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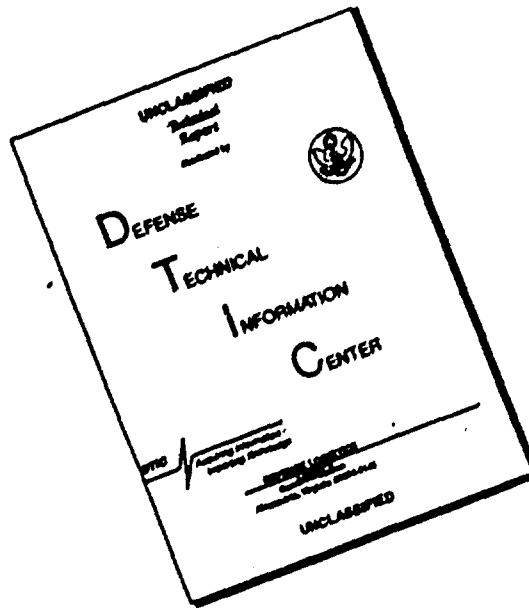
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DMIC Report 152

April 28, 1961

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BINARY AND TERNARY PHASE DIAGRAMS

OF

COLUMBIUM, MOLYBDENUM, TANTALUM, AND TUNGSTEN

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Contract No. AF 33(616)-7747

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

by

J. J. English

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

PREFACE

The following references were used extensively in compiling this report on refractory-metal phase diagrams:

- (1) Constitution of Binary Alloys, by M. Hansen and K. Anderko
- (2) Tantalum and Niobium, by G. Miller
- (3) Tantalum and Tantalum Alloys, DMIC Report 133, by F. F. Schmidt
- (4) Physical and Mechanical Properties of Columbium and Columbium-Base Alloys, DMIC Report 125, by E. S. Bartlett and J. A. Houck
- (5) A Study of Ternary Phase Diagrams of Tungsten and Tantalum, by W. Rostoker
- (6) Molybdenum Metal Technical Notes - Constitution Diagrams, by R. R. Freeman and J. Z. Briggs
- (7) Tungsten - Bibliography, 1953-1958, by P. W. Felten

These references were supplemented by library research and by interviews with Government contractors now conducting work in this field.

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BIBLIOGRAPHY

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

SUMMARY

This report contains a compilation or discussion of 93 binary and 68 ternary phase diagrams of the four refractory metals, columbium, molybdenum, tantalum, and tungsten. Included with each diagram is a discussion which lists information on the solubility and crystal structure of intermediate phases. When several investigations of a particular diagram are in disagreement, the discrepancies are discussed.

Many of the diagrams are incomplete, and are subject to revision as more definitive data become available. However, they are included in this report so that the readers may have as up-to-date information as possible on each of the systems.

INTRODUCTION

Because of the need for structural materials for use at higher and higher temperatures, much research and development emphasis has been placed on the refractory metals columbium, molybdenum, tantalum and tungsten. These four metals have the highest melting points and highest strength at high temperatures of all the metallic elements available in useful quantities. The emphasis in research and development activities has been on alloy development, physical metallurgy, oxidation behavior, protective-coating systems, and melting and fabrication methods. In almost all of these activities a knowledge of the alloying behavior as exemplified by the phase diagram is important.

This report consists of a compilation of the phase diagrams for alloys of columbium, molybdenum, tantalum, and tungsten. Many of the diagrams are not complete, while others are subject to revision as more definitive data become available. It is hoped that users of this report will supply DMIC with any additional phase-diagram information on these metals that is, or may become, available.

ORGANIZATION OF THE REPORT

The phase diagrams in this report are divided into two sections: binary systems and ternary systems. The binary diagrams are arranged into four groups, one for each of the four metals. Within each group the systems are arranged in alphabetical order according to the spelling of the second element in the system. A diagram involving two of the four subject metals is listed only in the first alphabetical grouping. For example, the columbium-molybdenum system is not repeated as the molybdenum-columbium system.

The ternary phase diagrams are also arranged alphabetically in four groups. When two or more refractory metals occur in a system they are listed first, in alphabetical order. For example, the columbium-tantalum-chromium system will not be listed as the columbium-chromium-tantalum system.

This report has been bound with a plastic binder. This will permit additional diagrams to be added as they become available. If desired, the diagrams can be removed from the present binder and inserted in an appropriate loose-leaf binder.

THE PHASE DIAGRAMS

The four refractory metals, whose phase diagrams are compiled in this report, have body-centered cubic structures. Columbium and tantalum are Group V-A elements and molybdenum and tungsten are Group VI-A elements. The melting points and lattice constants of each of the four elements are listed below:

	<u>Melting Point</u>		<u>Lattice Parameter, A</u>
	<u>C</u>	<u>F</u>	
Columbium	2460	4460	3.300
Molybdenum	2620	4750	3.147
Tantalum	2996	5430	3.303
Tungsten	3410	6170	3.165

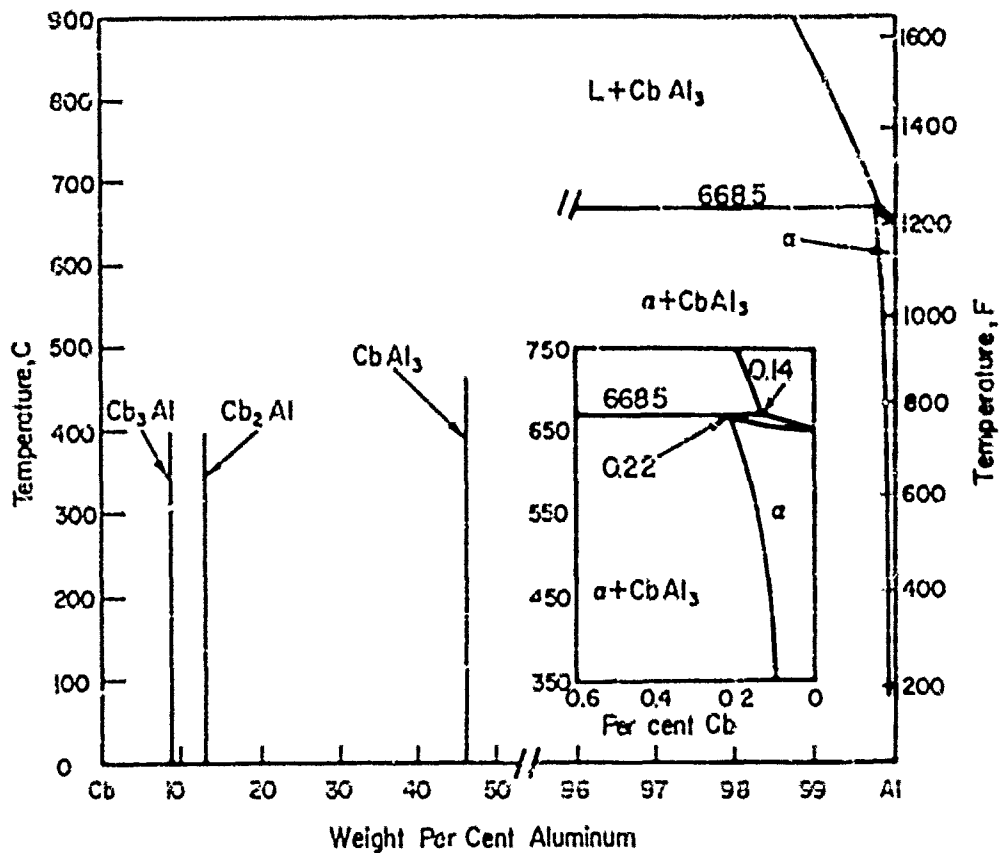
As would be expected from their lattice constants, these elements are mutually soluble in one another. However, the phase diagrams with other systems vary considerably from one base to another. For example, columbium and tantalum have high solubilities for interstitial elements while molybdenum and tungsten do not.

In the phase diagrams which follow, a short discussion is included below each diagram. It lists information such as maximum solubility and the crystal structure of intermediate phases. When several investigations of a particular diagram are in disagreement, the discrepancies are discussed.

In the discussions the numbers in parentheses refer to references listed in the Bibliography at the end of the report.

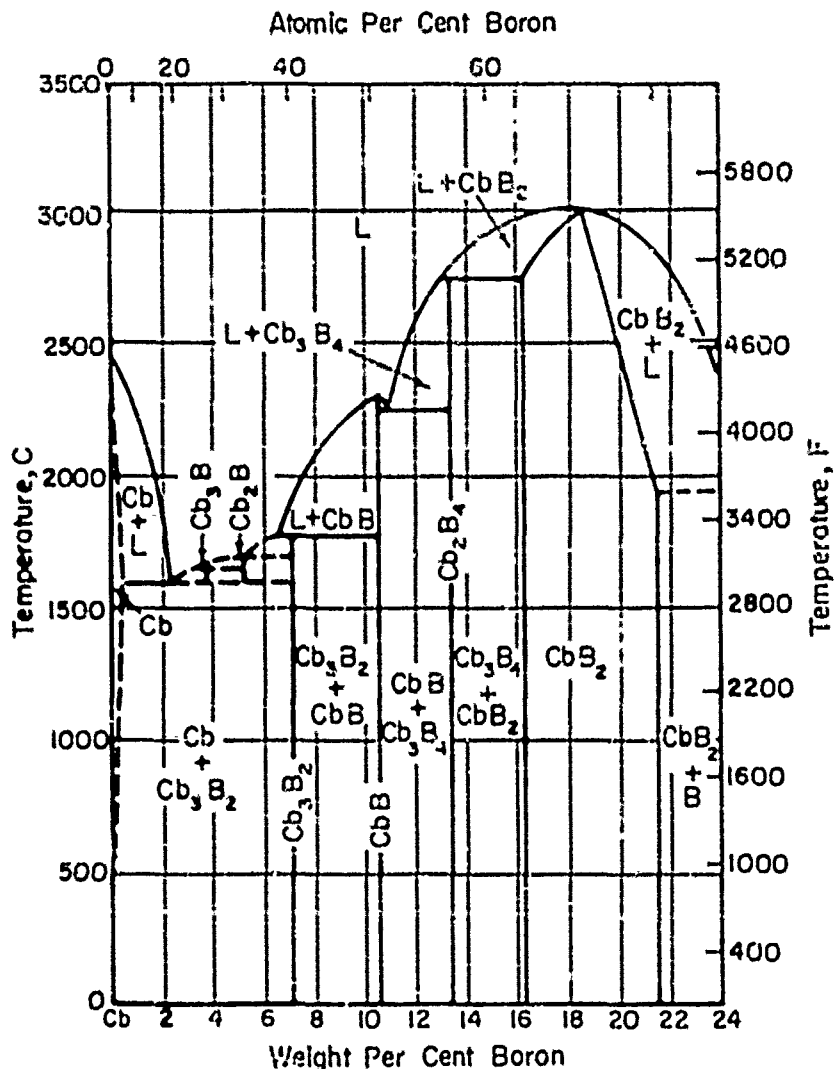
BINARY PHASE
DIAGRAMS

COLUMBIUM-ALUMINUM SYSTEM



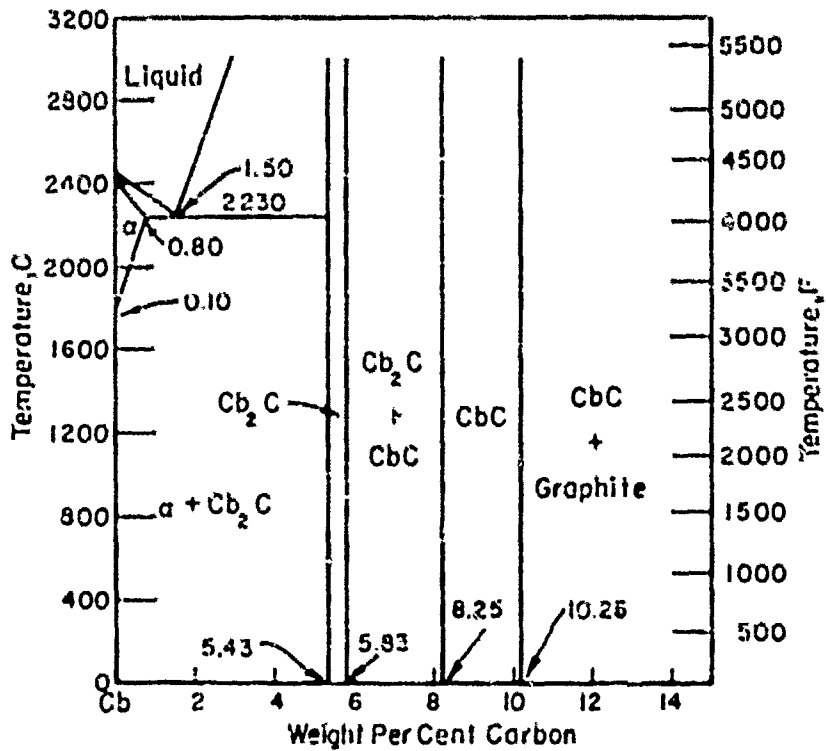
Three intermediate phases have been reported. Cb_3Al has a cubic, beta-tungsten structure with $a = 5.187 \text{ \AA}$.⁽¹⁾ Cb_2Al has a tetragonal, sigma-type structure with $a = 9.943 \text{ \AA}$, $c = 5.195 \text{ \AA}$, and $c/a = 0.522$.⁽²⁾ CbAl_3 is tetragonal with $a = 5.498 \text{ \AA}$, $c = 8.661 \text{ \AA}$, and $c/a = 1.582$.⁽³⁾

