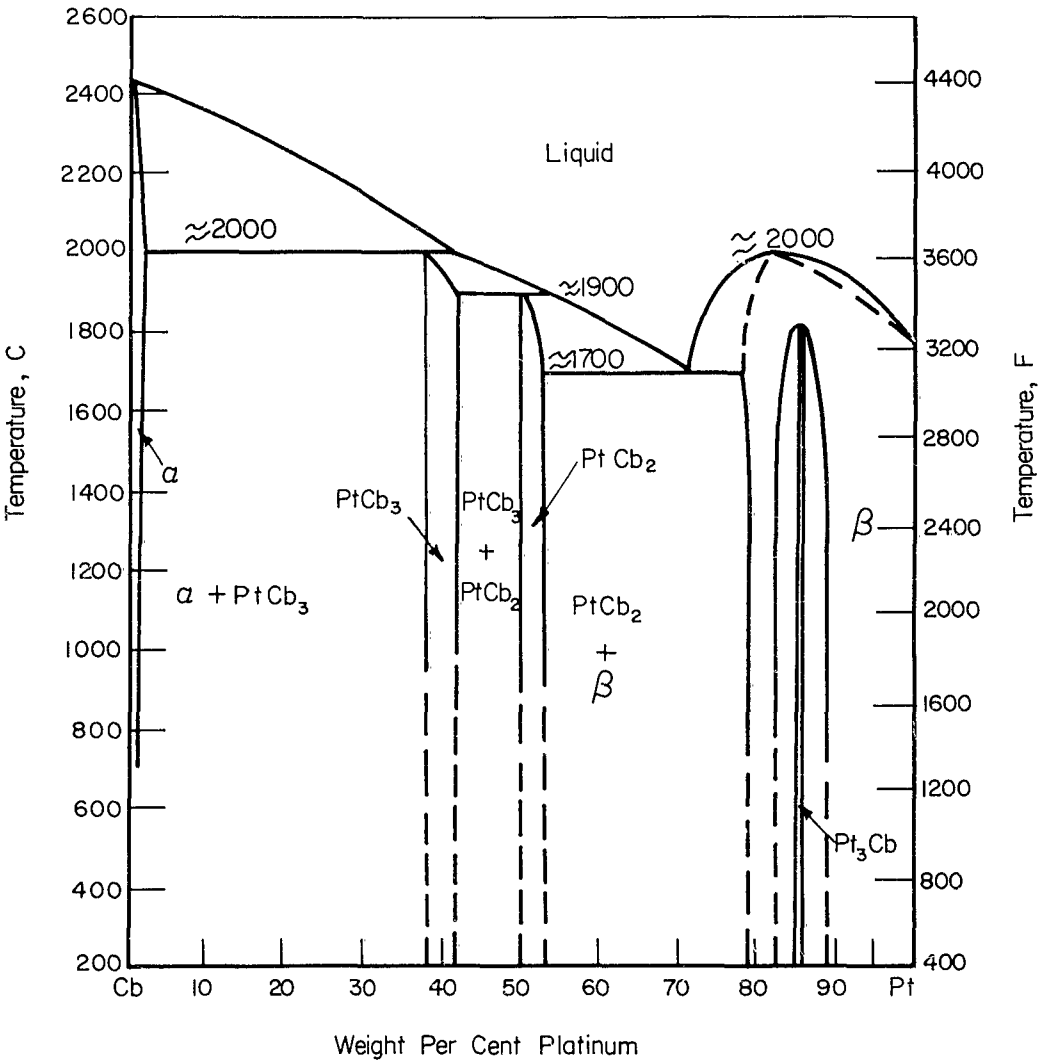
Cb_2N is a close-packed-hexagonal structure, with the lattice parameters varying between a = 3.057 A, c = 4.957 A (c/a = 1.622) and a = 3.050 A, c = 5.005 A (c/a = 1.641).[21, 243] The high-temperature structure of CbN is face-centered cubic with a = 4.386 to 4.394 A.[243] The low-temperature structure of CbN is hexagonal, with the lattice parameters varying between a = 2.953 A, c = 11.243 A (c/a = 3.804) and a = 2.953 A, c = 11.257 A (c/a = 3.813).[22, 243] The solubility of nitrogen in columbium is 0.25 weight per cent at 1200 C and 2.5 weight per cent at 2400 C.

COLUMBIUM-PALLADIUM SYSTEM



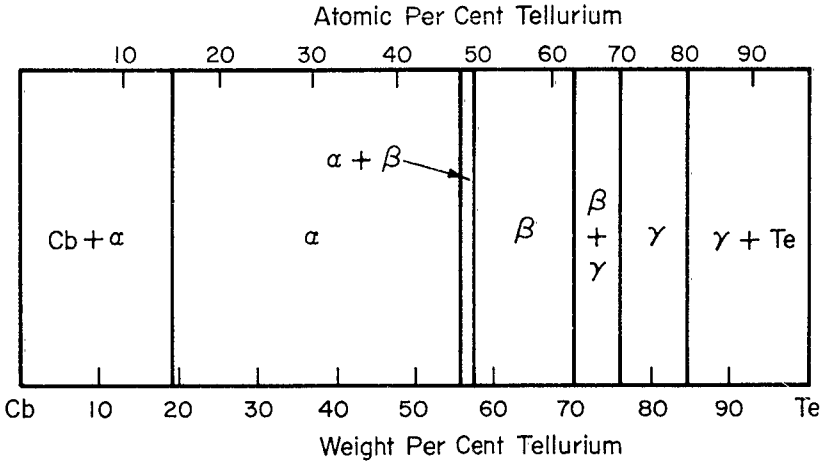
One intermediate phase having a tetragonal σ-phase structure, with a = 9.89 A, c = 5.11 A, c/a = 0.52, was reported.[30] An ordered structure is possibly present at the Cb_3Pd composition.[244]

COLUMBIUM-PLATINUM SYSTEM



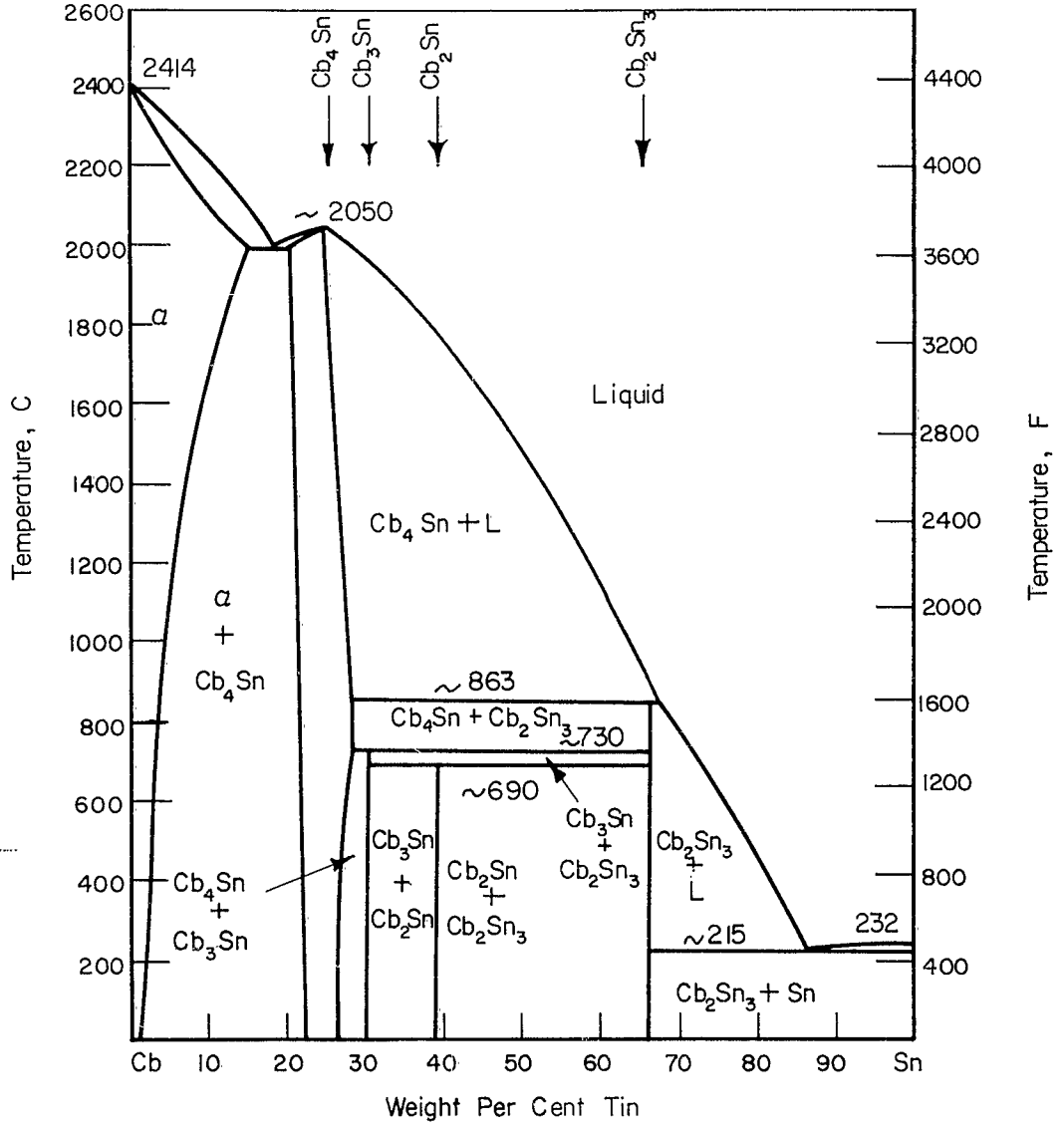
$PtCb_3$ has a β-tungsten type structure with its lattice parameters increasing from 5.137 to 5.156 kX with increasing columbium content. $PtCb_2$ has a tetragonal lattice and forms a eutectic with β at 55 atomic per cent platinum. Columbium is soluble in platinum up to 36 atomic per cent (21 weight per cent). The solubility limit of platinum in columbium is less than 1 atomic per cent. Pt_3Cb forms a superlattice near 1800 C.[245]

COLUMBIUM-TELLURIUM SYSTEM



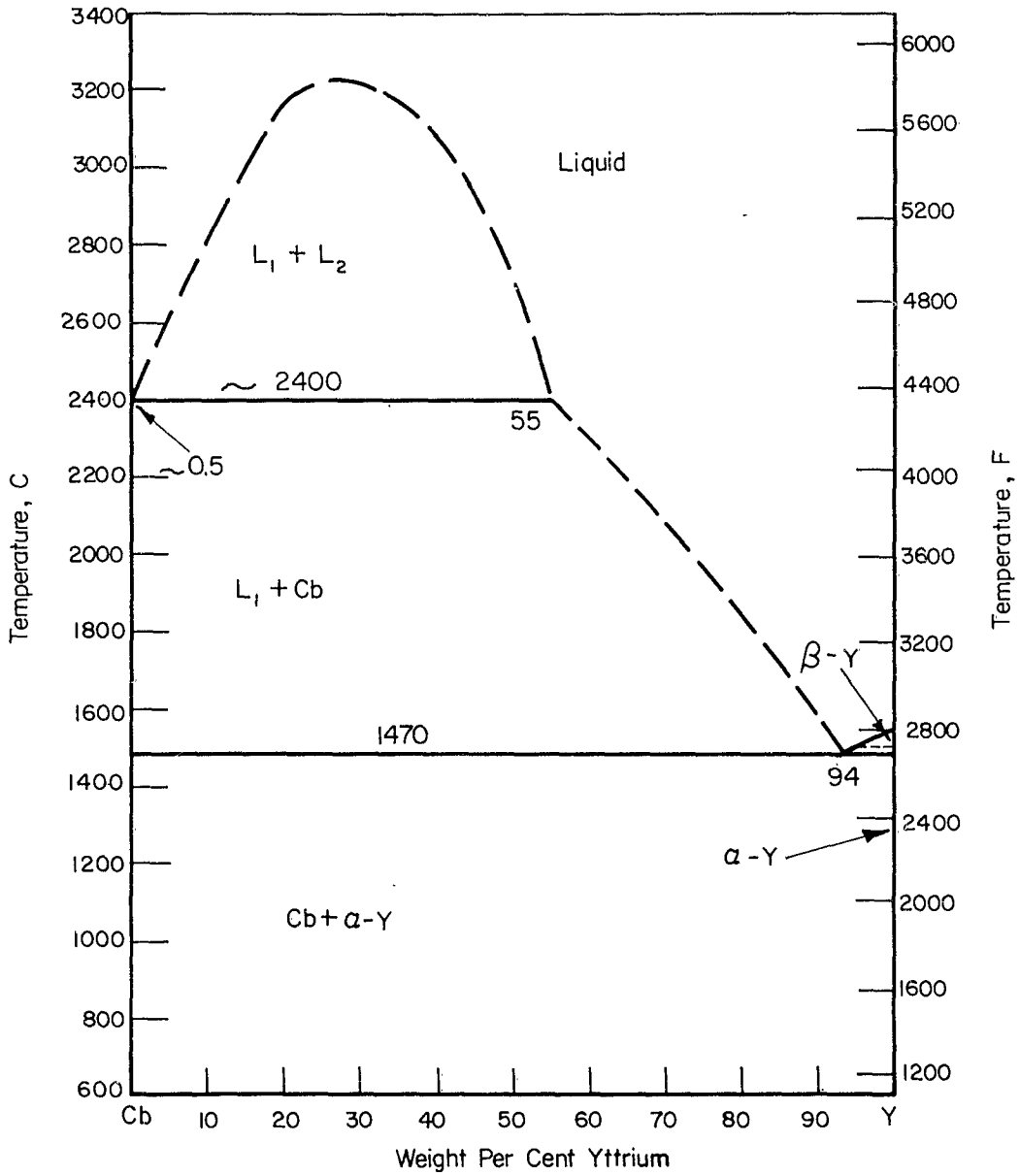
The above phase relationships are for 20 C.[246]

COLUMBIUM-TIN SYSTEM



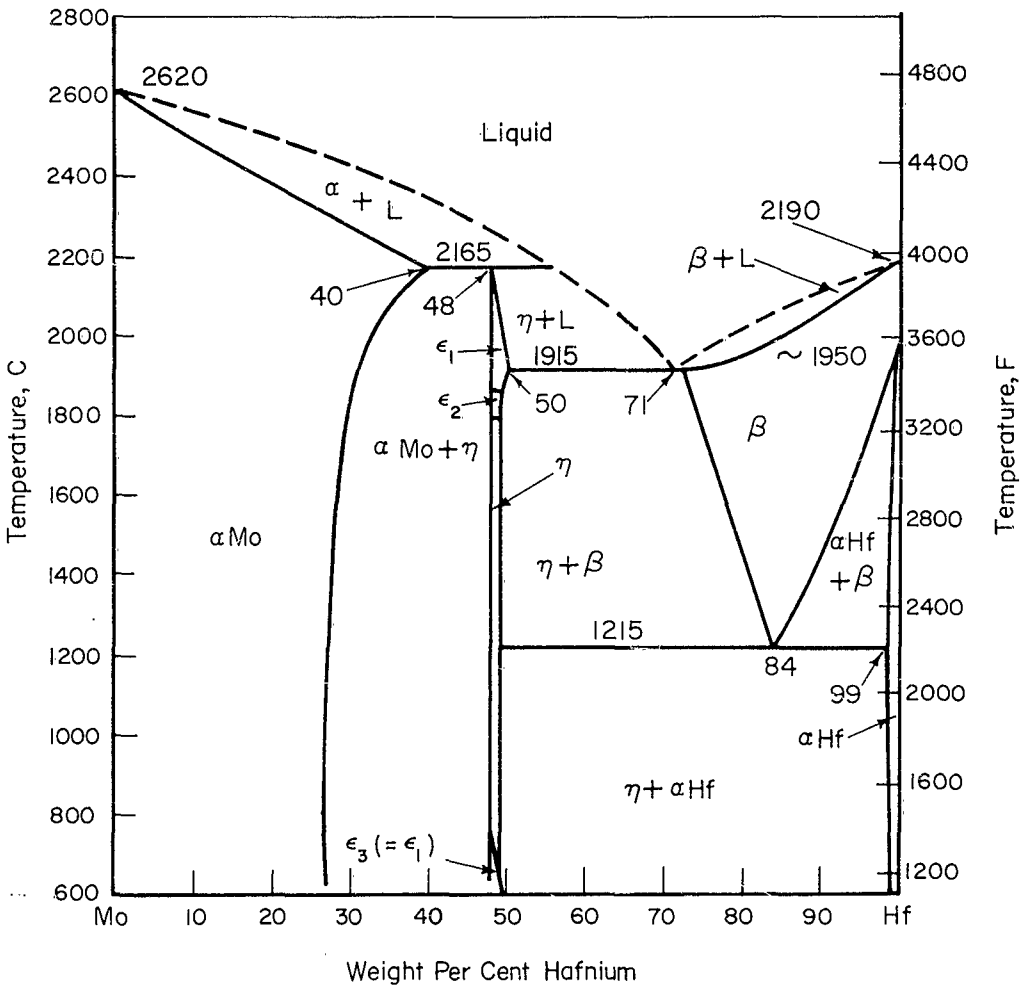
Cb_3Sn is a β-tungsten type structure with a = 5.29 A.[38, 39] Agafonova, et al., determined the solid solubility of tin in columbium as 9.7 weight per cent at room temperature, increasing to 14 per cent at 2000 C. The solubility of columbium in tin is less than 0.1 weight per cent at the melting point of tin.[38] L. L. Wyman, et al., identified three additional phases in the system, Cb_4Sn, Cb_2Sn, and Cb_2Sn_3. A slightly higher solid solubility of tin in columbium was also indicated. The modified diagram was suggested by Wyman, et al.[304]

COLUMBIUM-YTTRIUM SYSTEM



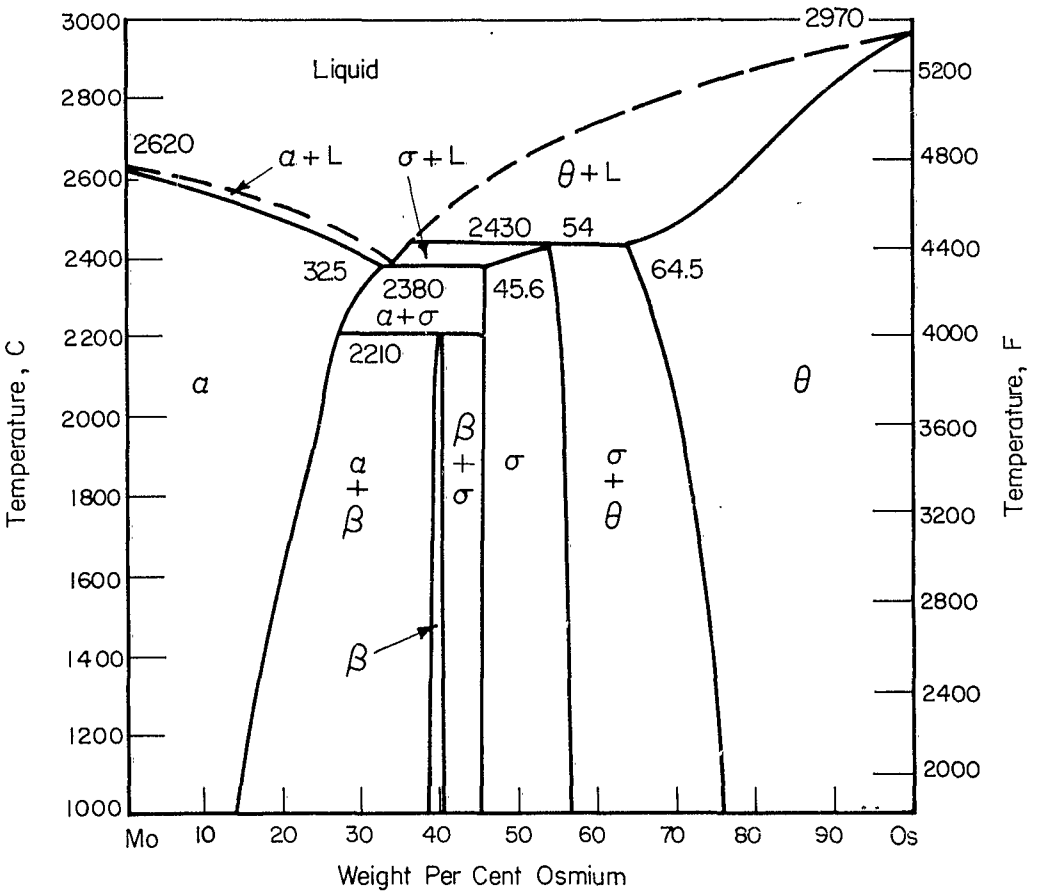
The maximum solubility of yttrium in columbium is less than 0.1 weight per cent, and the maximum solubility of columbium in yttrium is 0.2 ± 0.1 weight per cent.[247, 248, 249] An inverse peritectic reaction in the yttrium-rich region is postulated for this system.[249]

MOLYBDENUM-HAFNIUM SYSTEM



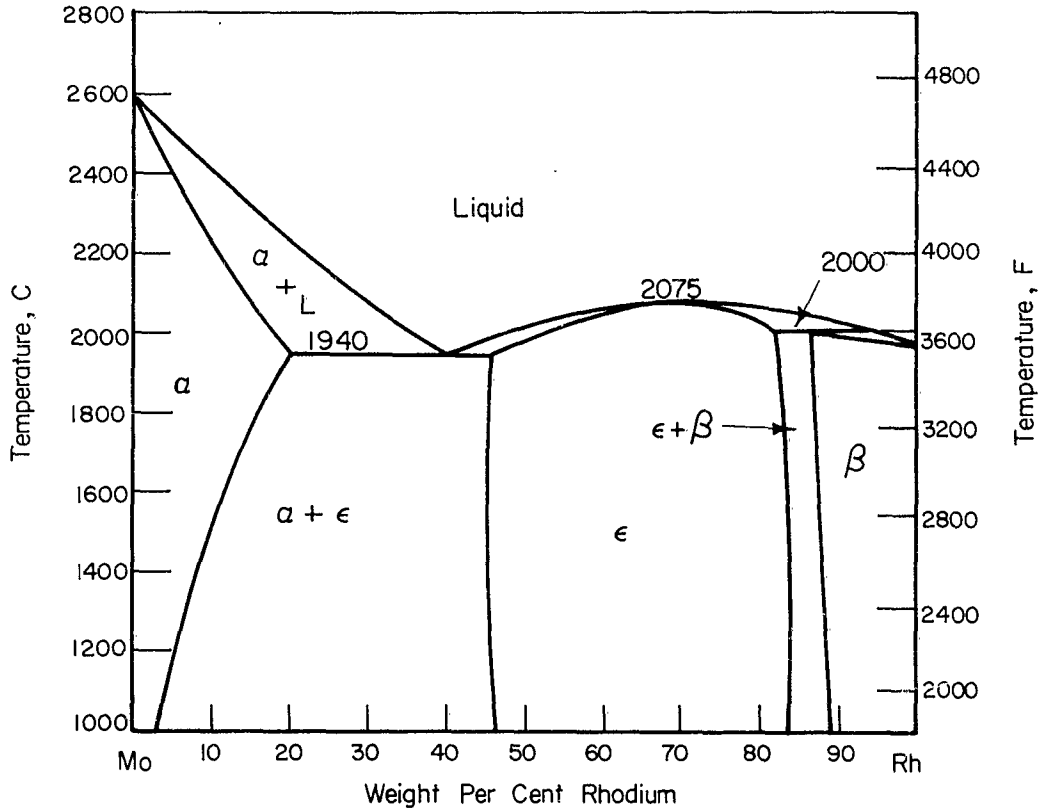
ϵ_1 (Mo_2Hf) is a hexagonal Laves phase of the C36-$MgNi_2$ type, with a = 5.341 A, c = 17.347 A, and c/a = 3.248. Between 1850 and 1816 C, ϵ_1 changes to ϵ_2 which is intermediate between the C36-$MgNi_2$ and C14-$MgZn_2$ structures; the lattice parameters are a = 5.349 A, c = 17.490 A, and c/a = 3.270. Upon annealing at 1752 C, ϵ_2 transforms to the cubic C15-$MgCu_2$ modification η with a = 7.560 A. Annealing Mo_2Hf at 700 C for 2 weeks and quenching transforms the structure to the original C36-$MgNi_2$ structure of the ϵ_1 high-temperature phase.[78, 250]

MOLYBDENUM-OSMIUM SYSTEM



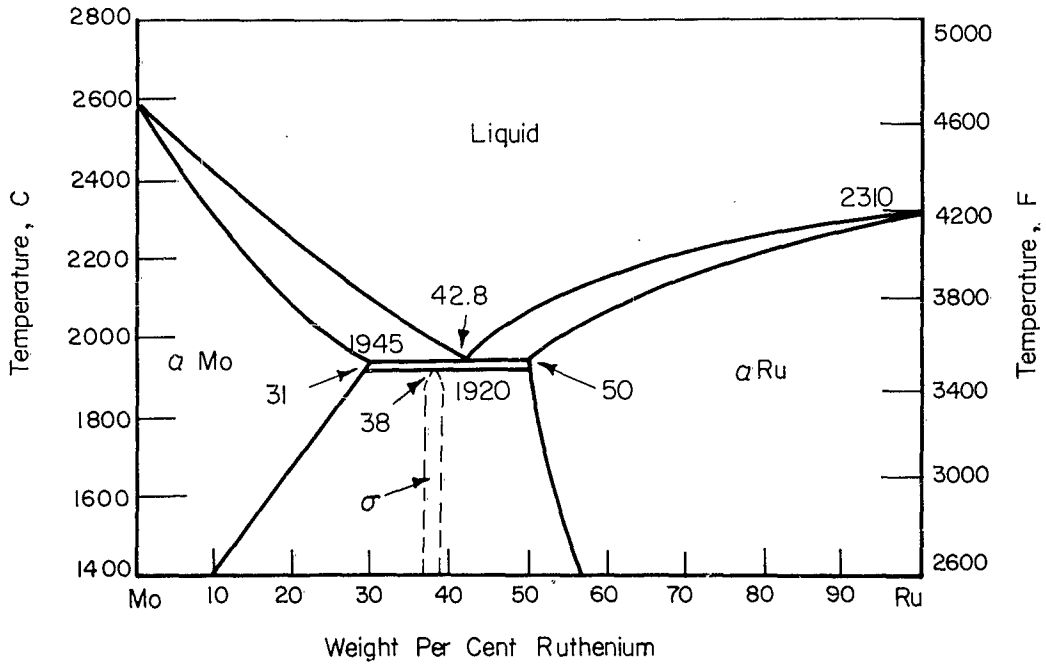
The β-Mo_3Os phase has a β-tungsten A15 type structure with the lattice parameters ranging from 4.971 A at 24.5 atomic per cent osmium to 4.969 A at 25 atomic per cent. The σ-phase is typical of σ-FeCe which has the atomic arrangement of tetragonal β-uranium; the lattice parameters decrease with the addition of osmium from a = 9.632 A and c = 4.950 A at 30 atomic per cent osmium (46 weight per cent) to a = 9.613 and c = 4.934 A at 37.5 atomic per cent osmium (55 weight per cent). Osmium is soluble in molybdenum up to 19.5 atomic per cent (32.5 weight per cent) at 2380 C, decreasing to 7.0 atomic per cent (14 weight per cent) at 1000 C. Molybdenum dissolves in osmium up to 52 atomic per cent (35.5 weight per cent) at 2430 C, decreasing to 40 atomic per cent (25 weight per cent) at 1100 C.[250]

MOLYBDENUM-RHODIUM SYSTEM



The ε-phase is close-packed hexagonal with a = 2.740 kX, c = 4.380 kX, and c/a = 1.5999 at 60 weight per cent rhodium.[90, 92] The maximum melting point for ε corresponds to the approximate composition $MoRh_2$. Rhodium is soluble in molybdenum up to 21 weight per cent at 1940 C, decreasing to less than 3 weight per cent at 1100 C.[90] Rhodium can dissolve about 14 weight per cent (15 atomic per cent) molybdenum near 2000 C.[307]

MOLYBDENUM-RUTHENIUM SYSTEM



The σ-phase forms by a peritectoid reaction at 1920 C; the lattice parameters are a = 9.538 kX, c = 4.925 kX, and c/a = 0.516. The composition Mo_5Ru_3 is included in the composition range of the σ-phase. The solubility of ruthenium in molybdenum decreases rapidly from 31 weight per cent at 1945 C to 14 weight per cent at 1500 C.[251]

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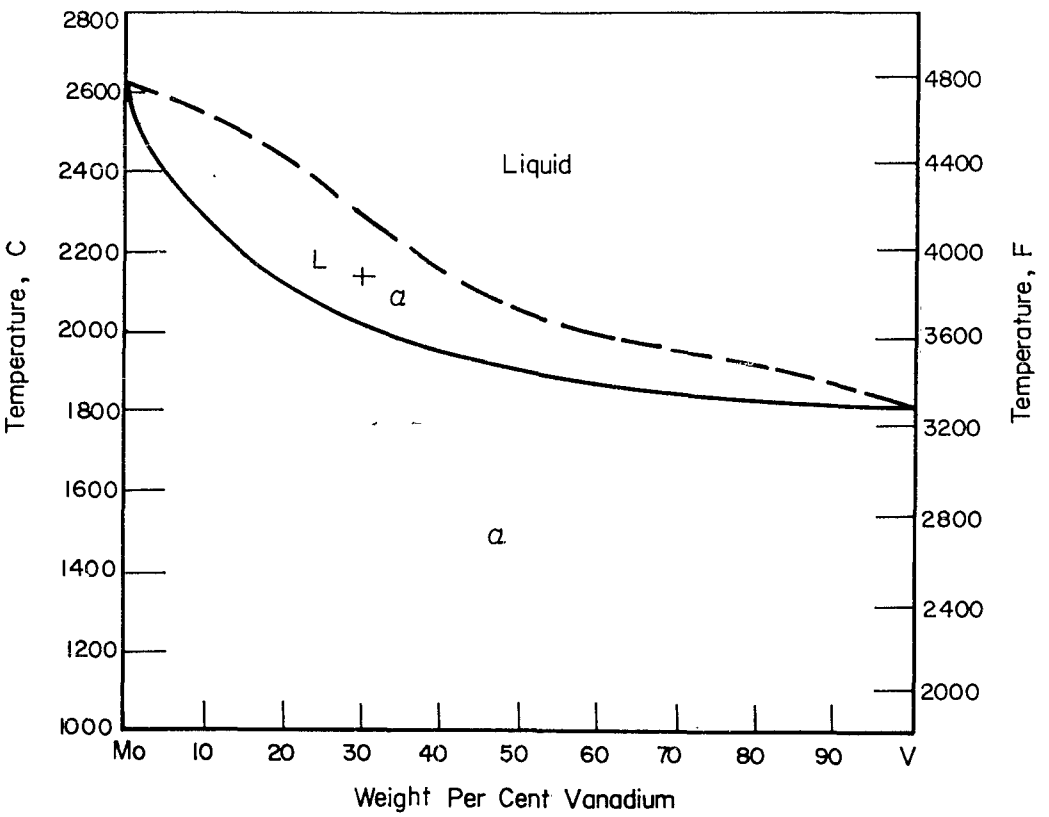
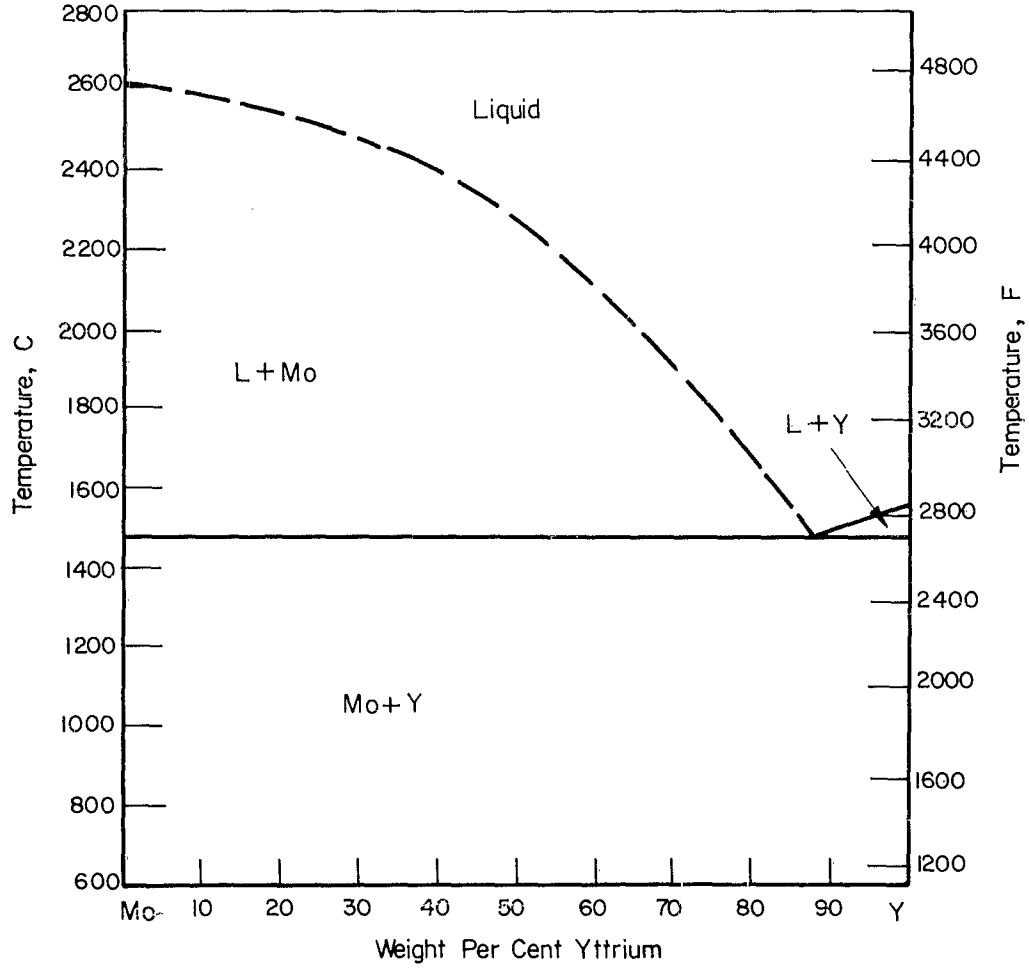
MOLYBDENUM-VANADIUM SYSTEM



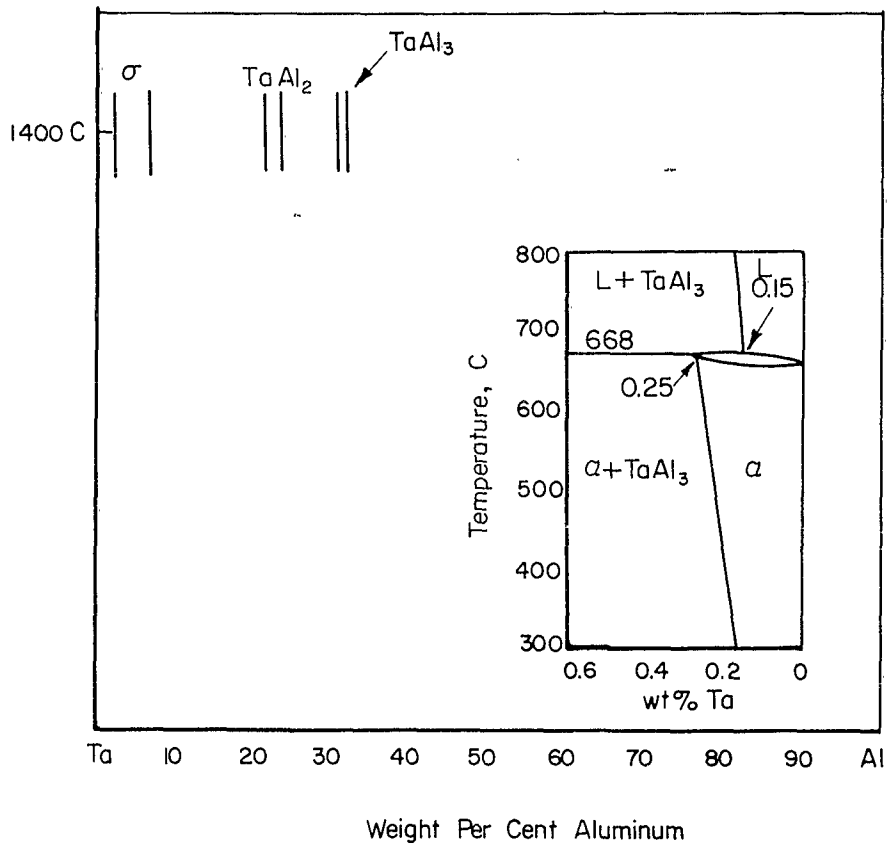
The molybdenum-vanadium system forms a continuous series of solid solutions.(311)

MOLYBDENUM-YTTRIUM SYSTEM



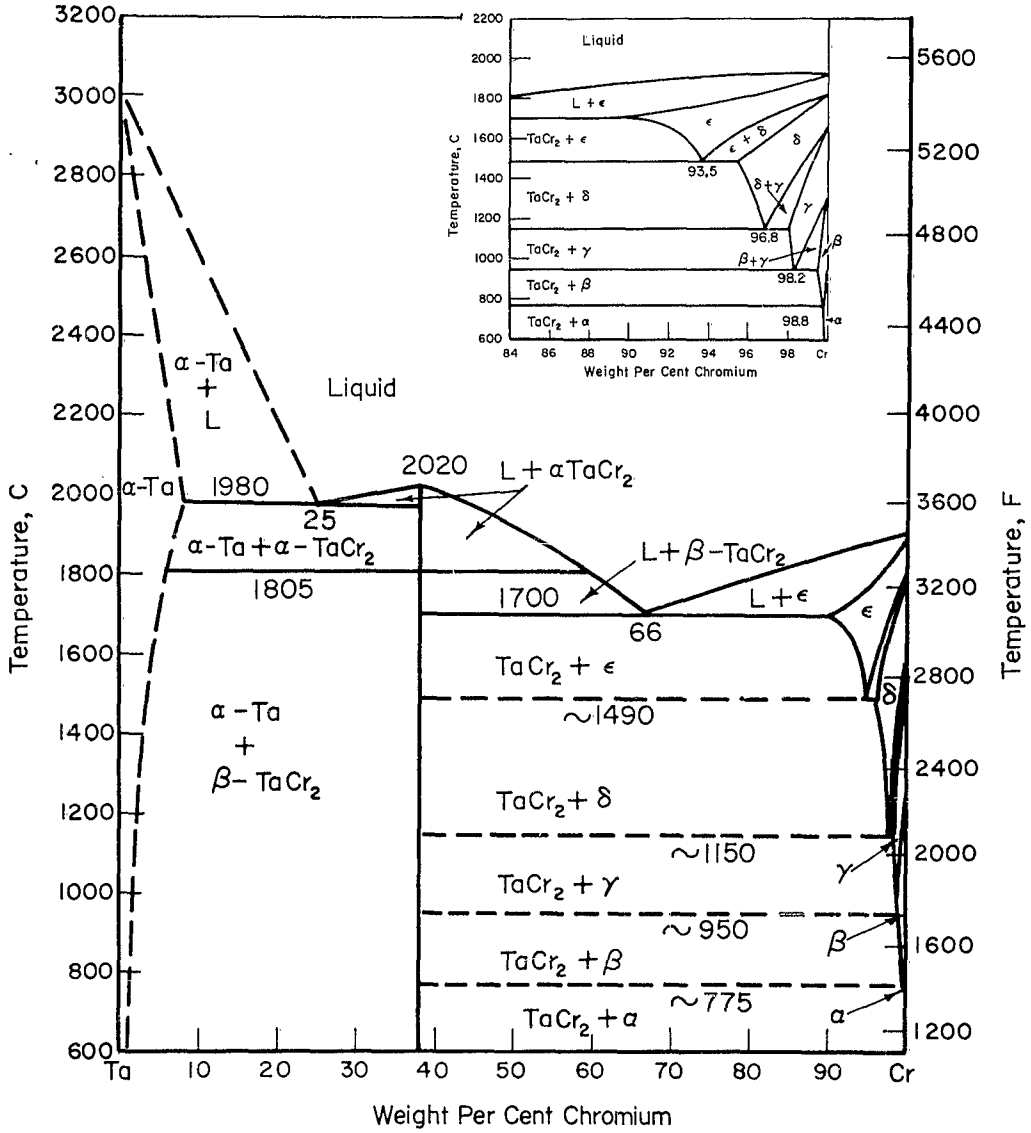
Terminal solubilities are probably less than 1 atomic per cent.[247, 248]

TANTALUM-ALUMINUM SYSTEM



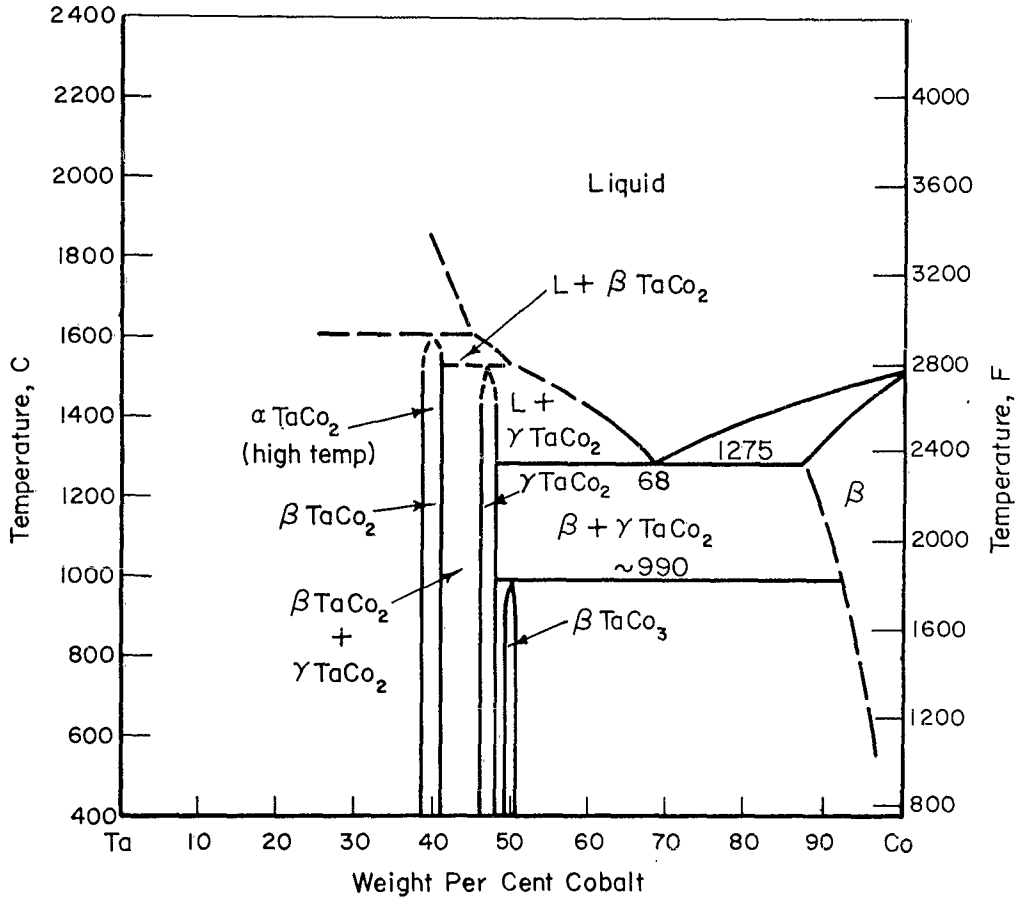
Three intermetallic compounds are present in the tantalum-aluminum system. $TaAl_3$ is isomorphorus to $CbAl_3$, having a tetragonal structure with a = 5.42 kX and c = 8.52 kX. A compound in the vicinity of 65 atomic per cent aluminum, possibly $TaAl_2$, exhibits a structure similar to the $ZrAl_3$ or $ZrSi_2$.(266) Ta_2Al is a tetragonal σ-type phase with a = 9.828 A, c = 5.232A, and c/a = 0.532.(267) The above intermediate phase boundaries are for 1400 C.(266) The solubility of tantalum in aluminum was determined by Glazov.(310)

TANTALUM-CHROMIUM SYSTEM



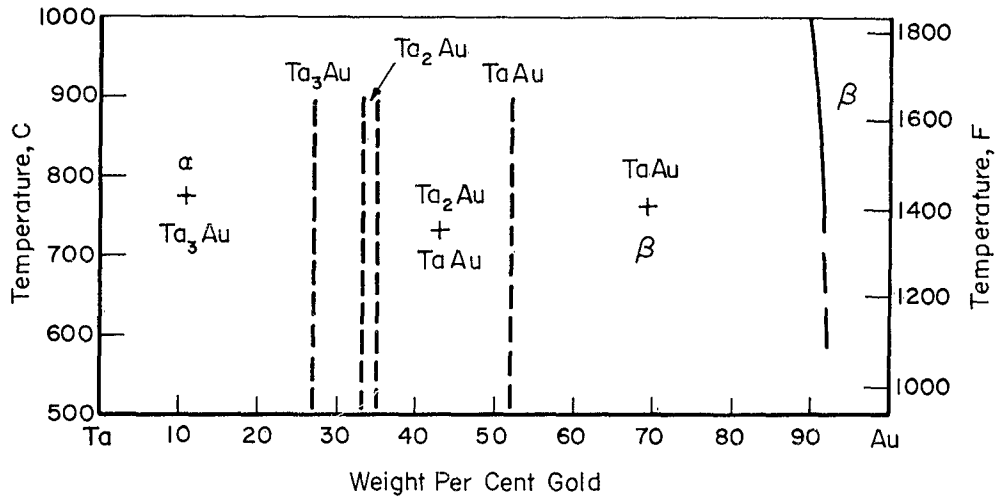
Duwez and Martens[123] reported that $TaCr_2$ has a polymorphic transformation between 1375 and 1590 C from the low-temperature cubic structure ($MgCu_2$-type with a = 6.961 A) to the high-temperature hexagonal structure (a = 4.925 A, c = 8.062 A, c/a = 1.637). Elliott considers the compound isomorphous with $MgZn_2$ at all temperatures from 600 to 1200 C.[124] Grigor'ev et al.[233] states that $TaCr_2$ undergoes a polymorphic transformation at 1805 C. They report that the solubility of chromium in tantalum is about 5 weight per cent at 1800 C, and the solubility of tantalum in chromium is about 10 weight per cent at 1700 C. Grigor'ev,[300] et al., reported five structural modifications in the chromium-rich region. The ϵ solid solution has a body-centered cubic lattice whose parameters can be extrapolated to α-chromium. Alloys in the region of the γ solid solution have a similar lattice. Alloys with 5 weight per cent tantalum quenched from 1550 C contained body-centered cubic ϵ and a second phase δ which has a hexagonal lattice with a = 2.841 kX, c = 4.786 kX, and c/a = 1.685.

TANTALUM-COBALT SYSTEM



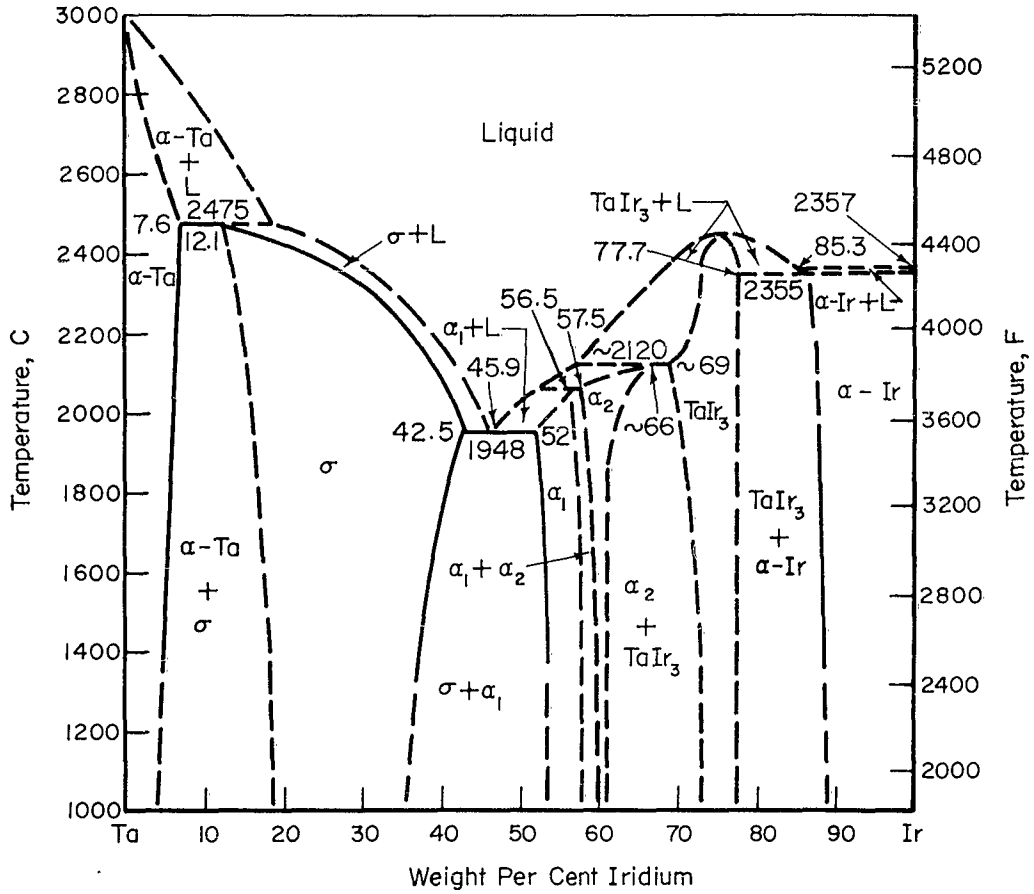
Two Laves phases were identified in a 39.4 weight per cent cobalt alloy.[305] α-$TaCo_2$, a hexagonal $MgZn_2$-type structure with a = 4.797 A, c = 7.827 A, and c/a = 1.632 was present in the as-cast microstructure. Aging at 1100 and 1200 C transformed α-$TaCo_2$ to a cubic $MgCu_2$-type phase β-$TaCo_2$ with a = 6.778. Elliot also observed both structures.[124] γ-$TaCo_2$ is also a Laves phase of the hexagonal $MgNi_2$ type with a = 4.700 A, c = 15.42 A, and c/a = 3.281.[120, 305] β-$TaCo_3$ is hexagonal with a = 9.411 A, c = 15.50 A, and c/a = 1.647.[305] A metastable ordered cubic phase (a = 3.647 A) of the $AuCu_3$ type was also reported.[305] Contributions to the above diagram were made by Köster and Mulfinger[121] and by Hoschimoto[122].

TANTALUM-GOLD SYSTEM



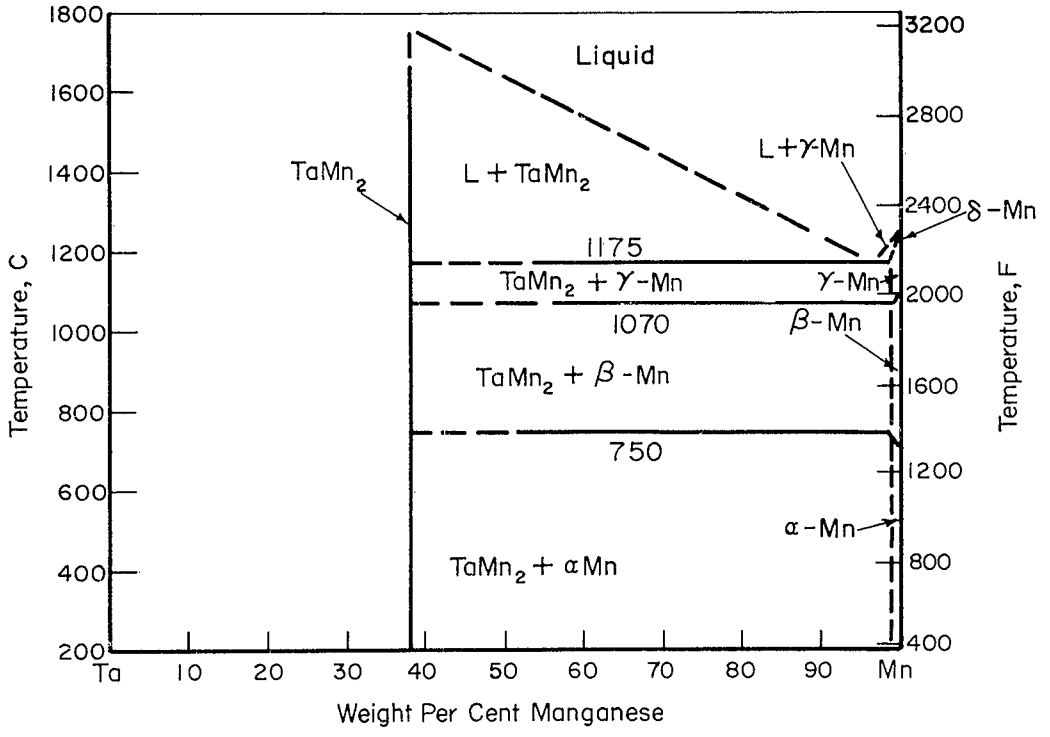
Ta_3Au has a cubic Cr_3O-type structure with a = 5.21 kX. Ta_2Au is a tetragonal σ-type phase with a = 10.04 kX and c/a = 0.520. TaAu has a tetragonal structure with a = 3.37 kX and c/a = 0.902. The solubility of tantalum in gold is 10 weight per cent at 1000 C, decreasing to 8.7 weight per cent at 800 C.(252)

TANTALUM-IRIDIUM SYSTEM



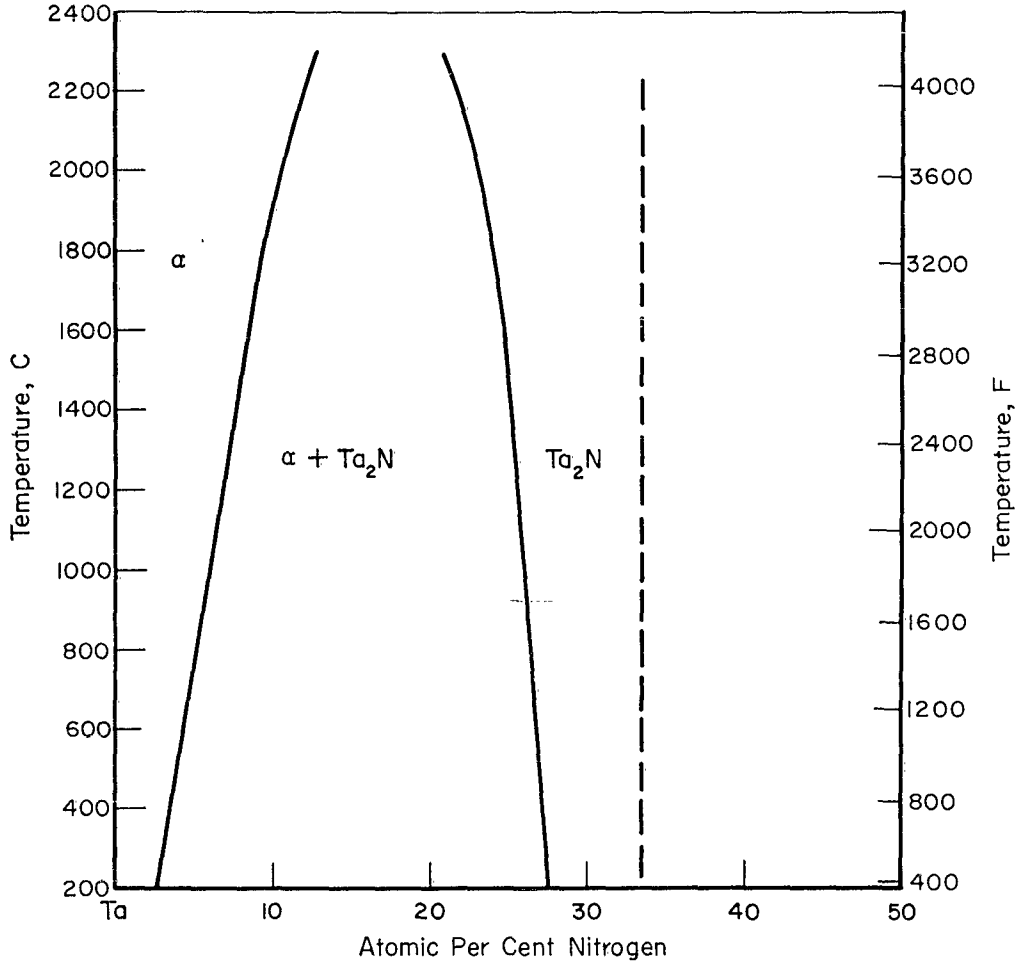
Sigma has a tetragonal σ(FeCr) structure with a = 9.938 A and c = 5.172 A at 25 atomic per cent (26 weight per cent) iridium.(253) α_1 has a structure similar to the α_1 phase in the tantalum-rhodium system.(254) α_2 has a tetragonal AuCu structure with a = 3.991 A, c = 3.856 A, and c/a = 0.966.(254) The structure of $TaIr_3$ is a cubic, $AuCu_3$ type with a = 3.889 A.(255) α-tantalum has a maximum solubility of 7.2 atomic per cent (7.6 weight per cent) iridium at 2475 C.(254)

TANTALUM-MANGANESE SYSTEM



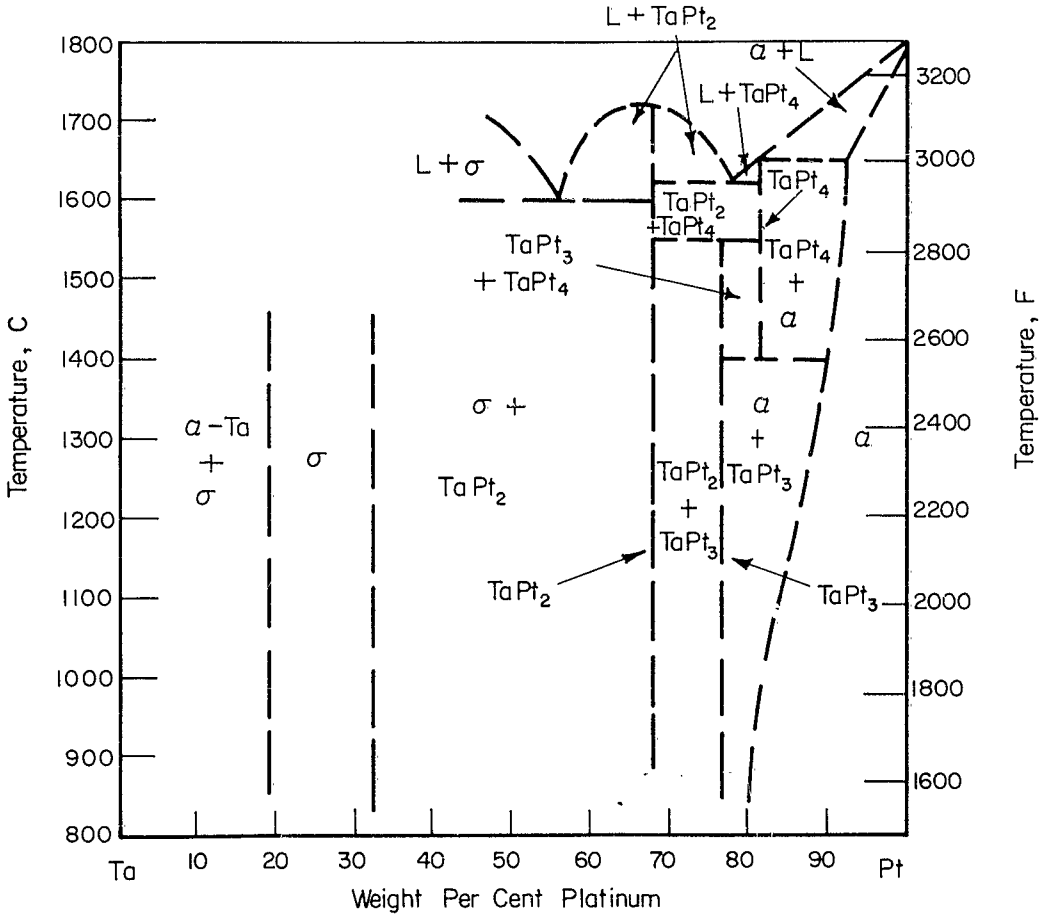
$TaMn_2$ has a hexagonal $MgZn_2$ Laves-phase-type structure with a = 4.864 A, c = 7.947 A, and c/a = 1.634.[124] This compound has a melting point above 1670 C.[298] At 1070 C, the $\beta \rightleftharpoons \gamma$ transition occurs by a eutectoid reaction. The δ-manganese $\rightleftharpoons \gamma$-manganese transformation is a peritectic reaction and occurs near the melting point.[298]

TANTALUM-NITROGEN SYSTEM



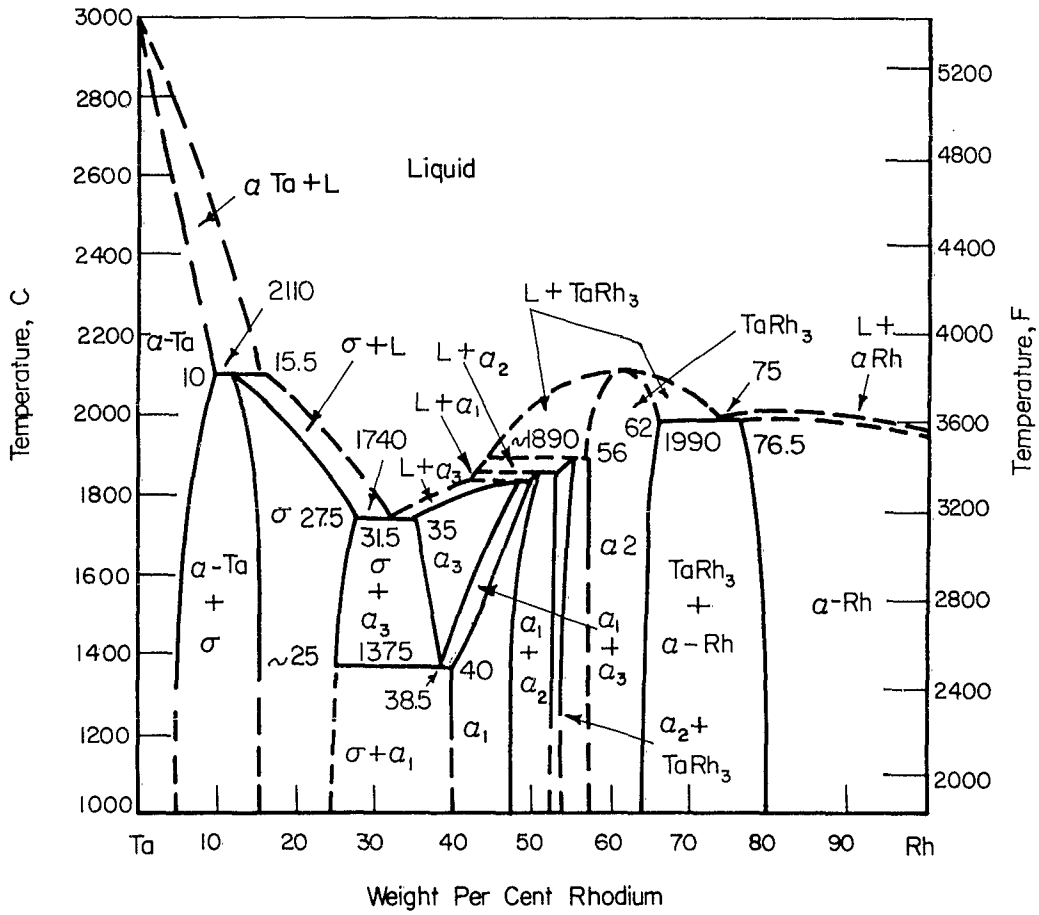
Two intermetallic compounds are definitely established for the tantalum-nitrogen system. TaN is close-packed hexagonal with a = 5.181 kX, c = 2.905 kX, and c/a = 0.561.[132] Ta_2N is also close-packed hexagonal with a = 3.042 kX, c = 4.909 kX, and c/a = 1.614.[132,133] The melting point of TaN has been given as 2890 C[134] and 3090 C[135]. Chiotti has shown that TaN dissociates at high temperatures, forming the lower nitride, Ta_2N, and nitrogen.[136] The phase diagram was obtained from Reference (256).

TANTALUM-PLATINUM SYSTEM



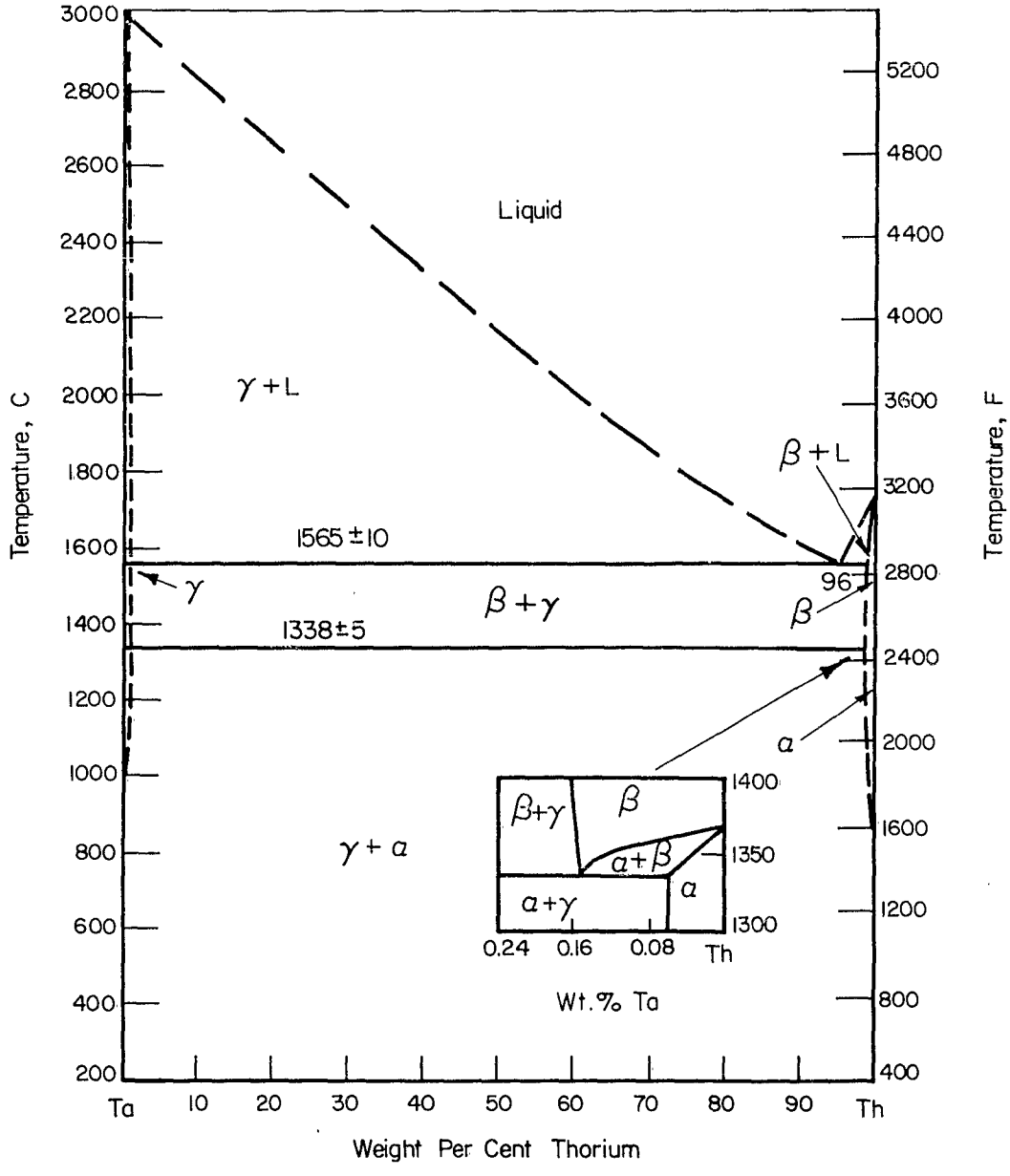
Four intermediate phases were observed between 50 and 100 per cent platinum. The σ-phase has a complex tetragonal structure with 30 atoms per unit cell;[257] cell dimensions are a = 9.95 A, c = 5.16 A, and c/a = 0.52.[30] $TaPt_4$ is stable above 1000 C and has an tetragonal structure with a = 8.58 A, c = 10.60 A, and c/a = 1.24. $TaPt_3$ is tetragonal with a = 6.45 A, c = 6.98 A, and c/a = 1.08. The $TaPt_2$ phase was not clearly established by the X-ray results. The solubility of tantalum in platinum is about 10 atomic per cent (9 weight per cent) at 1500 C and 20 atomic per cent (19 weight per cent) at 1000 C. The exact phase boundaries and reaction isotherms were not determined in this investigation by Browning.[257]

TANTALUM-RHODIUM SYSTEM



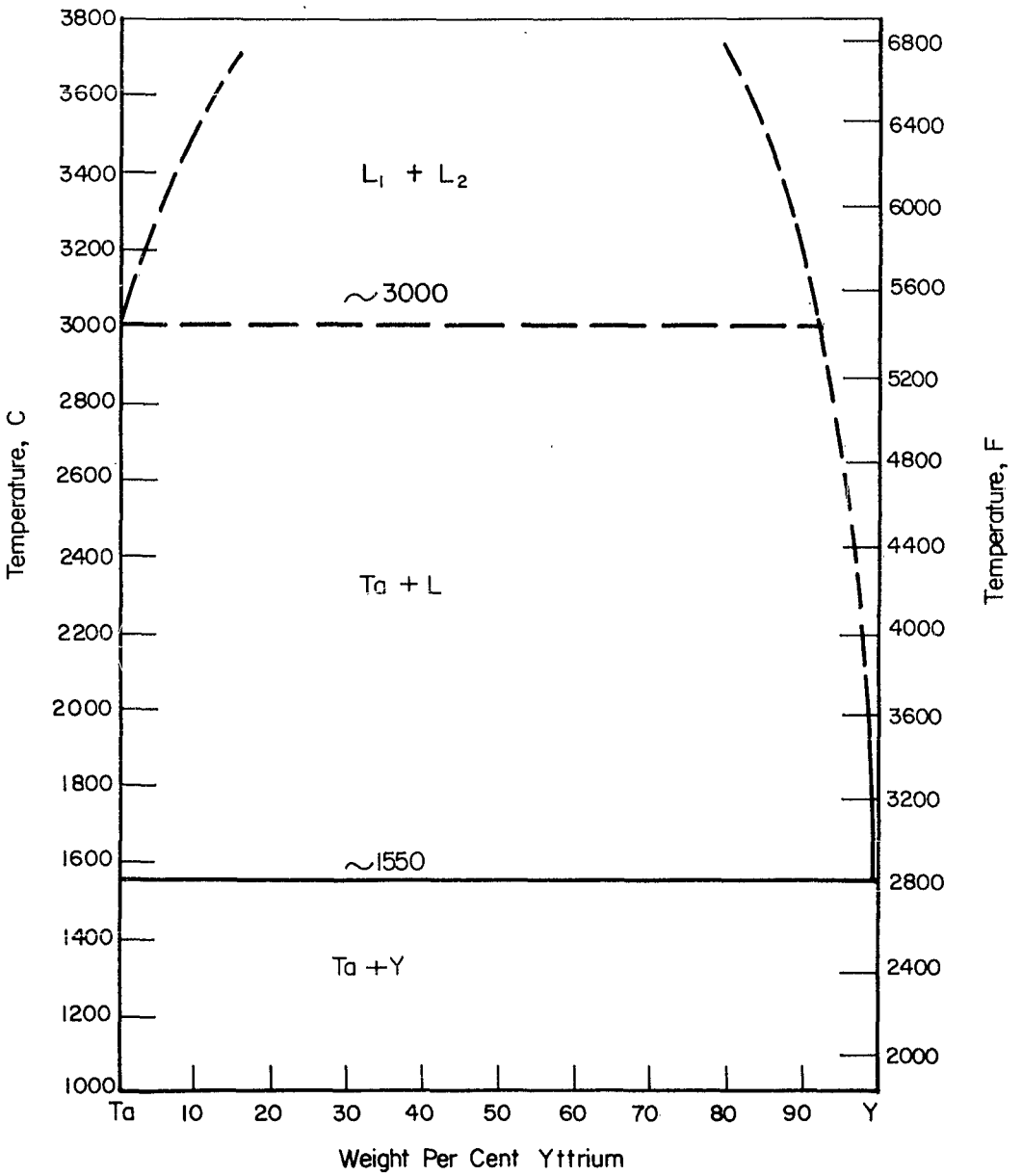
Five intermediate phases occur in the system. Sigma has a tetragonal σ(FeCr) type structure with a = 9.754 A, c = 5.058 A, and c/a = 0.518 at the rhodium-rich side.[91] α_1 is orthorhombic, similar to VCo_3, with a = 5.62 A, b = 9.48 A, and c = 13.61 A.[254] α_2 is orthorhombic and probably isomorphous with Co_2Si with a = 5.45 A, b = 8.15 A, and c = 4.01 A.[254] The structure of α_3 is unknown.[254] $TaRh_3$ has a cubic $AuCu_3$-type structure with a = 3.86 A.[255] The maximum solubility of rhodium in tantalum is 16 ± 1 atomic per cent (10 weight per cent) at 2110 C; tantalum is soluble in rhodium up to 15 ± 0.5 atomic per cent (23.5 weight per cent) at 1990 C.[254]

TANTALUM-THORIUM SYSTEM



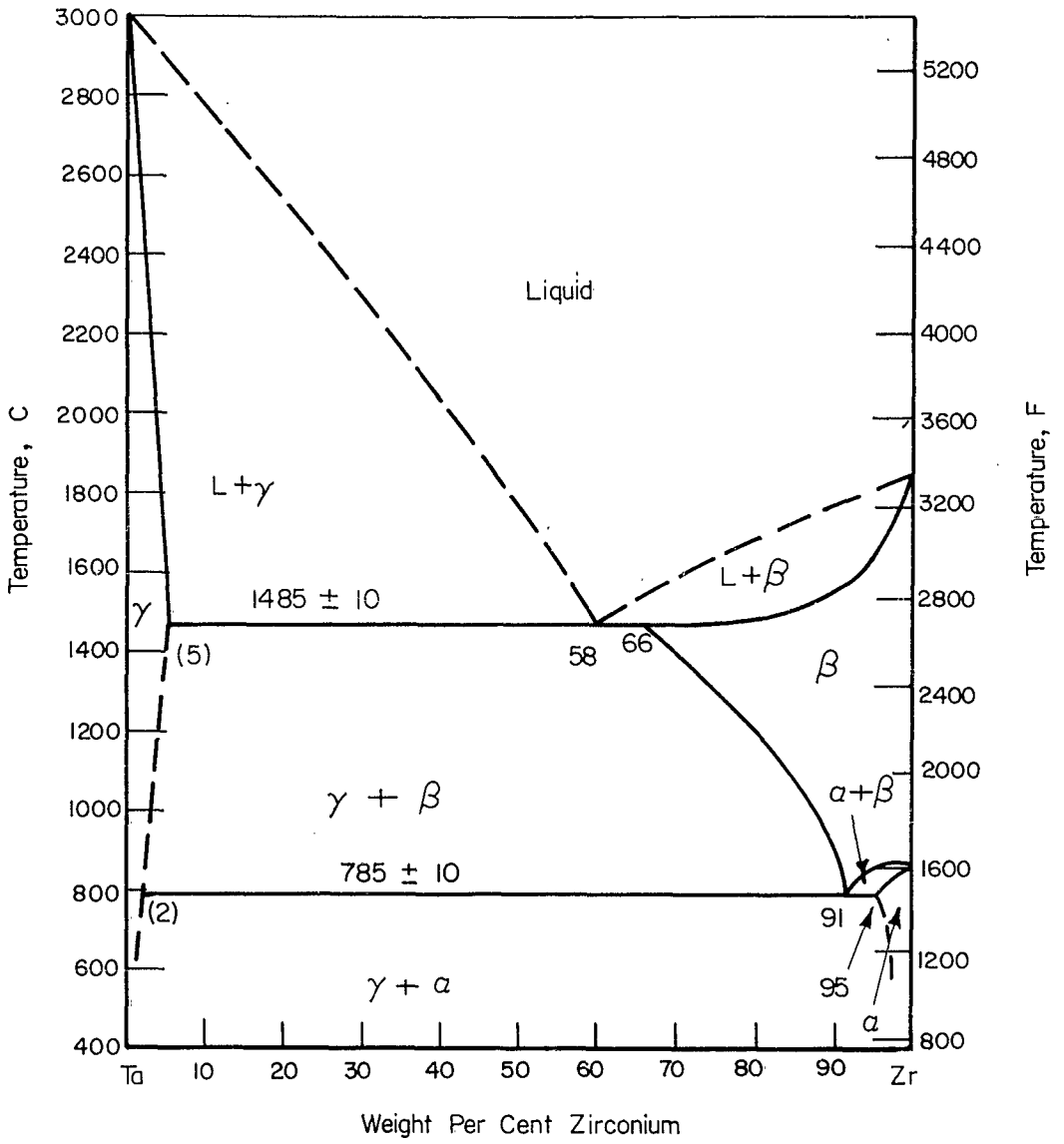
The solubility of thorium in tantalum is less than 0.2 weight per cent at the eutectic temperature. The solubility of tantalum in thorium at the eutectic temperature is about 0.4 weight per cent, and below 1340 C, is less than 0.2 weight per cent. No evidence of intermediate phases was found.(306)

TANTALUM-YTTRIUM SYSTEM



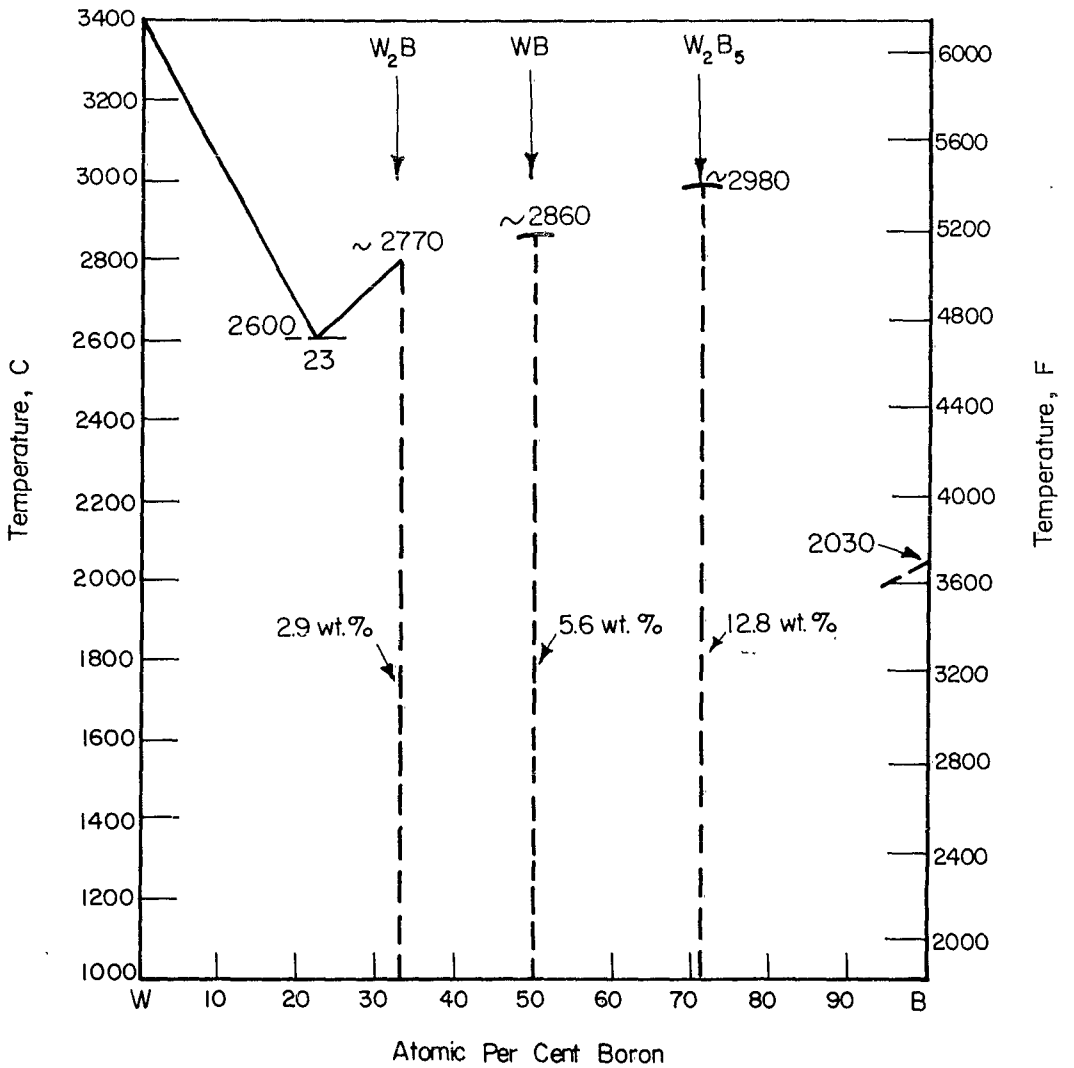
Terminal solubilities are about 0.1 weight per cent.[248, 249]

TANTALUM-ZIRCONIUM SYSTEM



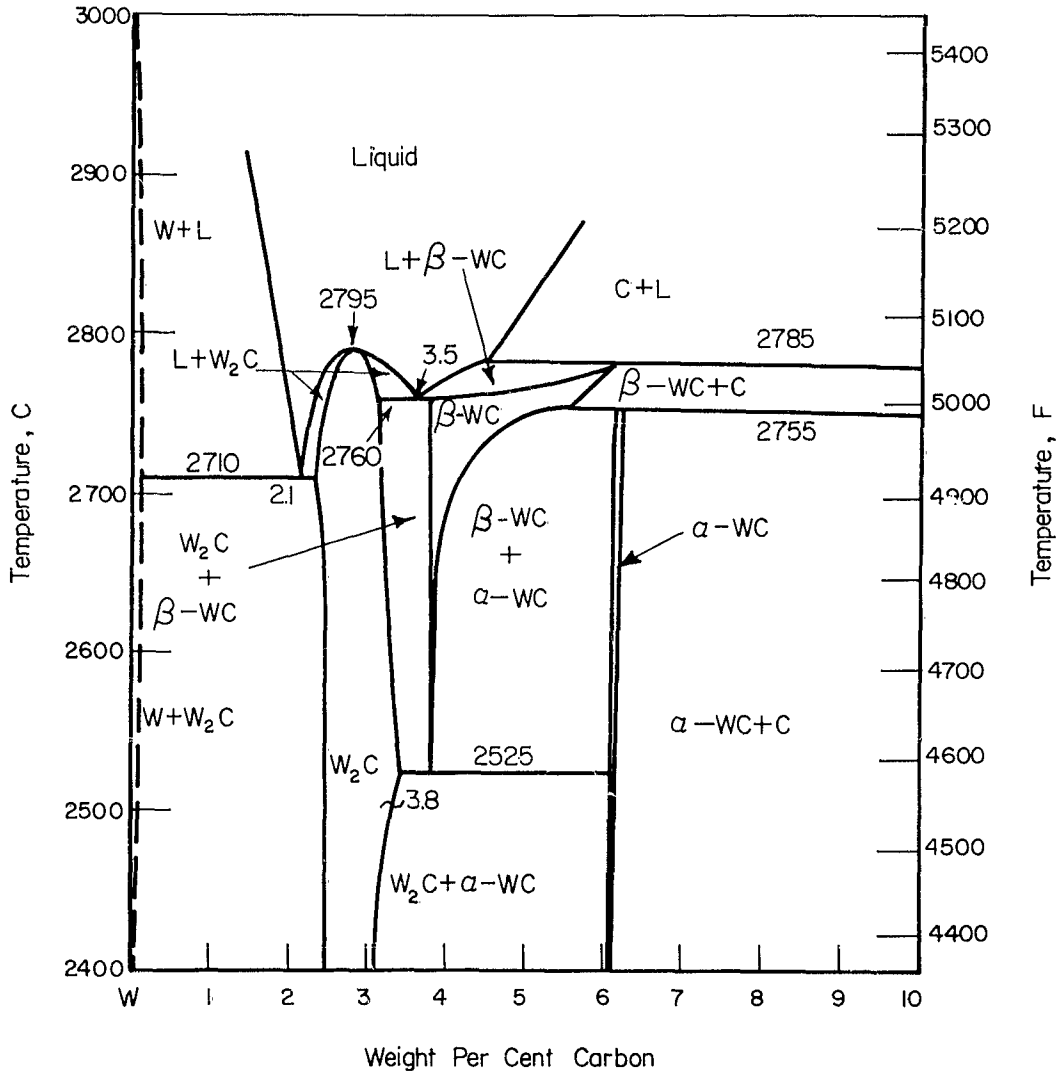
Pease, et al.,[258] locate the eutectic temperature at 1485 C with the eutectic composition at 58 weight per cent (73 atomic per cent) zirconium. The eutectoid composition was given as 91 weight per cent (95.5 ± 1 atomic per cent) zirconium at 785 ± 10 C, the temperature agreeing with Emilyanov, et al.[160] Possible oxygen contamination could have affected Pease's results.