COLUMBIUM-BORON SYSTEM



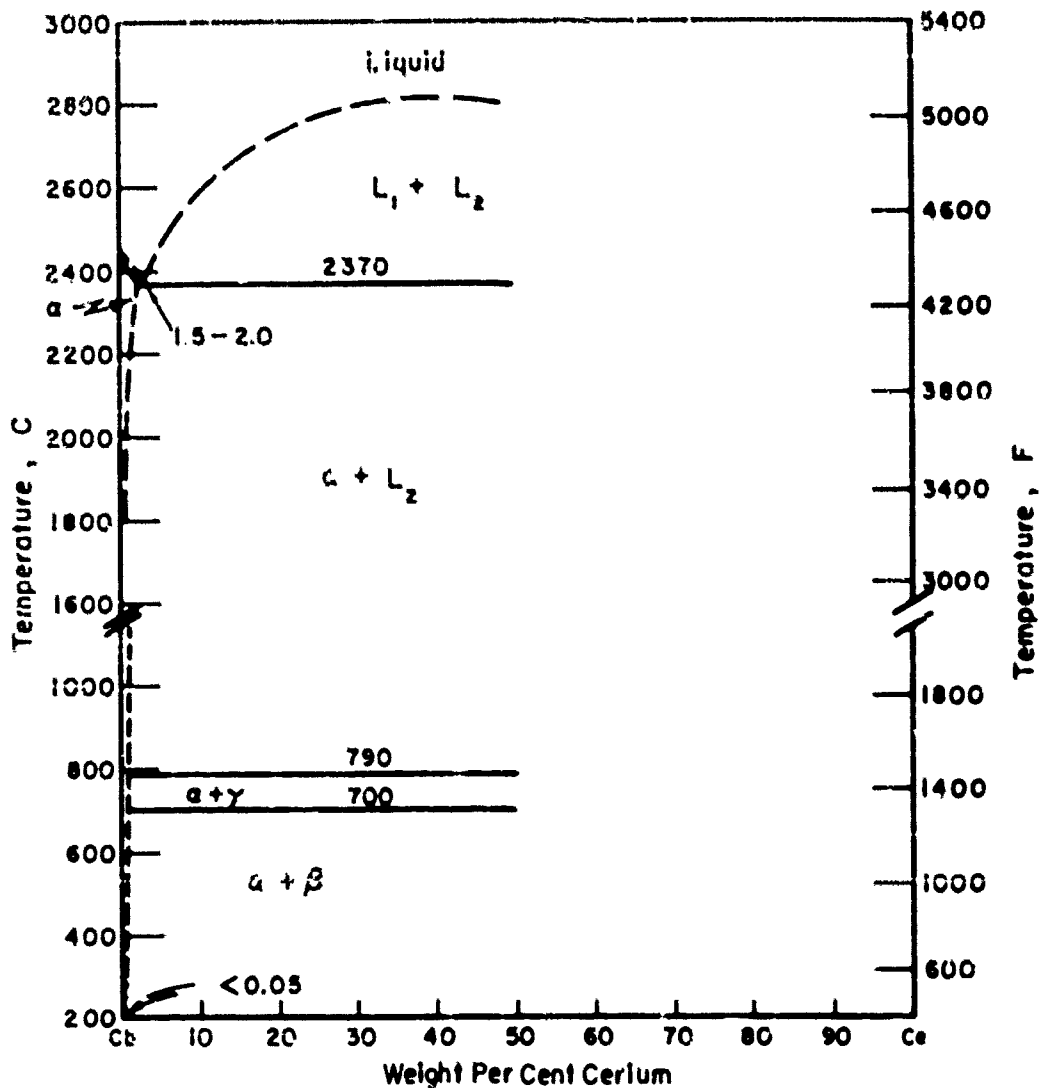
Cb₃B₂ has a tetragonal, U₃Si₂-type structure with $a = 6.173$ Å, and $c = 3.214$ Å.⁽⁴⁾ CbB is an orthorhombic, C₁B-type structure with $a = 3.298$ Å, $b = 8.724$ Å, and $c = 2.166$ Å.^(5, 6) Cb₃B₄ is an orthorhombic, Mn₃Si₄-type structure with $a = 2.355$ Å, $b = 14.08$ Å, and $c = 3.137$ Å.⁽⁶⁾ CbB₂ is a hexagonal, C₃2-type structure with $a = 3.689$ Å, $c = 3.993$ Å, and $\alpha = 120^\circ$.^(6, 7) Cb₂B and Cb₂B₄ also exist over limited temperature ranges.^(5, 6) The solubility of boron in columbium is less than 0.025 weight per cent at 1500°C.⁽¹⁵⁸⁾

COLUMBIUM-CARBON SYSTEM



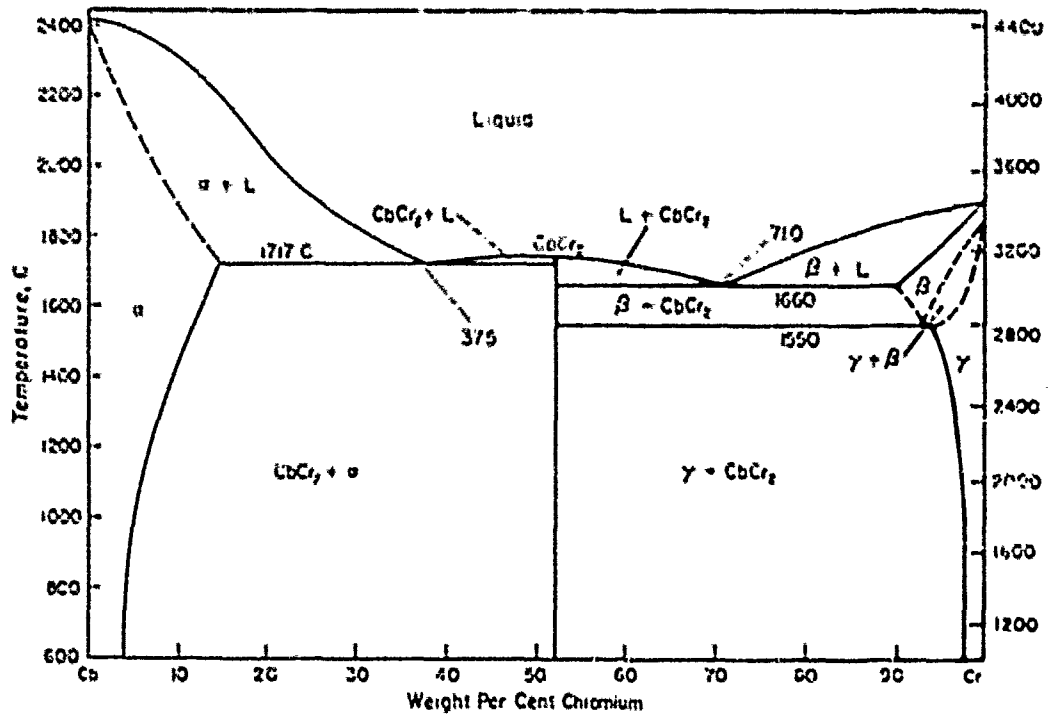
Two carbides of columbium exist. Cb_2C is hexagonal, having a limited region of solubility between 5.43 and 5.93 weight per cent carbon. CbC is a face-centered cubic with a lattice parameter $a = 4.470 \text{ \AA}$.^(8,9) Metallographic evidence indicates the existence of a peritectic reaction $L + CbC \rightarrow Cb_2C$ at some undetermined temperature. Alloys richer in carbon than the CbC phase freeze by the eutectic reaction $L \rightarrow CbC + \text{graphite}$ at approximately 3250 C.⁽¹⁰⁾

COLUMBIUM-CERIUM SYSTEM



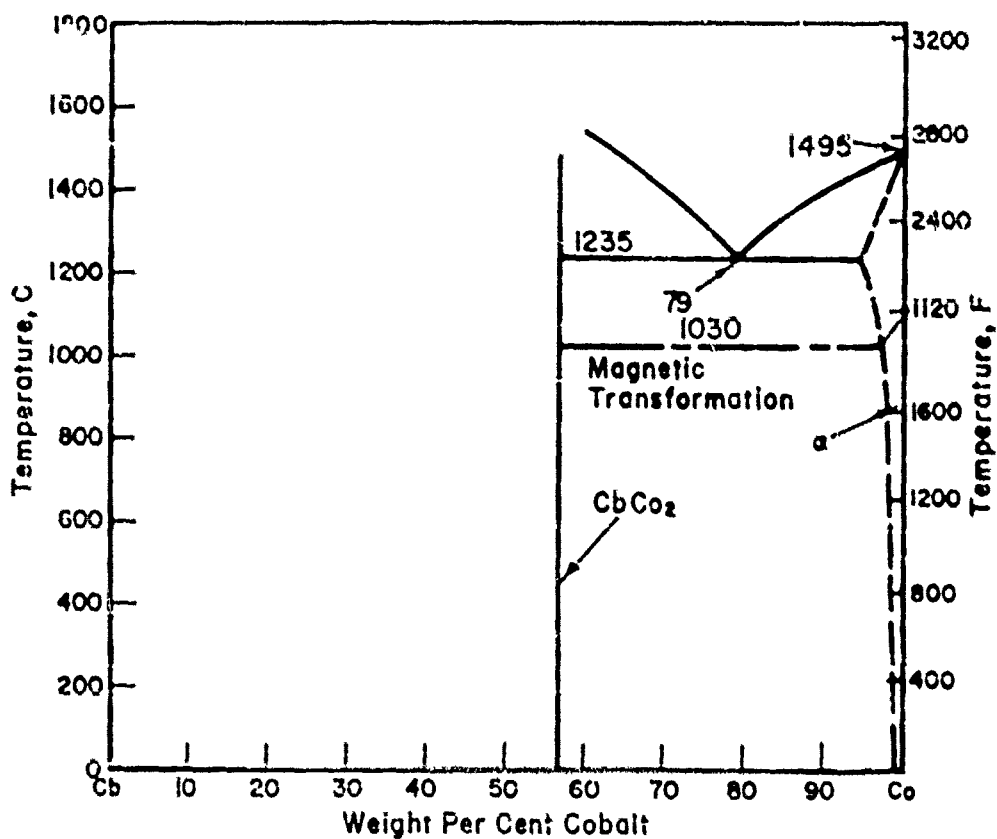
The phase diagram shows an extensive region of immiscibility in both the liquid and the solid states. The monotectic horizontal line at $2370 \pm 20^\circ\text{C}$. The melting temperature was reduced from 2415°C for pure columbium to $2360\text{--}2380^\circ\text{C}$ with 0.2 weight per cent cerium. Separation into two liquid layers starts at 1.0 to 2.0 weight per cent cerium. (11)

COLUMBIUM-CHROMIUM SYSTEM



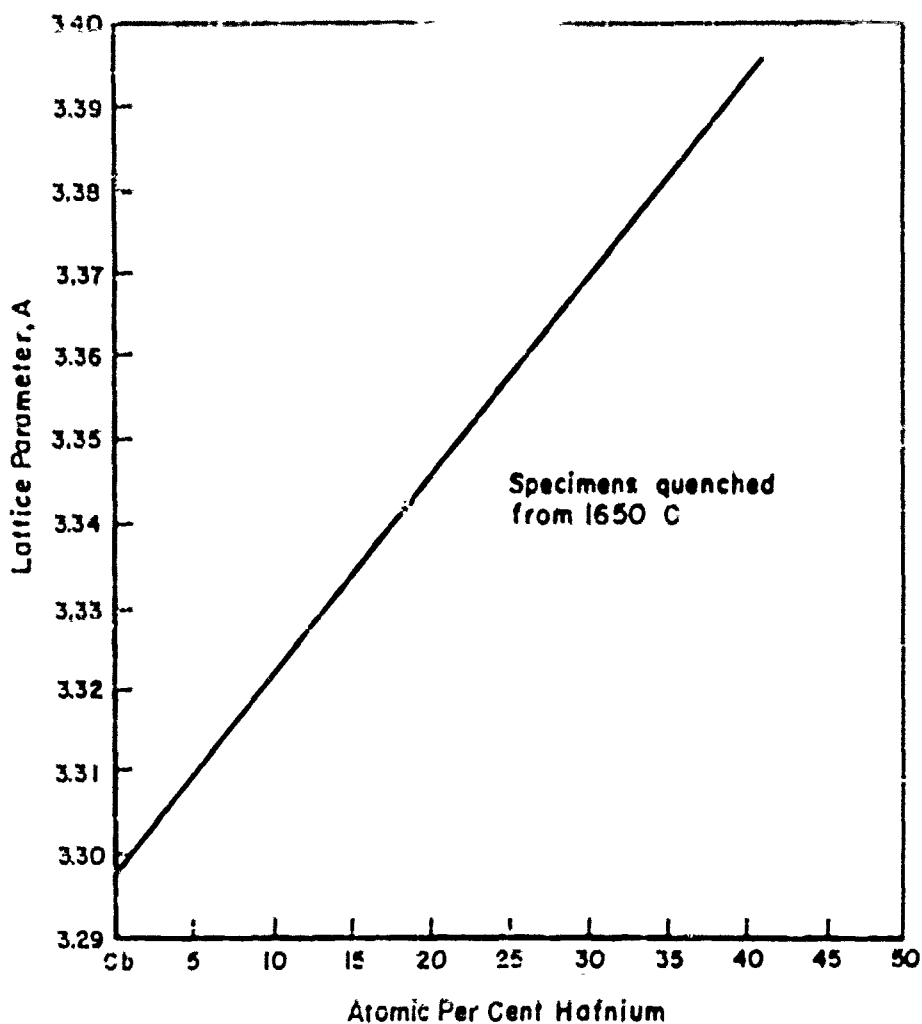
The solubility of chromium in columbium is approximately 12 weight per cent at 1500 C, decreasing to 4 weight per cent at 800 C. The solubility of columbium in chromium is 5 weight per cent at 1500 C, decreasing to 2 weight per cent at 800 C. (12) CbCr_2 is face-centered cubic with $a = 0.95\text{--}0.97 \text{ nm}$. (13)