TUNGSTEN-BORON SYSTEM



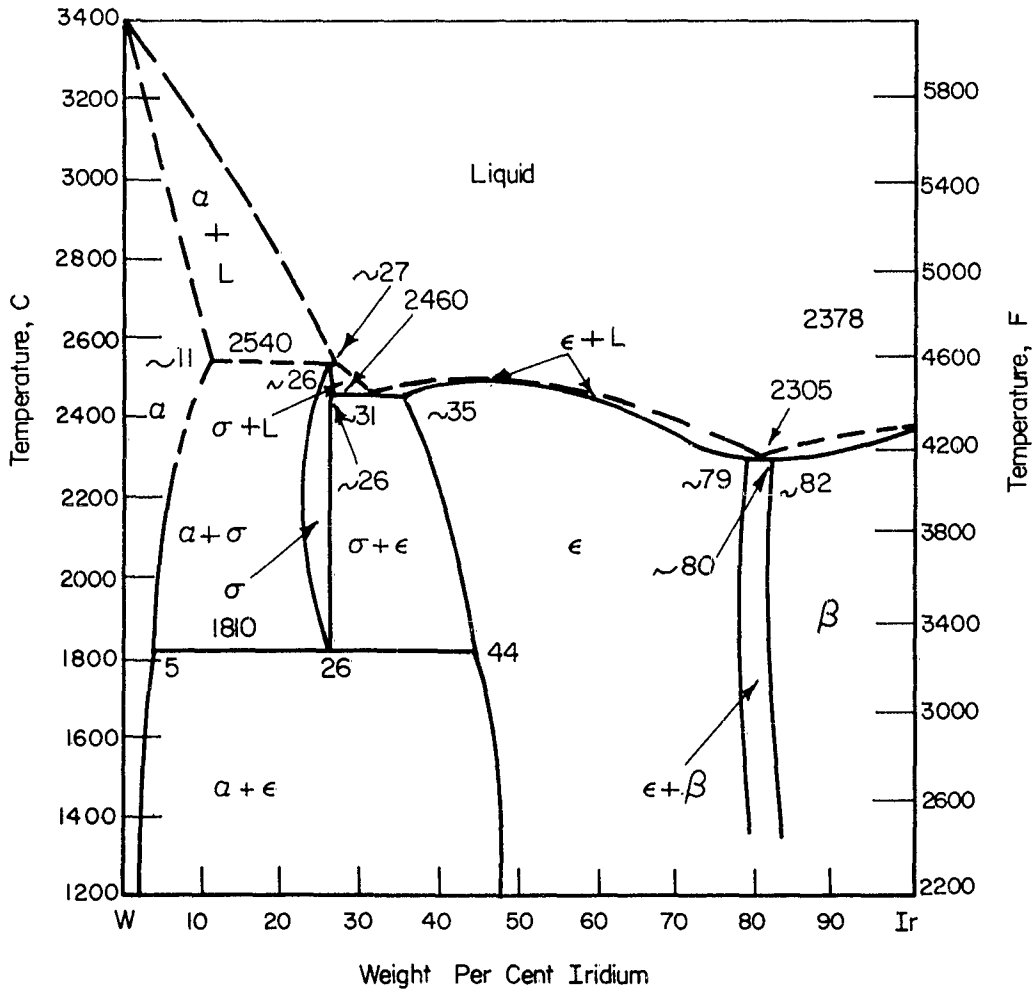
W_2B is tetragonal of the $CuAl_2$ (C16) type with a = 5.564 A, c = 4.740 A, and c/a = 0.852.[58] A low-temperature form of WB, stable below 1850 C, is tetragonal (MoB type) with a = 3.115 A, c = 16.93 A, and c/a = 5.44.[58] The high-temperature modification, corresponding to β-MoB, is orthorhombic (CrB type) with a = 3.19 A, b = 8.40 A, c = 3.07 A.[164] W_2B_5 has a hexagonal defect structure with a = 2.982 A, c = 13.87 A, and c/a = 4.65.[164] The W-W_2B eutectic temperature in 2600 C at 23 atomic per cent boron.[259]

TUNGSTEN-CARBON SYSTEM



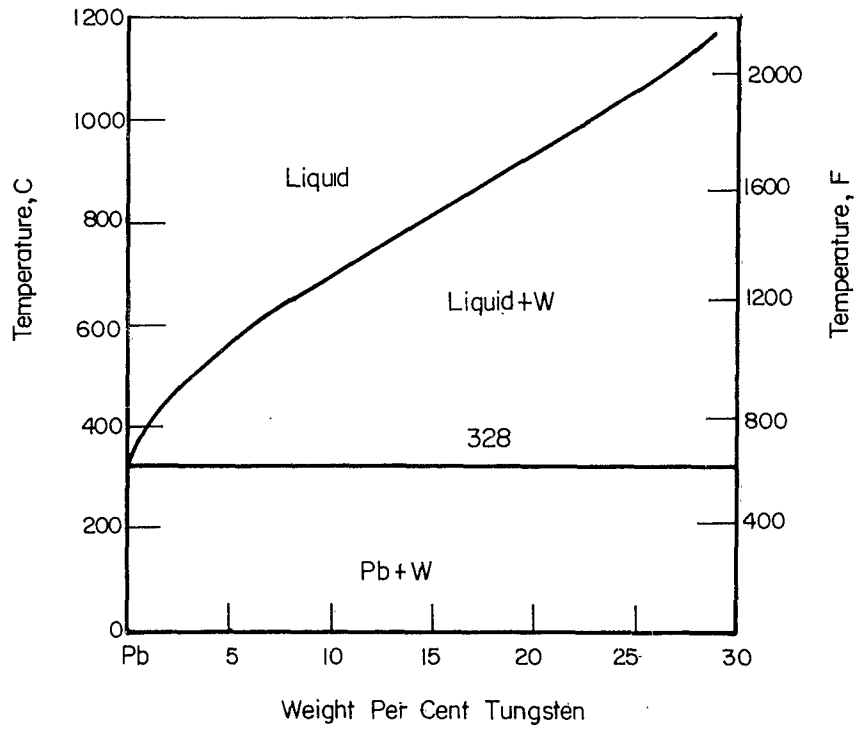
Three intermediate phases were identified by Dolloff, W_2C, α-WC, and β-WC.[260] Only one crystal modification of W_2C was found by Dolloff in contrast to Becker's[165] and Goldschmidt's[259] results of two structures — the low-temperature modification being hexagonal with a = 2.994 A, c = 4.724 A, and c/a = 1.578, and the high-temperature W_2C modification having a face-centered cubic structure with a = 4.16 A. A newly reported phase, β-WC, has a face-centered cubic structure with a = 4.125 A for the composition $WC_{0.82}$.[260] Hexagonal α-WC is essentially a line compound with a = 2.906 A, c = 2.837 A, and c/a = 0.976.[165] Goldsmith reported the solubility of carbon in tungsten as 0.30 atomic per cent near 2400 C, decreasing to 0.05 atomic per cent near 2000 C and to insignificant amounts at lower temperatures.[259]

TUNGSTEN-IRIDIUM SYSTEM



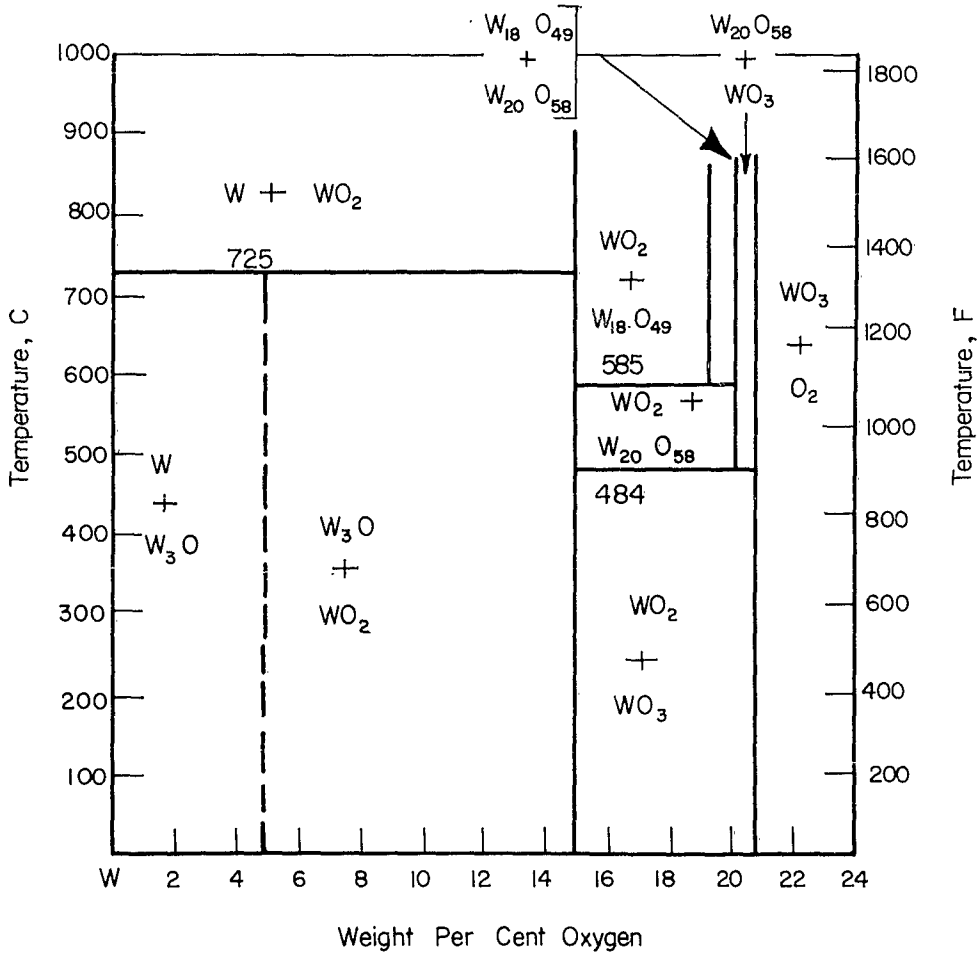
ε has been identified as a close-packed-hexagonal structure with a = 2.736 A and c/a = 1.602 at the iridium side and a = 2.764 A and c/a = 1.611 at the tungsten side of the homogeneity range.[261] The solubility of iridium in tungsten is about 11 weight per cent (~10 atomic per cent) at 2540 C, decreasing to about 5 weight per cent (~4 atomic per cent) at 1810 C. Tungsten is soluble in iridium up to 18 weight per cent (~19 atomic per cent) at 2305 C.[262]

TUNGSTEN-LEAD SYSTEM



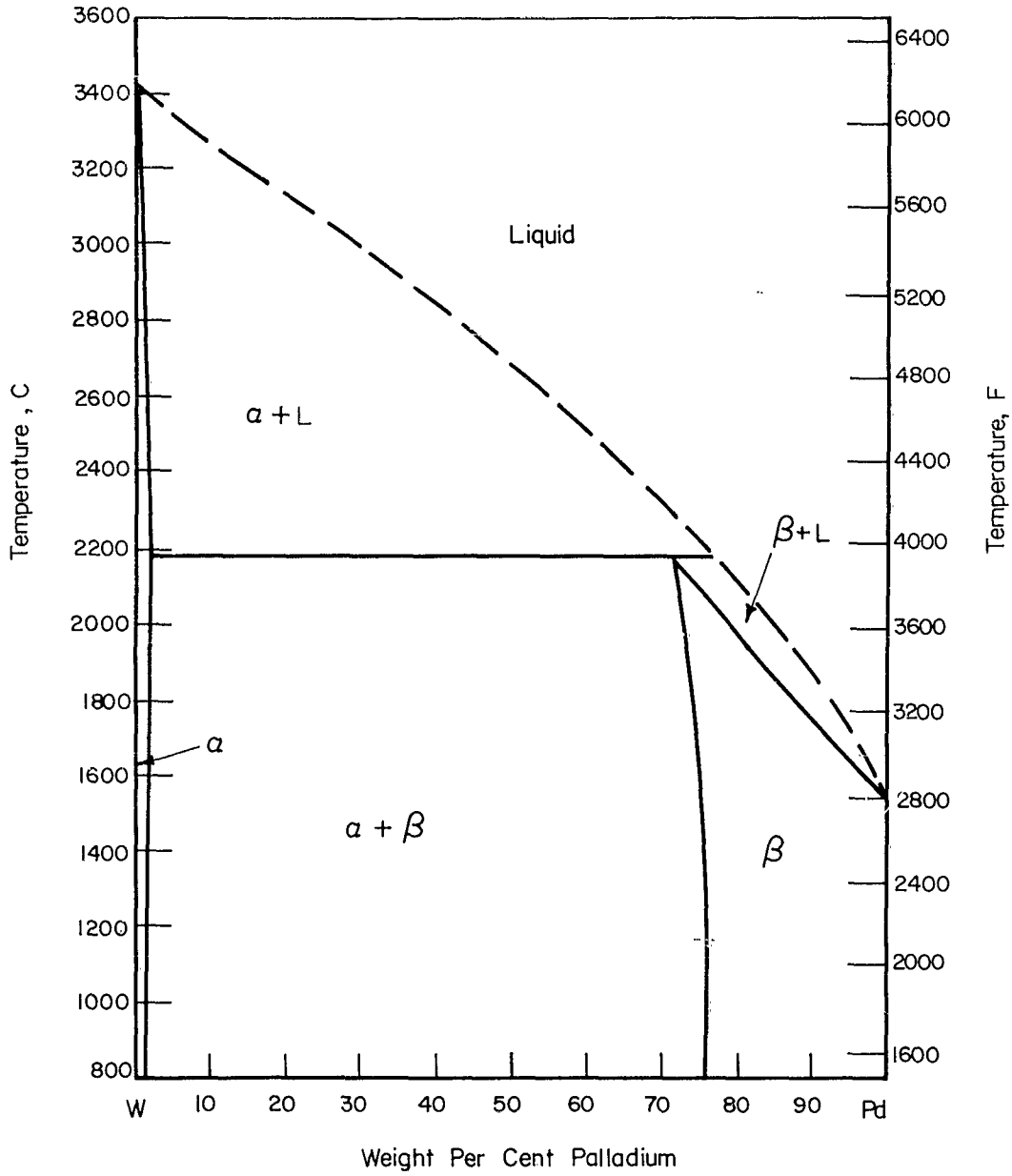
No intermetallic compounds exist in the system.[263]

TUNGSTEN-OXYGEN SYSTEM



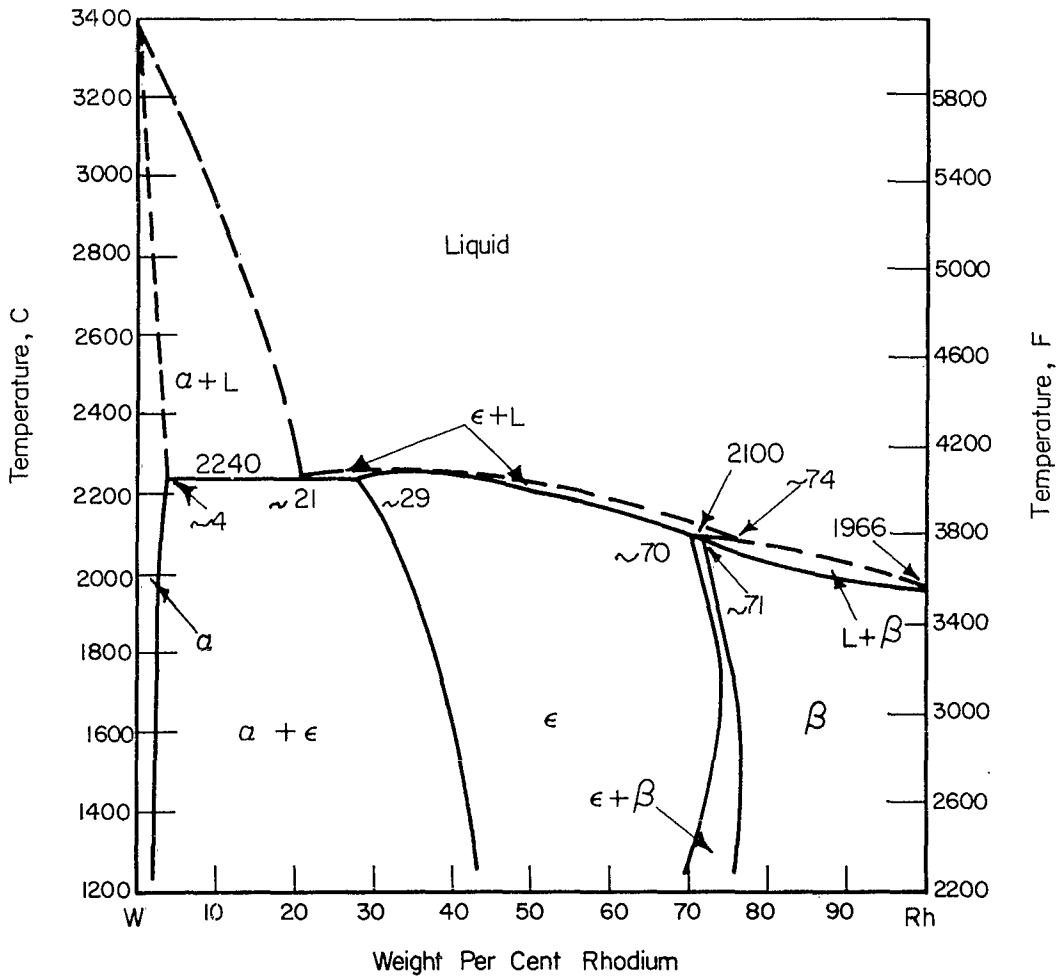
WO_2 has a monoclinic structure isomorphous with MoO_2, with a = 5.560 A, b = 4.884 A, c = 5.546 A, β = 118.93°, and 12 atoms per unit cell.(199) $W_{18}O_{49}$ has a monoclinic structure with a = 18.32 A, b = 3.79 A, C = 11.04 A, β = 115°2', and 67 atoms per unit cell.(200) The structure of $W_{20}O_{58}$ is closely related to monoclinic ReO_3 (DO_9 type) with a = 12.1 A, b = 3.78 A, c = 23.4 A, and β = 95°.(200) WO_3 is reported to have three structural modifications. The room temperature form is monoclinic with a = 7.285 A, b = 7.517 A, c = 3.835 A, and β = 90.90°.(201) At -50 C, a polymorphic transformation occurs, resulting in a structure of higher symmetry than the room-temperature modification.(202) Between 700 and 750 C, a polymorphic transformation occurs, resulting in a tetragonal structure with a = 5.25 A, c = 3.92 A, c/a = 0.746, and 8 atoms per unit cell.(203) The homogeneity ranges (oxygen/tungsten ratios) of the oxides at 1258 C are: WO_2 (1.99 to 2.02), $W_{18}O_{49}$ (2.66 to 2.77), and $W_{20}O_{58}$ (2.90 to 2.94).(200) The diagram is from Reference (264).

TUNGSTEN-PALLADIUM SYSTEM



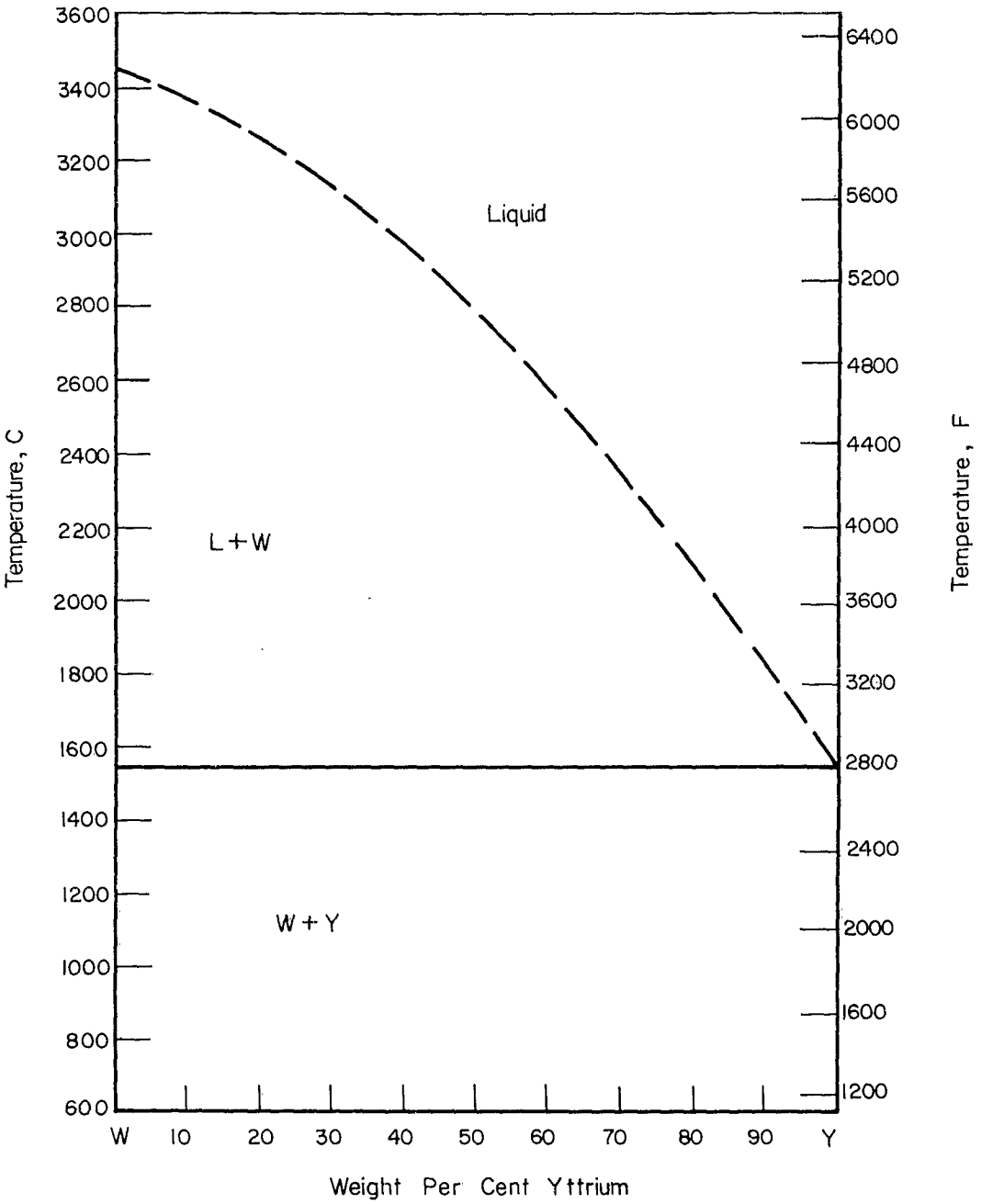
No intermediate phases are found in this system. The solubility of palladium in tungsten is 1.6 weight per cent at 1500 C. Tungsten dissolves in palladium up to 24 weight per cent at 1000 C.[265]

TUNGSTEN-RHODIUM SYSTEM



ε has a close-packed-hexagonal structure with a = 2.708 A, c = 4.328 A, and c/a = 1.598 at 70 weight per cent (80.8 atomic per cent) rhodium.[30] The solubility of rhodium in tungsten is about 4 weight per cent (6 atomic per cent) at 2240 C, decreasing to about 3 weight per cent (4 atomic per cent) at 1300 C. Tungsten is soluble in rhodium up to 29 weight per cent (19 atomic per cent) at 2100 C, decreasing to about 23 weight per cent (14 atomic per cent) at 1400 C.[262]

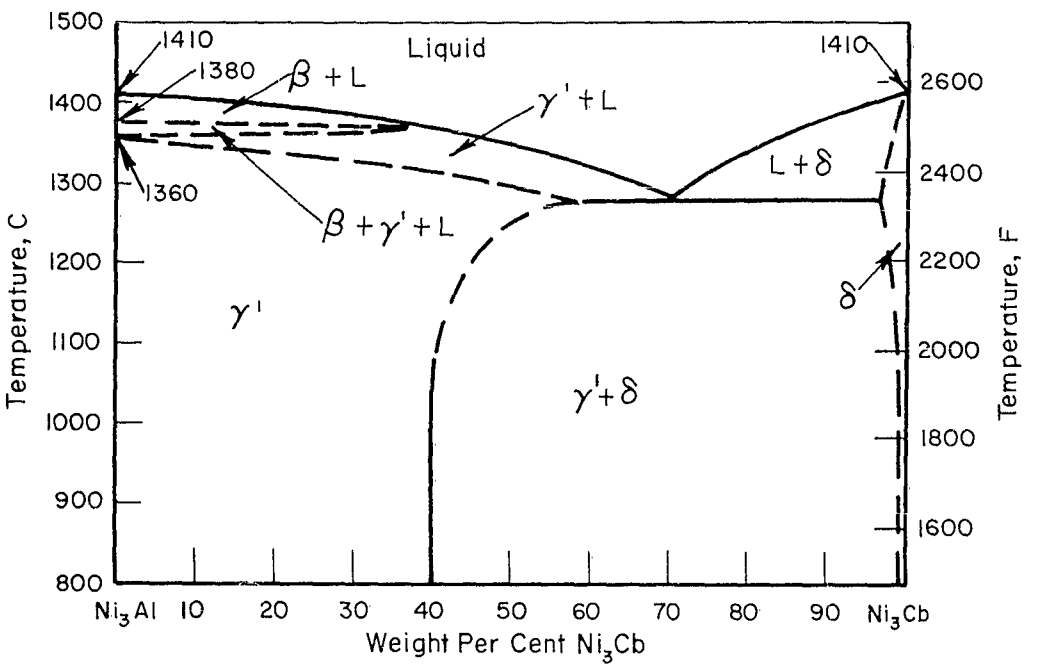
TUNGSTEN-YTTRIUM SYSTEM



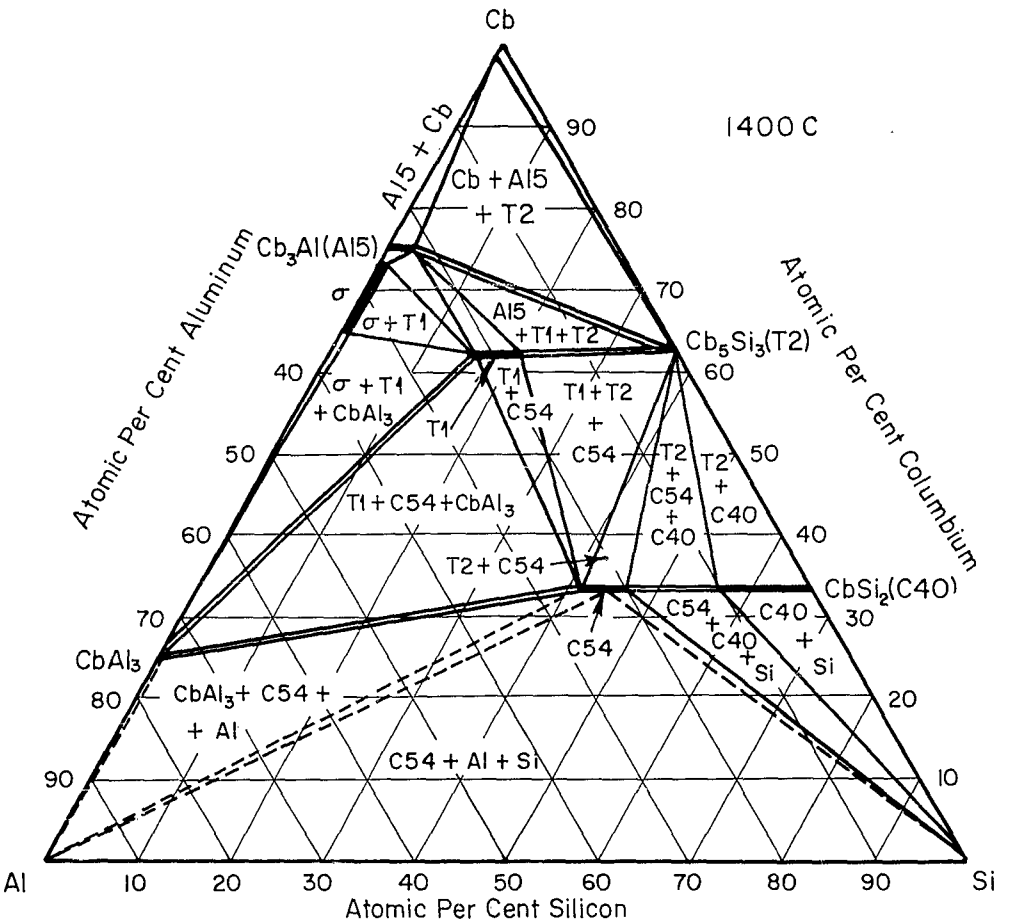
Terminal solubilities are probably less than 1 atomic per cent.[247]

TERNARY PHASE DIAGRAMS

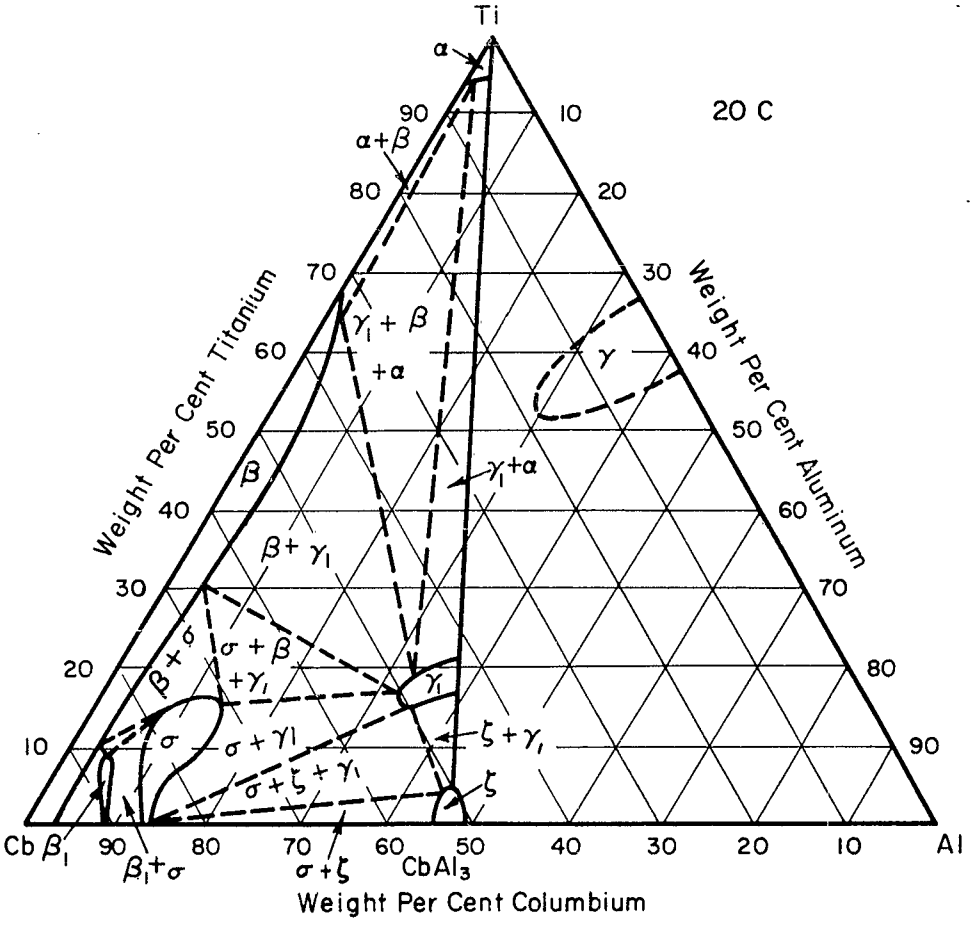
COLUMBIUM-ALUMINUM-NICKEL SYSTEM (Ni_3Al-Ni_3Cb SYSTEM)[317]



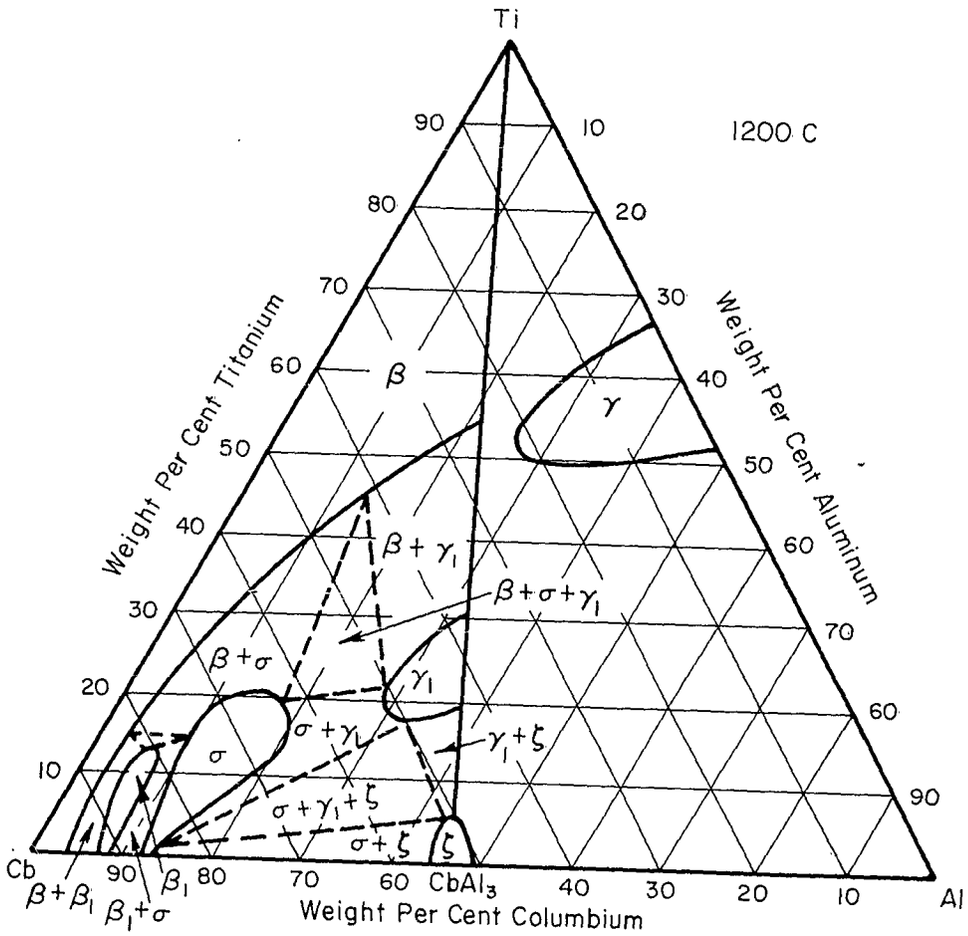
COLUMBIUM-ALUMINUM-SILICON SYSTEM (1400 C)[268]



COLUMBIUM-ALUMINUM-TITANIUM SYSTEM (20 C)[269]

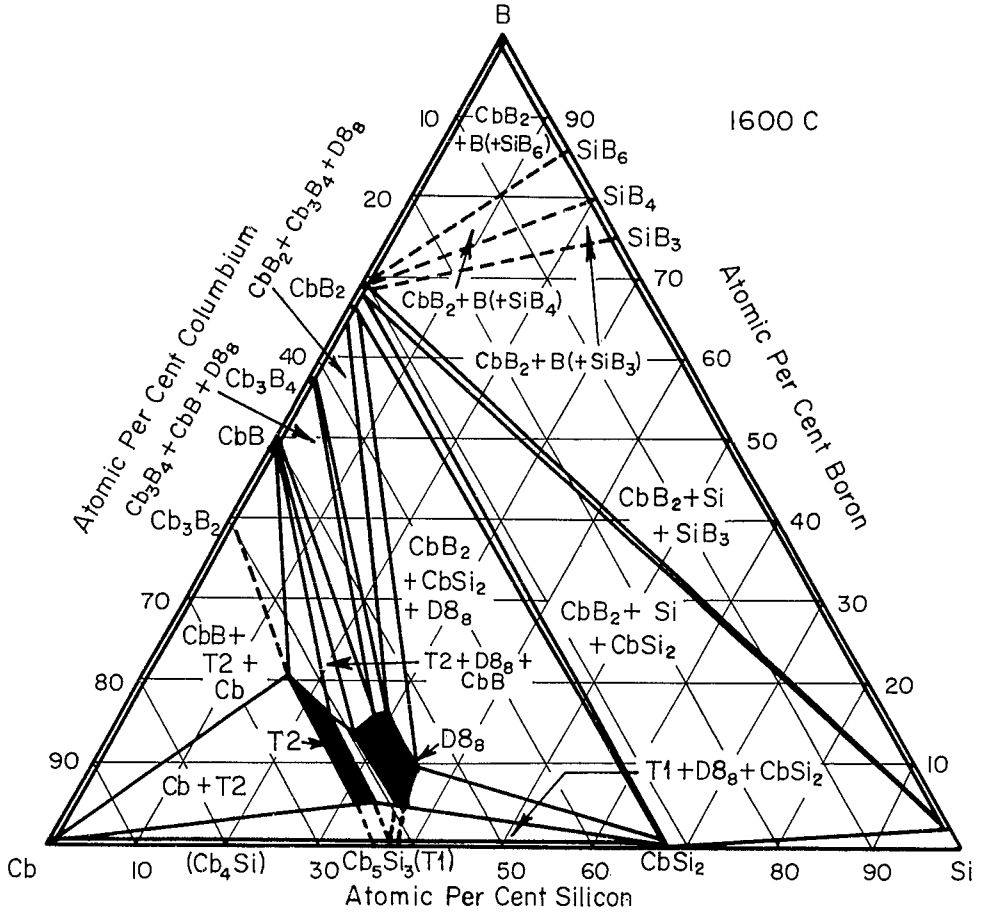


COLUMBIUM-ALUMINUM-TITANIUM SYSTEM (1200 C)(269)

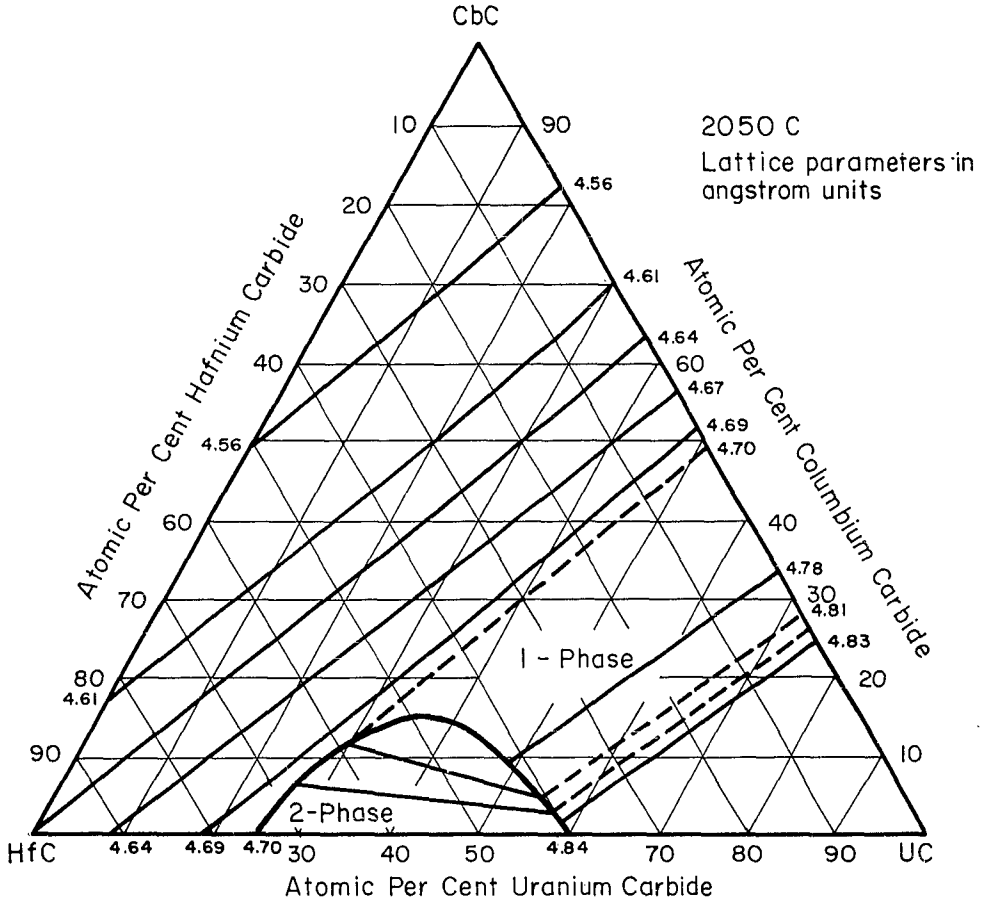


(99-4)-63

COLUMBIUM-BORON-SILICON SYSTEM (1600 C)[270]

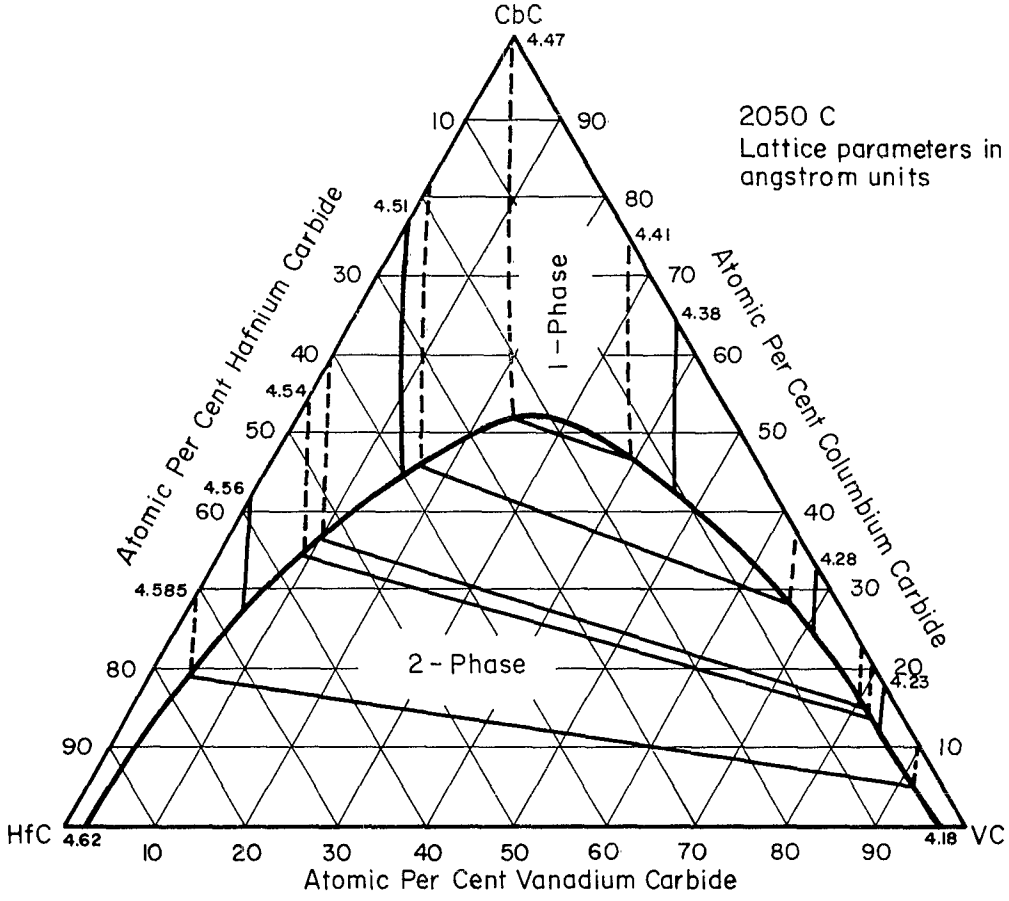


COLUMBIUM CARBIDE-HAFNIUM CARBIDE-URANIUM CARBIDE SYSTEM (2050 C)[271]

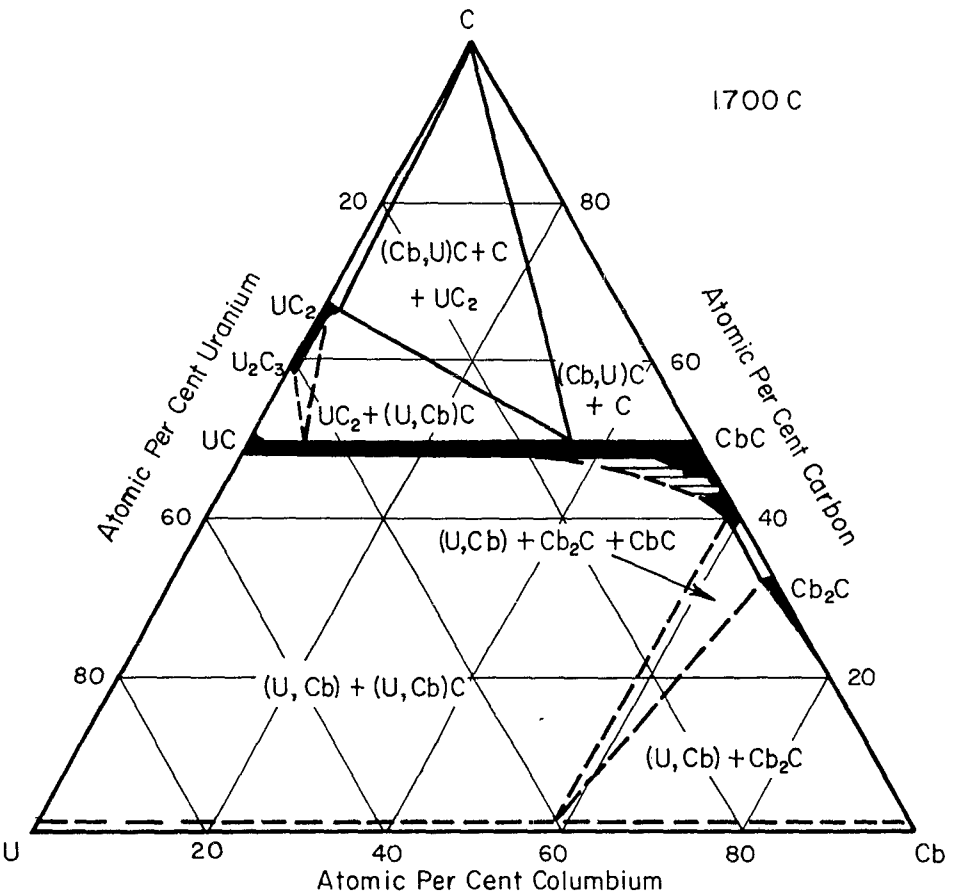


(99-6)-63

COLUMBIUM CARBIDE-HAFNIUM CARBIDE-VANADIUM CARBIDE SYSTEM (2050 C)[271]

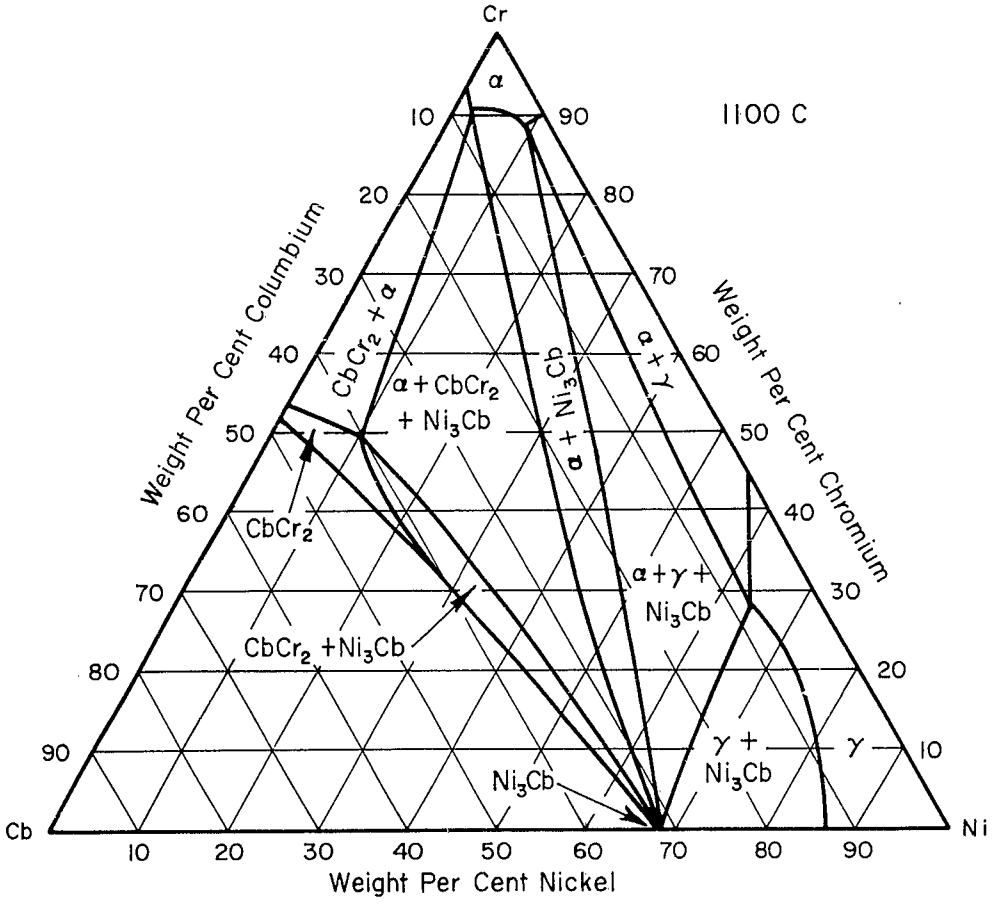


COLUMBIUM-CARBON-URANIUM SYSTEM (1700 C)[272]

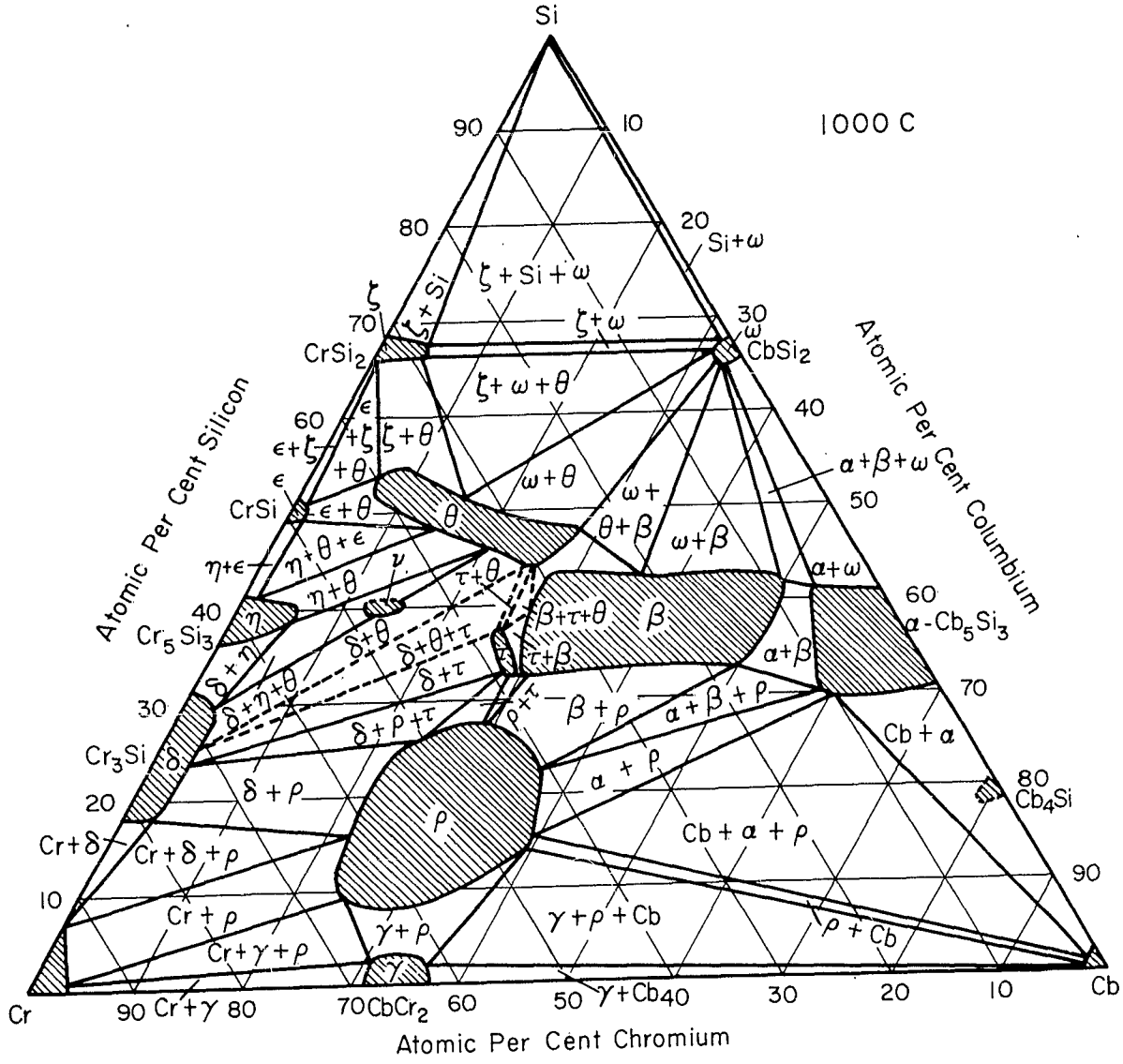


(99-8)-63

COLUMBIUM-CHROMIUM-NICKEL SYSTEM (1100 C)[273]

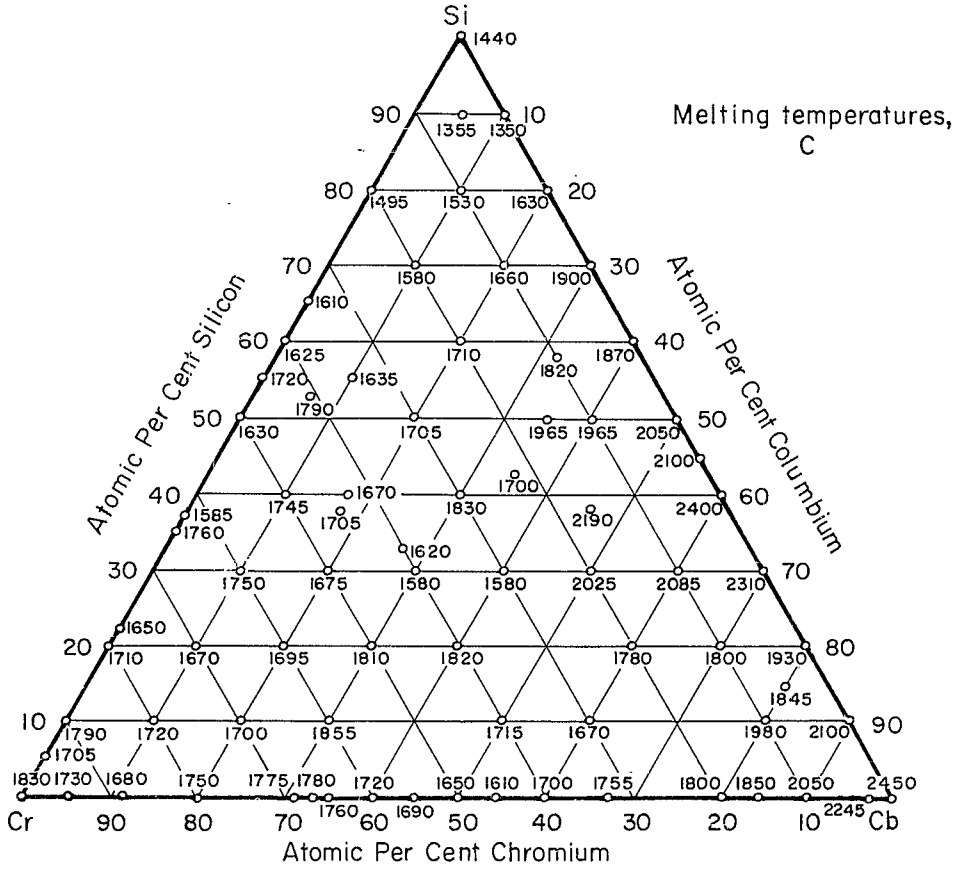


COLUMBIUM-CHROMIUM-SILICON SYSTEM (1000 C)[274]

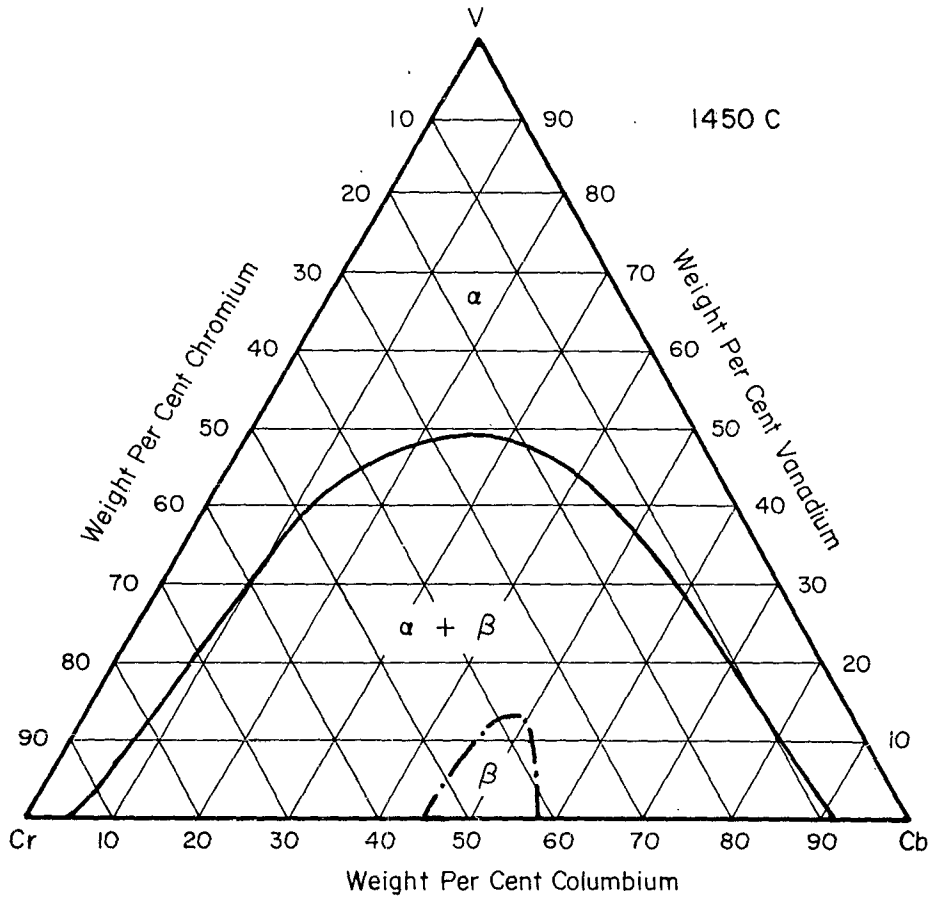


ρ has an hexagonal Laves-type structure with a = 4.893 kX, c = 7.996 kX at $Cb_{0.3}Cr_{0.2}Si_{0.5}$. β has the W_5Si_3-type structure ($=\beta Cb_5Si_3$). The approximate composition of τ is $Cr_{37}Cb_{27}Si_{36}$; it has a body-centered cubic lattice with a = 8.11 kX. θ is orthorhombic with a = 15.82 kX, b = 4.90 kX and c = 7.51 kX. ν has the approximate composition $Cr_{45}Cb_{15}Si_{40}$ and appears to be metastably retained in an irregular fashion.[274]

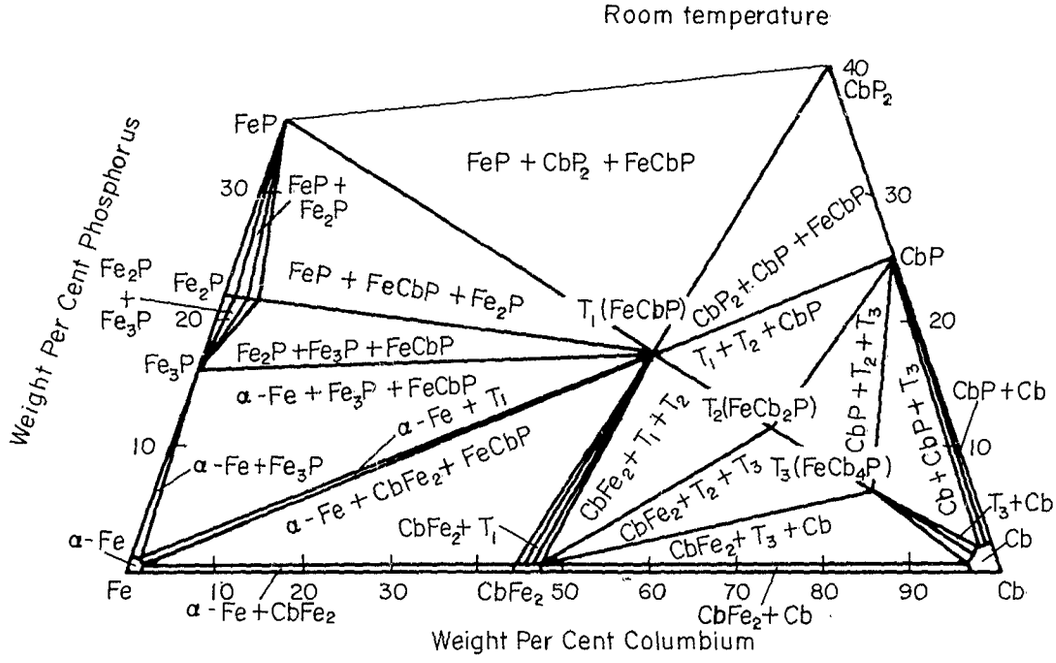
COLUMBIUM-CHROMIUM-SILICON SYSTEM (MELTING TEMPERATURES, C)[274]



COLUMBIUM-CHROMIUM-VANADIUM SYSTEM (1450 C)[275]

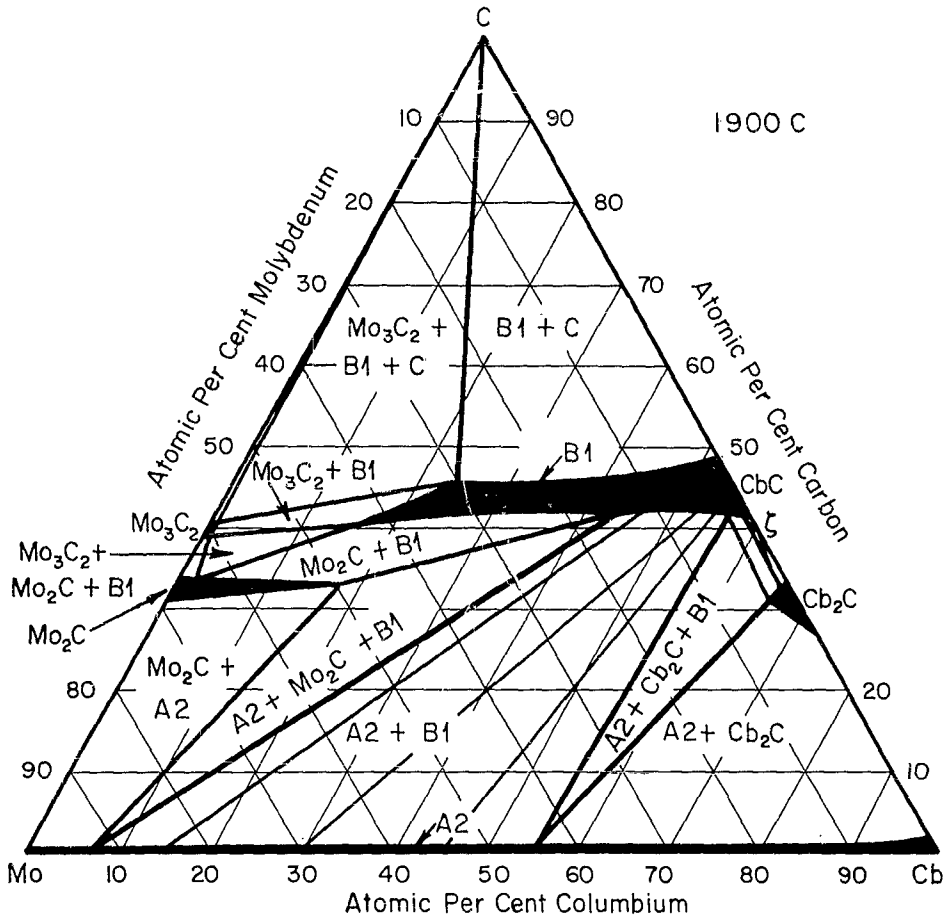


COLUMBIUM-IRON-PHOSPHORUS SYSTEM (ROOM TEMPERATURE)[276]



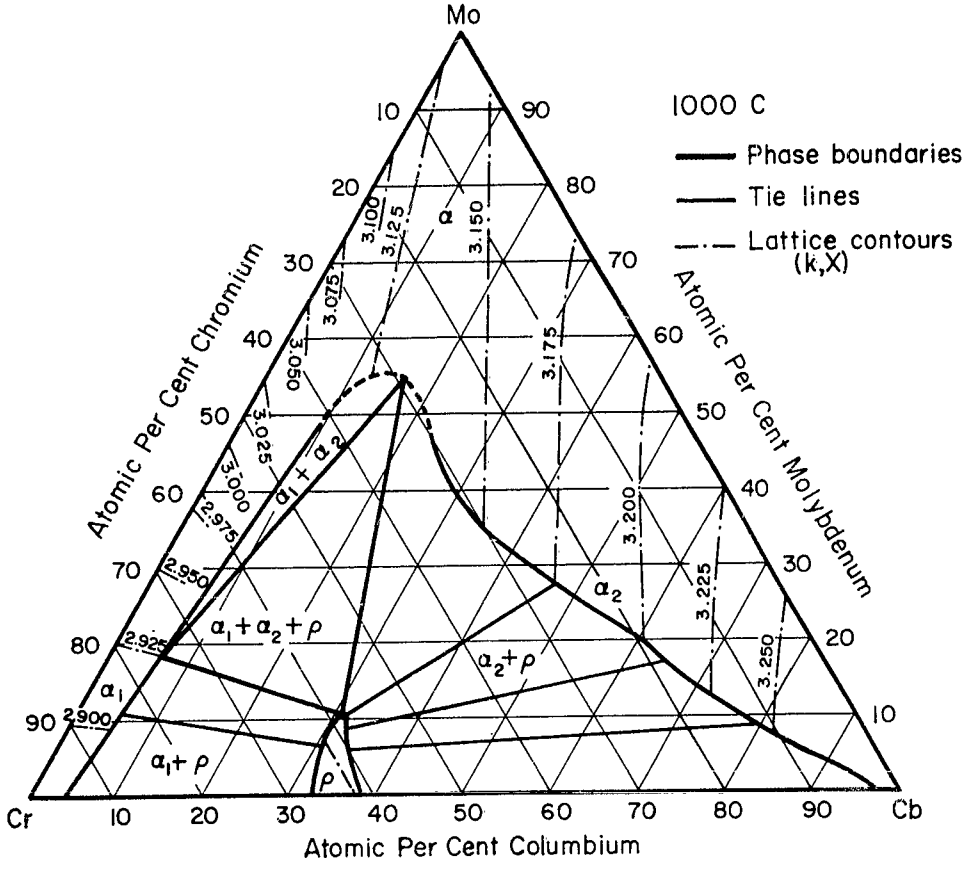
(99-13)-63

COLUMBIUM-MOLYBDENUM-CARBON SYSTEM (1900 C)[277]

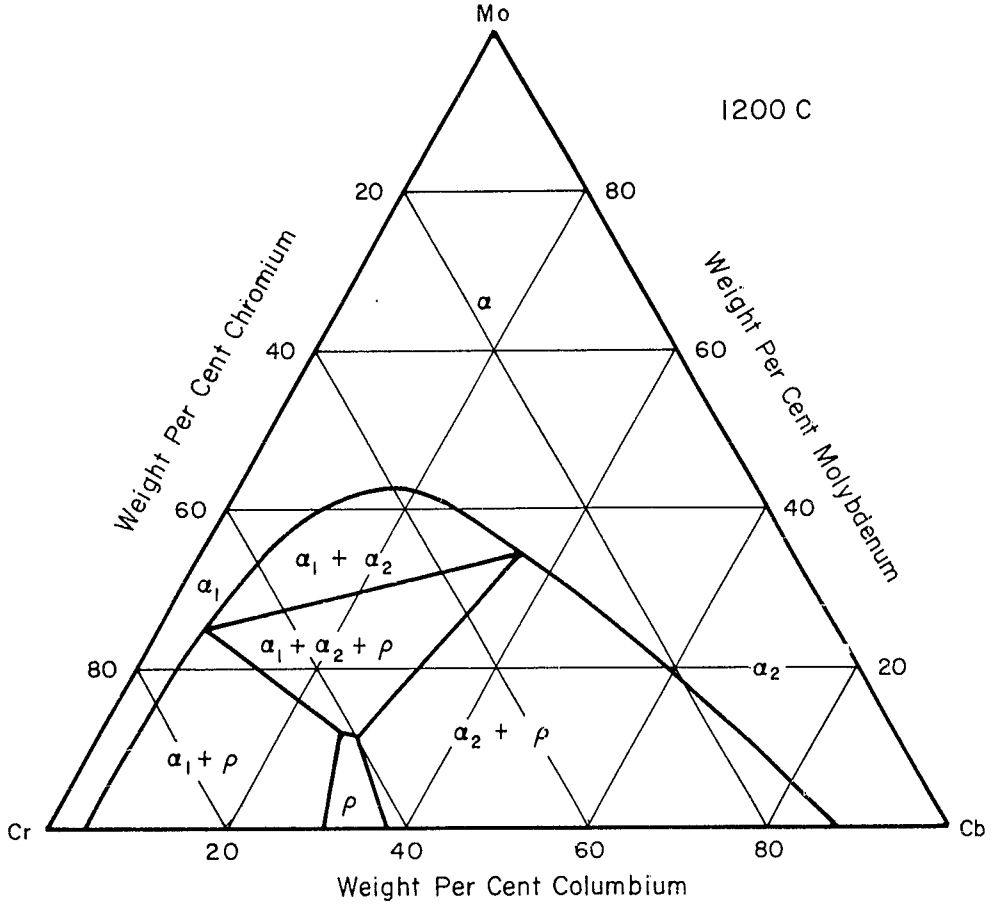


(102-1)-63

COLUMBIUM-MOLYBDENUM-CHROMIUM SYSTEM (1000 C)[278]

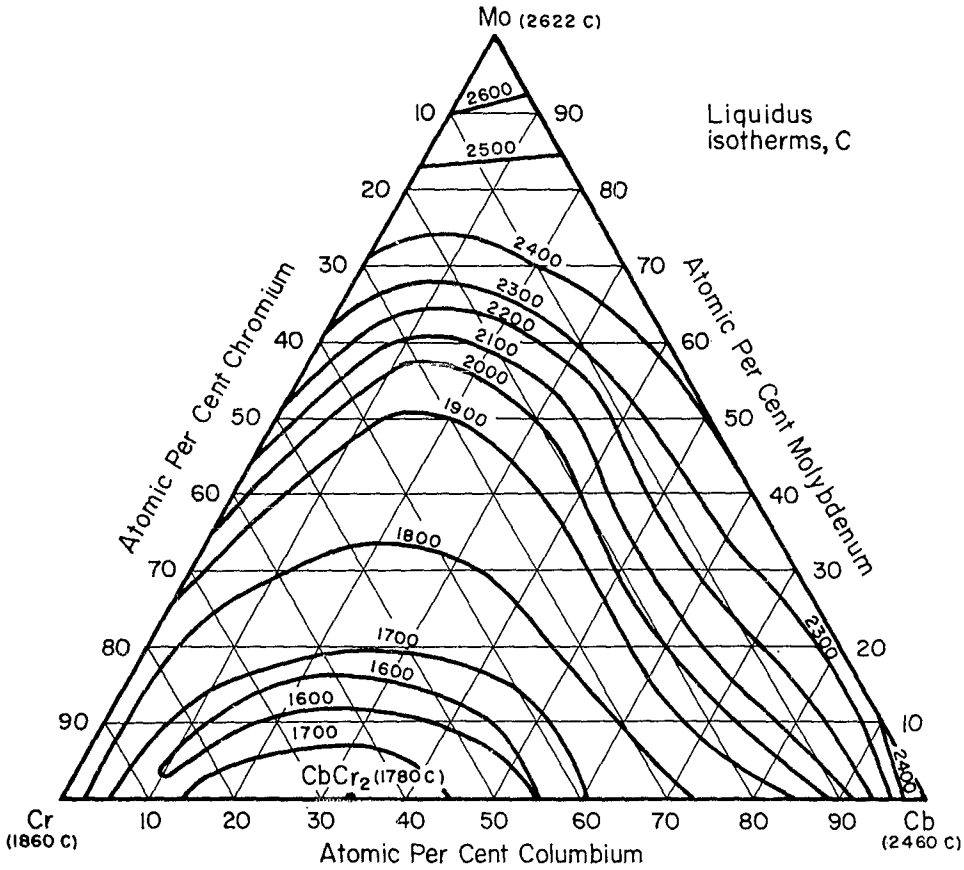


COLUMBIUM-MOLYBDENUM-CHROMIUM SYSTEM (1200 C)[279]

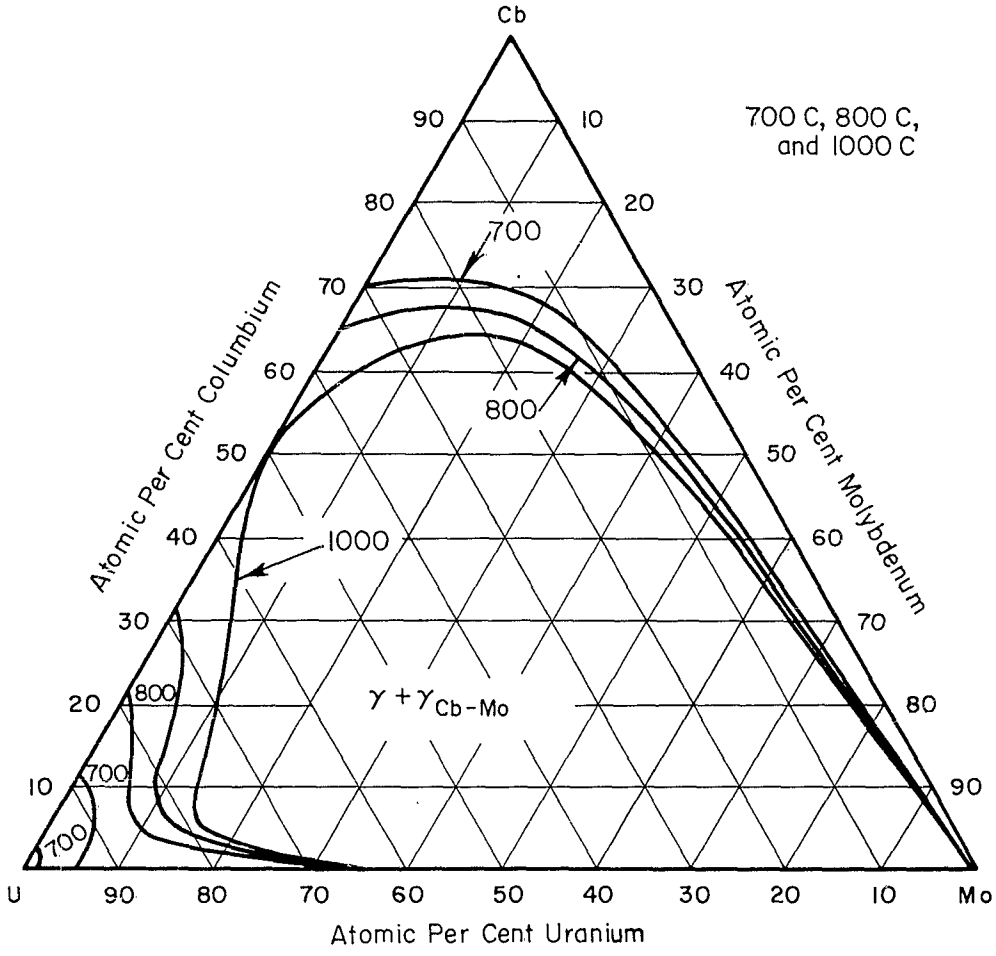


(102-3)-63

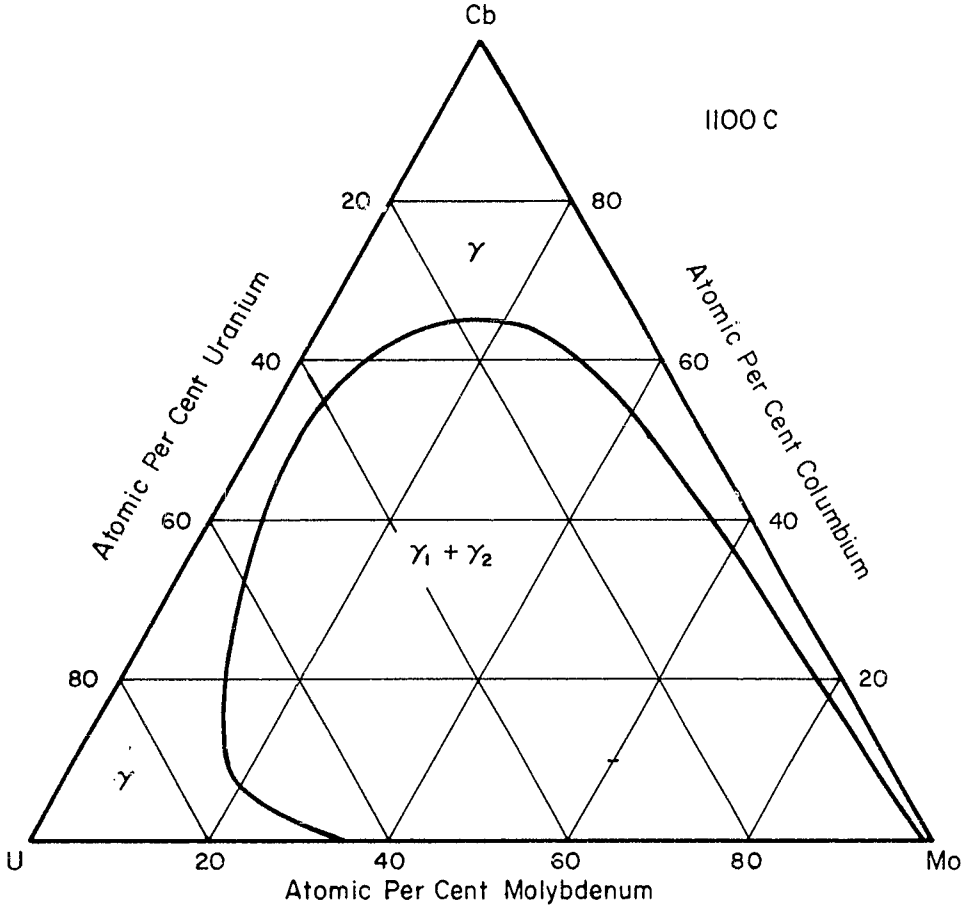
COLUMBIUM-MOLYBDENUM-CHROMIUM SYSTEM (LIQUIDUS ISOTHERMS)[278]



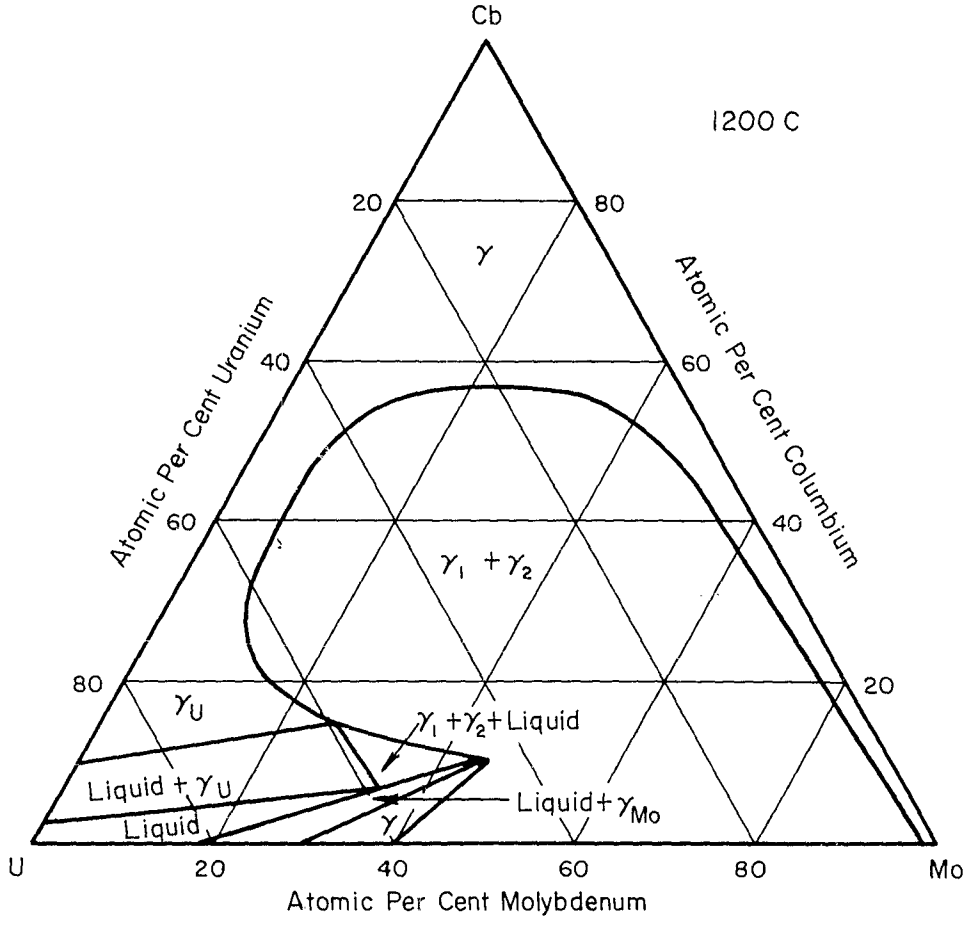
COLUMBIUM-MOLYBDENUM-URANIUM SYSTEM (700 C, 800 C, 900 C)[280]