COLUMBIUM-COBALT SYSTEM



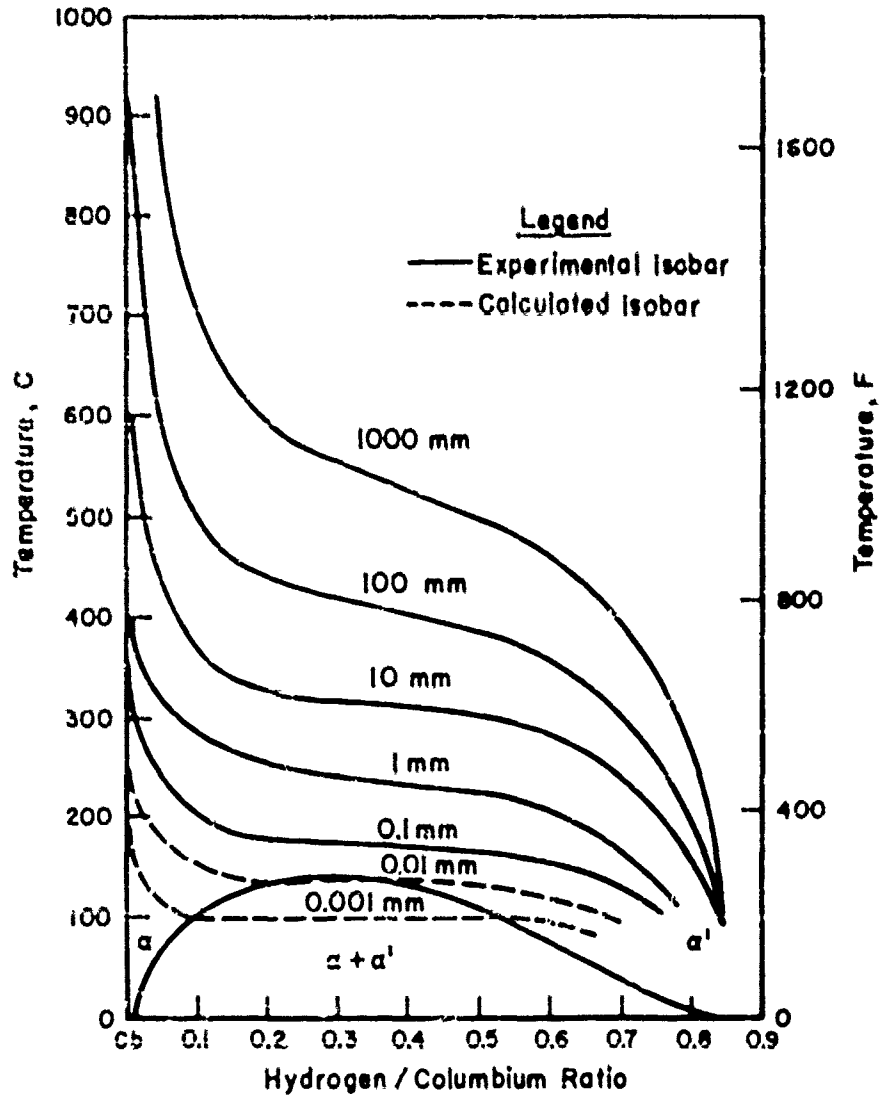
CbCo_2 is believed to exist in two modifications. One is at 33.3 atomic per cent columbium having a cubic $\text{MgCu}_2(\text{C15})$ type of structure with $a = 6.758 \text{ \AA}$. The second structure exists around 27 atomic per cent and is the $\text{MgNi}_2(\text{C36})$ type of structure. The lattice spacings for this structure were reported as $a = 4.735 \text{ \AA}$, $c = 15.46 \text{ \AA}$, and $c/a = 1.631$. (14, 15, 16)

COLUMBIUM-HAFNIUM SYSTEM



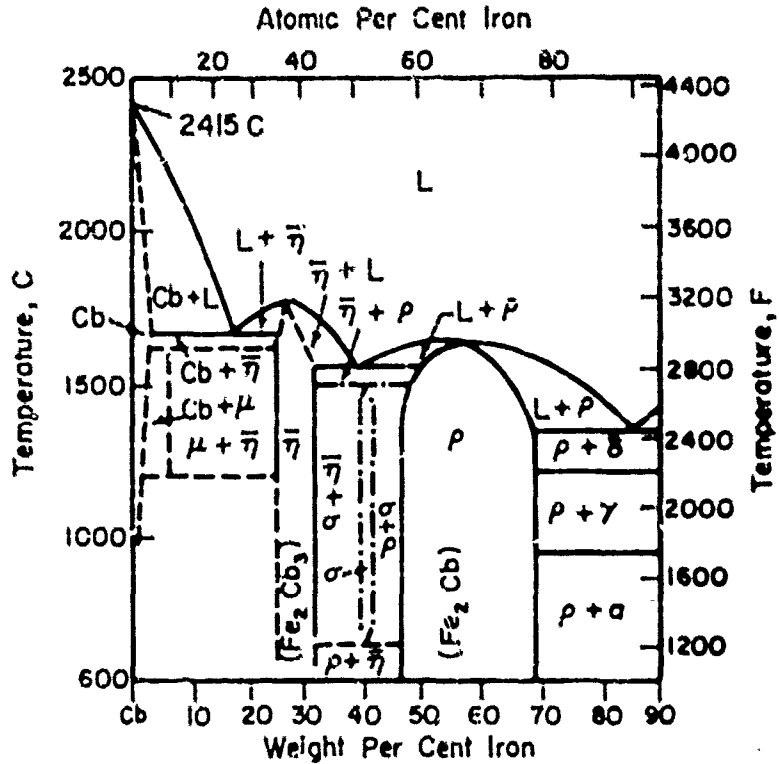
The solubility of hafnium in columbium is expected to be greater than 40 atomic per cent (49 weight per cent) at 1650 C. (169)

COLUMBIUM-HYDROGEN SYSTEM



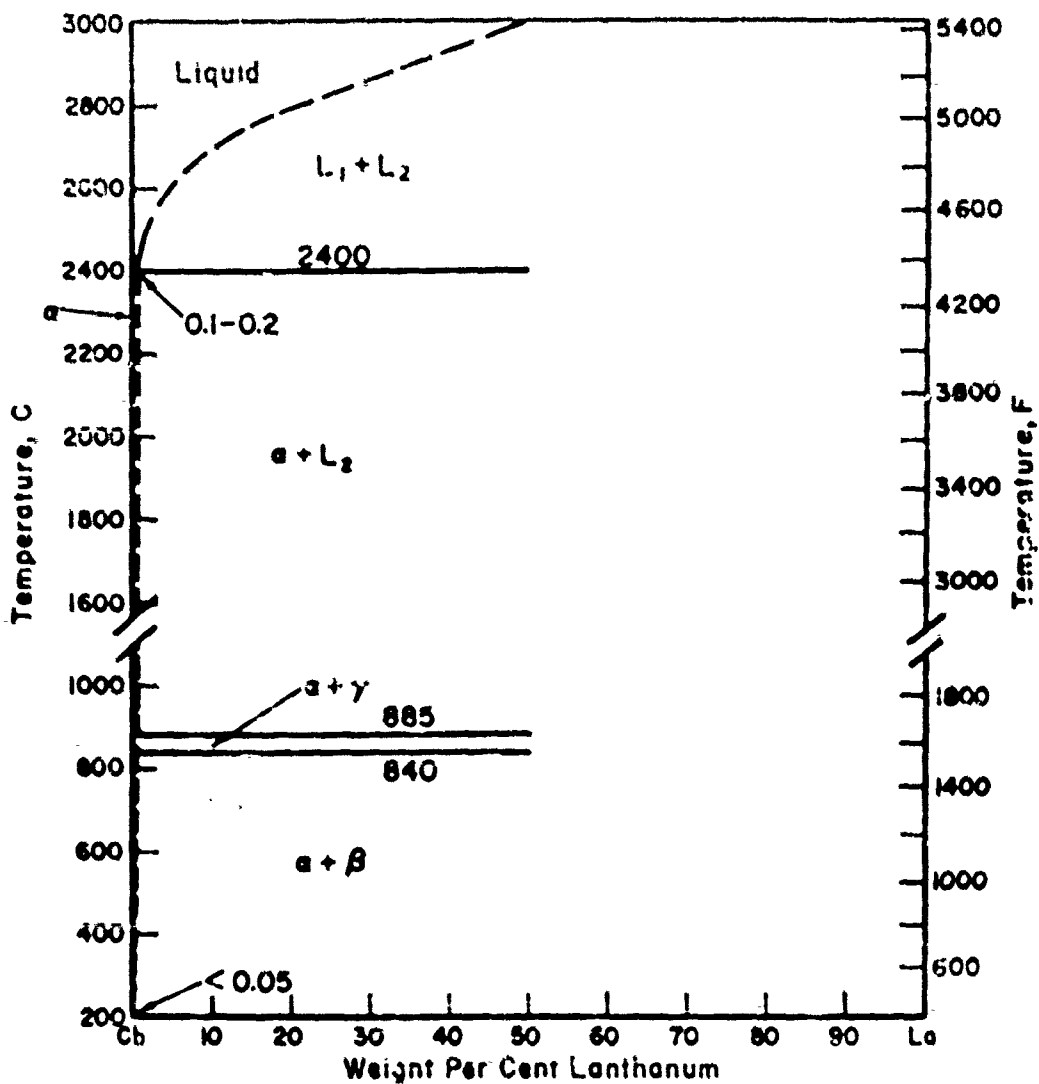
Equilibrium and X-ray studies show that in the ranges 100 to 900 C, 0.1 to 1000 mm Hg pressure, and 0.01 to 0.85 H/Cb ratio, the columbium-hydrogen system consists of a single-phase body-centered cubic structure. A two-phase region is present at relatively low temperatures and pressures with the critical point located at 140 C, 0.01 mm of Hg pressure, and 0.3 H/Cb ratio.(18)

COLUMBIUM-IRON SYSTEM



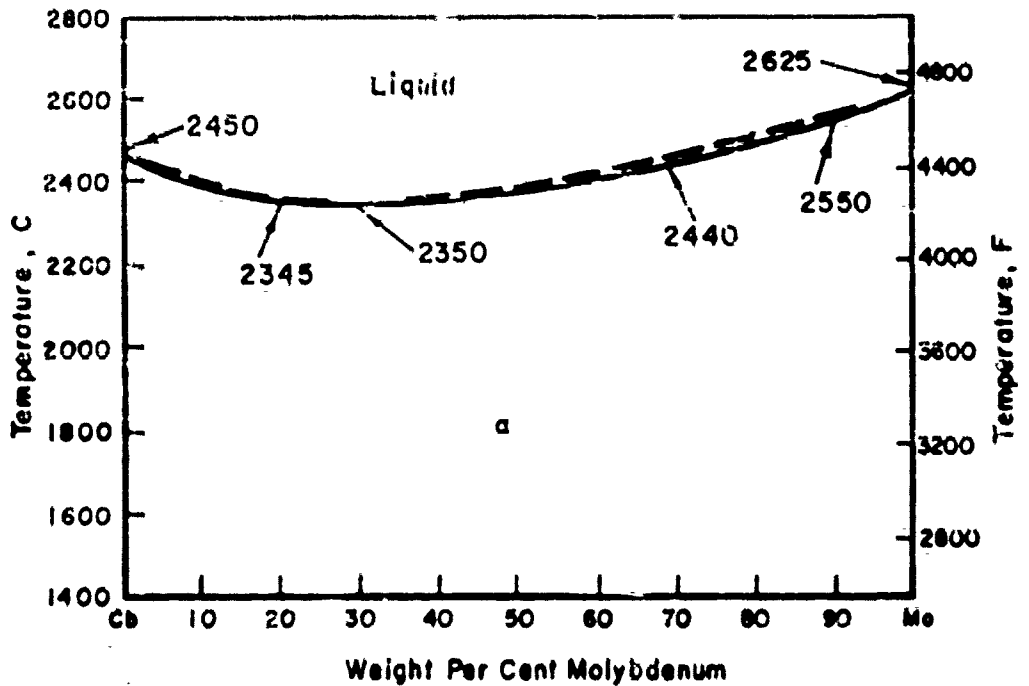
The phase diagram prepared by Goldschmidt shows a high-temperature σ -phase similar to other transition-metal systems. Fe₂Cb₃ is an η -carbide-type structure with $a = 11.233 \text{ \AA}$.⁽¹⁷⁾ Fe₂Cb is isotypic with MgZn₂ with $a = 4.630 \text{ \AA}$, $c = 7.822 \text{ \AA}$, and $c/a = 1.632$.⁽¹⁴⁾ The terminal solid solutions of columbium in iron and of iron in columbium are small and decrease with decreasing temperature.