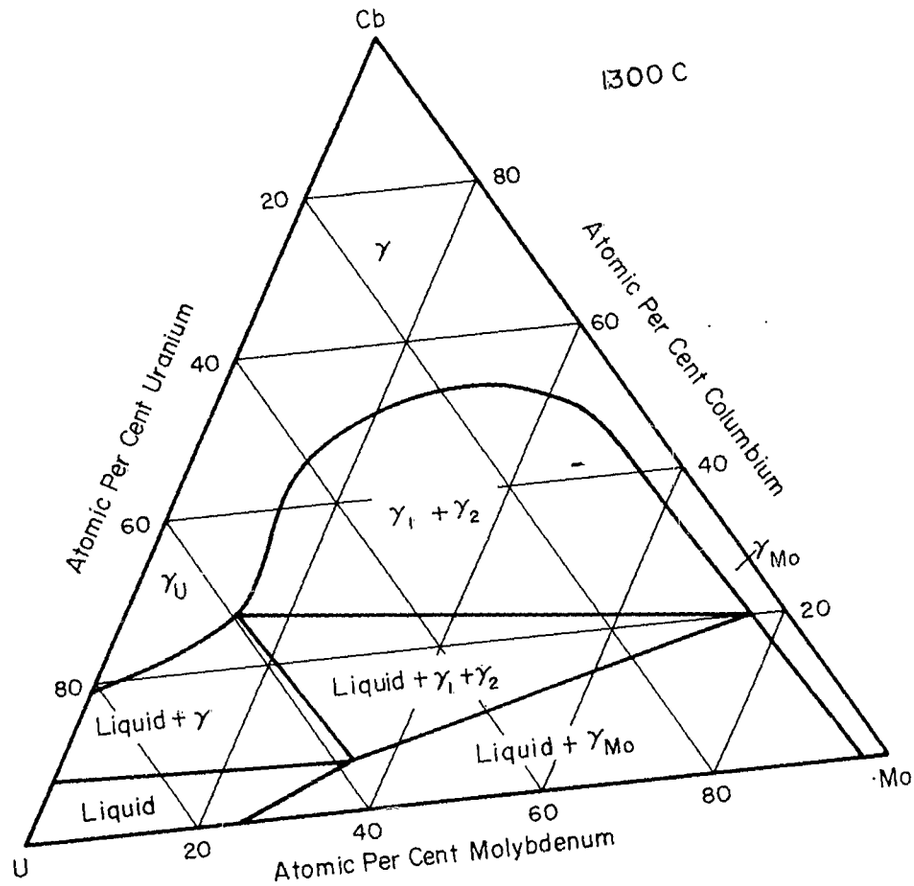
COLUMBIUM-MOLYBDENUM-URANIUM SYSTEM (1100 C)[318]



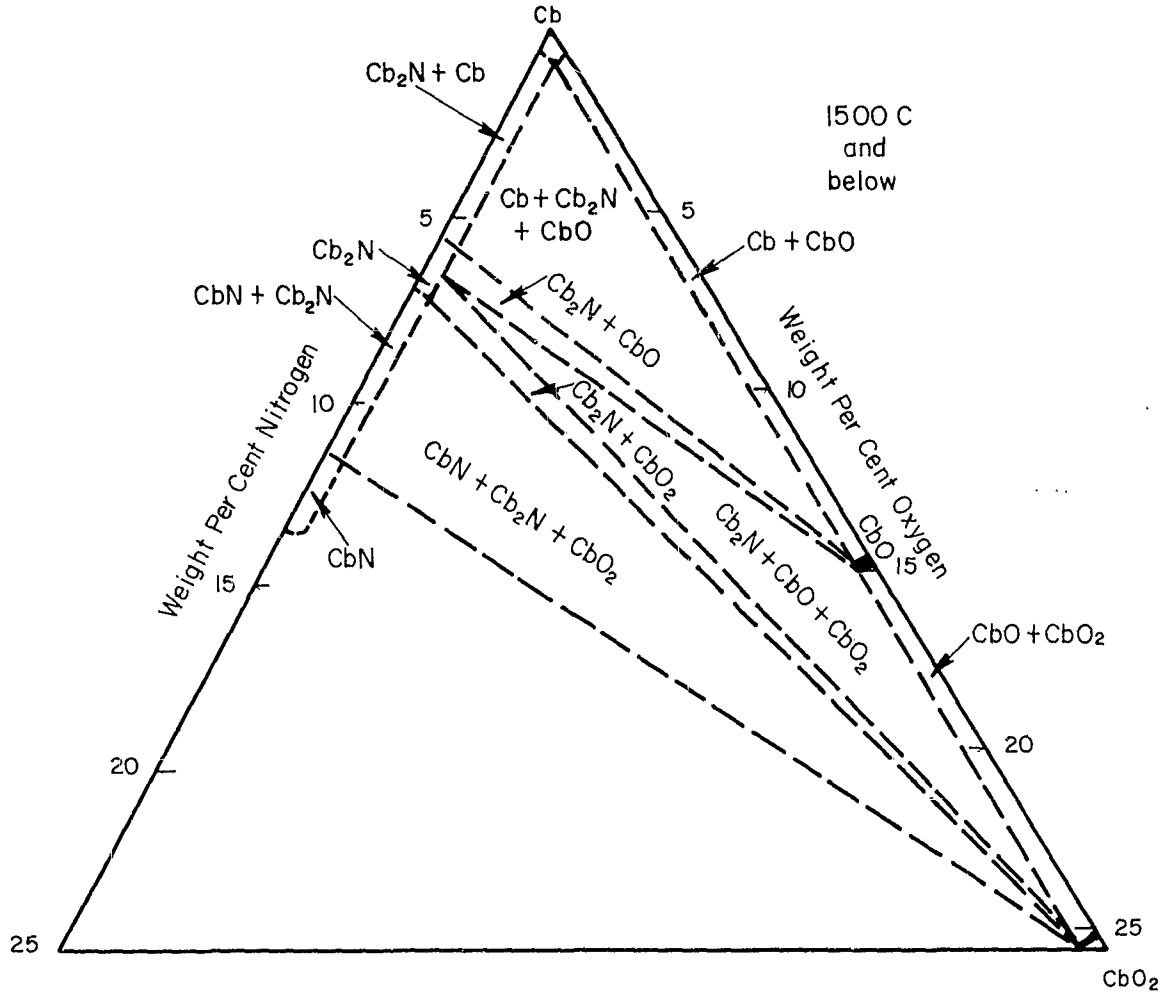
COLUMBIUM-MOLYBDENUM-URANIUM SYSTEM (1200 C)[318]



COLUMBIUM-MOLYBDENUM-URANIUM SYSTEM (1300 C)[318]

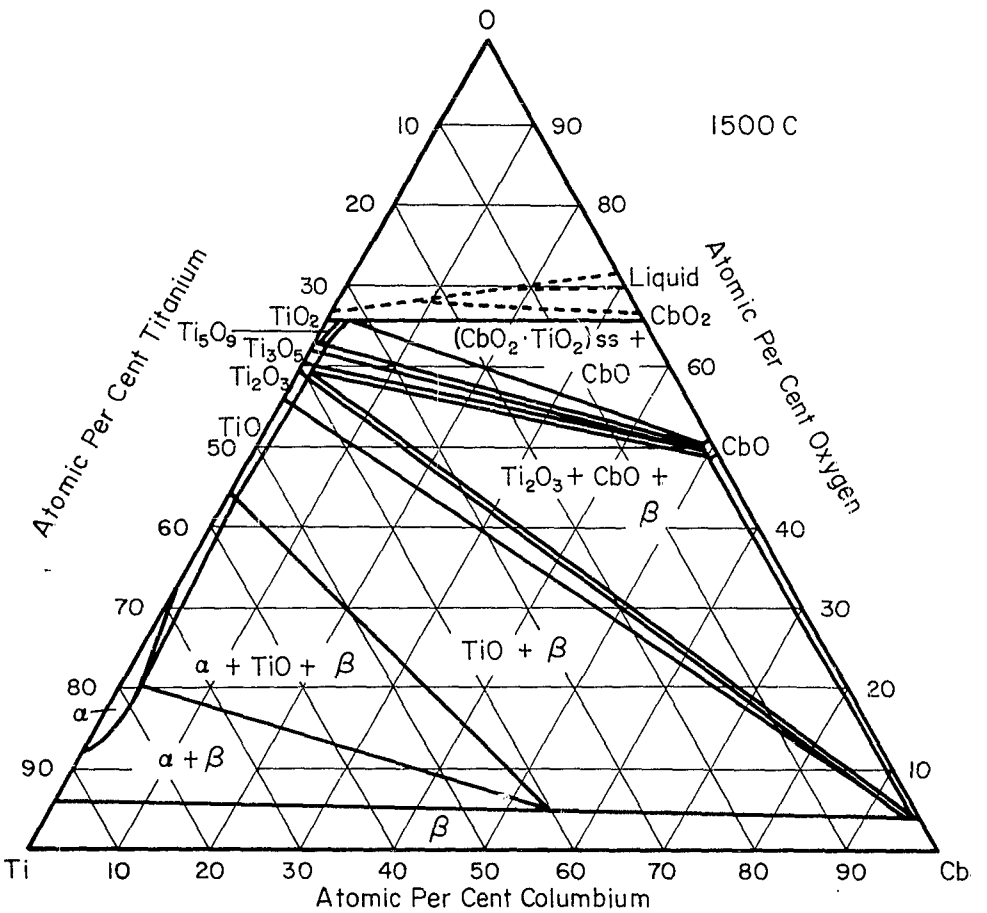


COLUMBIUM-NITROGEN-OXYGEN SYSTEM (1500 C)[281]



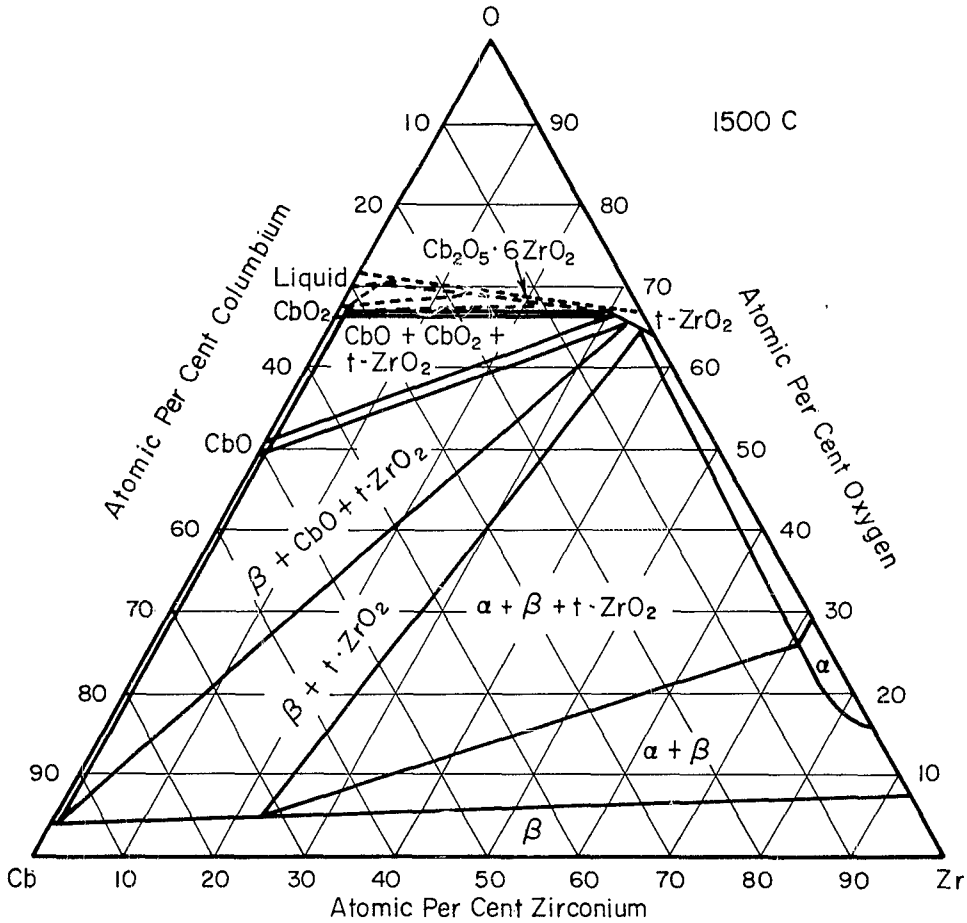
(107-1)-63

COLUMBIUM-OXYGEN-TITANIUM SYSTEM (1500 C)[301]



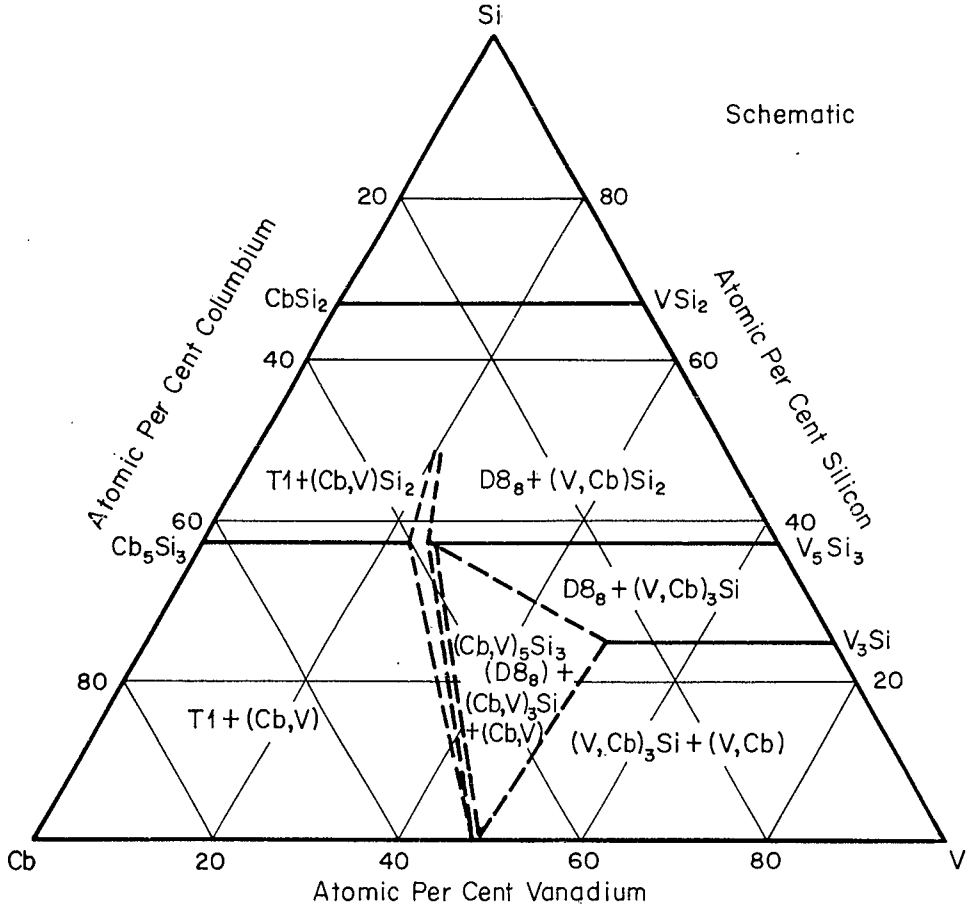
(107-2)-63

COLUMBIUM-OXYGEN-ZIRCONIUM SYSTEM (1500 C)[301]

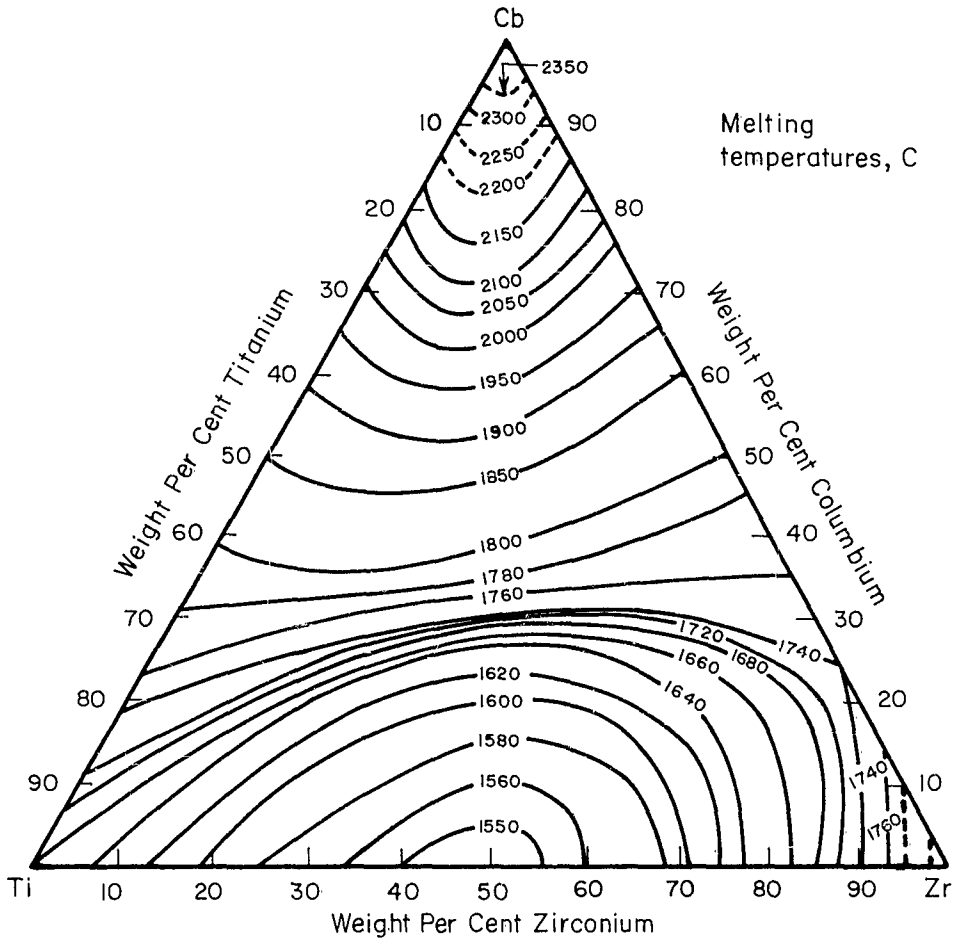


(107-3)-63

COLUMBIUM-SILICON-VANADIUM SYSTEM (SCHEMATIC)[315]

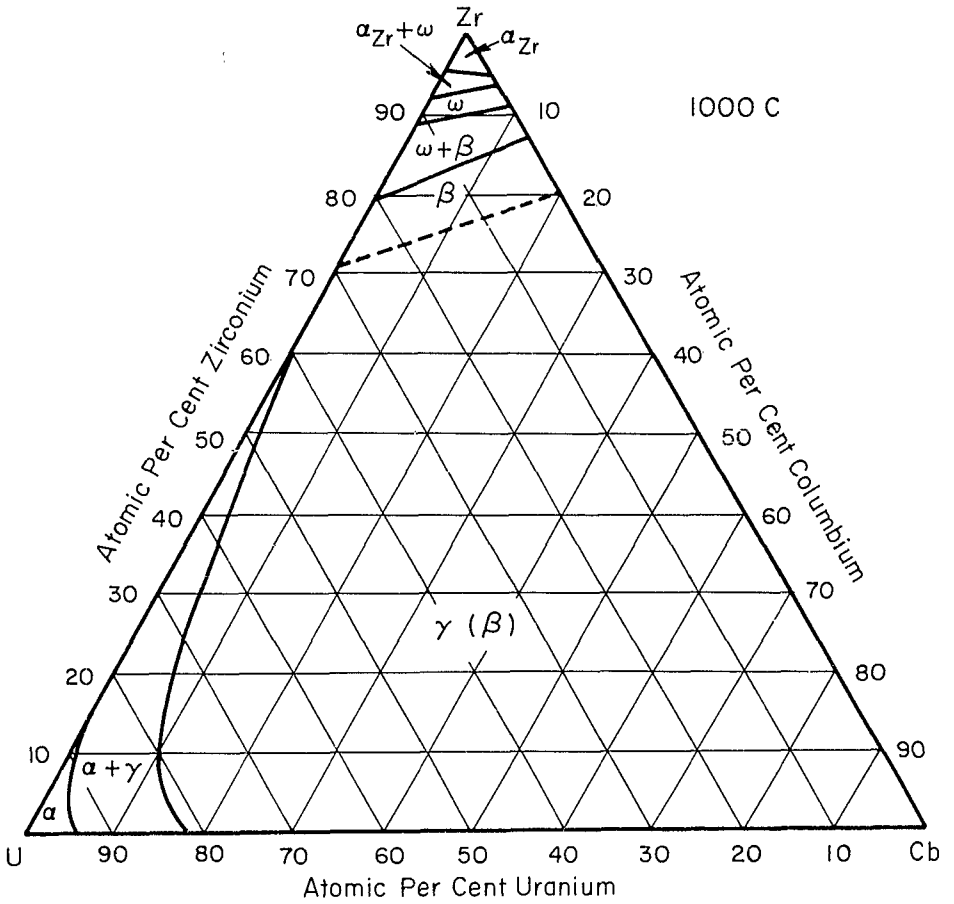


COLUMBIUM-TITANIUM-ZIRCONIUM SYSTEM (MELTING TEMPERATURES, C)[282]



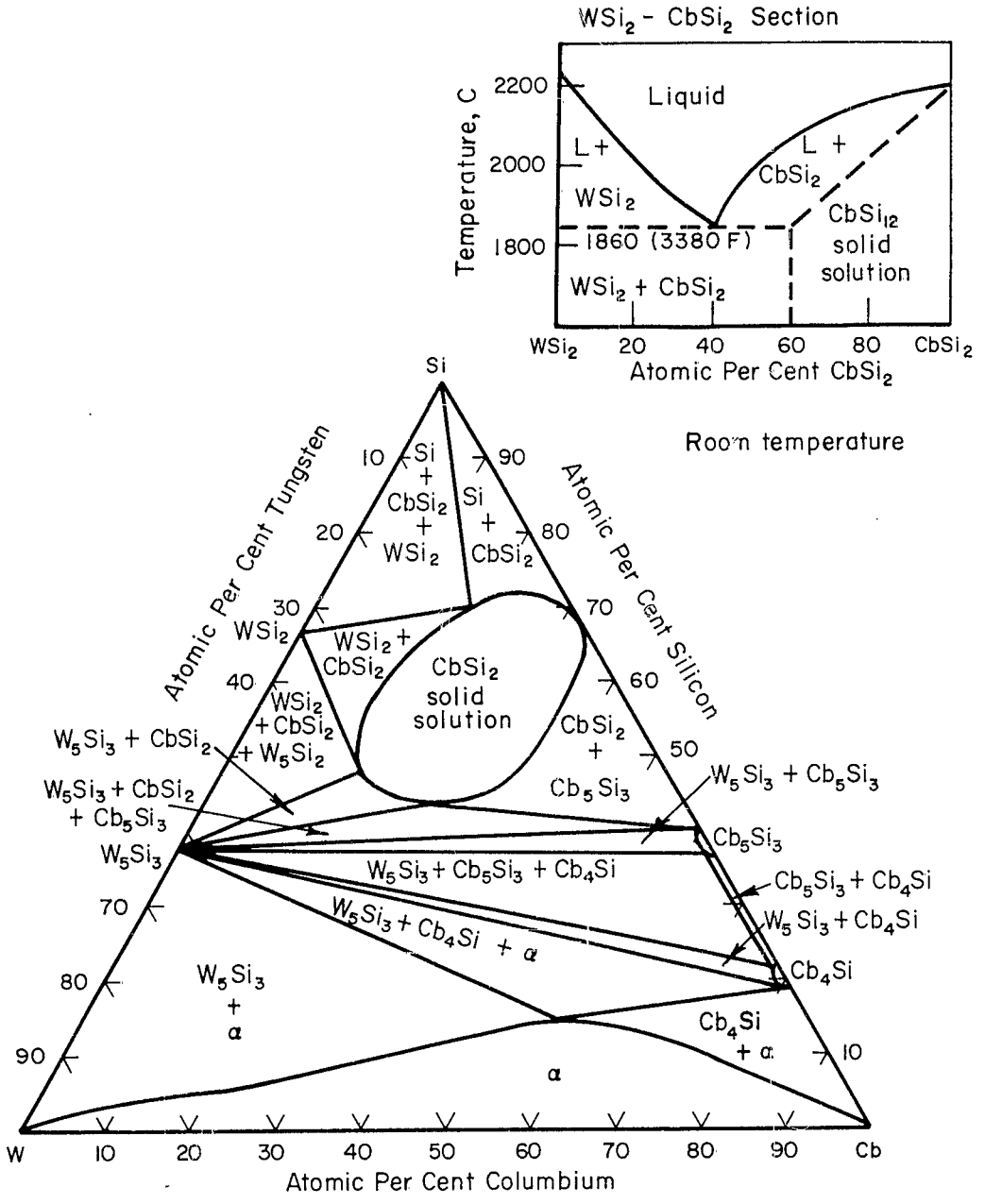
(116-1)-63

COLUMBIUM-URANIUM-ZIRCONIUM SYSTEM (1000 C)[280]



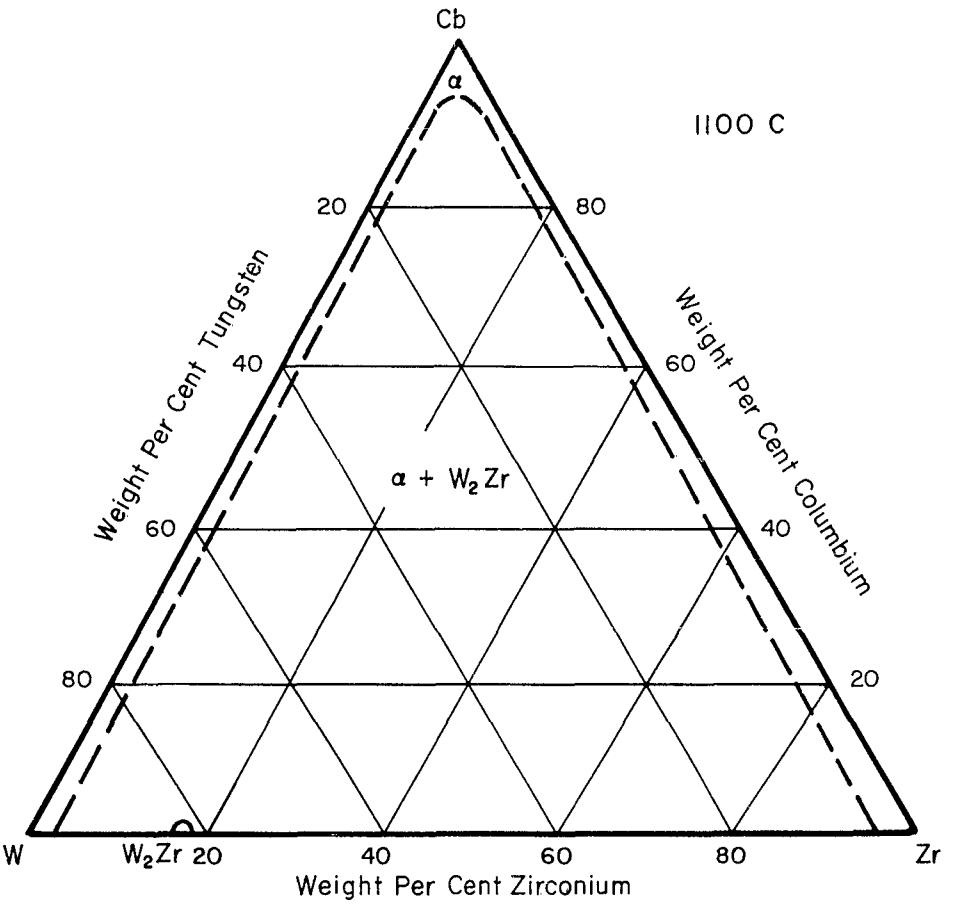
(118-1)-63

COLUMBIUM-TUNGSTEN-SILICON SYSTEM (ROOM TEMPERATURE)[321]



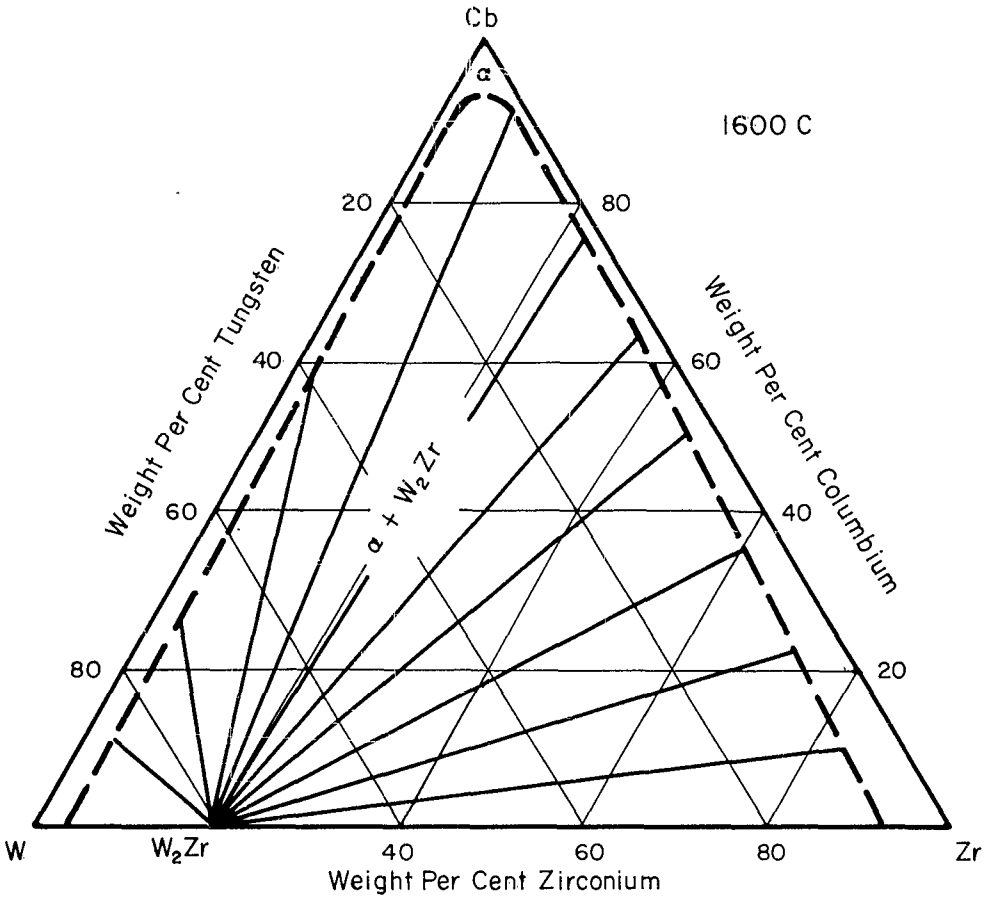
(122-1)-63

COLUMBIUM-TUNGSTEN-ZIRCONIUM SYSTEM (1100 C)[319]



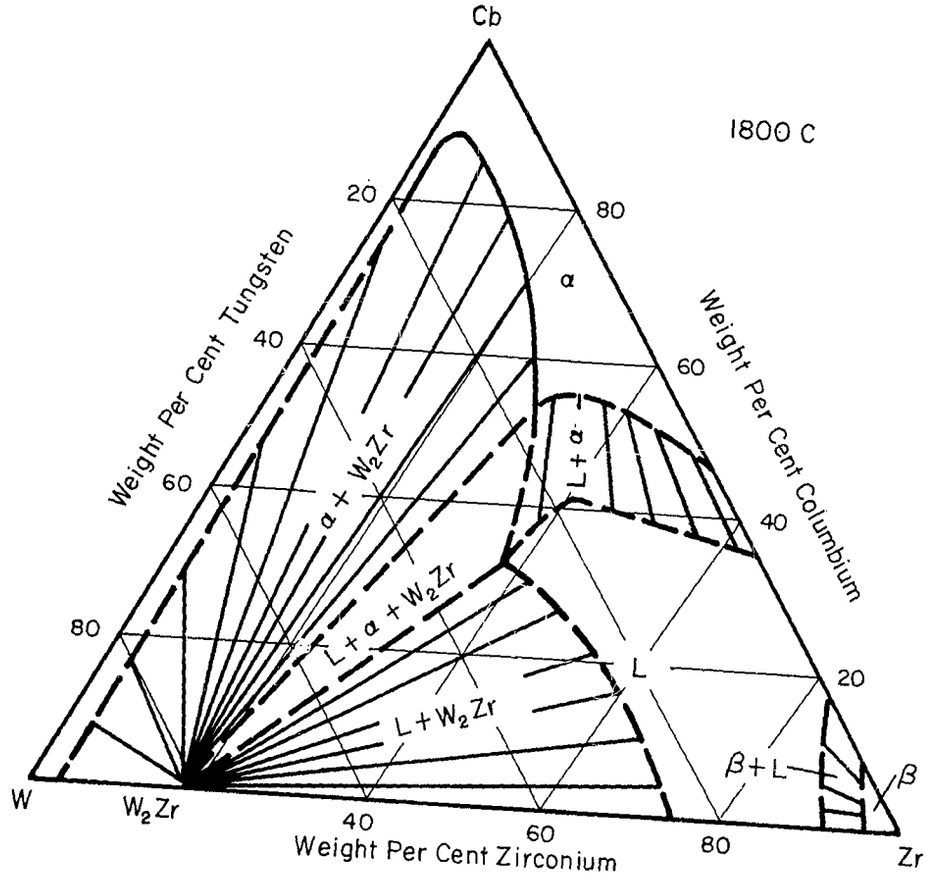
(123-1)-63

COLUMBIUM-TUNGSTEN-ZIRCONIUM SYSTEM (1600 C)[319]

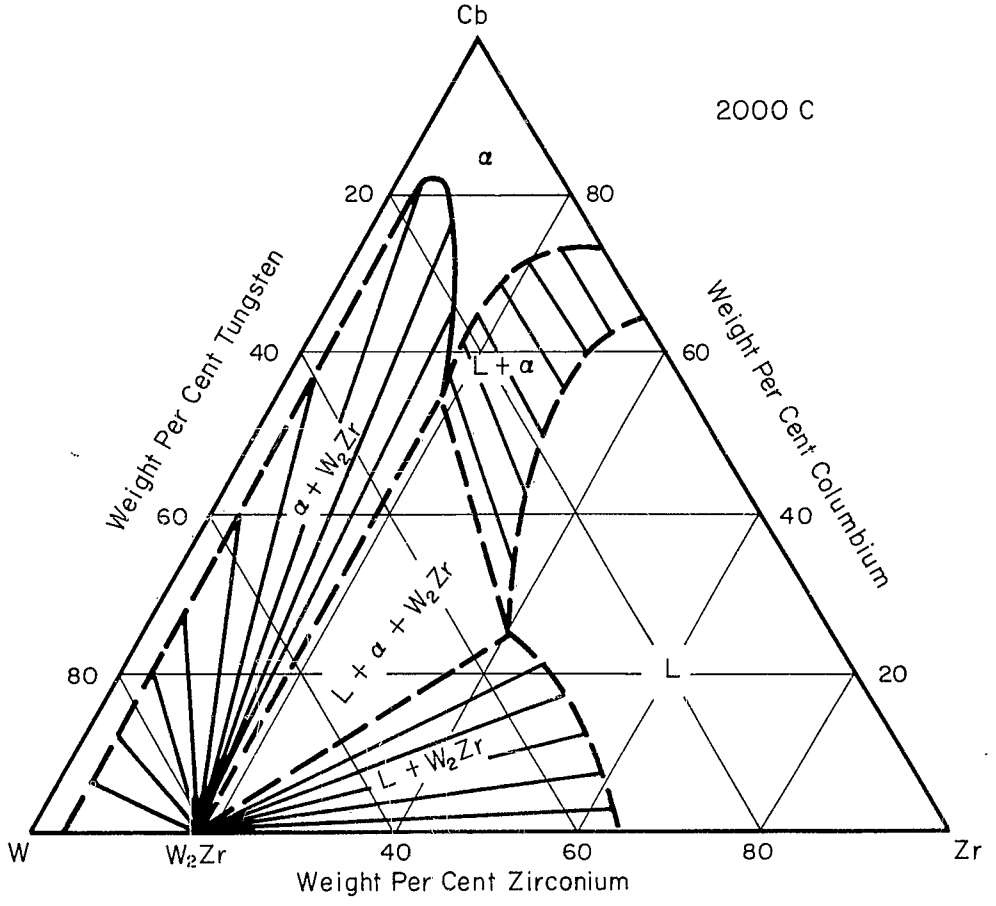


(123-2)-63

COLUMBIUM-TUNGSTEN-ZIRCONIUM SYSTEM (1800 C)(319)

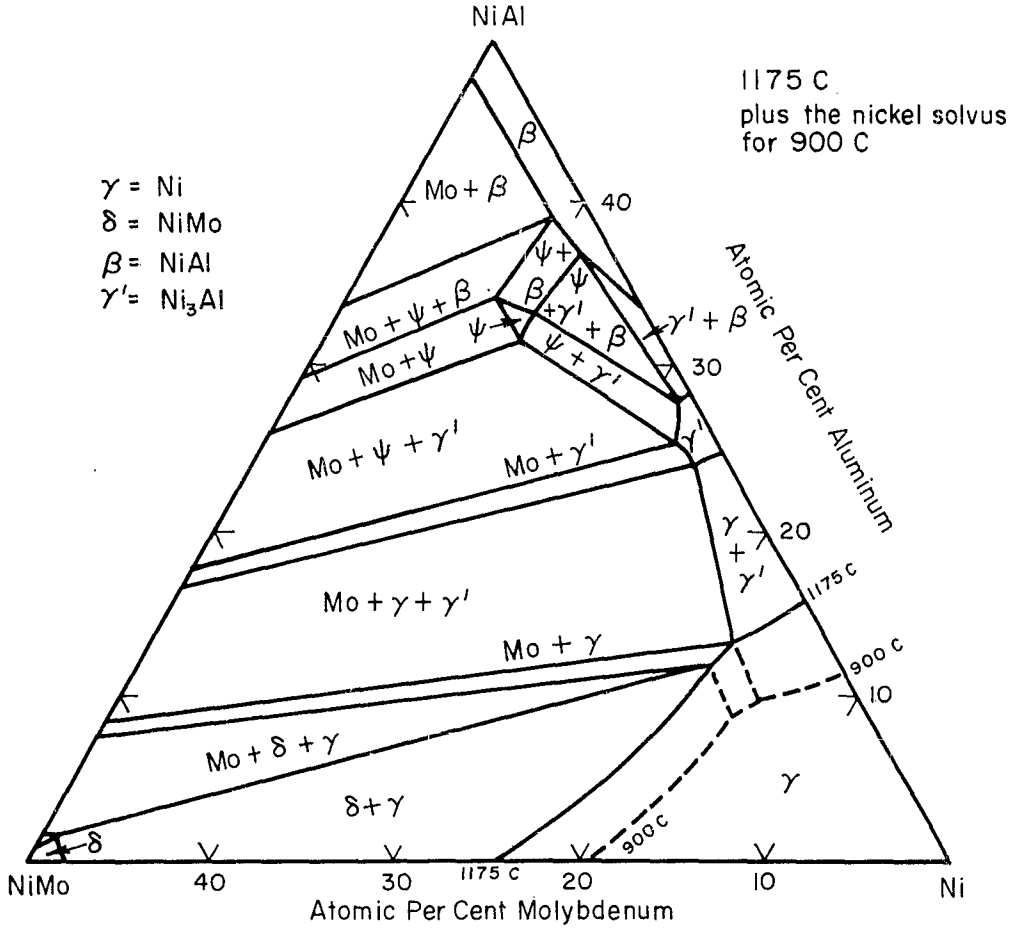


COLUMBIUM-TUNGSTEN-ZIRCONIUM SYSTEM (2000 C)[319]



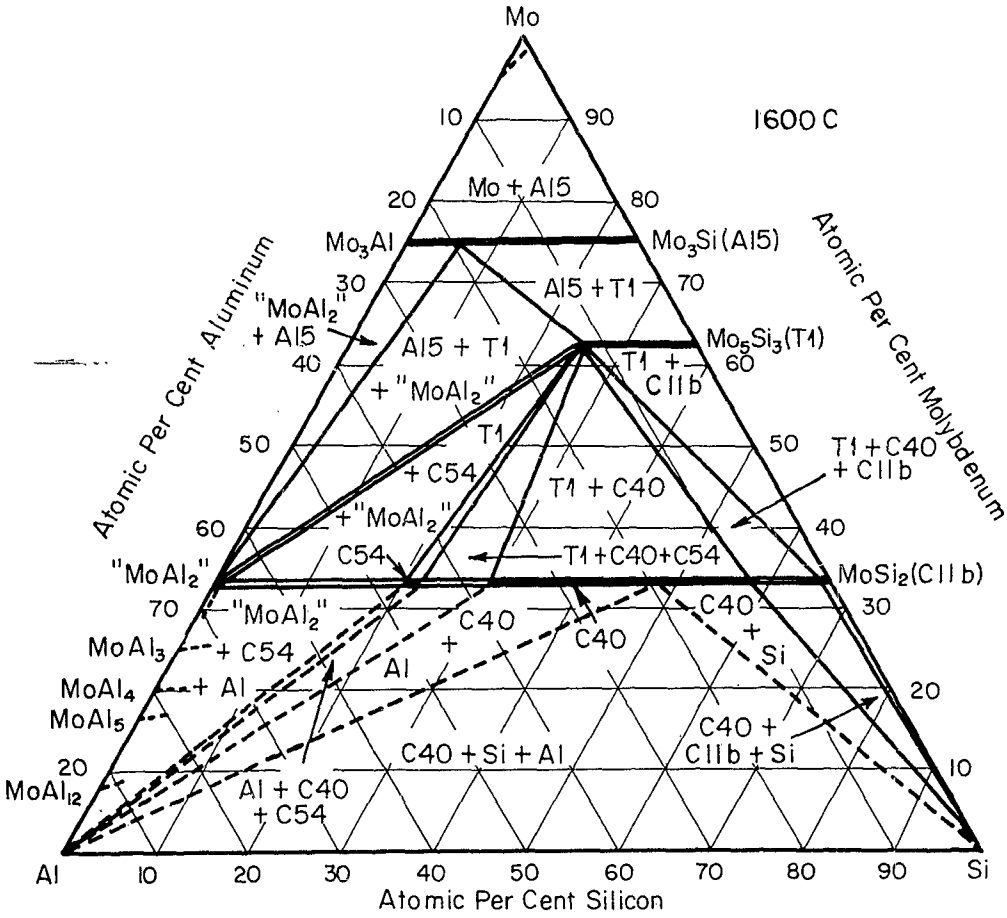
(123-4)-63

MOLYBDENUM-ALUMINUM-NICKEL SYSTEM (1175 C)[283]



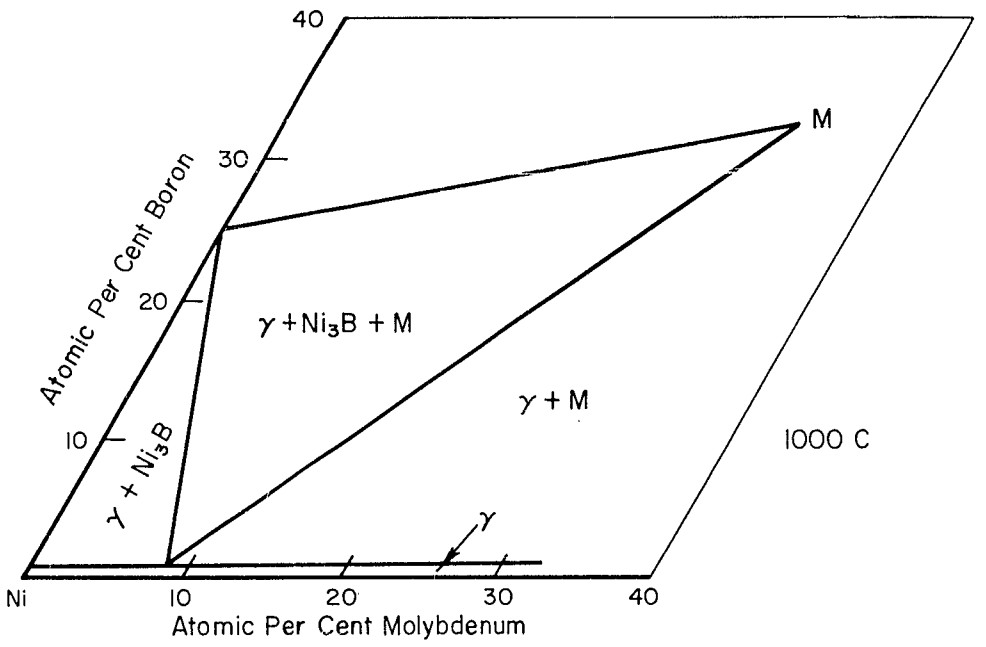
(123-5)-63

MOLYBDENUM-ALUMINUM-SILICON SYSTEM (1600 C)[268]



(123-6)-63

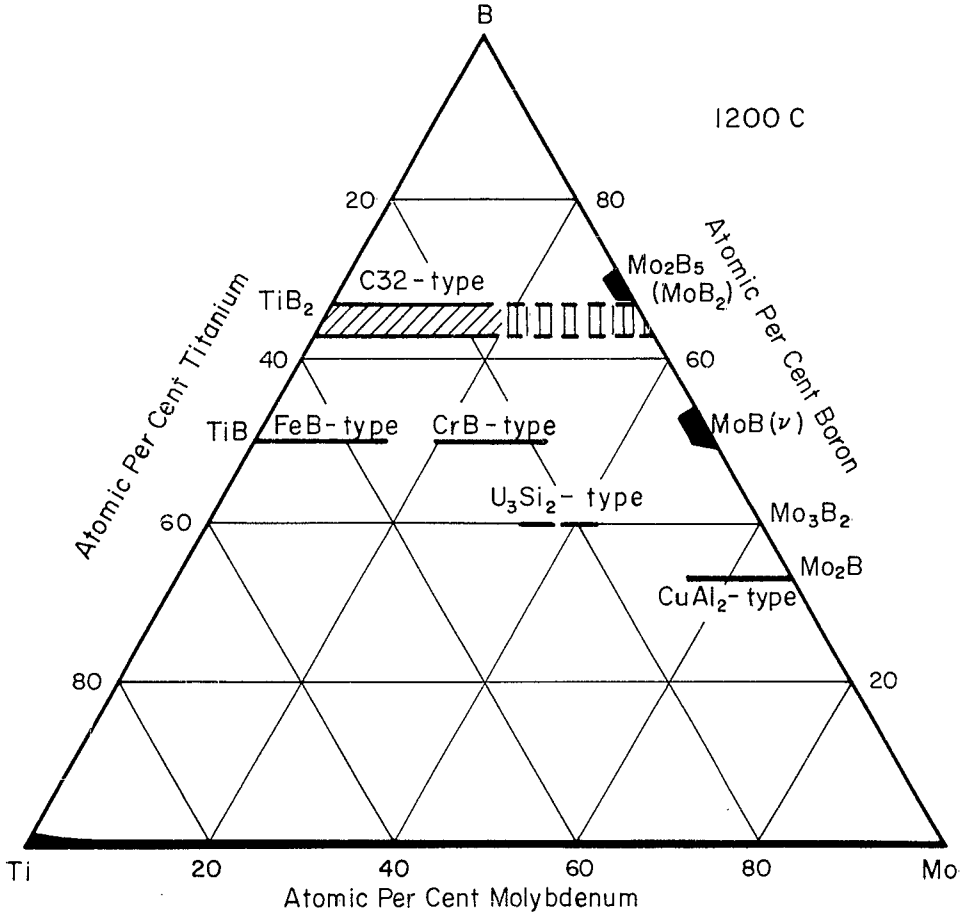
MOLYBDENUM-BORON-NICKEL SYSTEM (1000 C)[284]



M = NiMoB

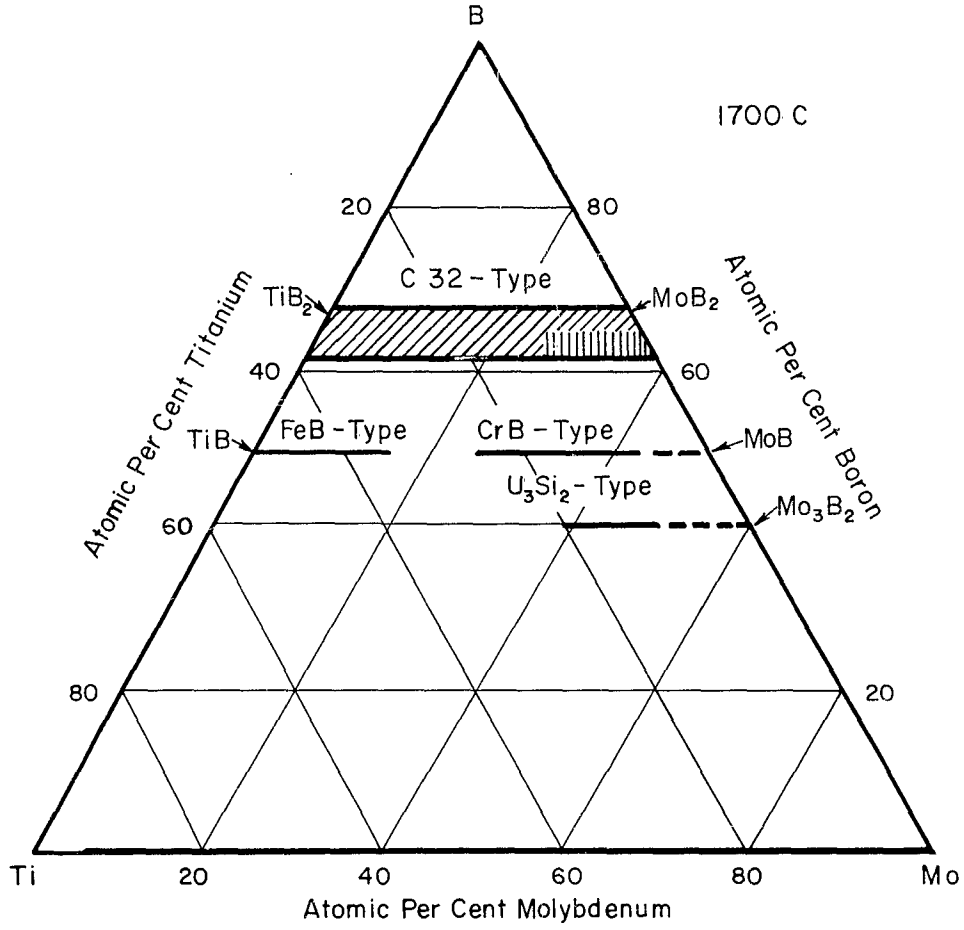
(129-1)-63

MOLYBDENUM-BORON-TITANIUM SYSTEM (1200 C)[285]



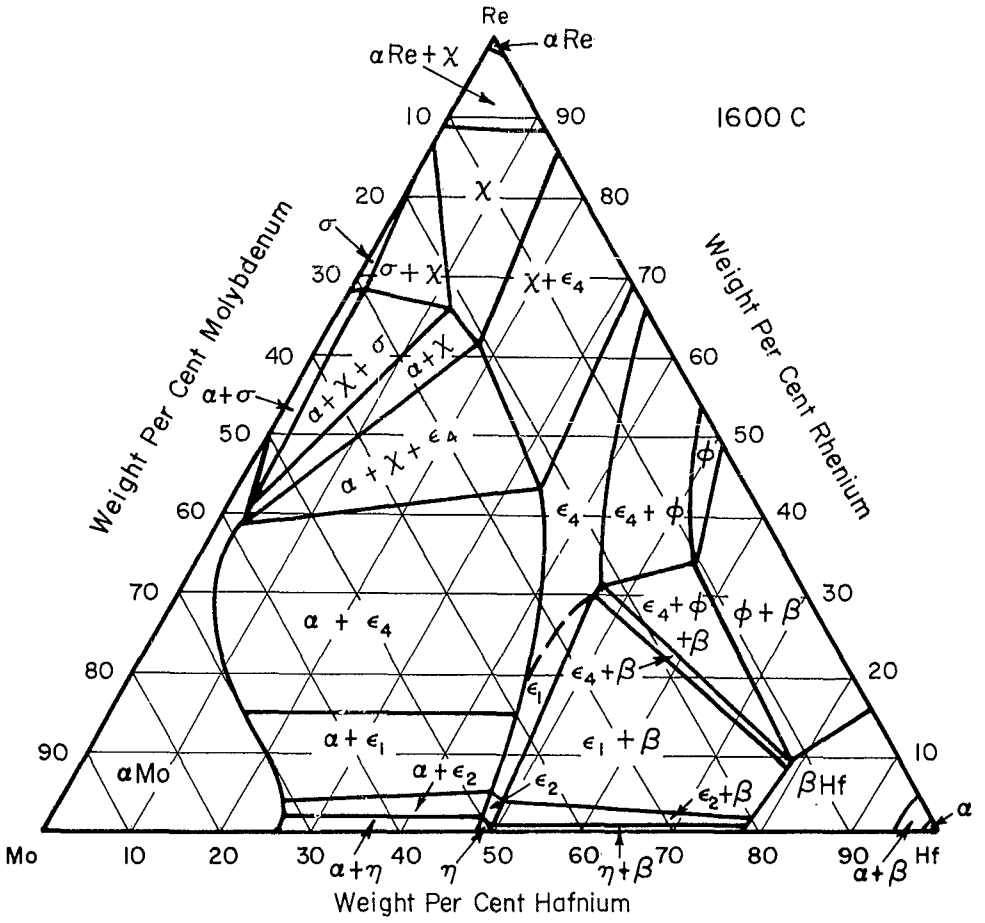
(130-1)-63

MOLYBDENUM-BORON-TITANIUM SYSTEM (1700 C)[285]



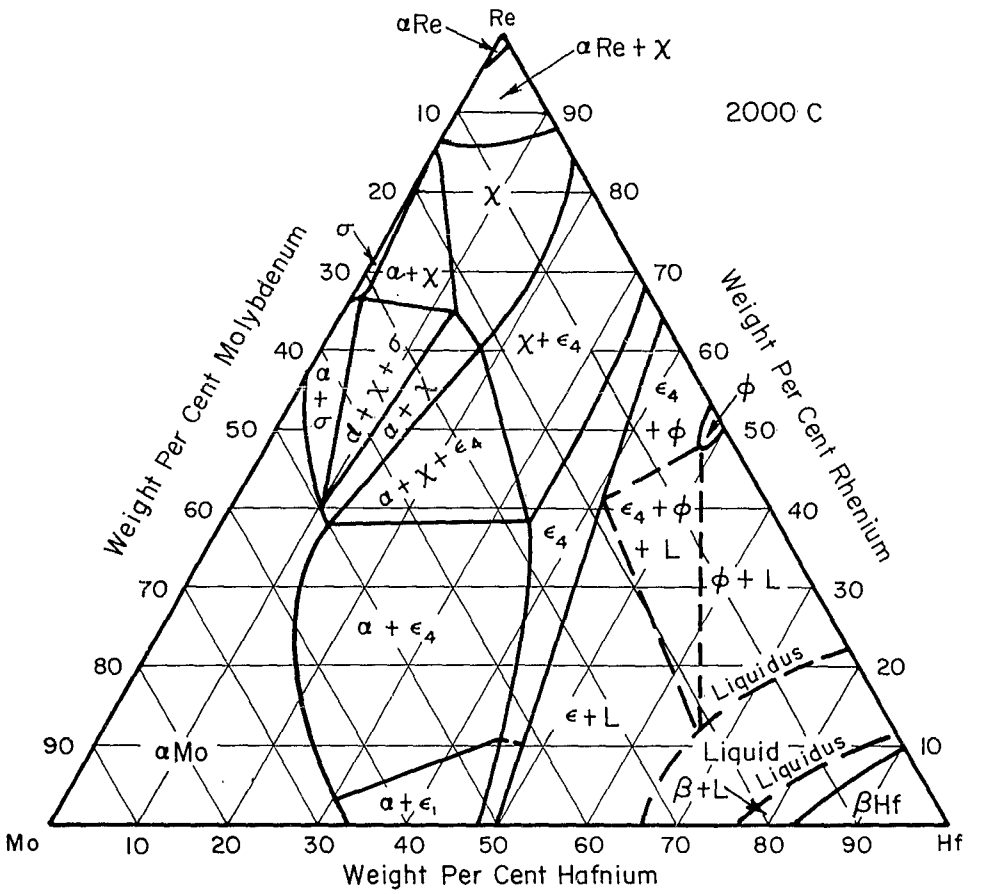
(130-2)-63

MOLYBDENUM-HAFNIUM-RHENIUM SYSTEM (1600 C)[250]

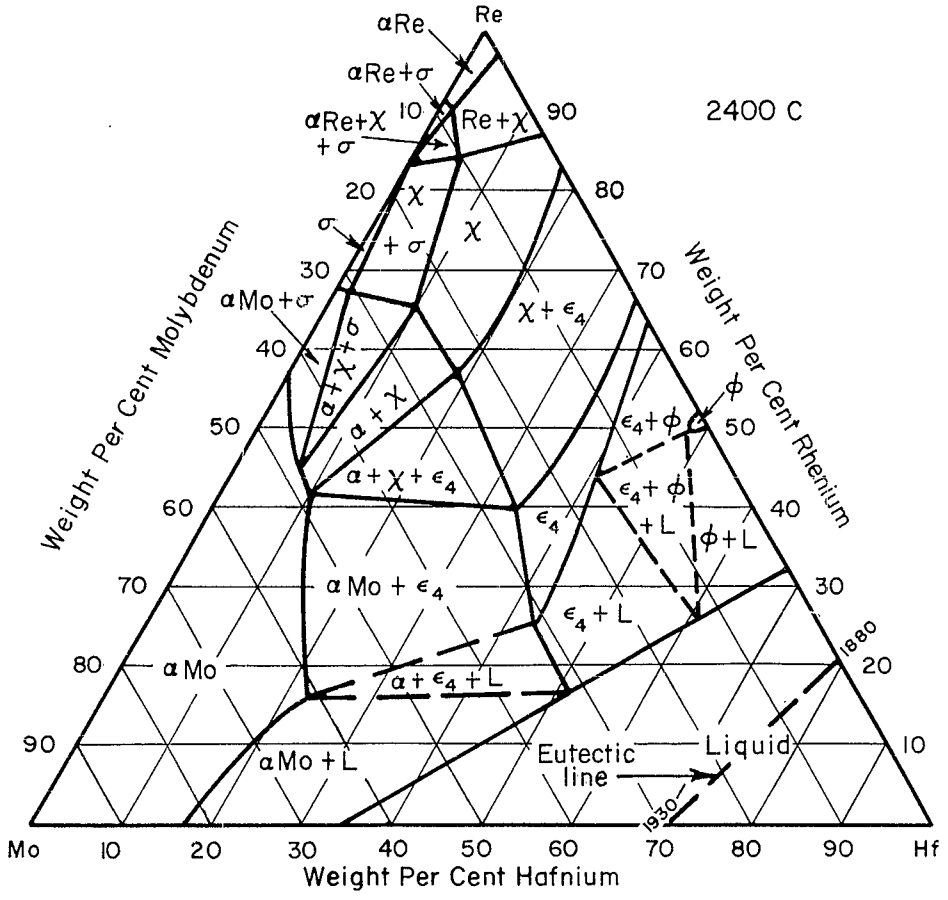


The phase ϕ has a tetragonal structure with a = 8.90 A and c = 13.97 A; this phase forms peritectically at 2745 C and about 47.5 per cent hafnium in the binary rhenium-hafnium system. An intermediate Laves phase ϵ_4 (based on Re_2Hf) has the C14-$MgZn_2$ type of structure with a = 5.239 A, c = 8.584 A, and c/a = 1.638.[250]

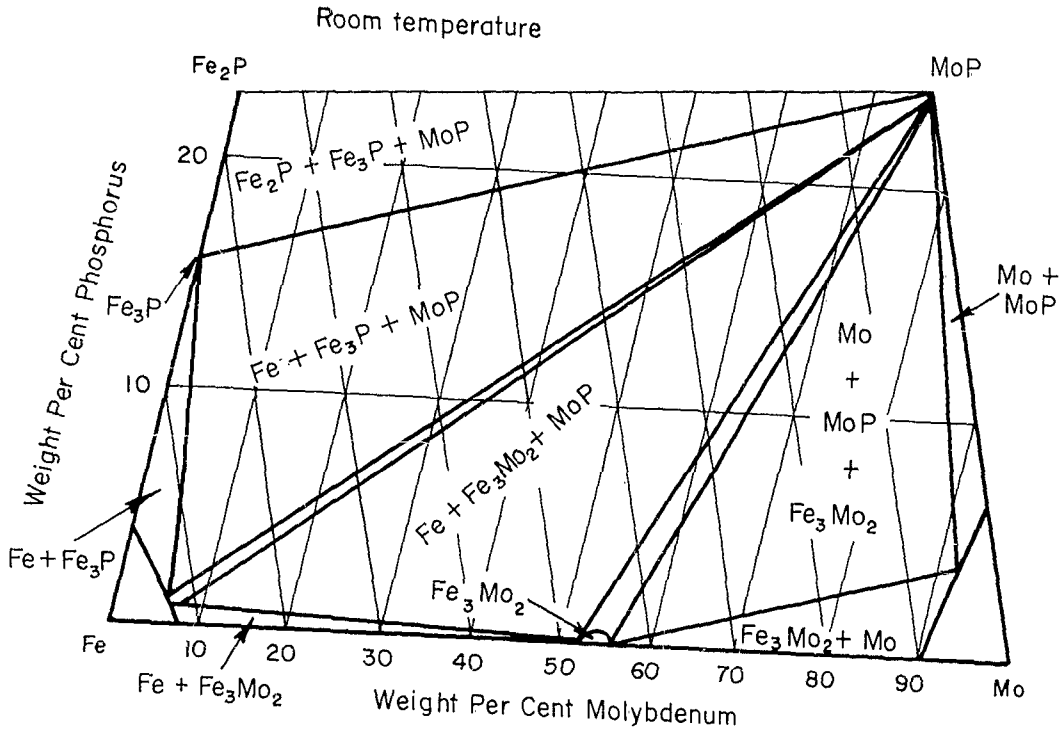
MOLYBDENUM-HAFNIUM-RHENIUM SYSTEM (2000 C)[250]



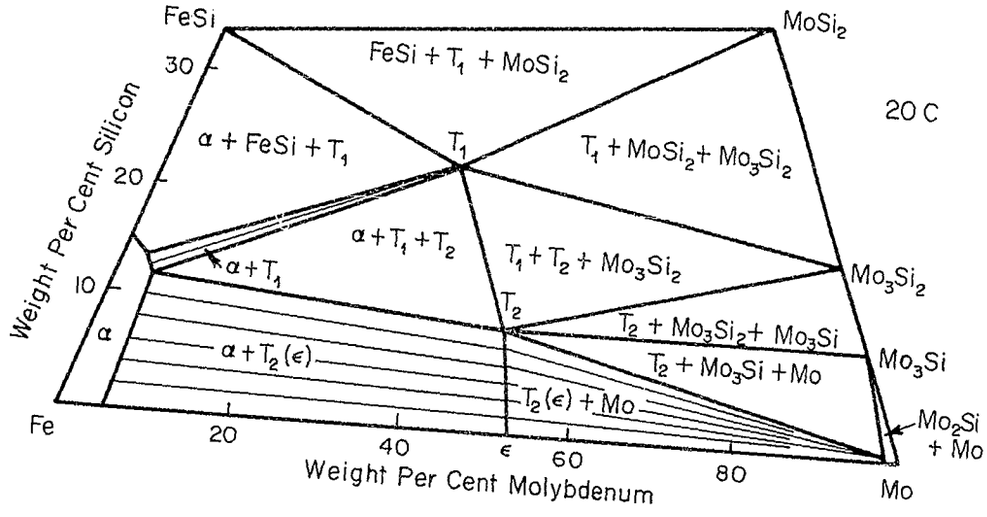
MOLYBDENUM-HAFNIUM-RHENIUM SYSTEM (2400 C)[250]



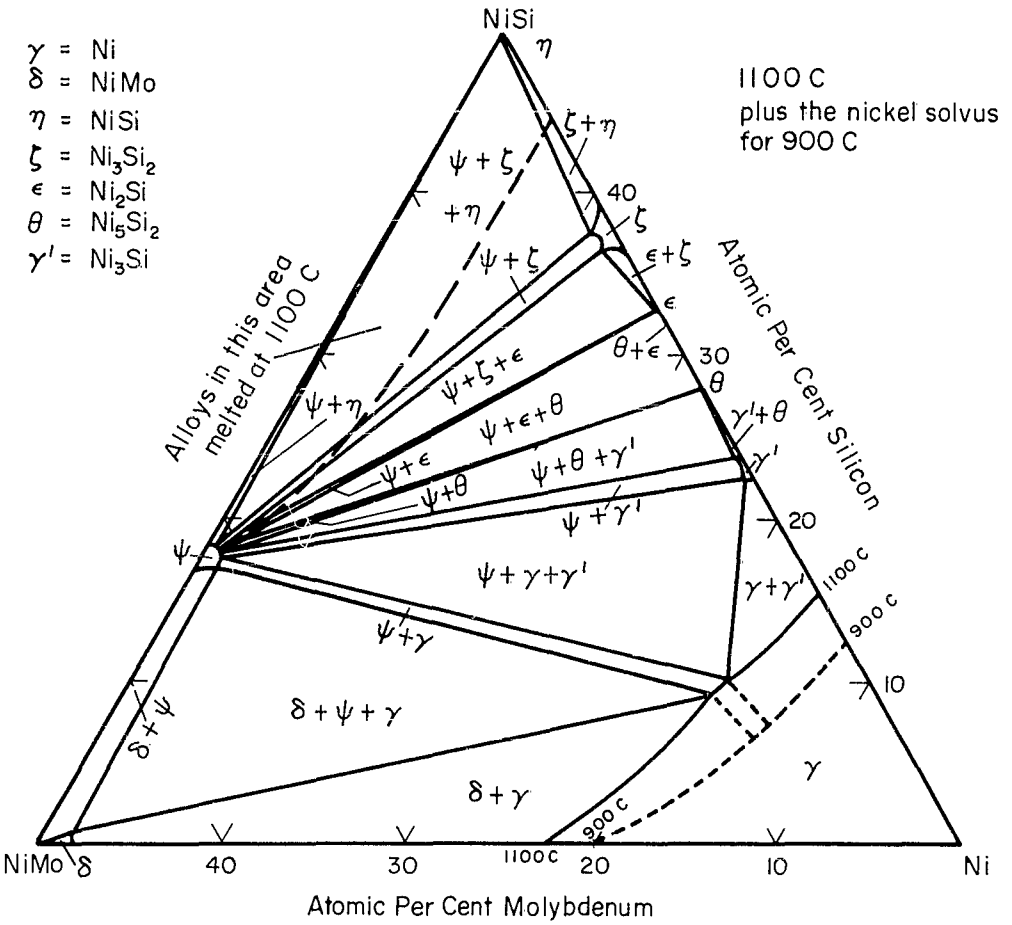
MOLYBDENUM-IRON-PHOSPHORUS SYSTEM (ROOM TEMPERATURE)(313)



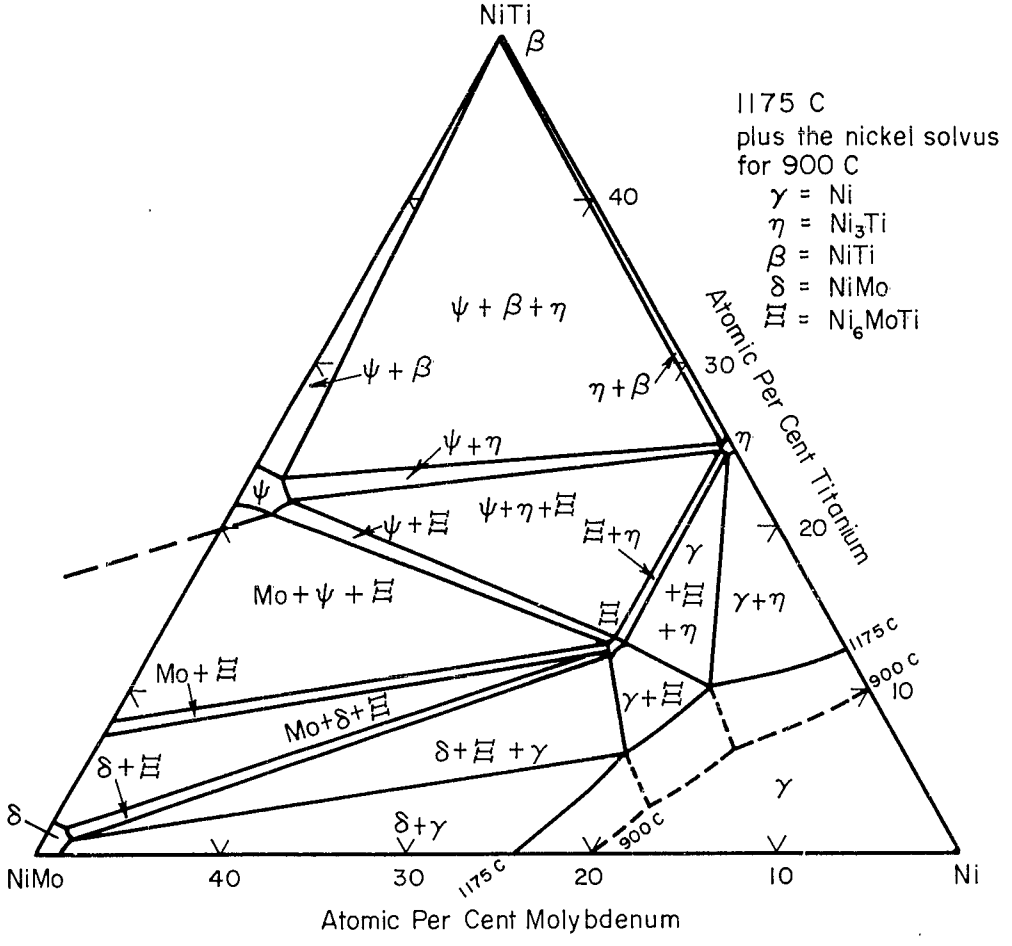
MOLYBDENUM-IRON-SILICON SYSTEM (20 C)(286)



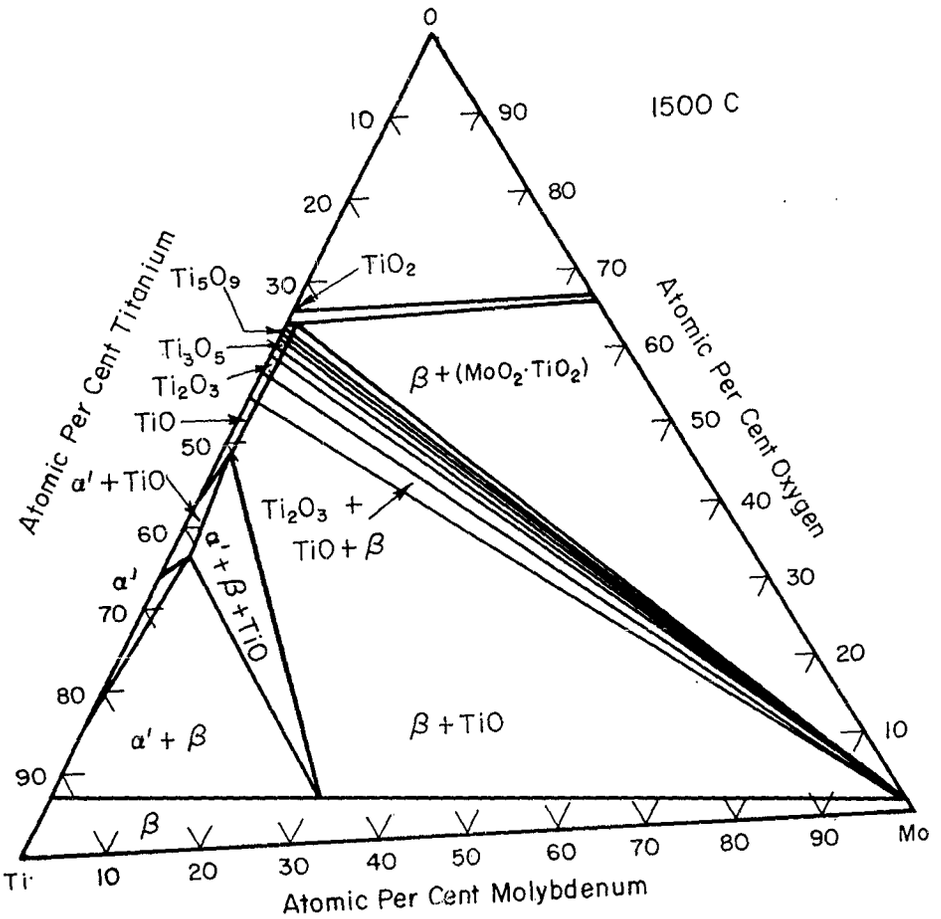
MOLYBDENUM-NICKEL-SILICON SYSTEM (1100 C)[283]



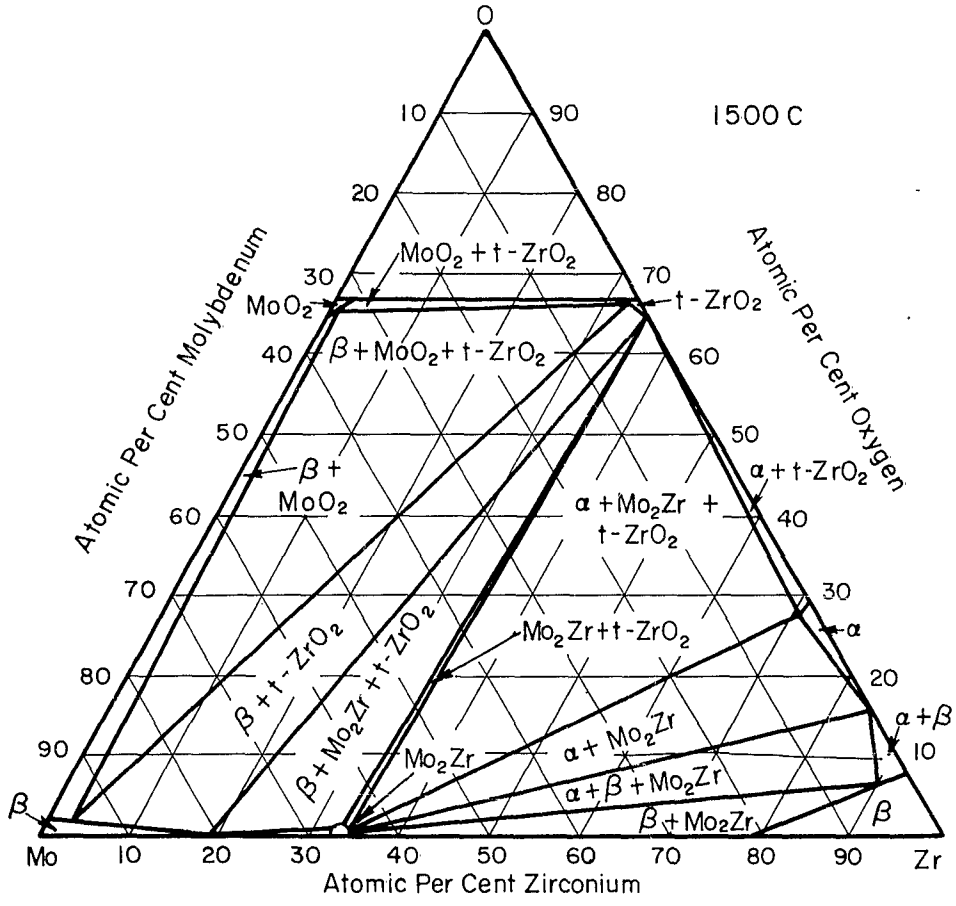
MOLYBDENUM-NICKEL-TITANIUM SYSTEM (1175 C)[312]



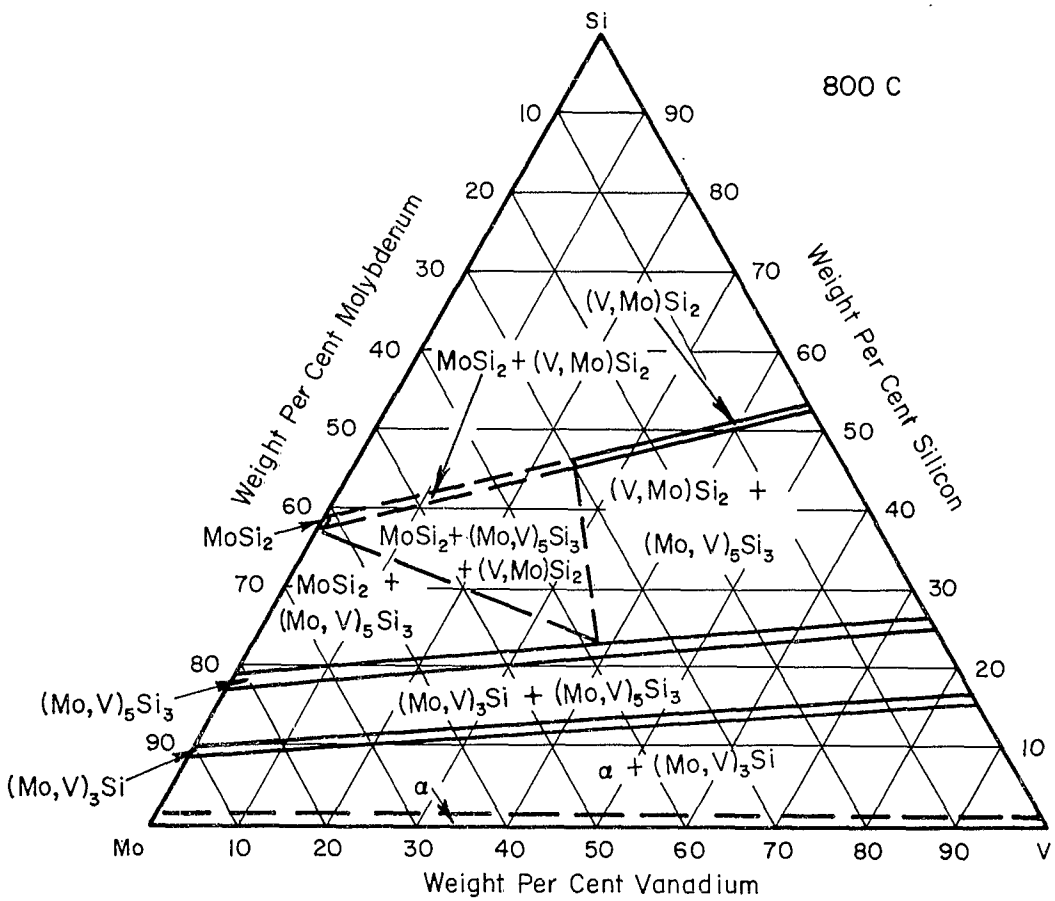
MOLYBDENUM-OXYGEN-TITANIUM SYSTEM (1500 C)[314]



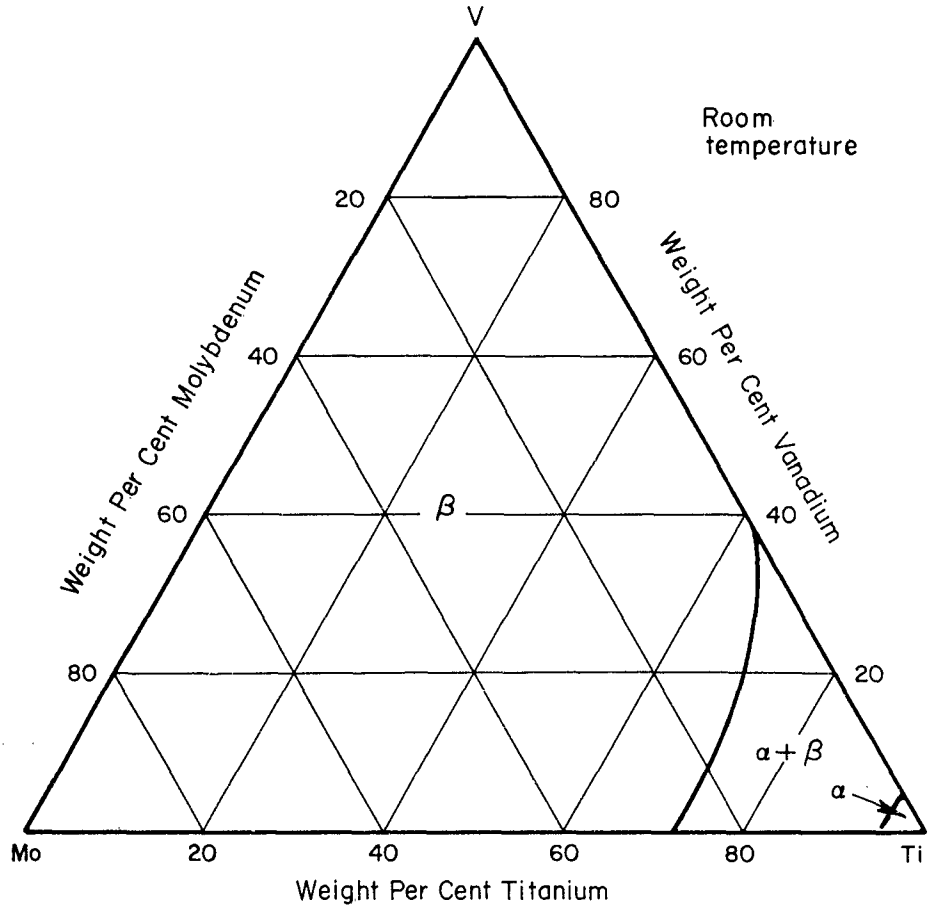
MOLYBDENUM-OXYGEN-ZIRCONIUM SYSTEM (1500 C)[314]



MOLYBDENUM-SILICON-VANADIUM SYSTEM (800 C)[303]



MOLYBDENUM-TITANIUM-VANADIUM SYSTEM (ROOM TEMPERATURE)[287]



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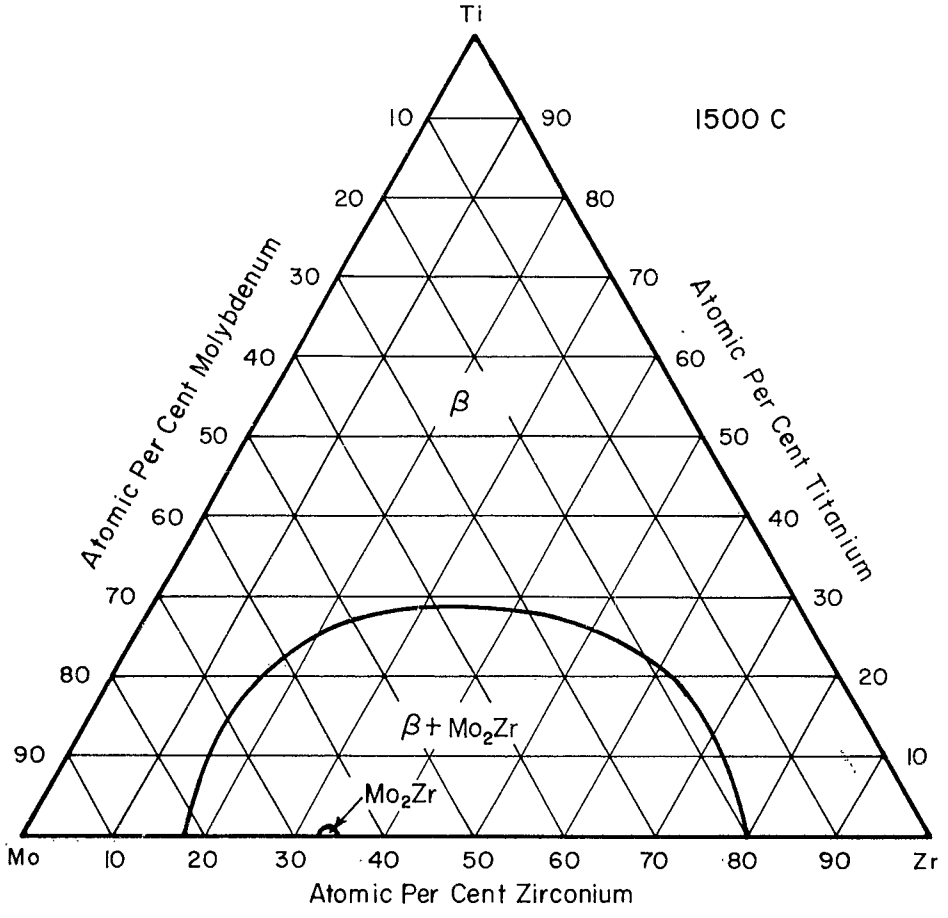
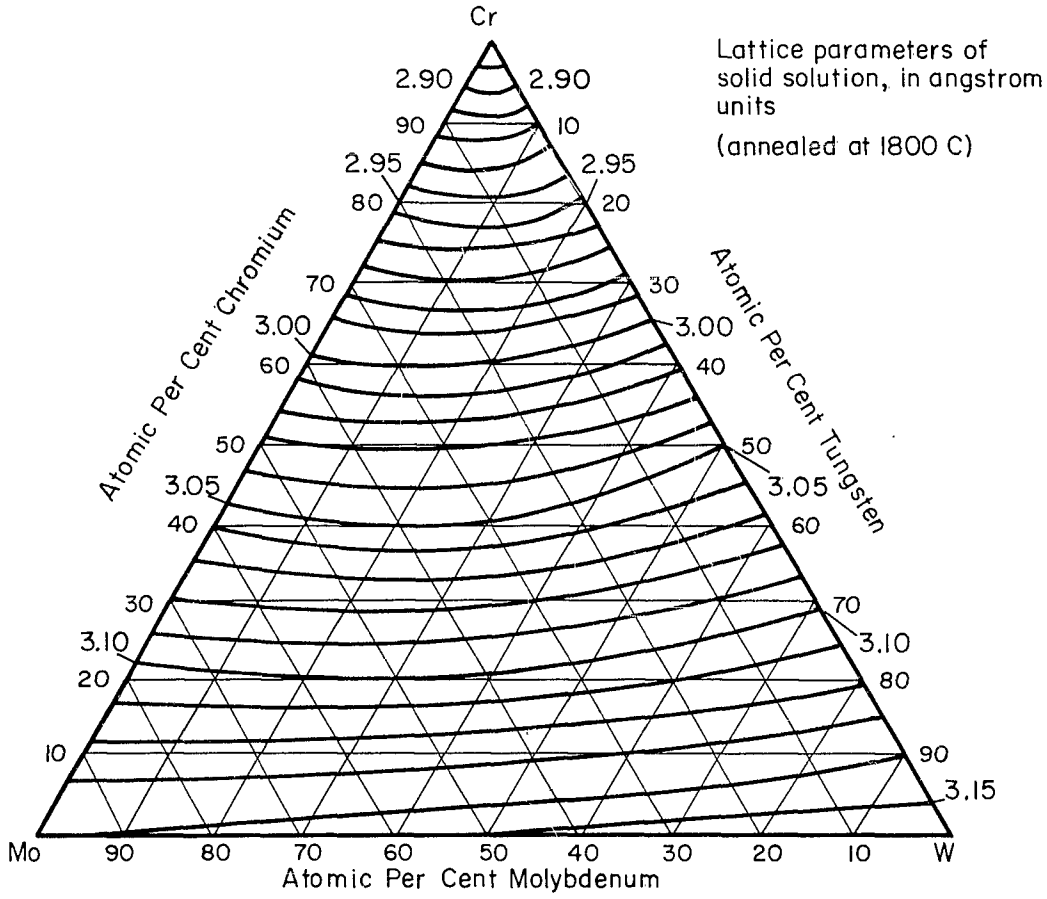
MOLYBDENUM-TITANIUM-ZIRCONIUM SYSTEM (1500 C)[314]