COLUMBIUM-LANTHANUM SYSTEM



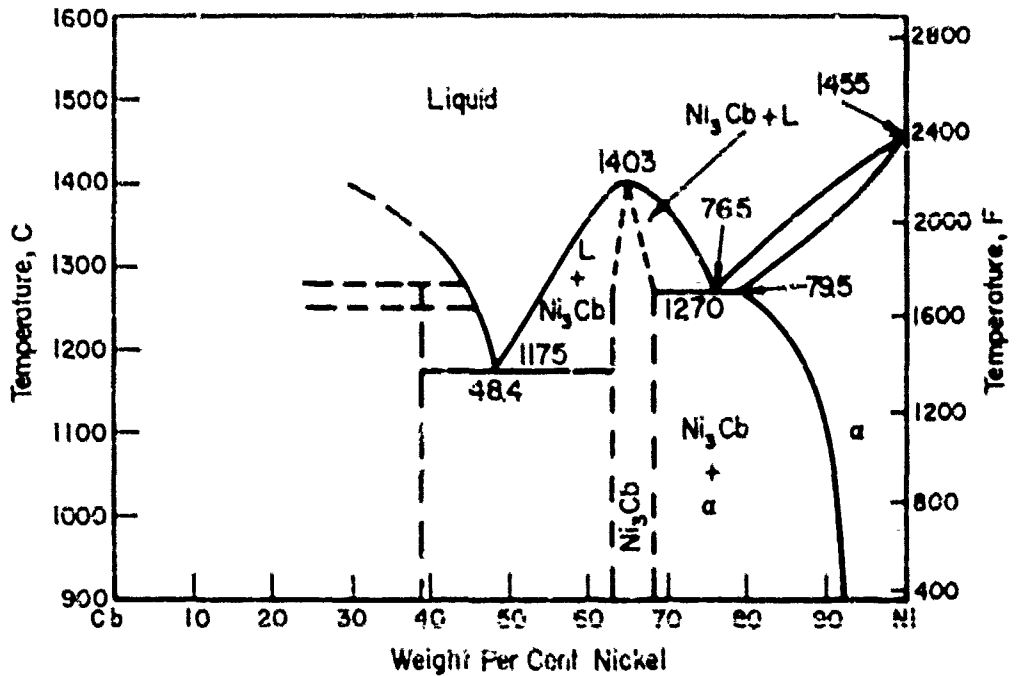
Extensive regions of immiscibility occur in the liquid and the solid regions. The monotectic horizontal line at 2400 ± 20°C. Separation into two layers occurs at 0.1 to 0.2 weight per cent lanthanum. The solubility in the solid state is less than 0.05 weight per cent at room temperature. (11)

COLUMBIUM-MOLYBDENUM SYSTEM



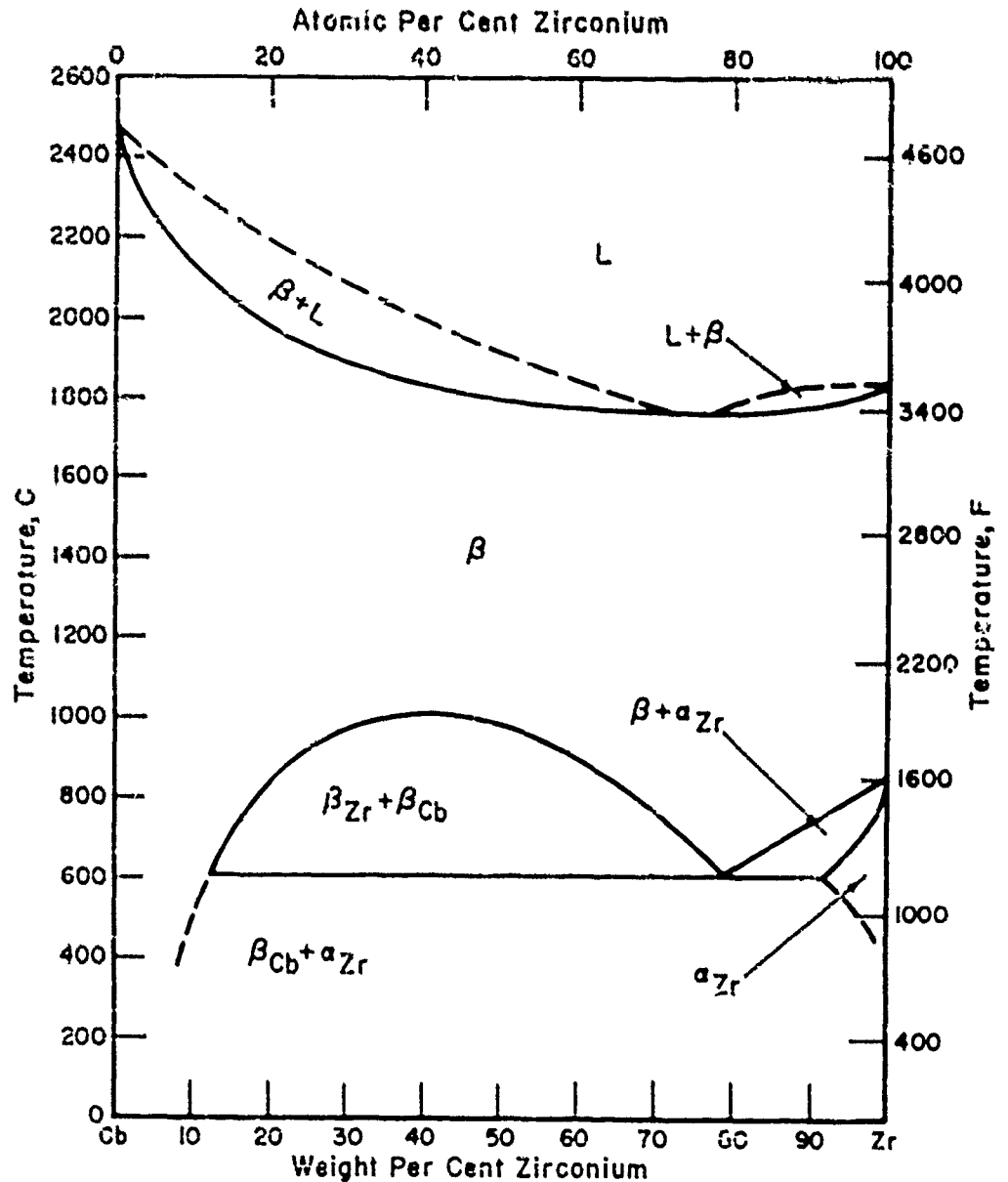
Columbium and molybdenum form a continuous series of solid solutions.⁽¹⁹⁾ Korabely determined the melting point of alloys containing 20, 30, 70, and 90 weight per cent molybdenum.⁽²⁰⁾

COLUMBIUM-NICKEL SYSTEM



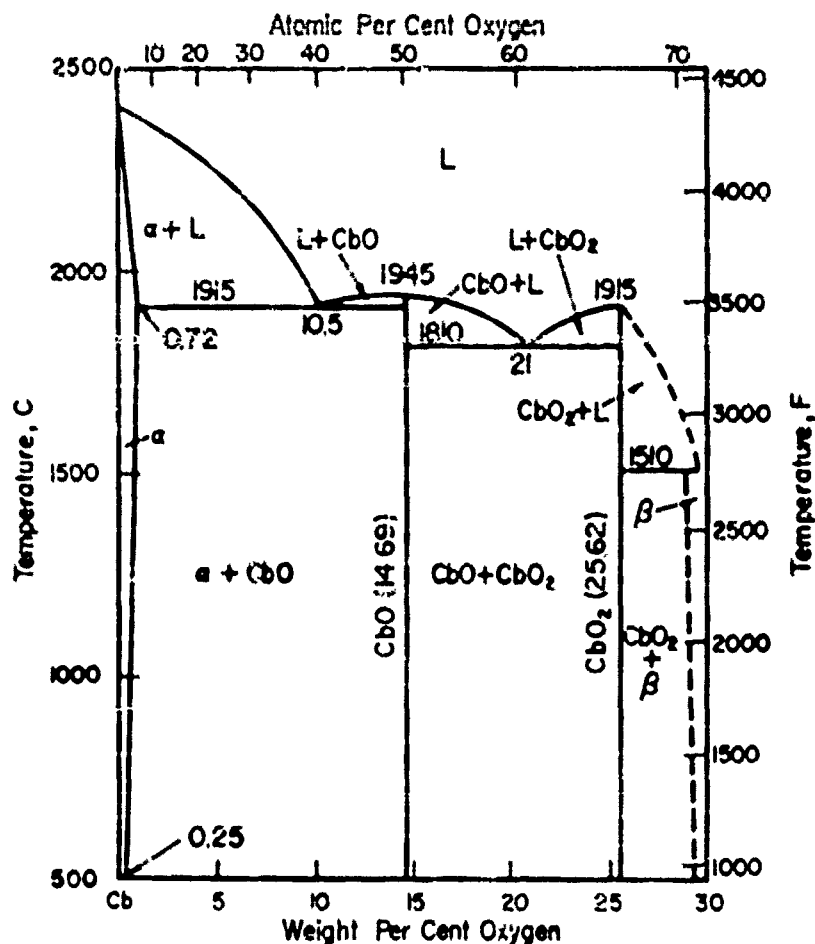
CbNi₃ has an orthorhombic TiCu₃-type structure with lattice parameters: $a = 5.10 \text{ \AA}$, $b = 4.55 \text{ \AA}$, and $c = 4.25 \text{ \AA}$.⁽²³⁾ The solubility of columbium in nickel is approximately 15 weight per cent at 1250°C. The solubility of nickel in columbium is less than 5 weight per cent.⁽²⁴⁾ The diagram was constructed from the data prepared by Bogdan and Selekman.⁽²⁵⁾

COLUMBIUM-ZIRCONIUM SYSTEM



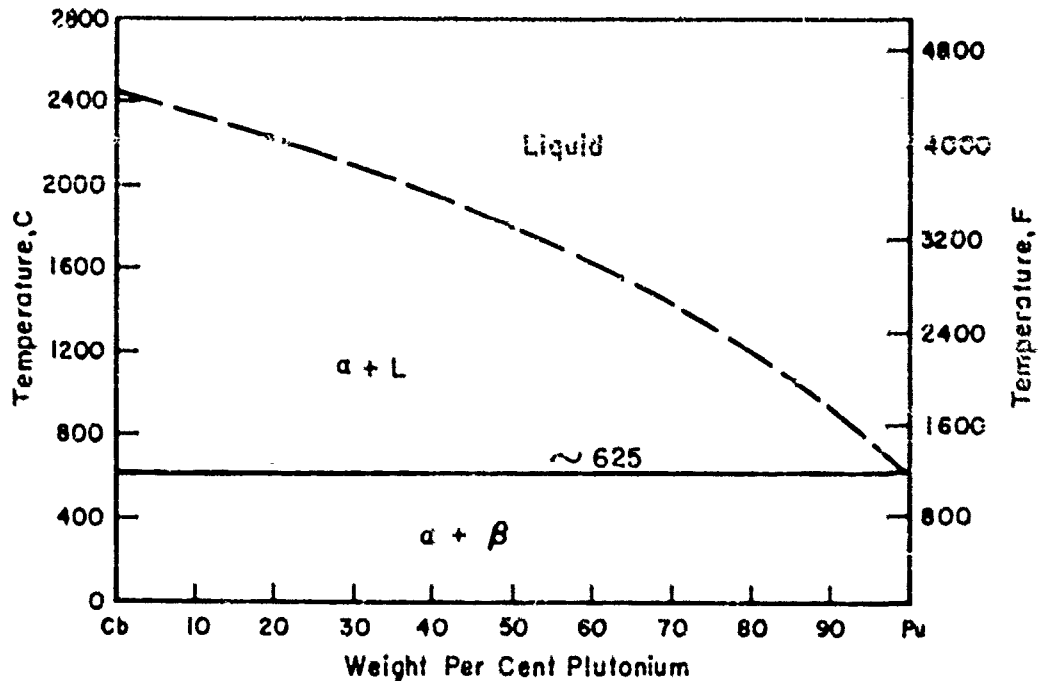
The diagram developed by Rogers and Atkins shows that complete solid solubility exists above 1000 C.⁽⁵³⁾ A eutectoid occurs at approximately 625 C and 82.5 weight per cent zirconium. The horizontal extends from 13 to 93.5 per cent zirconium. Domagala placed the eutectoid temperature at 800 C, with the continuous series of solid solutions existing above 1180 C.⁽⁵⁴⁾