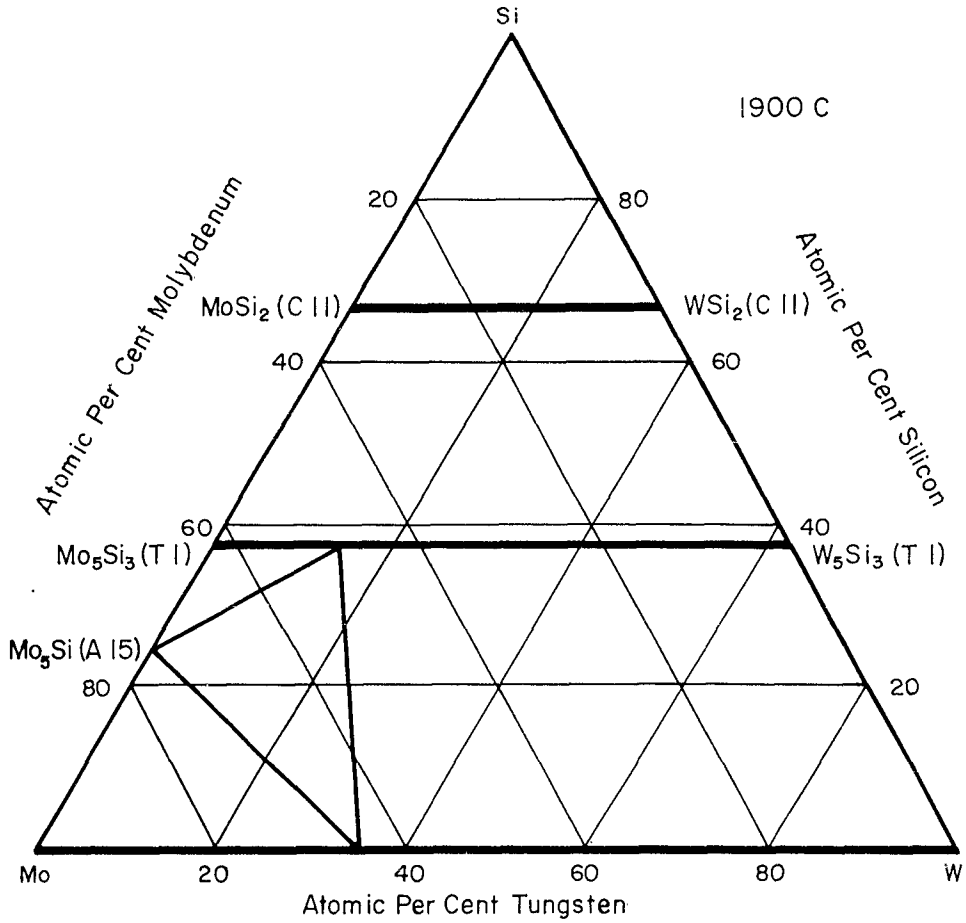
(162-2)-63

MOLYBDENUM-TUNGSTEN-CHROMIUM SYSTEM (1800 C)[288]

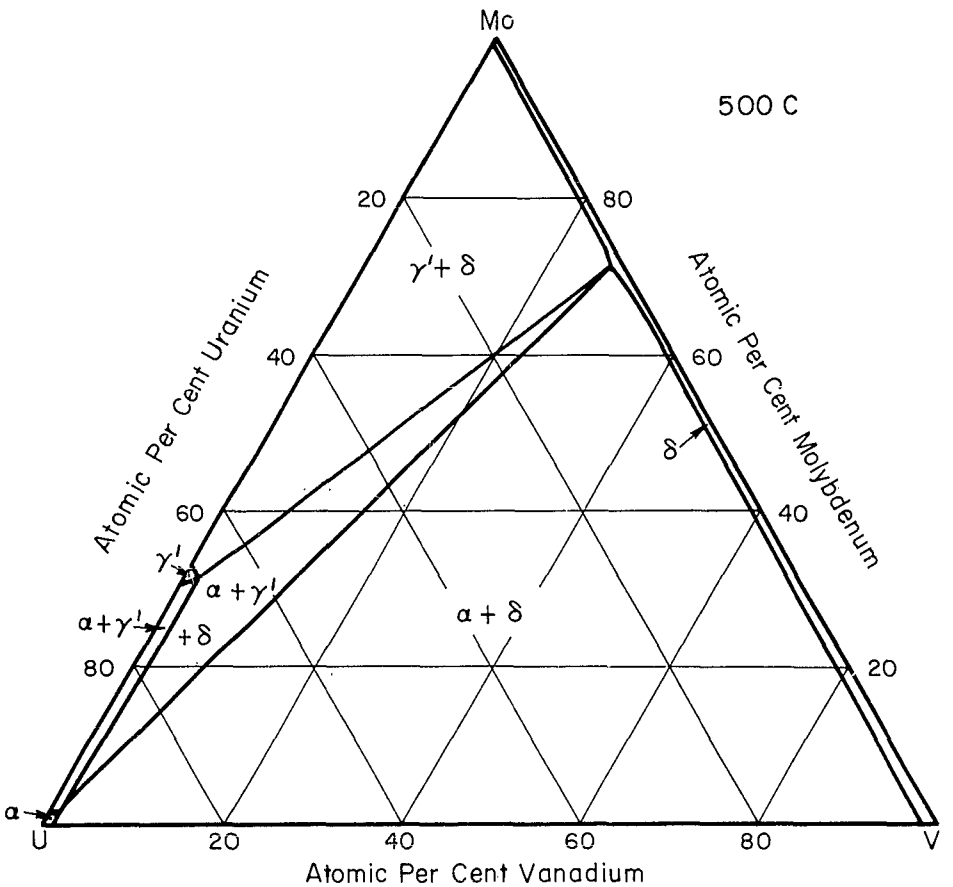


(164-1)-63

MOLYBDENUM-TUNGSTEN-SILICON SYSTEM (1900 C)[294]

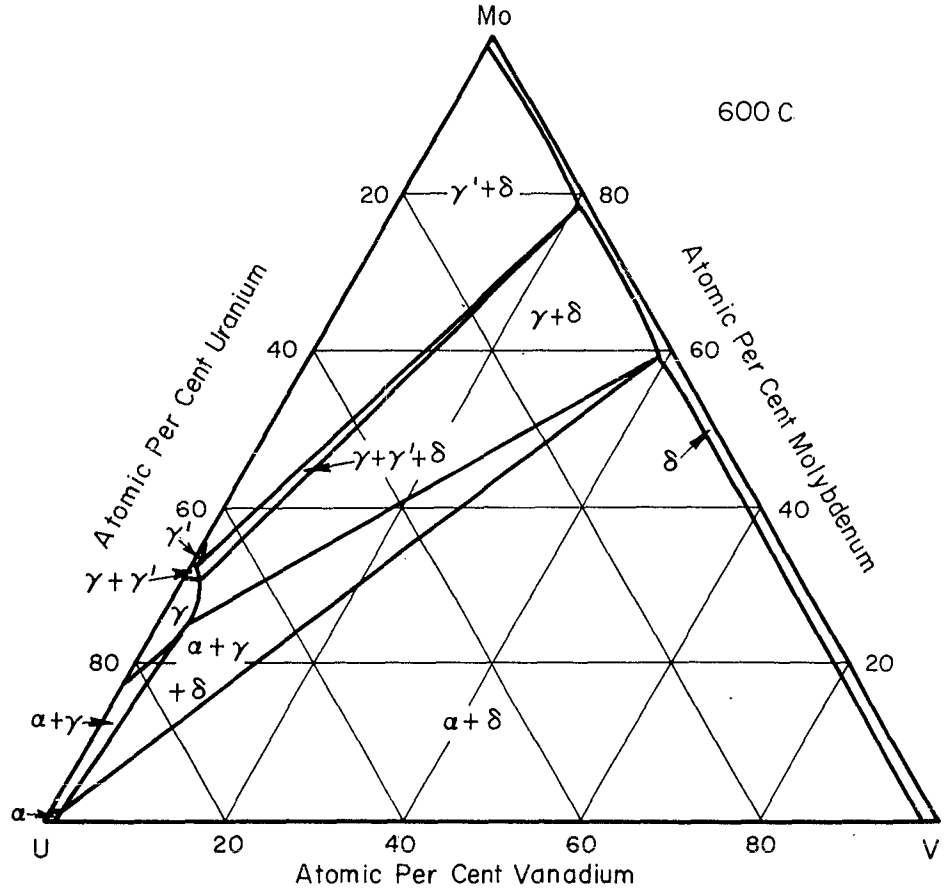


MOLYBDENUM-URANIUM-VANADIUM SYSTEM (500 C)[308]



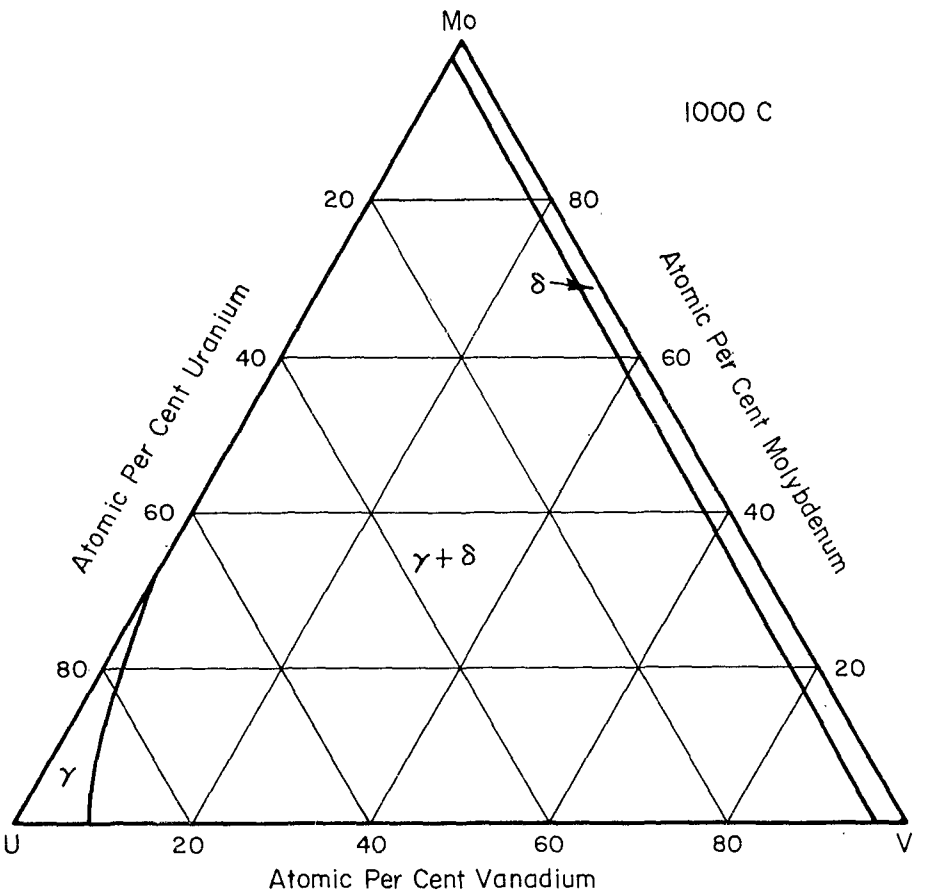
(167-2)-63

MOLYBDENUM-URANIUM-VANADIUM SYSTEM (600 C)[308]



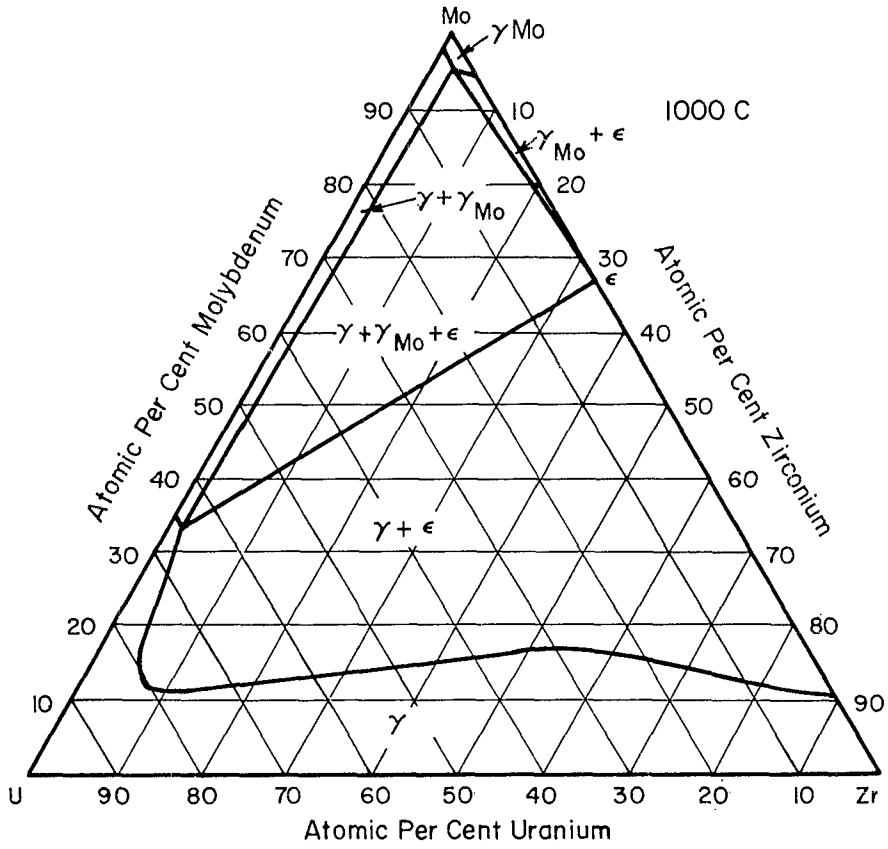
(167-3)-63

MOLYBDENUM-URANIUM-VANADIUM SYSTEM (1000 C)[308]



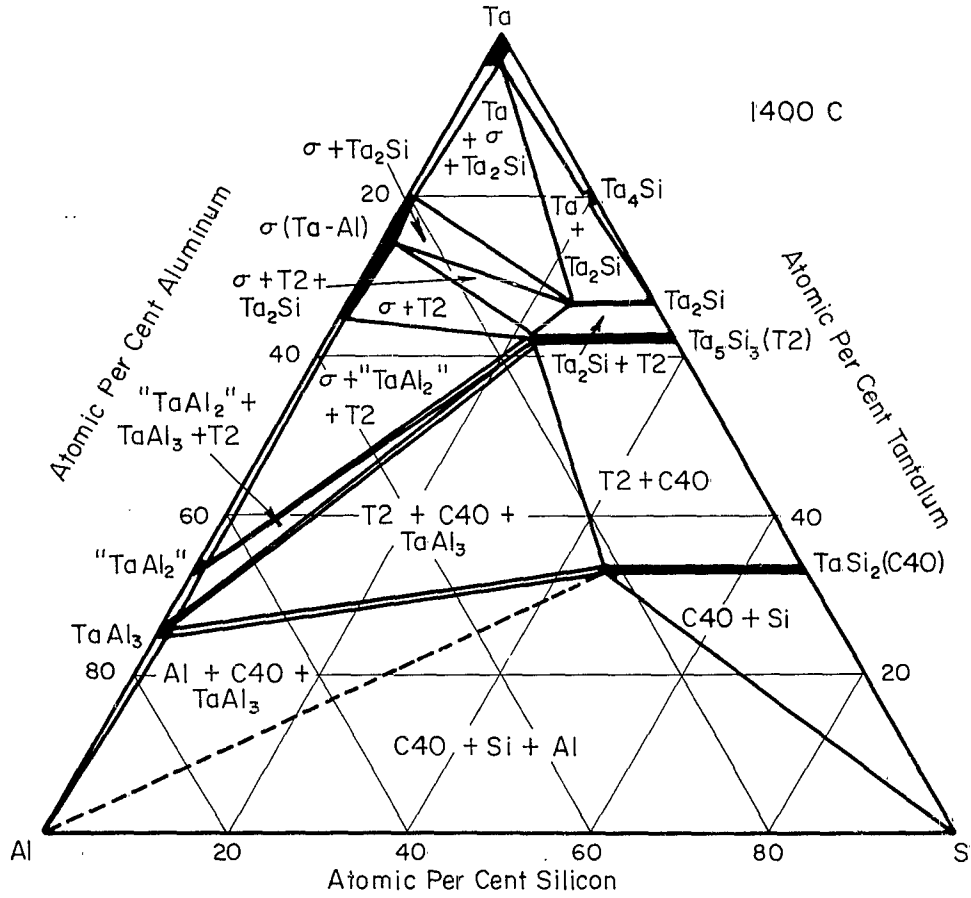
(167-4)-63

MOLYBDENUM-URANIUM-ZIRCONIUM SYSTEM (1000 C)[280]



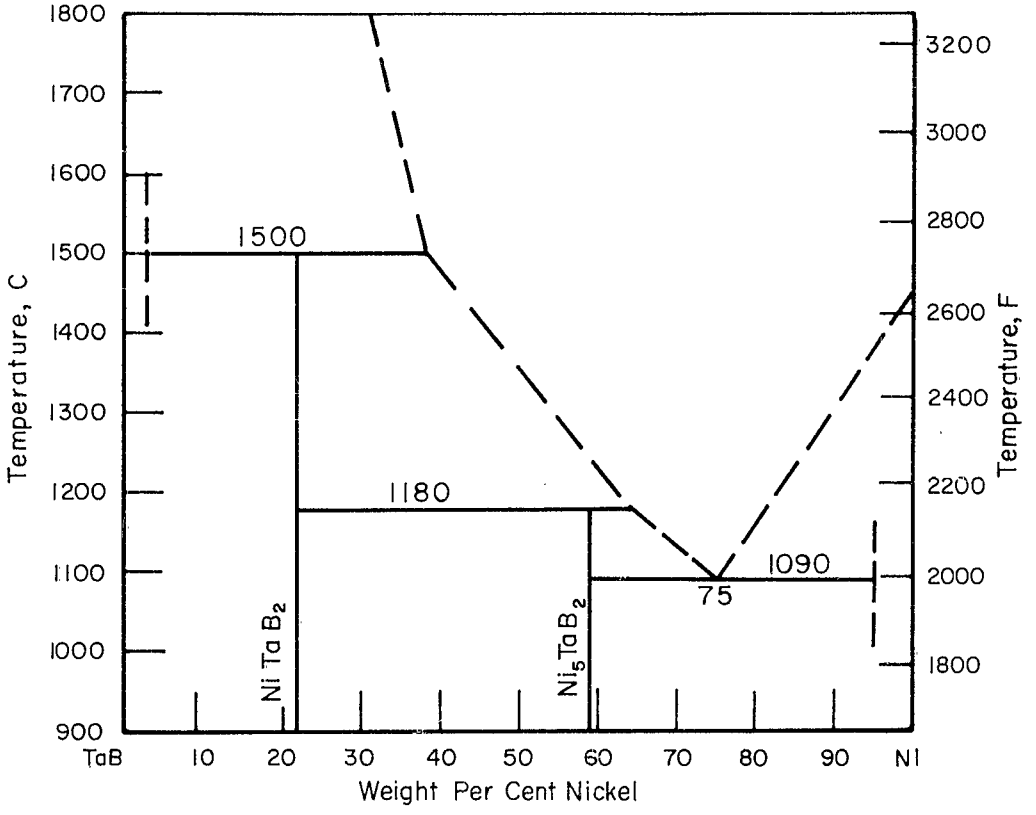
(167-5)-63

TANTALUM-ALUMINUM-SILICON SYSTEM (1400 C)[266]



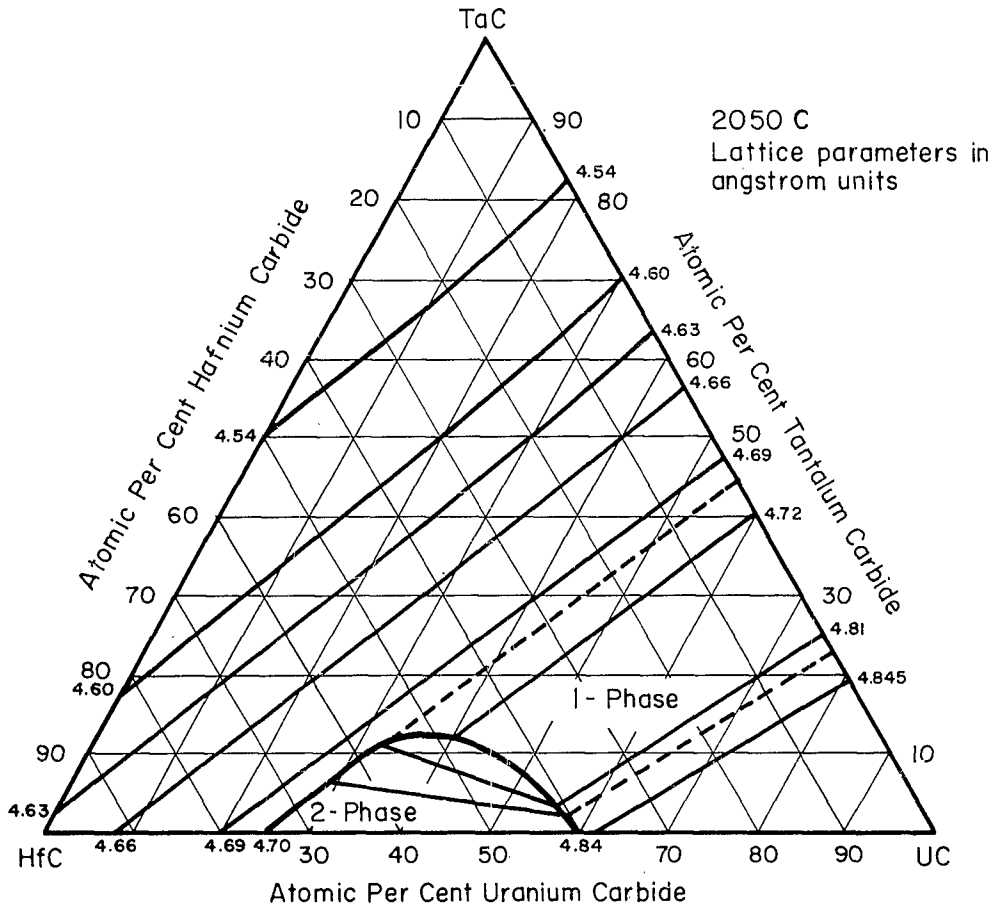
(167-6)-63

TANTALUM-BORON-NICKEL SYSTEM (TaB_2-Ni)



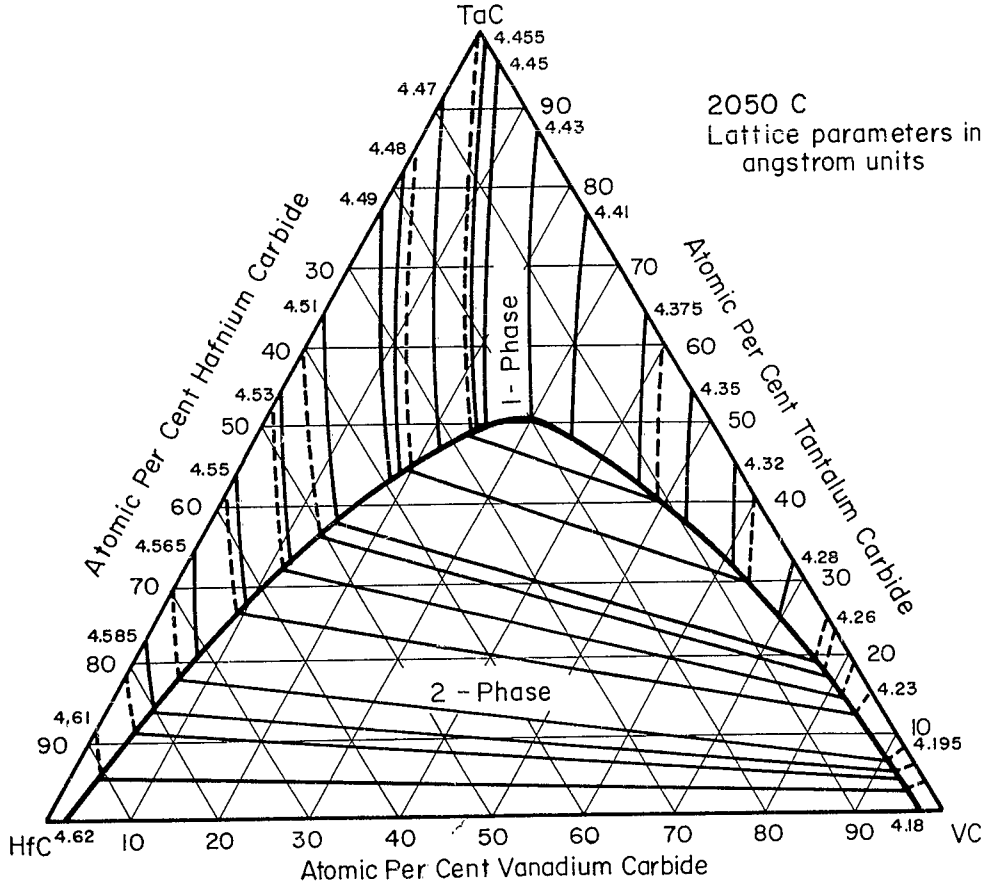
Ni_5TaB_2 has a face-centered cubic structure with a = 10.56 A.[289] The structure of $NiTaB_2$ was not identified.

TANTALUM CARBIDE-HAFNIUM CARBIDE-URANIUM CARBIDE SYSTEM (2050 C)[271]



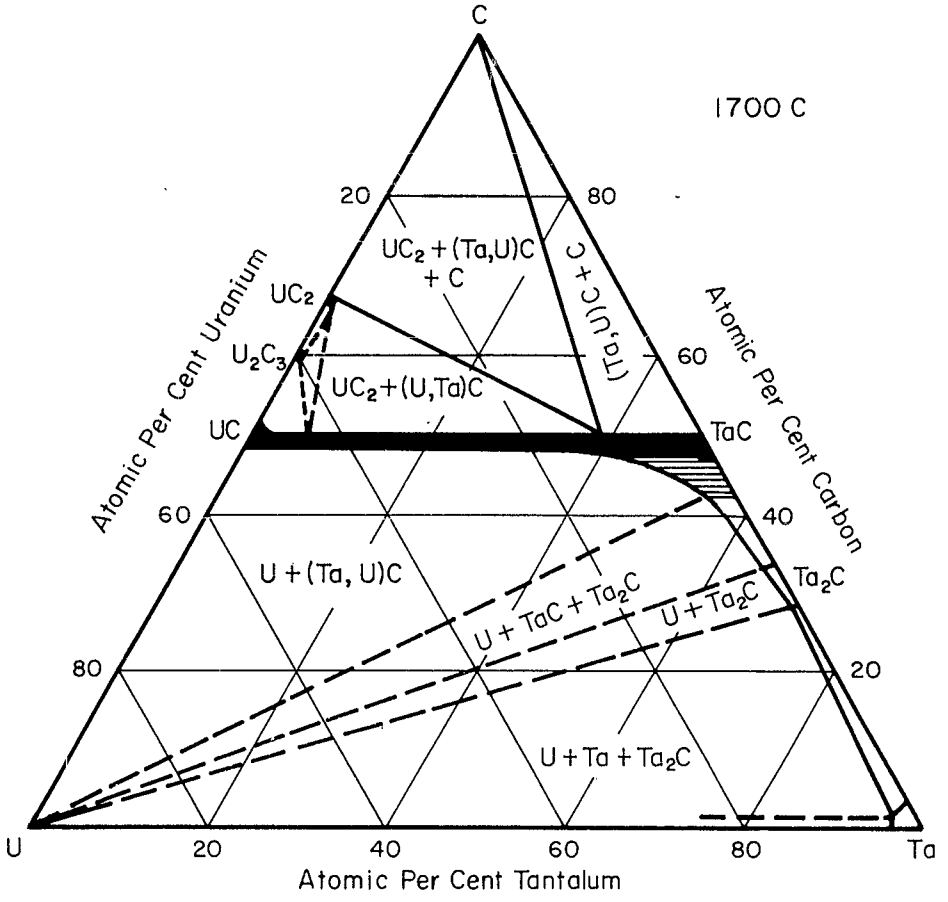
(168-1)-63

TANTALUM CARBIDE-HAFNIUM CARBIDE-VANADIUM CARBIDE SYSTEM (2050 C)[271]



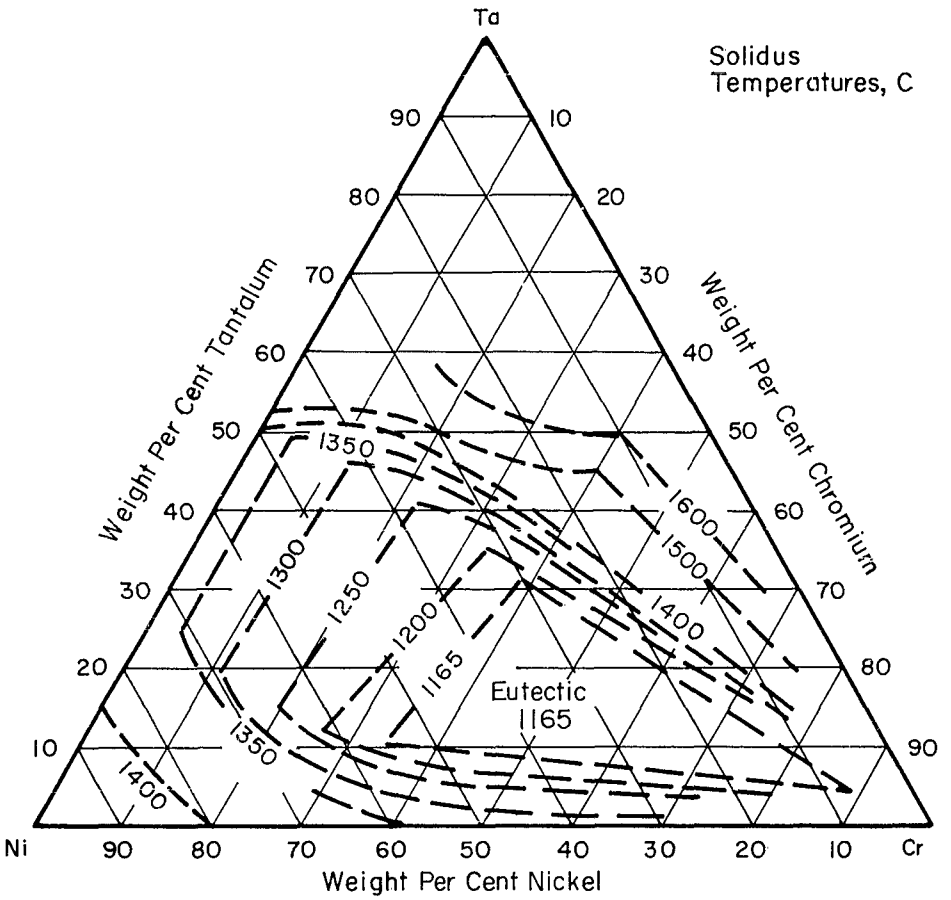
(168-2)-63

TANTALUM-CARBON-URANIUM SYSTEM (1700 C)[272]



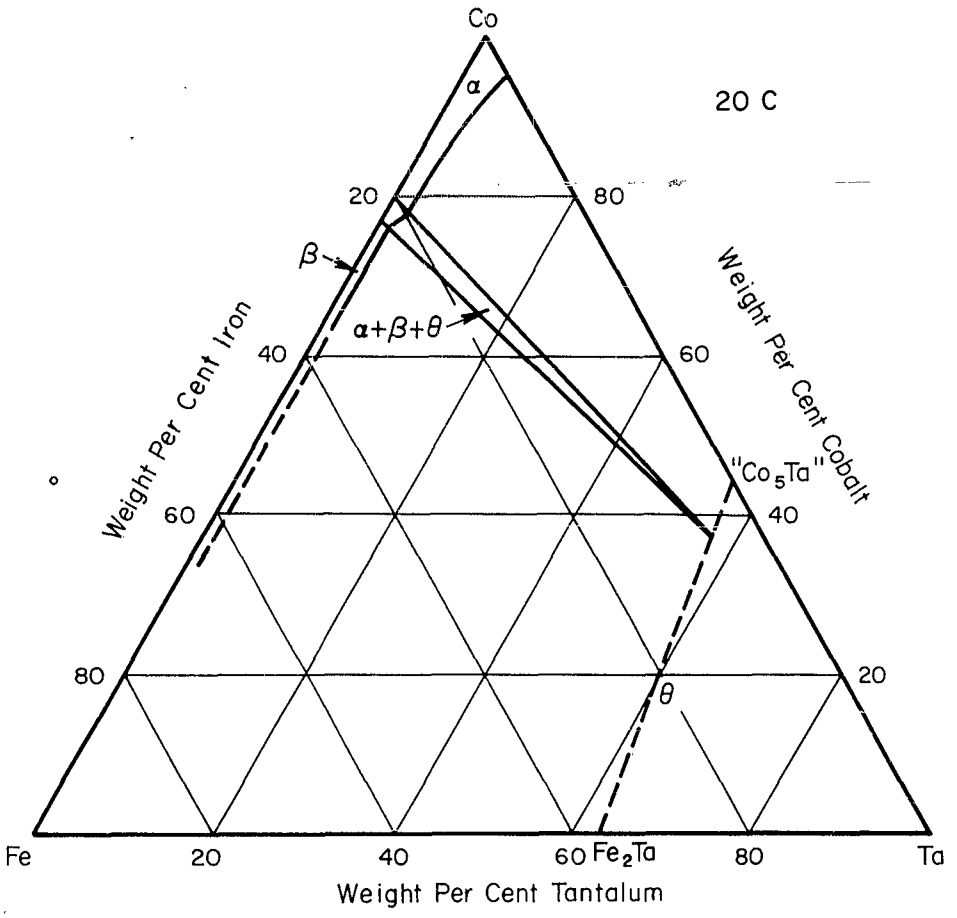
(169-1)-63

TANTALUM-CHROMIUM-NICKEL SYSTEM (SOLIDUS TEMPERATURE)[320]

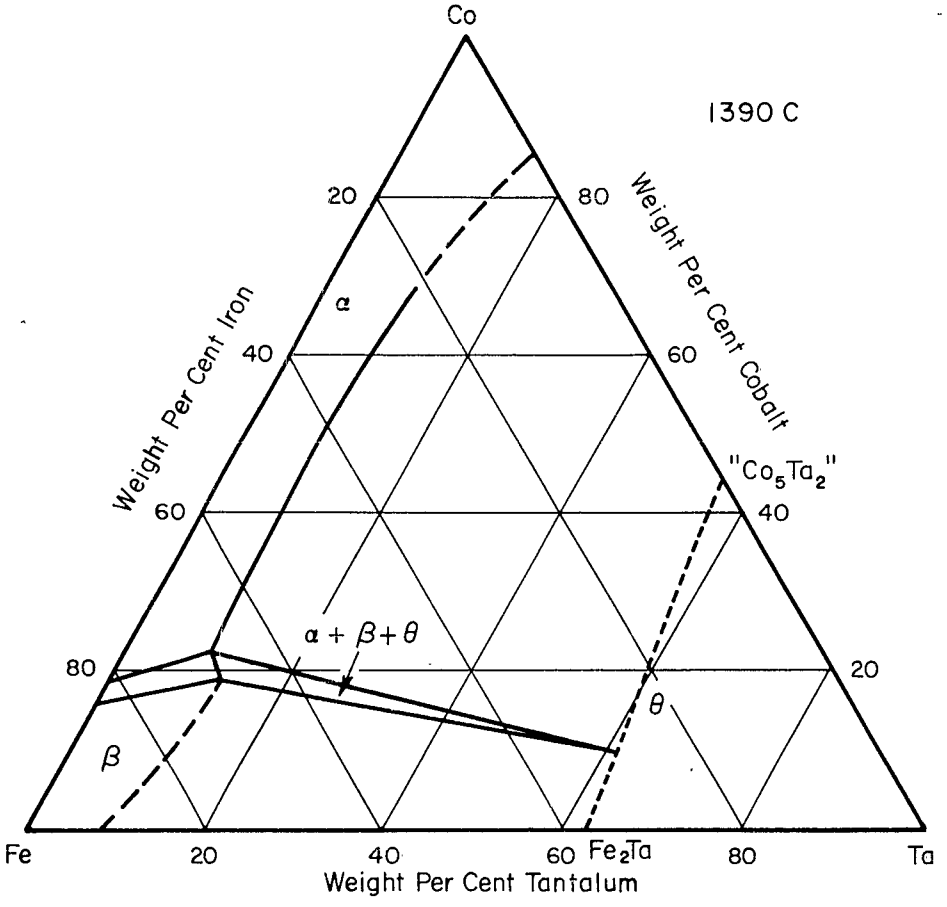


(169-2)-63

TANTALUM-COBALT-IRON SYSTEM (20 C)[290]

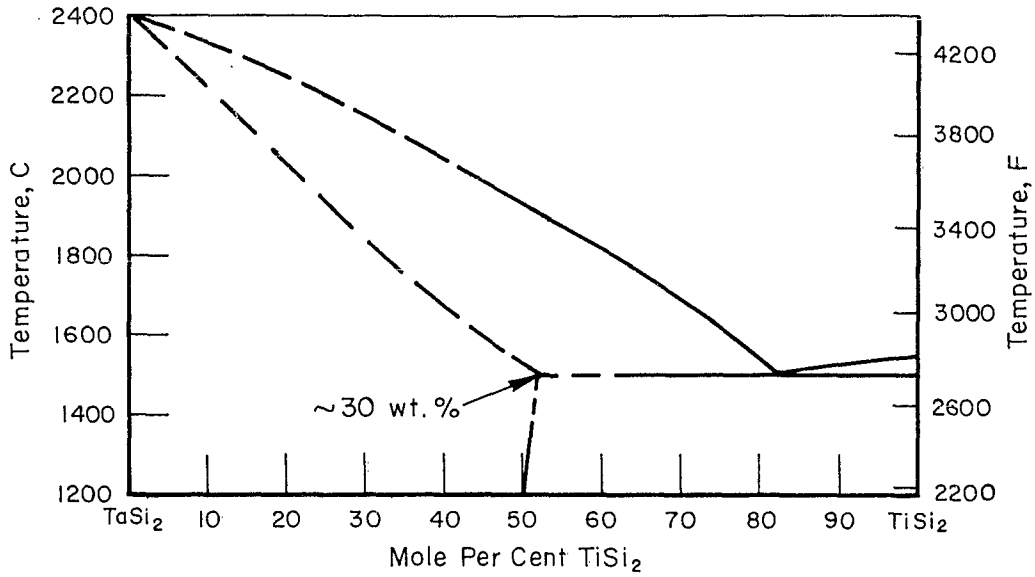


TANTALUM-COBALT-IRON SYSTEM (1390 C)[290]