COLUMBIUM-OXYGEN SYSTEM



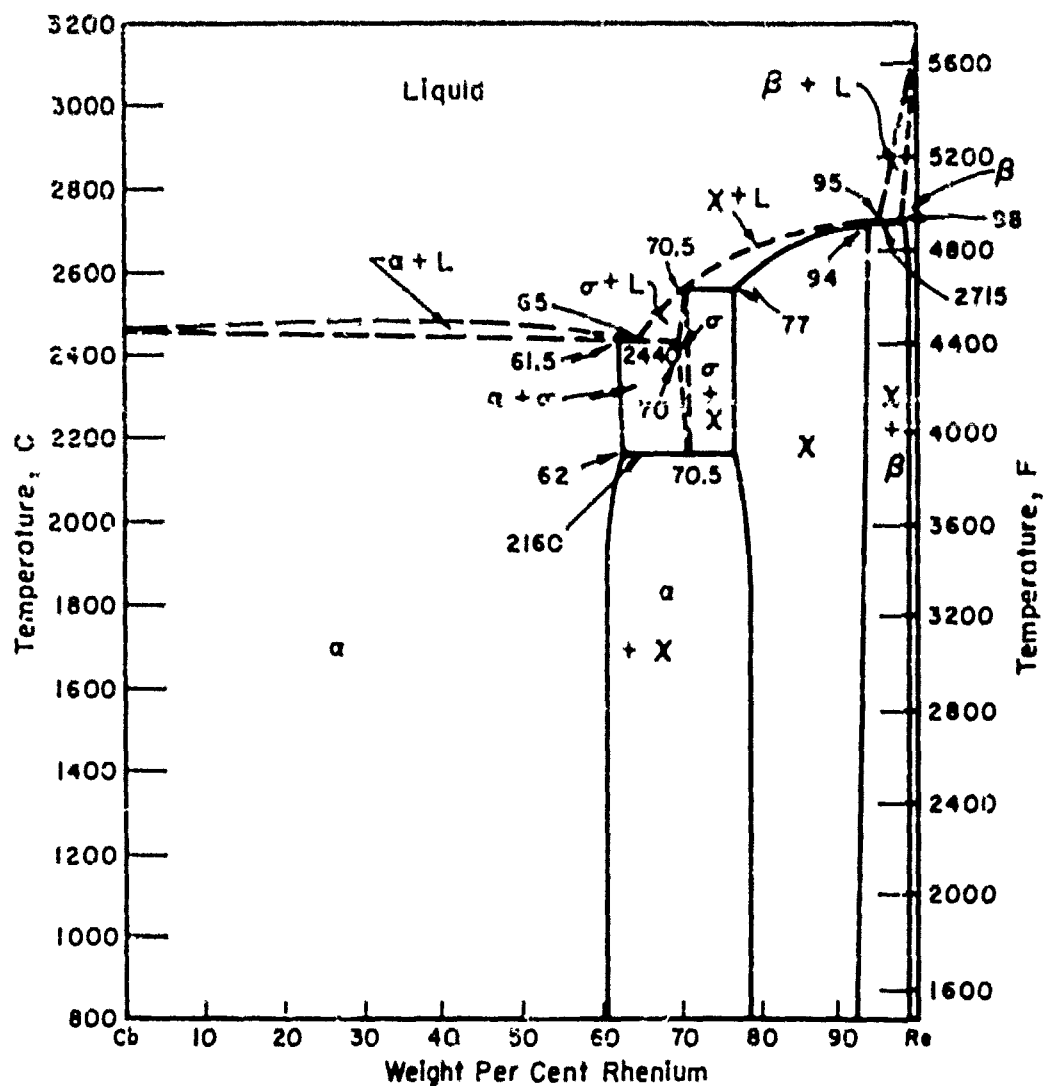
Bruest reported that three oxides of columbium exist with limited regions of homogeneity. CbO possesses a cubic structure with $a = 4.211 \text{ \AA}$ and six atoms per unit cell (NaCl lattice with ordered vacancies). The CbO₂ structure is similar to the rutile structure.⁽²⁶⁾ Cb₂O₅ occurs as three crystalline modifications.⁽²⁷⁾ The solid solubility of oxygen in columbium varies from 0.25 weight per cent at 500 C to 0.72 weight per cent at the eutectic temperature 1915 C.⁽²⁸⁾

COLUMBIUM-PLUTONIUM SYSTEM



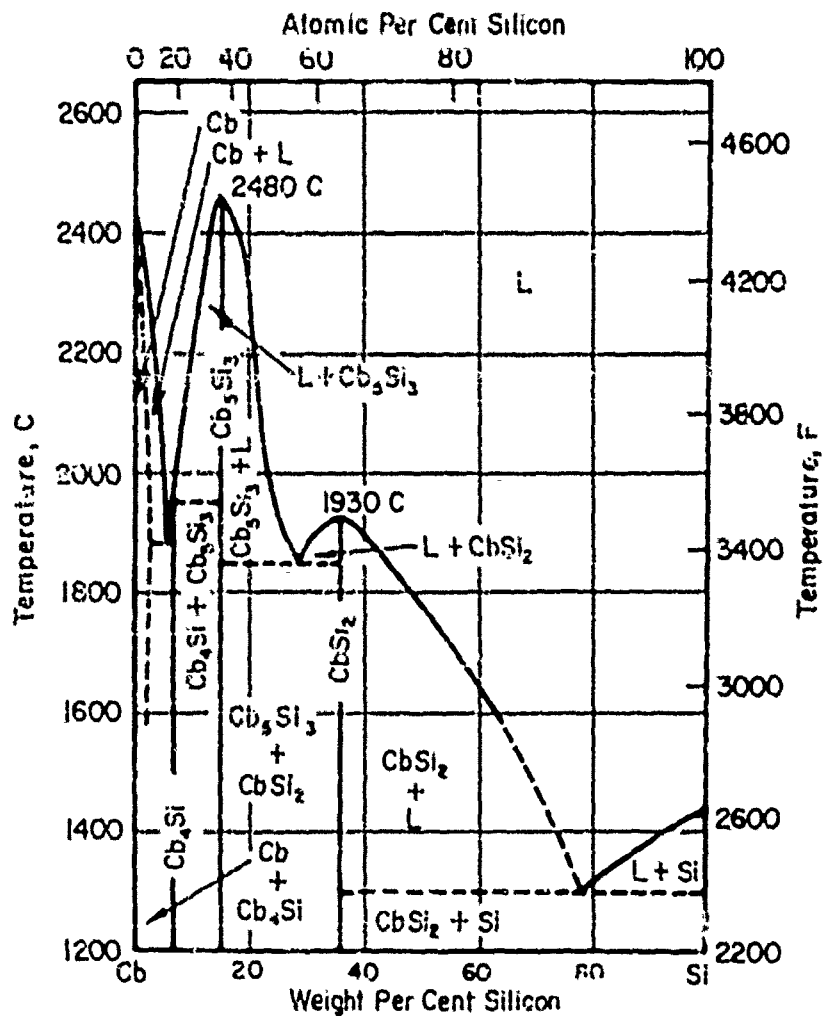
It is believed that no intermediate phases exist in this system. (2)

COLUMBIUM-RHENIUM SYSTEM



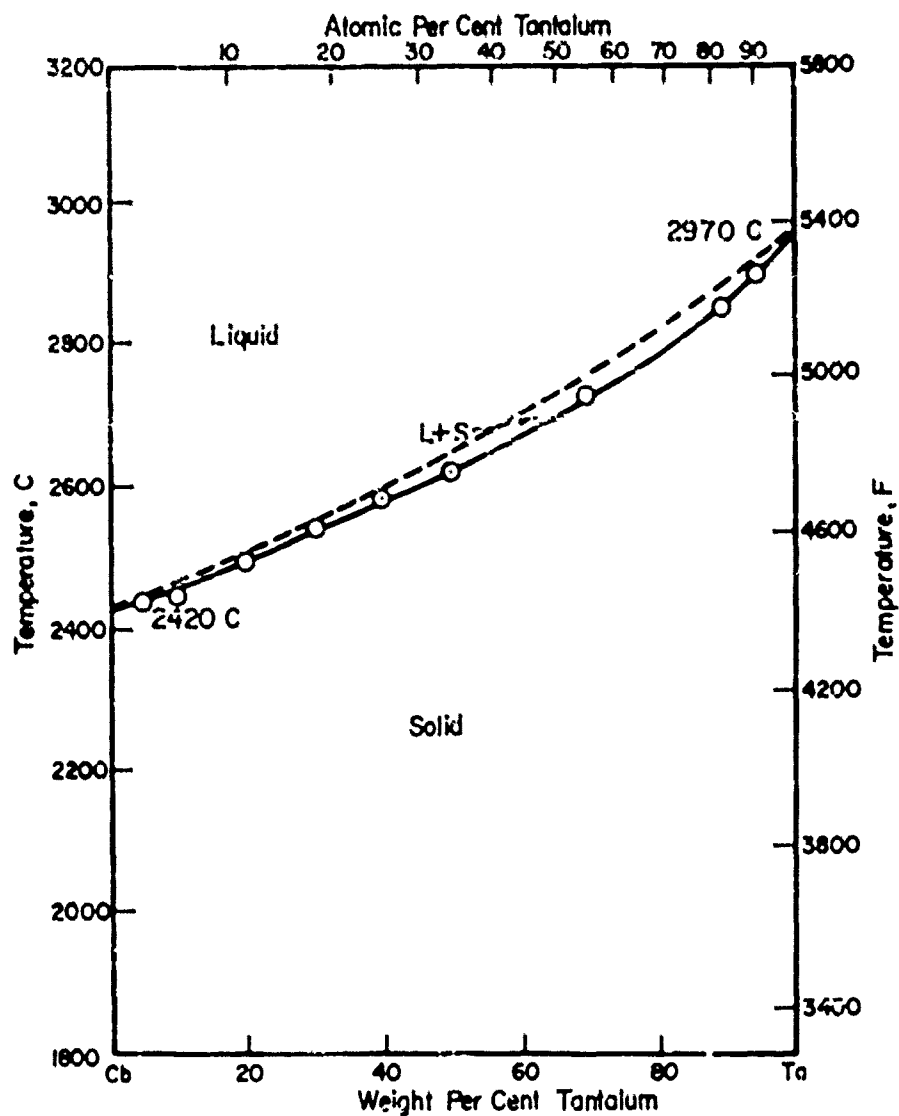
Two compounds are present in this system. The sigma phase is isomorphous with iron-chromium sigma with $a = 9.72 \text{ \AA}$, $c = 5.07 \text{ \AA}$, and $c/a = 0.52$.⁽³⁰⁾ The chi phase is an $\alpha\text{-Mn}$ -type structure with $a = 9.87 \text{ \AA}$.⁽³¹⁾ The diagram shown is the result of work performed by Grant and Glessen.⁽³²⁾ It differs from prior work in the stability range for the sigma phase. Greenfield and Beck⁽³⁰⁾ and Levesque, Bekebrede, and Brown⁽³³⁾ state that the sigma phase is stable only in the temperature range below 1075 C. Knapton's hypothesis that sigma is stable at high temperatures⁽³⁴⁾ agrees with Grant's results.

COLUMBIUM-SILICON SYSTEM



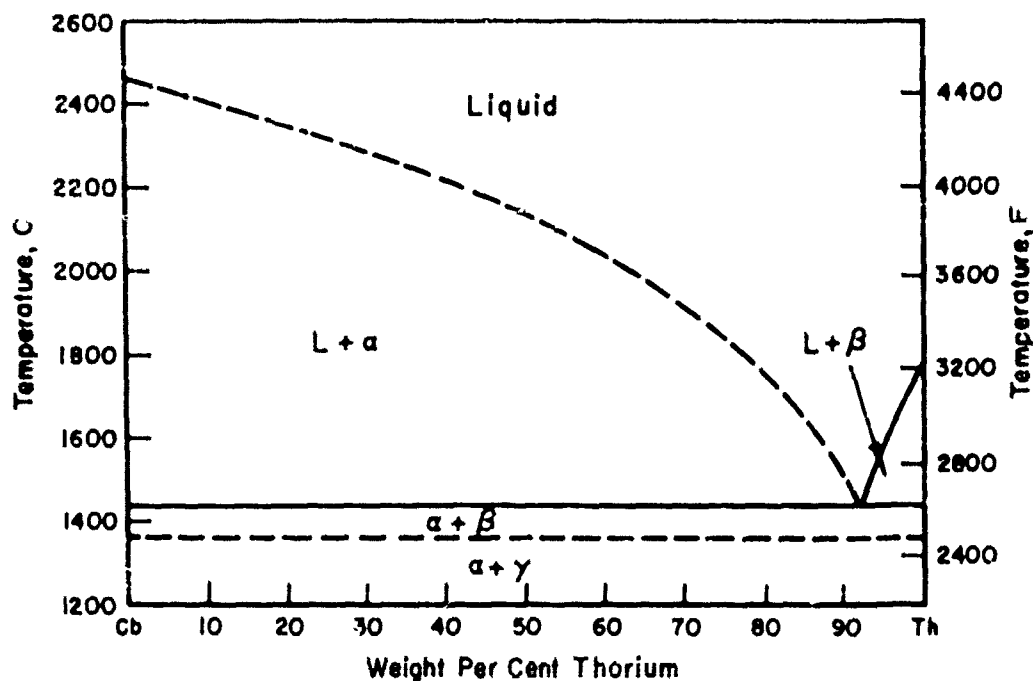
Three intermediate phases were reported by Knapton.⁽³⁵⁾ Cb₃Si is isomorphous with Ta₃Si and Zr₃Si. Samsonov reported the structure to have a hexagonal ϵ -Fe₃N-type structure with $a = 3.59 \text{ \AA}$ and $c = 4.46 \text{ \AA}$.⁽³⁶⁾ Cb₃Si₂ exists in two modifications, with the transformation between 2900 and 2100 C.⁽³⁷⁾ CbSi₂ has a hexagonal CrSi₂-type structure with $a = 4.795 \text{ \AA}$, $c = 6.689 \text{ \AA}$, and $c/a = 1.374$.⁽³⁷⁾

COLUMBIUM-TANTALUM SYSTEM



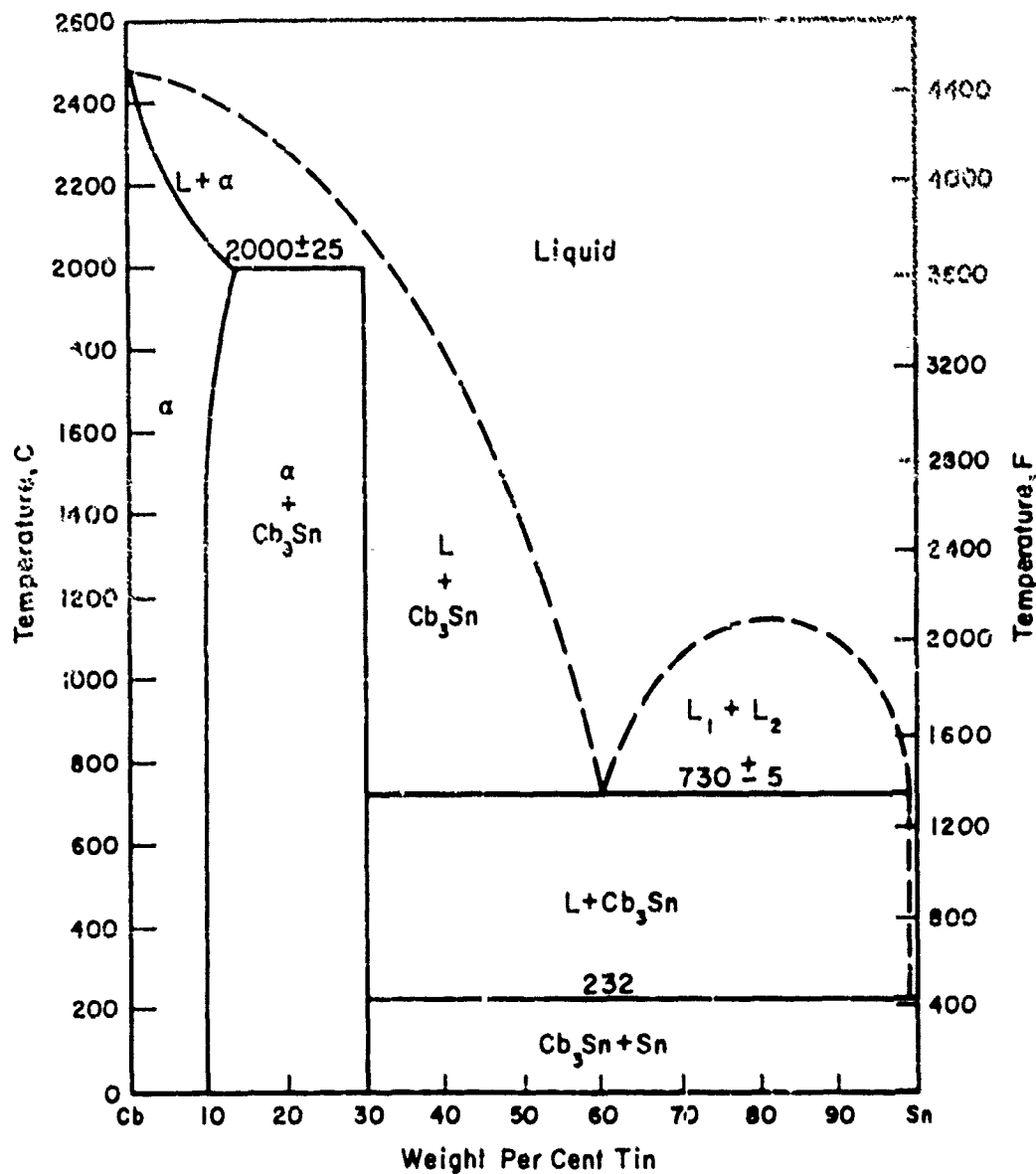
The columbium-tantalum system forms a continuous series of solid solutions. (40, 41) Williams and Pechin⁽⁴¹⁾ determined the location of the solidus curve for the system. The melting points of the pure metals are slightly lower than the accepted values and may be attributed to the presence of oxygen.

COLUMBIUM-THORIUM SYSTEM



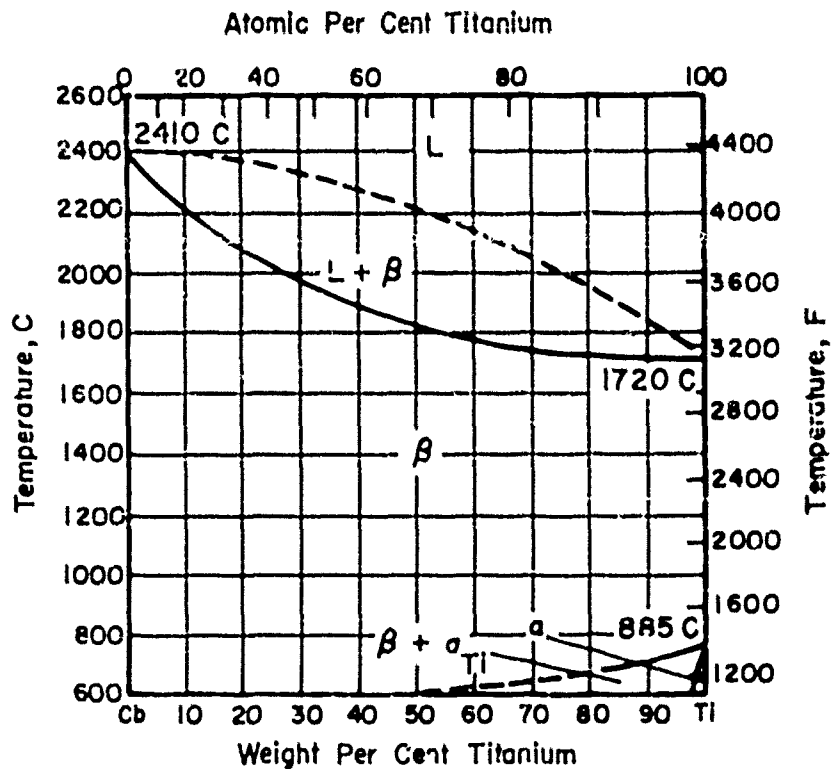
There are no compounds in the system. A eutectic reaction occurs at 1435 C and 8 weight per cent columbium. Solubility of columbium is very limited in all terminal phases. The maximum solubility is less than 1 weight per cent columbium at 1435 C, and less than 0.1 weight per cent in alpha thorium. Thorium solubility in columbium is negligible. (42)

COLUMBIUM-TIN SYSTEM



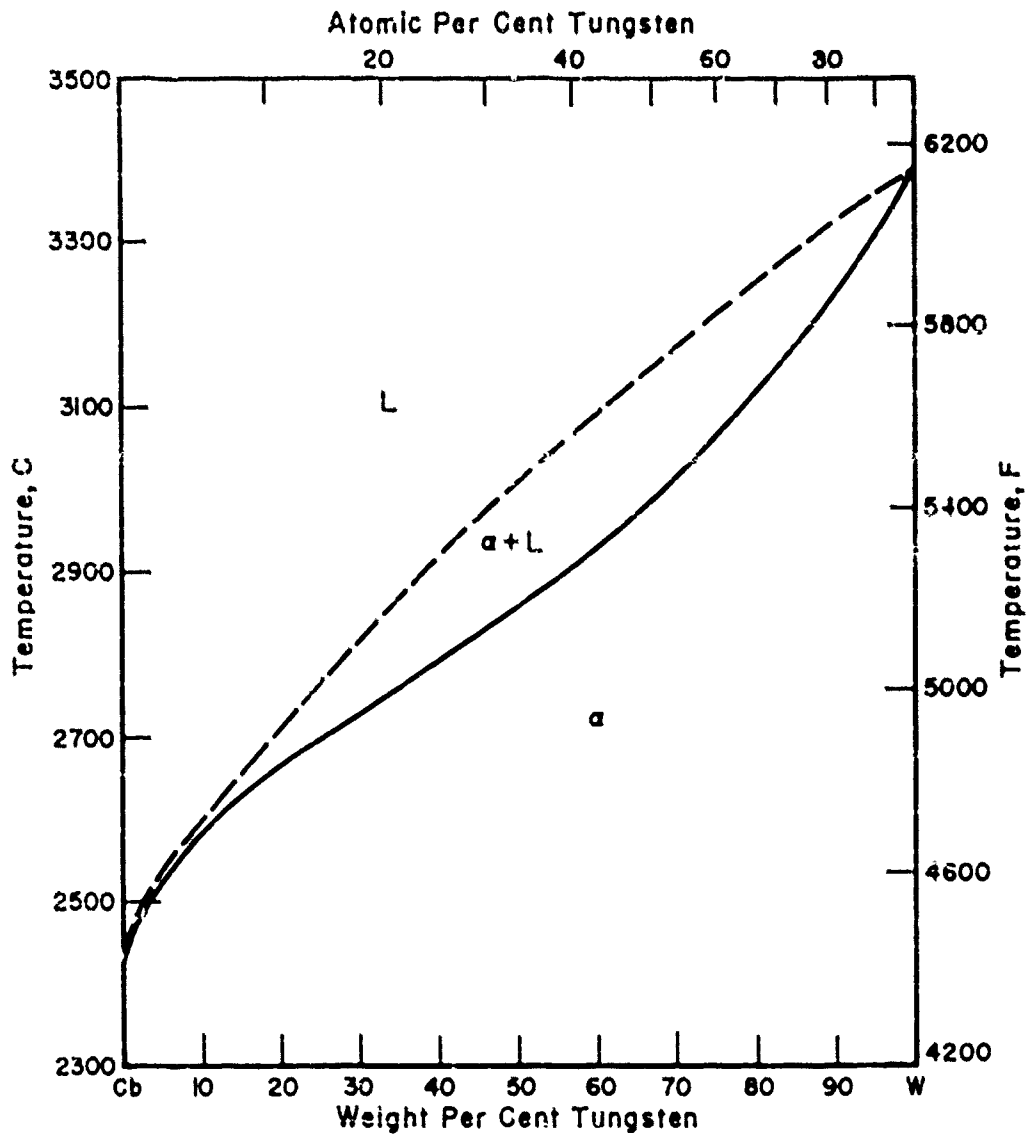
Cb_3Sn is a β -tungsten-type structure with $a = 5.29 \text{ \AA}$. (35, 35) The solid solubility of tin in columbium is 9.7 weight per cent at room temperature, increasing to 14 per cent at the peritectic temperature. The solubility of columbium in tin is less than 0.1 weight per cent at the melting point of tin. (38, 39)

COLUMBIUM-TITANIUM SYSTEM



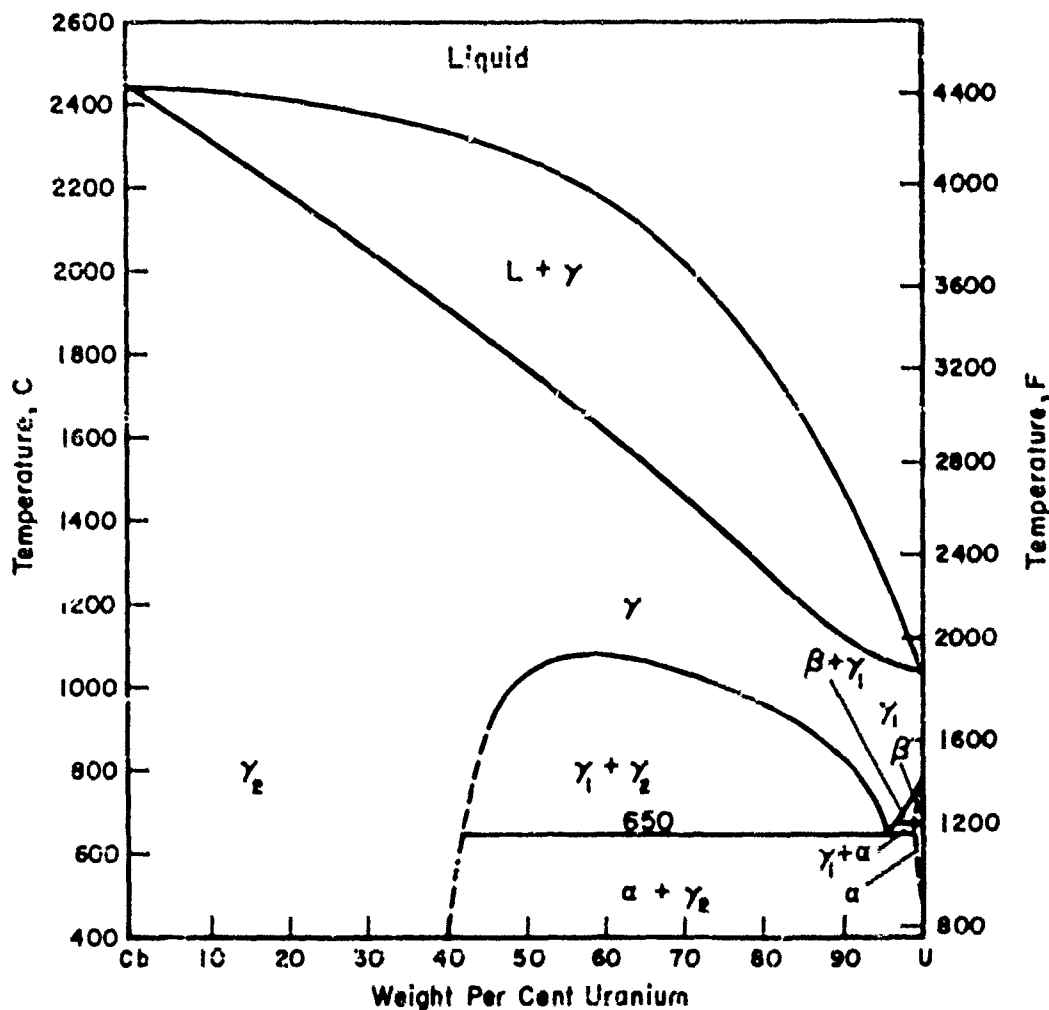
Beta-titanium and columbium form a continuous series of solid solutions.⁽⁴³⁾ Martensitic transformation occurs in alloys up to 28 weight per cent columbium under cooling rates of 100 to 10,000 deg/sec.⁽⁴⁴⁾ The minimum concentration for retaining bcc beta structure by quenching is 36 per cent columbium.⁽⁴⁵⁾