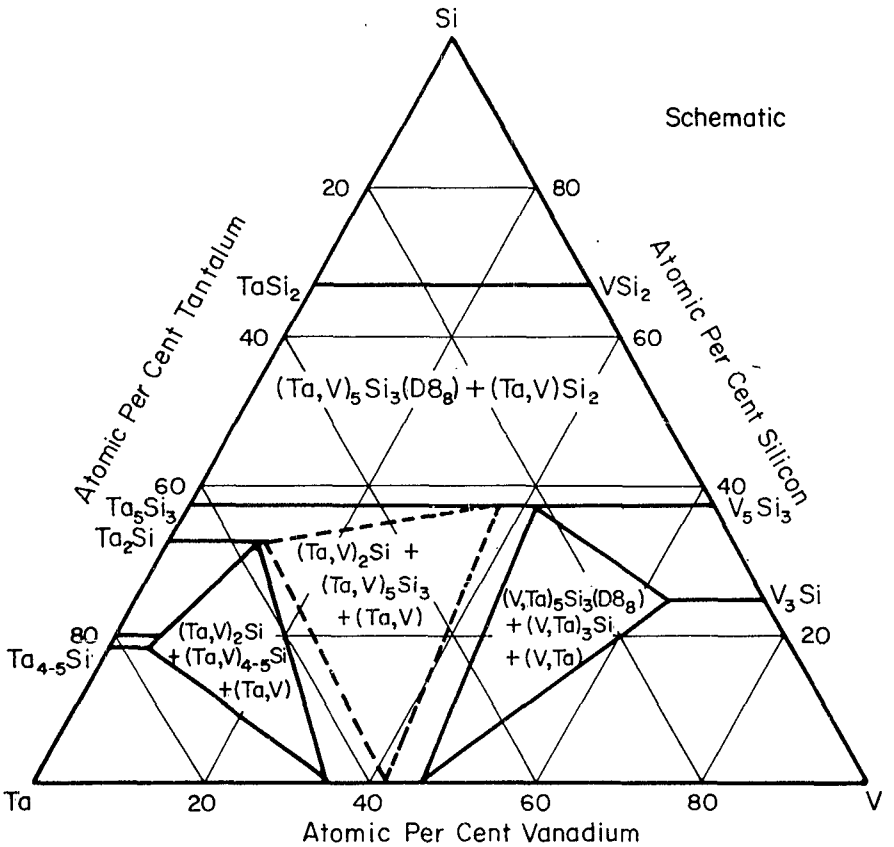


(173-2)-63

TANTALUM-SILICON-TITANIUM SYSTEM ($TaSi_2$-$TiSi_2$)[316]

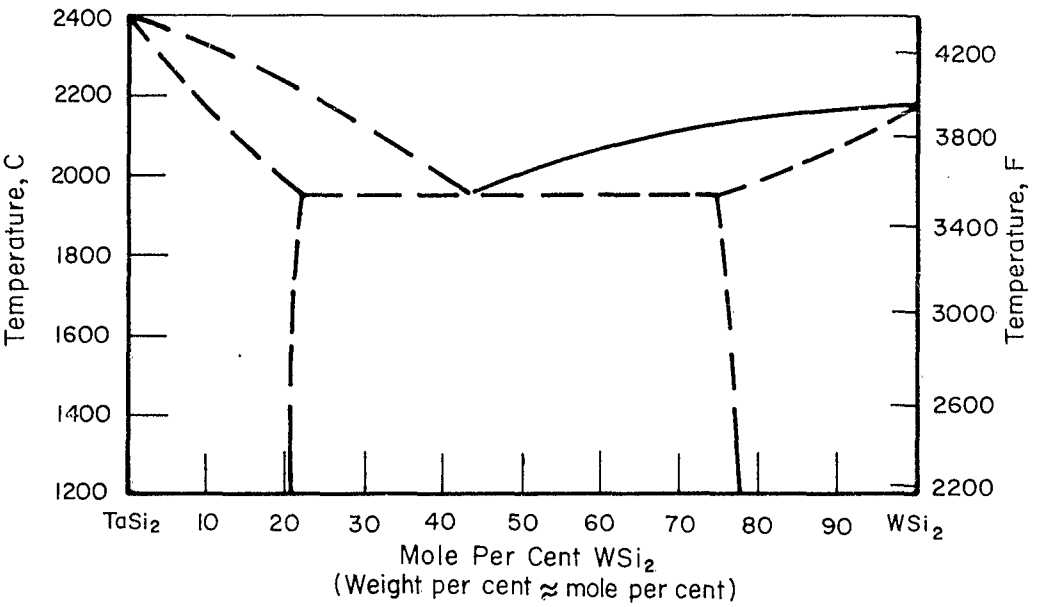


TANTALUM-SILICON-VANADIUM SYSTEM (SCHEMATIC)[315]

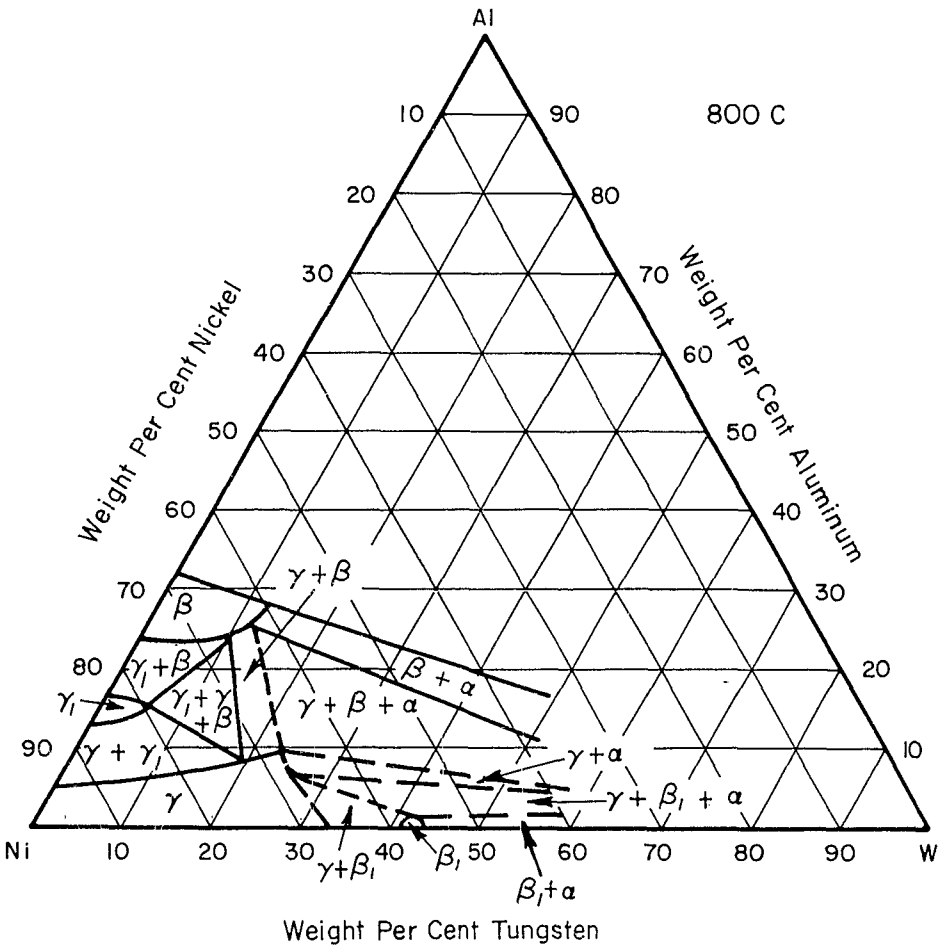


(178-2)-63

TANTALUM-TUNGSTEN-SILICON SYSTEM ($TaSi_2$-WSi_2)[316]

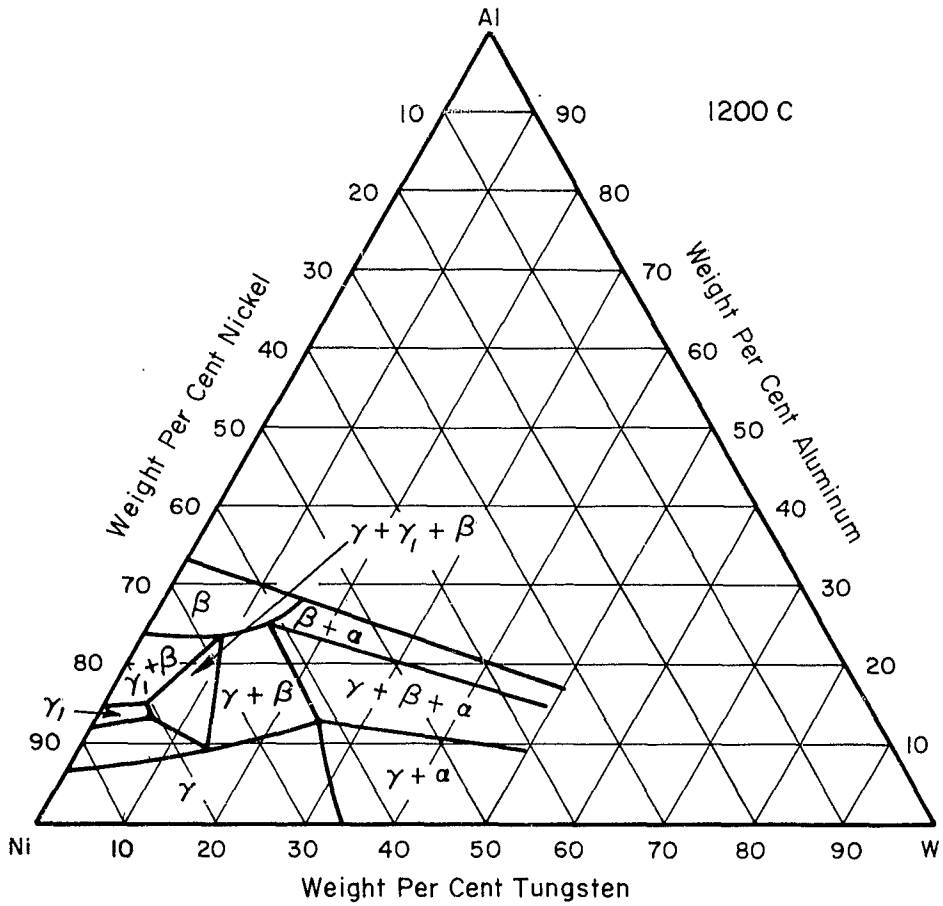


TUNGSTEN-ALUMINUM-NICKEL SYSTEM (800 C)[302]



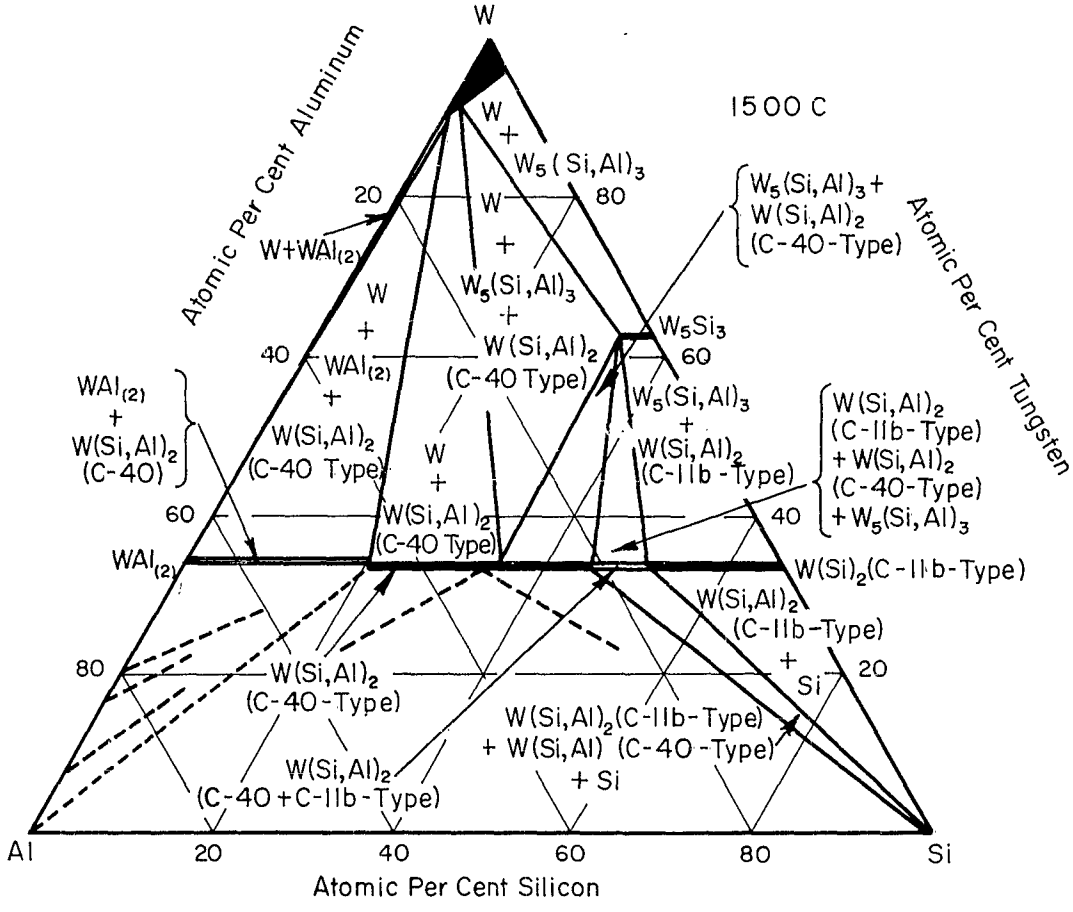
(187-1)-63

TUNGSTEN-ALUMINUM-NICKEL SYSTEM (1200 C)[302]



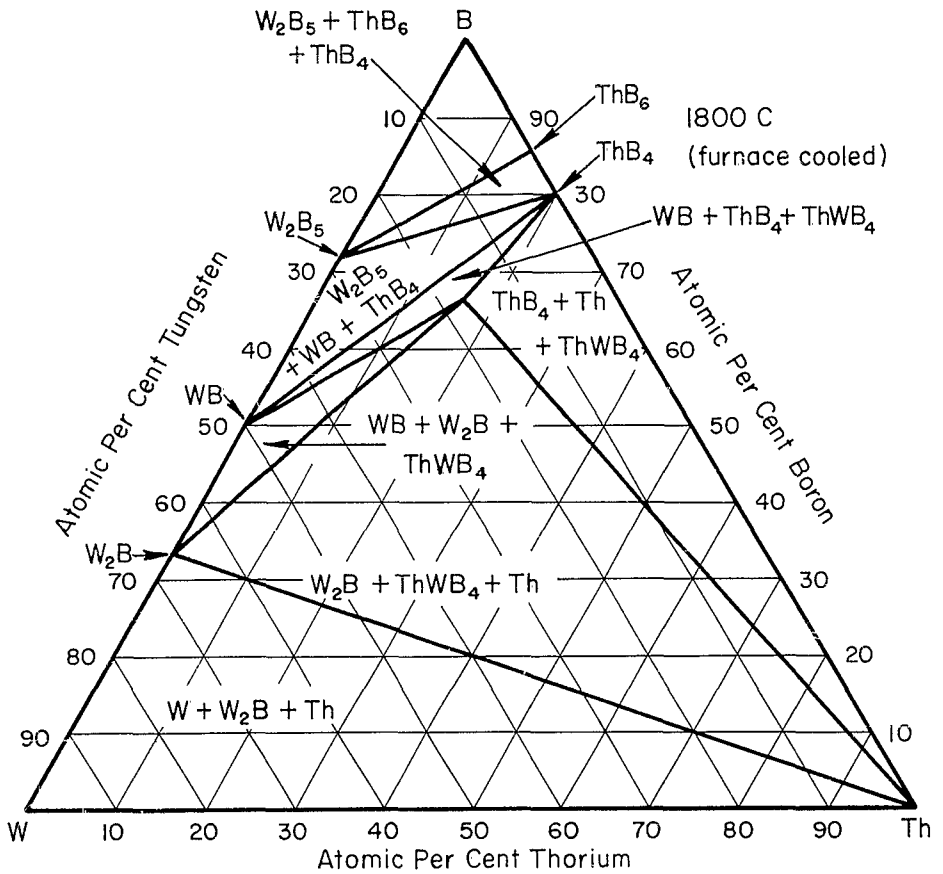
(187-2)-63

TUNGSTEN-ALUMINUM-SILICON SYSTEM (1500 C)[266]



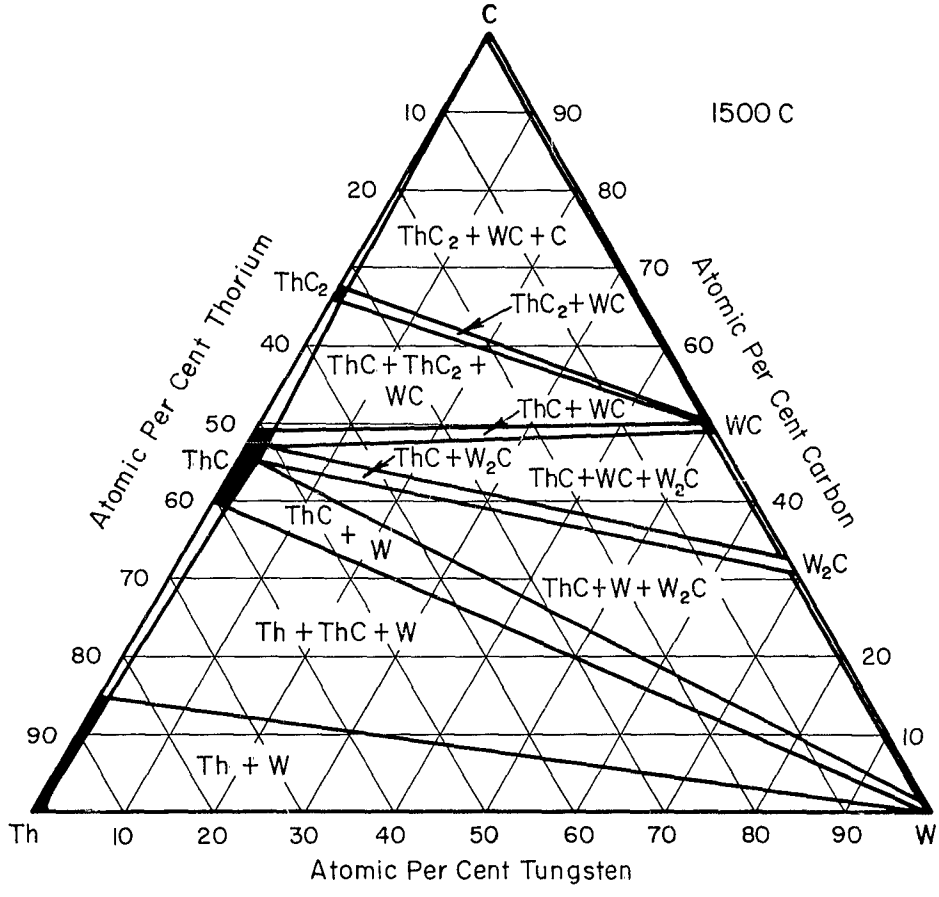
(187-3)-63

TUNGSTEN-BORON-THORIUM SYSTEM (1800 C)[291]



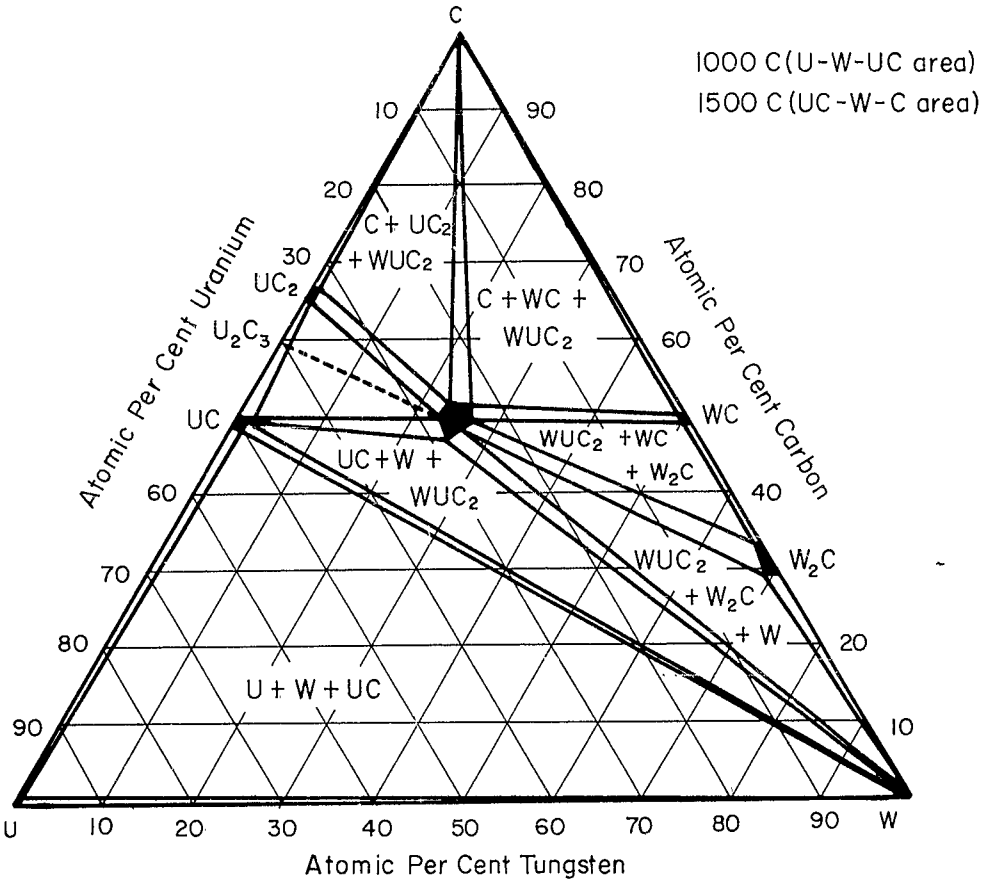
A ternary compound was found with a probable composition $ThWB_4$. The compound is monoclinic with a = 12.25 A, b = 3.75 A, c = 6.14 A, and β = 104.1°.[291]

TUNGSTEN-CARBON-THORIUM SYSTEM (1500 C)[292]



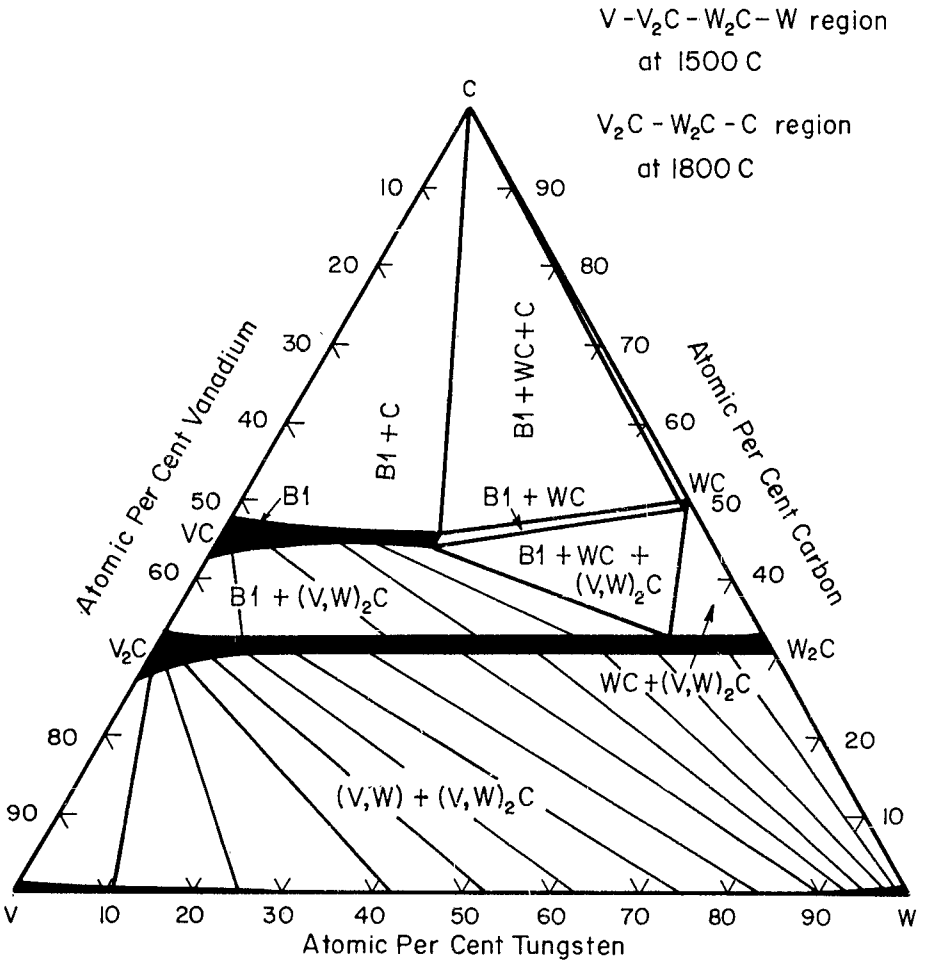
(194-1)-63

TUNGSTEN-CARBON-URANIUM SYSTEM (1000 AND 1500 C)[292]



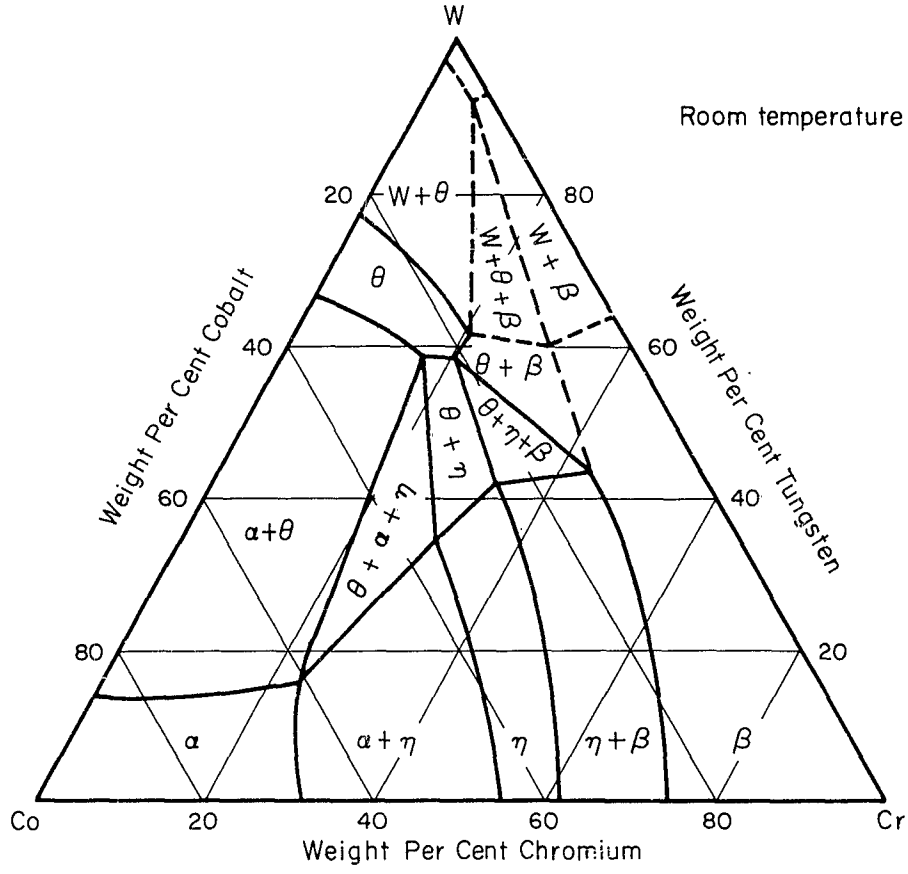
(195-1)-63

TUNGSTEN-CARBON-VANADIUM SYSTEM (1500 AND 1800 C)[309]



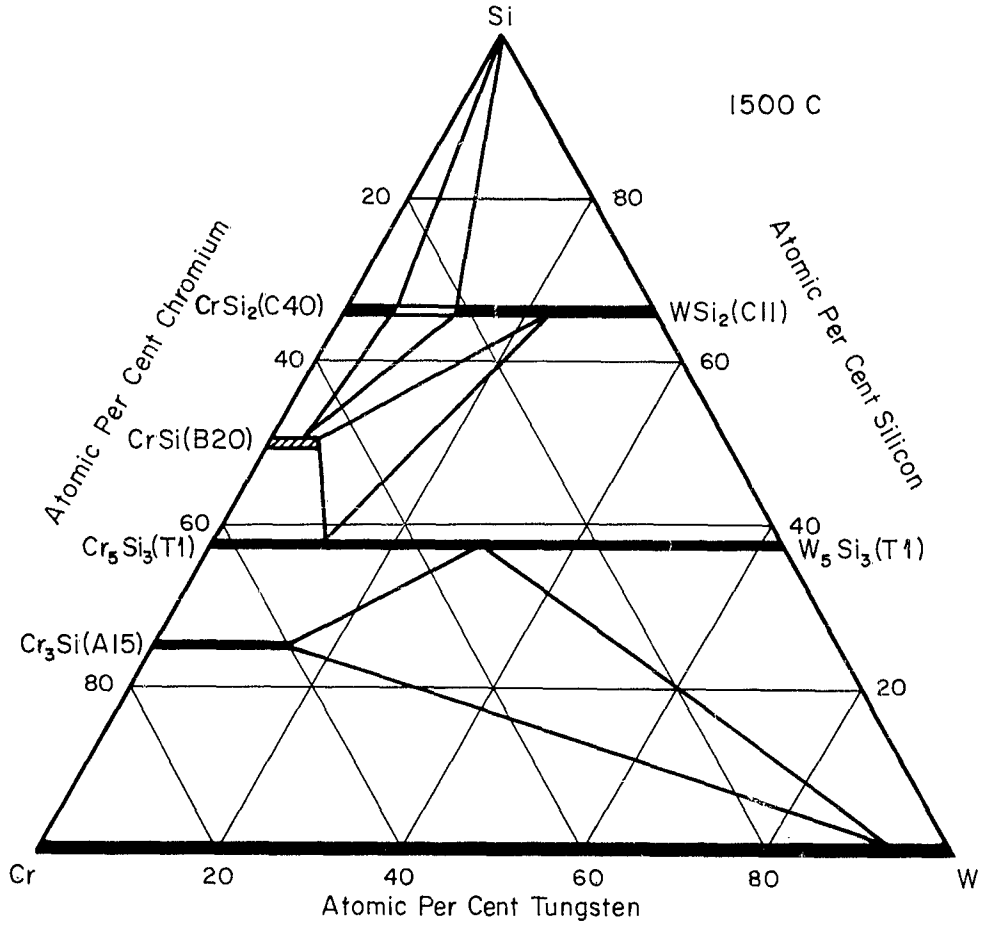
(195-2)-63

TUNGSTEN-CHROMIUM-COBALT SYSTEM (ROOM TEMPERATURE)[293]

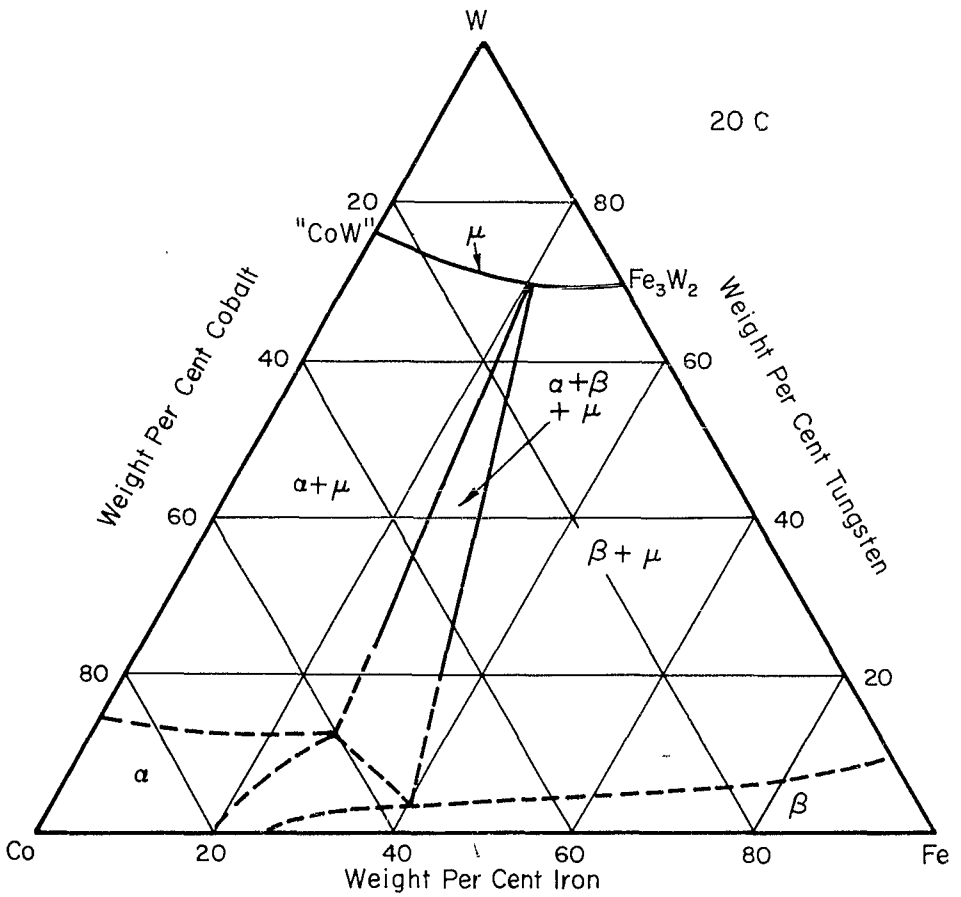


(195-3)-63

TUNGSTEN-CHROMIUM-SILICON SYSTEM (1500 C)[294]

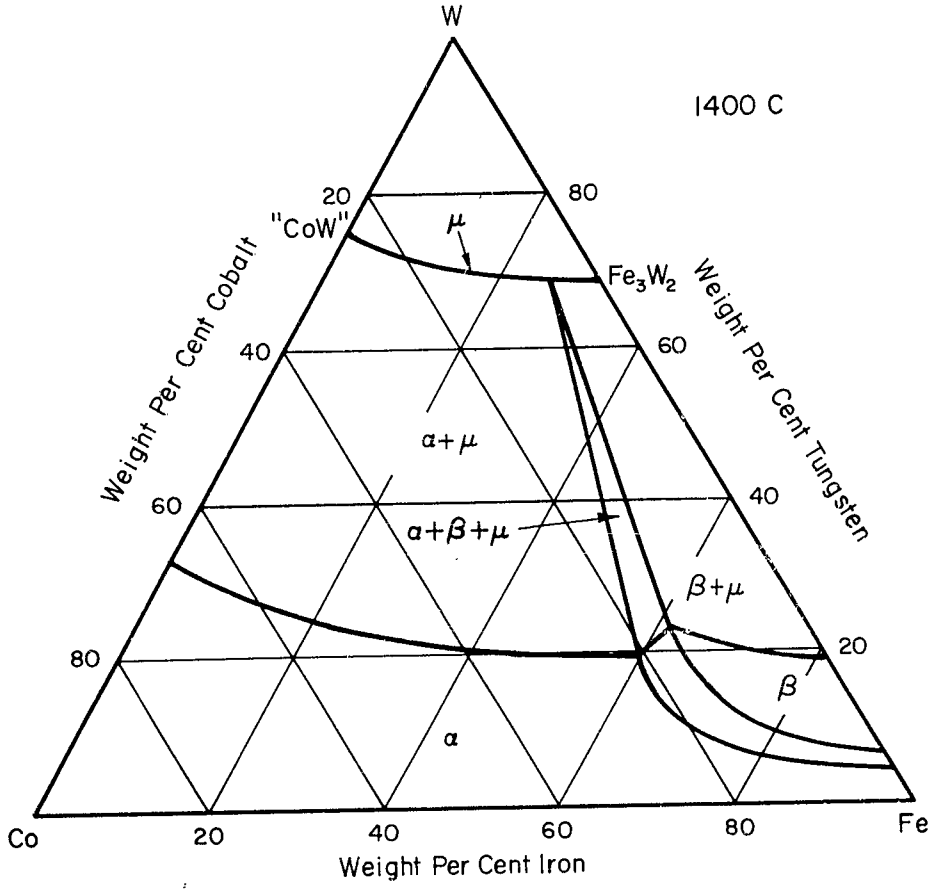


TUNGSTEN-COBALT-IRON SYSTEM (20 C)[295]

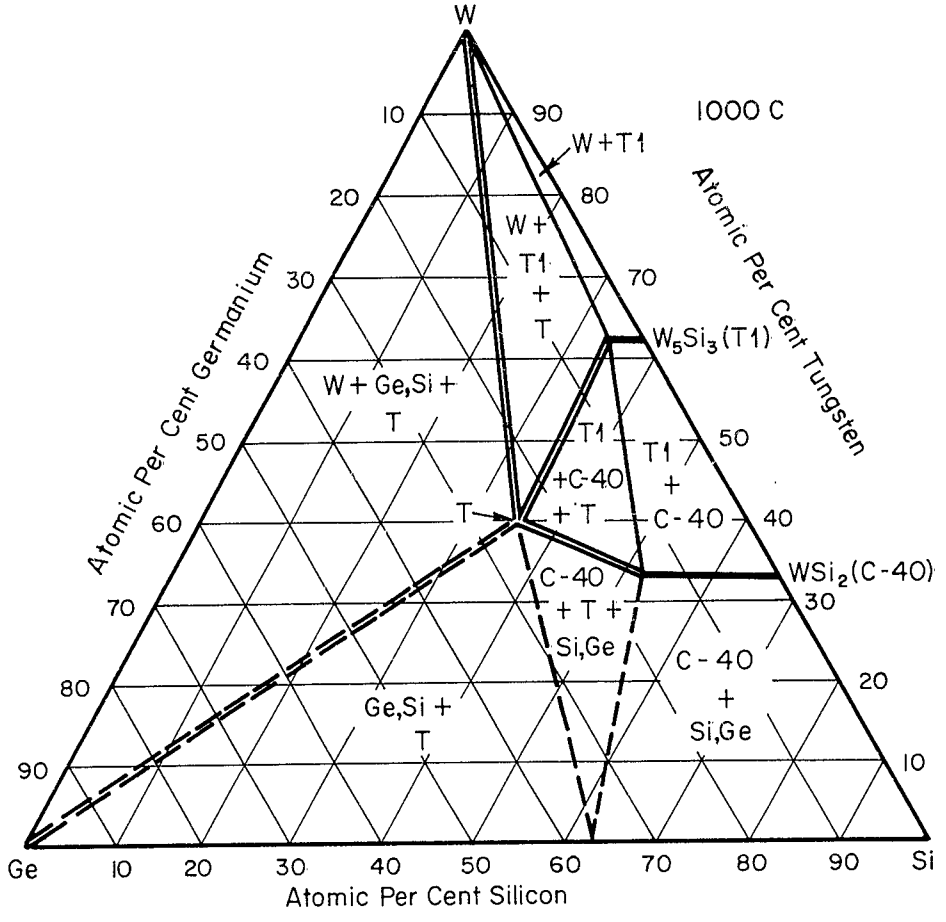


(203-1)-63

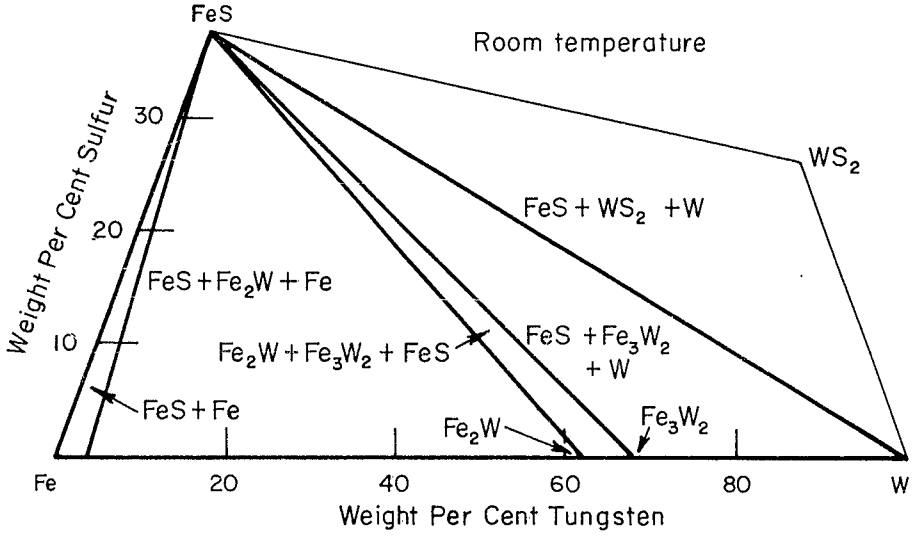
TUNGSTEN-COBALT-IRON SYSTEM (1400 C)[295]



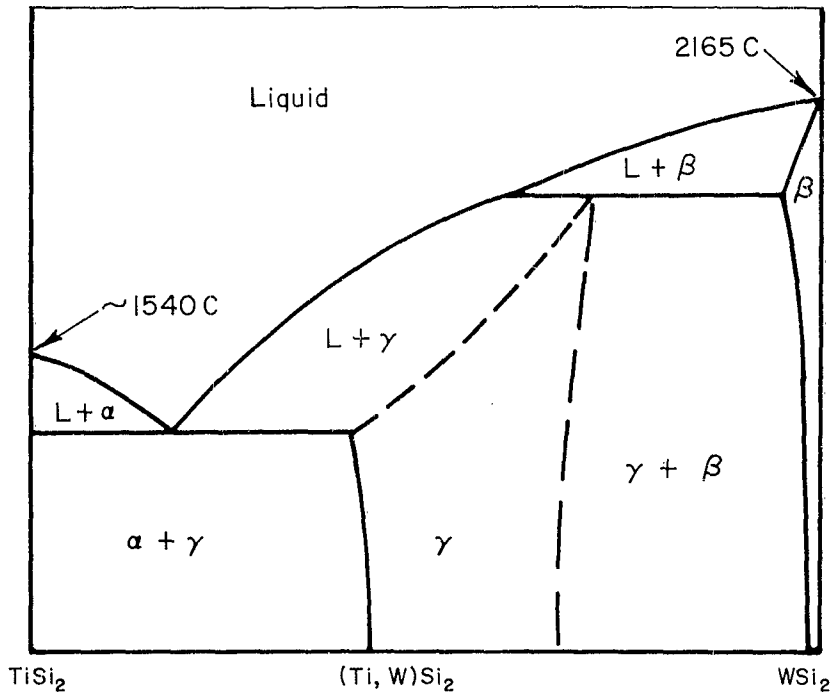
TUNGSTEN-GERMANIUM-SILICON SYSTEM (1000 C)[297]



TUNGSTEN-IRON-SULFUR SYSTEM (ROOM TEMPERATURE)[296]



TUNGSTEN-SILICON-TITANIUM SYSTEM ($TiSi_2$-WSi_2 SCHEMATIC)[316]



Schematic Diagram

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