COLUMBIUM-TUNGSTEN SYSTEM



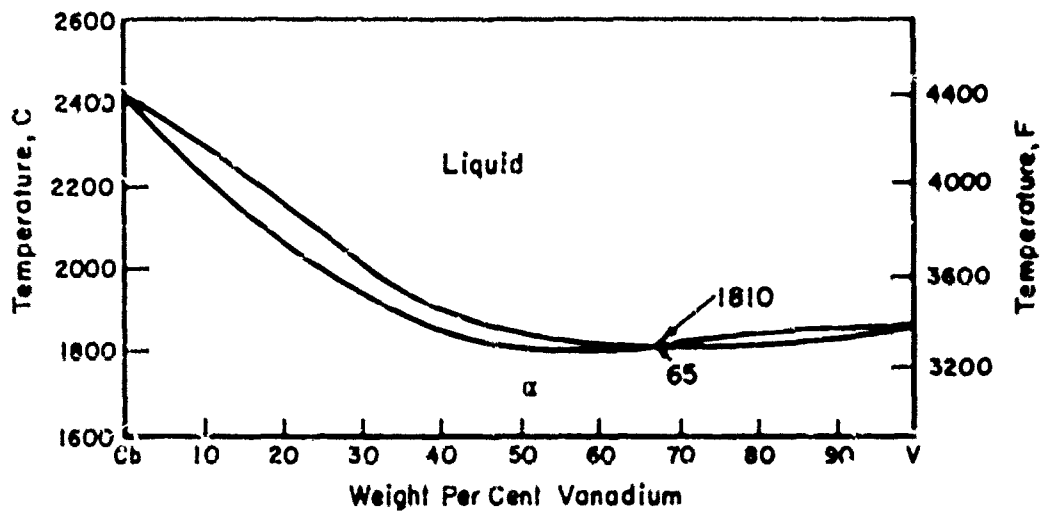
Mikheev and Pevsner⁽⁵¹⁾ Von Bolton⁽⁵²⁾, and Buckle⁽⁴⁰⁾ stated that the columbium-tungsten system formed a continuous series of solid solutions.

COLUMBIUM-URANIUM SYSTEM



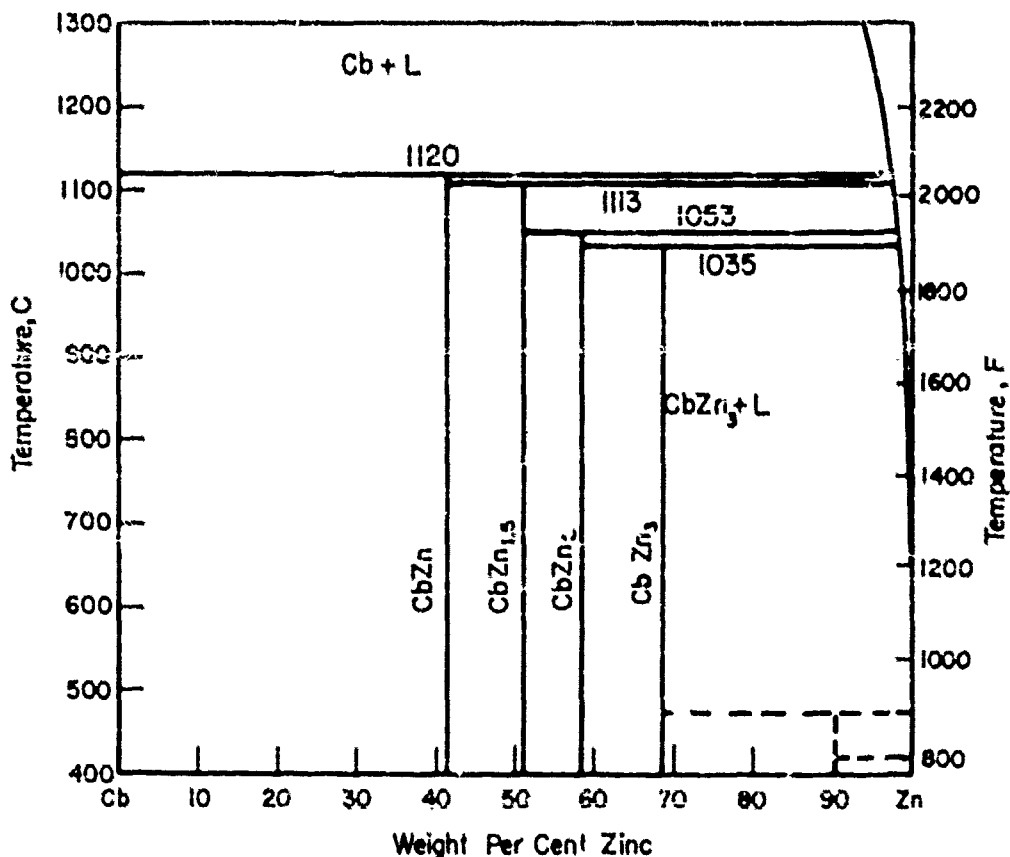
Columbium and gamma uranium form a continuous series of solid solutions above 950 C. (46-49) The monotectoid reaction occurs between 91 and 93 weight per cent uranium at 635 to 645 C. (46, 47, 49) The alpha-to-beta transformation occurs by a peritectoid reaction. (47-49)

COLUMBIUM-VANADIUM SYSTEM



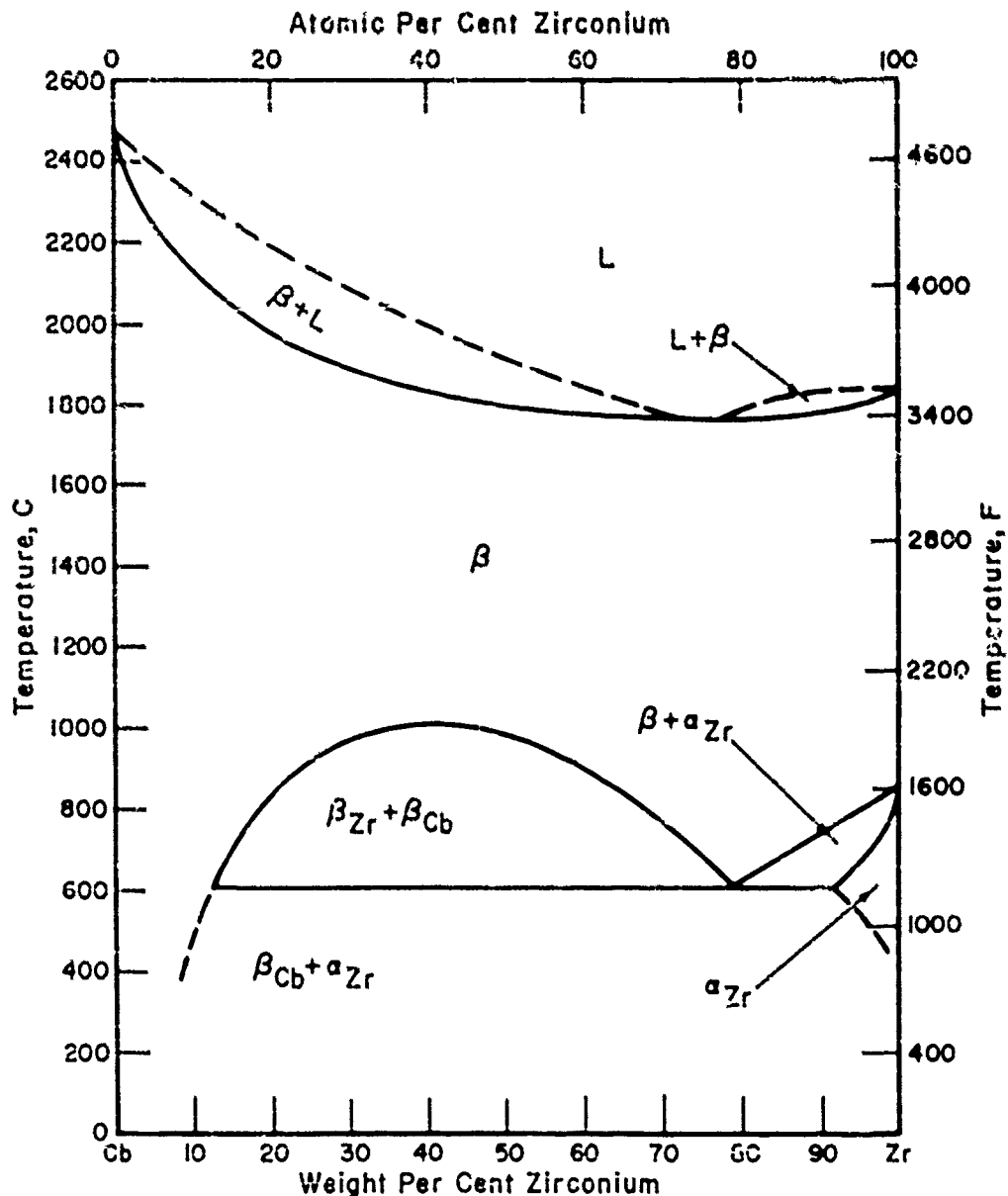
Wilhelm, Carlson, and Dickinson found that the system was a continuous series of solid solutions. (50)

COLUMBIUM-ZINC SYSTEM



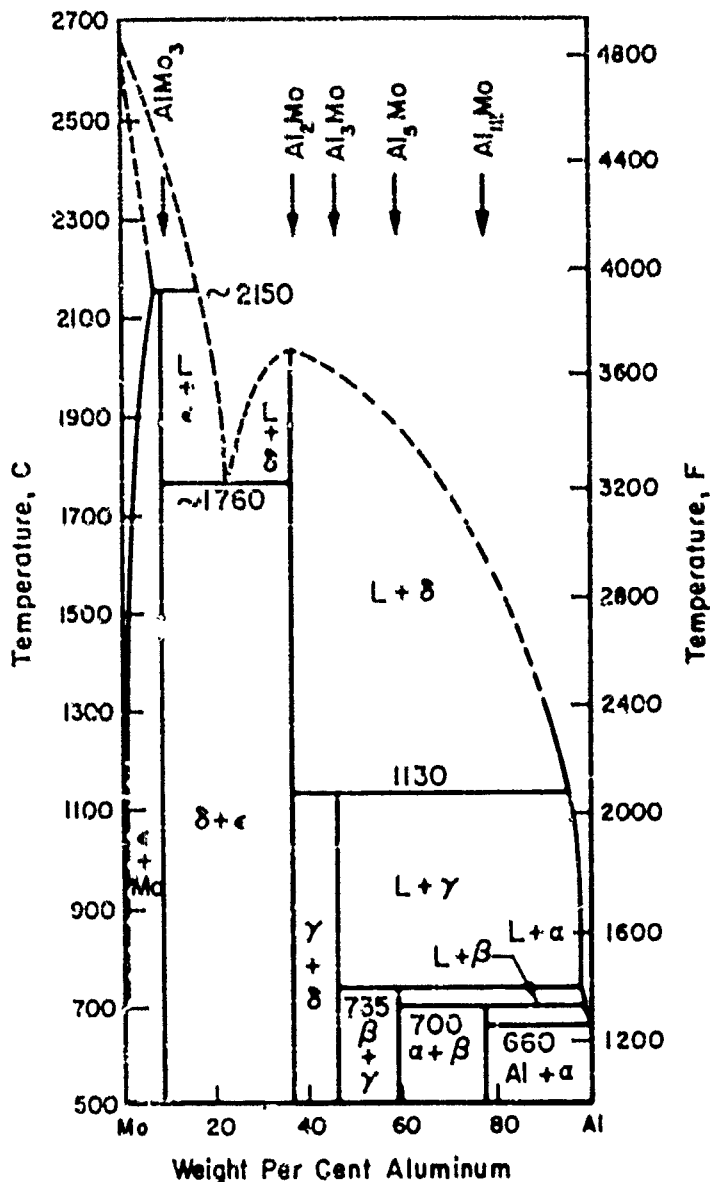
CbZn_3 is a cubic AuCu_3 -type structure with $a = 3.93 \text{ \AA}$.⁽²²⁹⁻²³¹⁾ $\text{CbZn}_{1.5}$ is hexagonal with $a = 5.283 \text{ \AA}$ and $c = 26.43 \text{ \AA}$. The structures of the other two compounds, CbZn and CbZn_2 , have not been determined. The temperatures given for the peritectic reactions represent equilibrium temperatures under 6 to 8 atmospheres pressure of zinc vapor.⁽²²⁹⁾ Two unidentified phases possibly form by peritectic reaction at the low-temperature zinc-rich portion of the diagram. A eutectic is suspected at less than 0.2 weight per cent columbium, a few degrees below the melting point of zinc. No solubility of zinc in columbium has been found.⁽²³⁰⁾

COLUMBIUM-ZIRCONIUM SYSTEM



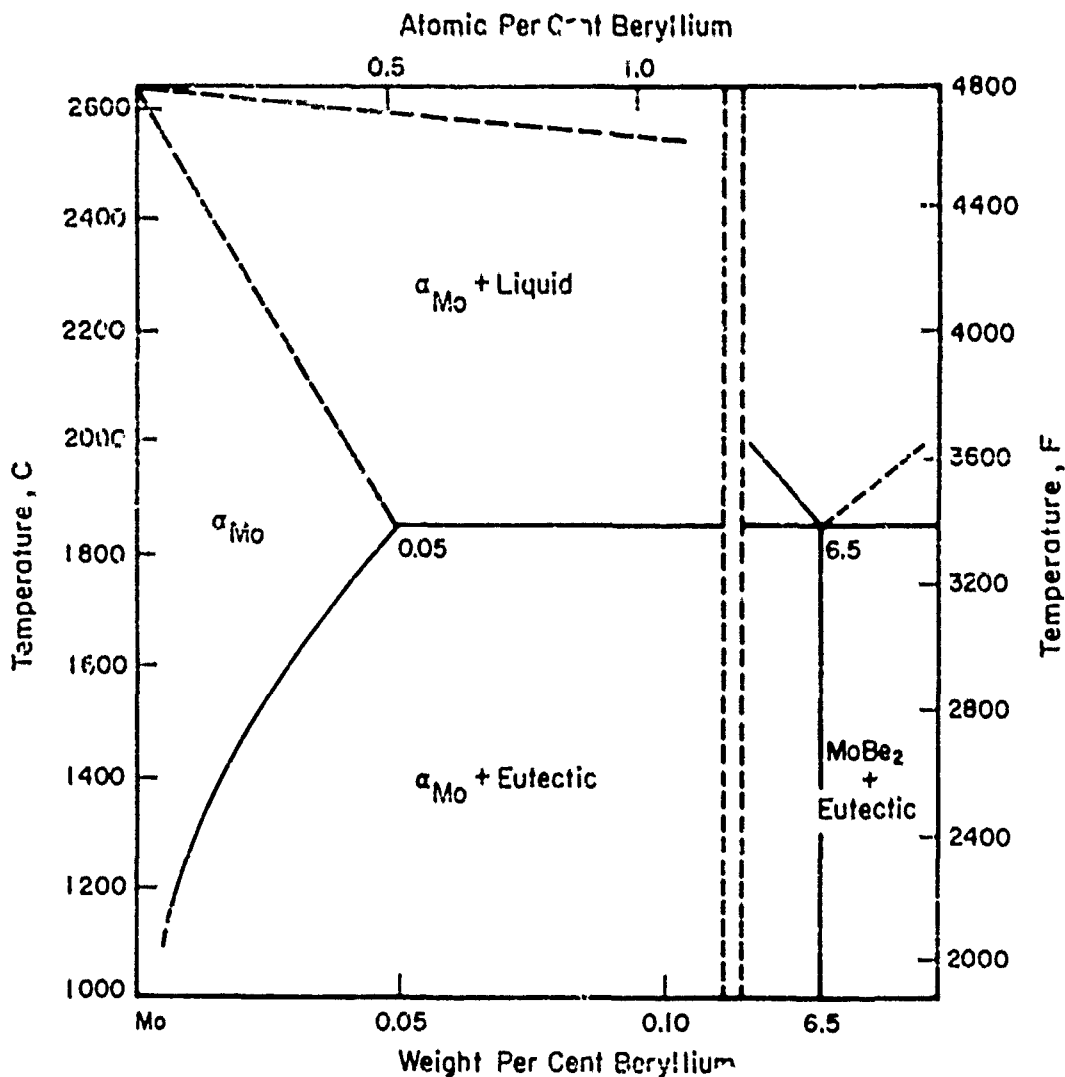
The diagram developed by Rogers and Atkins shows that complete solid solubility exists above 1000 C.⁽⁵³⁾ A eutectoid occurs at approximately 625 C and 32.5 weight per cent zirconium. The horizontal extends from 13 to 33.5 per cent zirconium. Donagala placed the eutectoid temperature at 800 C, with the continuous series of solid solutions existing above 1180 C.⁽⁵⁴⁾

MOLYBDENUM-ALUMINUM SYSTEM



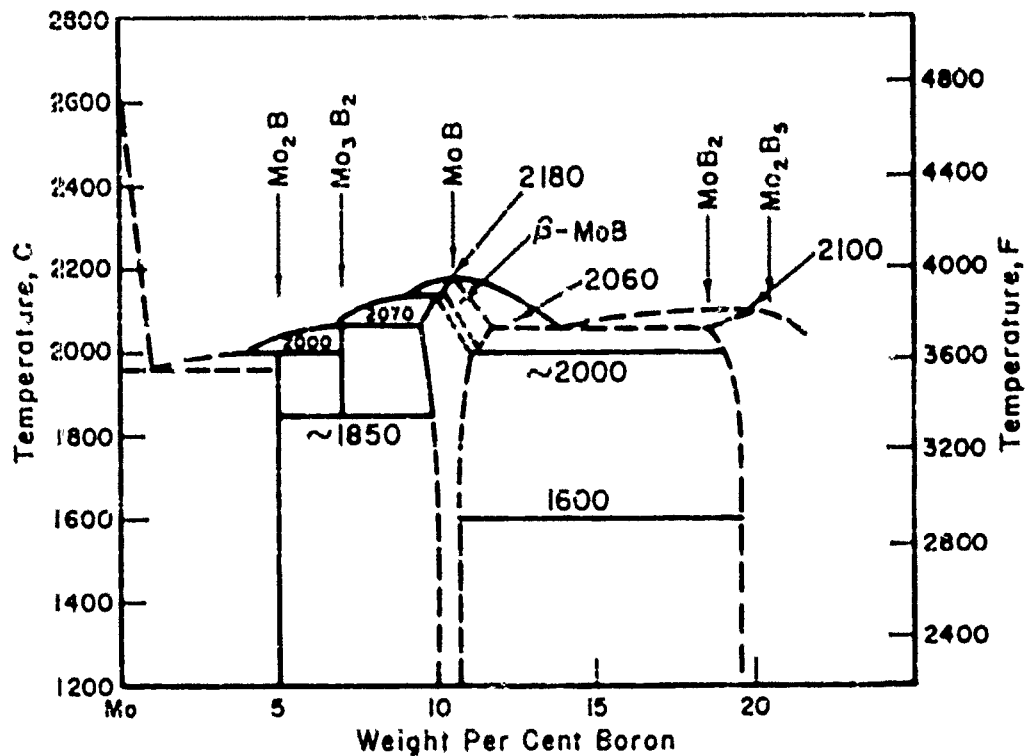
$\text{AlMo}(\epsilon)$ has the structure of $\beta\text{-W}(\text{Al5})$ with $a = 4.95 \text{ \AA}$.⁽⁵⁵⁾ The crystal structure of $\text{Al}_2\text{Mo}(\delta)$ has not been determined. $\text{Al}_3\text{Mo}(\gamma)$ is tetragonal with $a = 6.297 \text{ \AA}$ and $c/a = 1.588$.⁽⁵⁶⁾ $\text{Al}_5\text{Mo}(\beta)$ has a hexagonal structure isomorphous with Al_5W with $a = 4.89 \text{ \AA}$ and $c/a = 1.80$.⁽⁵⁶⁾ $\text{Al}_{12}\text{Mo}(\alpha)$ is body-centered cubic with $a = 7.572 \text{ \AA}$, 26 atoms per unit cell, and is isotypic with WAl_{12} .⁽⁵⁷⁾ The solubility of aluminum in molybdenum is 6.4 weight per cent at 2150 C and 1.5 weight per cent at 1200 C.⁽⁵⁸⁾

MOLYBDENUM-BERYLLIUM SYSTEM



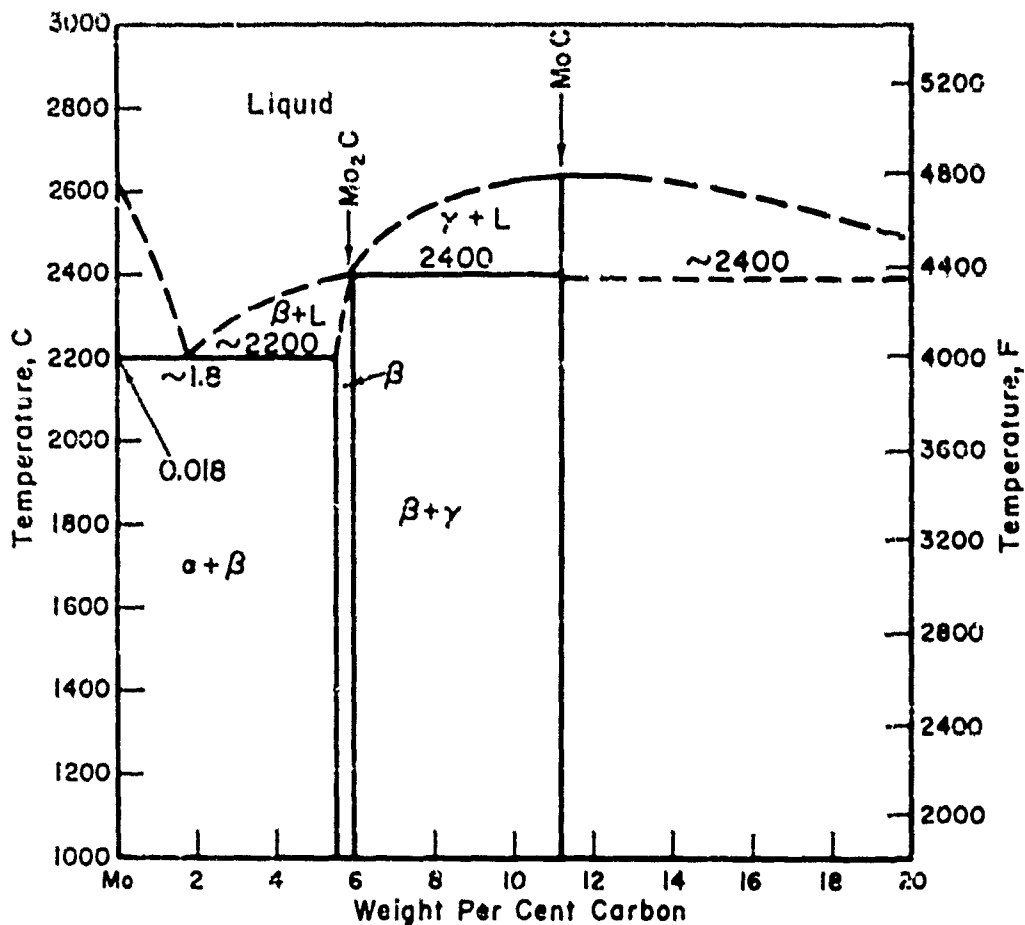
Two intermediate phases occur in the system. Be_2Mo has a hexagonal $\text{MgZn}_2(\text{C14})$ type of structure with $a = 4.433 \text{ \AA}$ and $c = 7.341 \text{ \AA}$.⁽⁶¹⁾ Be_{12}Mo is body-centered tetragonal with $a = 7.27 \text{ \AA}$, $c = 4.23 \text{ \AA}$, with 26 atoms per unit cell.⁽⁶²⁾ There is a eutectic at approximately 6.5 per cent beryllium and 1870 C.^(63,64)

MOLYBDENUM-BORON SYSTEM



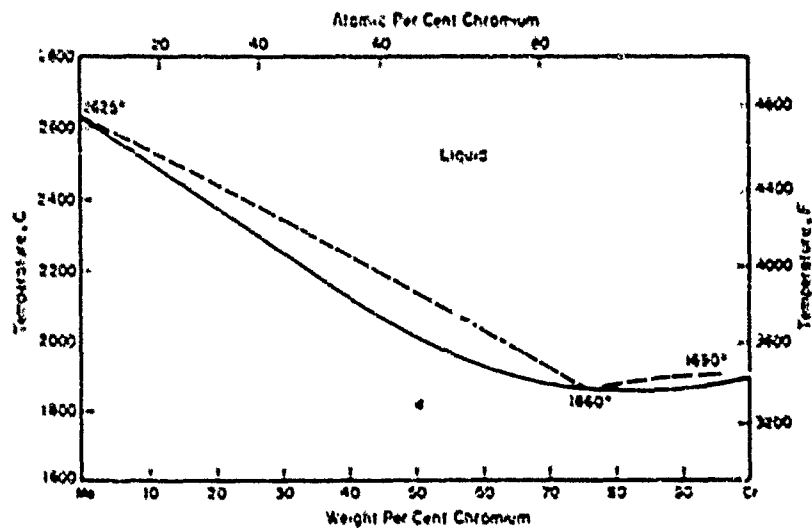
The following borides have been identified: Mo₂B is tetragonal of the CuAl₂(C16) type with $a = 5.543 \text{ \AA}$, $c = 4.735 \text{ \AA}$, and $c/a = 0.854$.^(58,59) Mo₃B₂ is tetragonal and isotypic with Cr₃B₂. The low-temperature form of MoB is tetragonal with 8 MoB molecules per unit cell, and $a = 3.110 \text{ \AA}$, $c = 16.95 \text{ \AA}$, and $c/a = 5.45$.^(58,59) The high-temperature modification, β -MoB, is orthorhombic and isotypic with CoB, Cb₆, and TaB, with $a = 3.16 \text{ \AA}$, $b = 8.61 \text{ \AA}$, and $c = 3.08 \text{ \AA}$.⁽⁵⁹⁾ MoB₂ is a hexagonal AlB₂ (C32) type, with $a = 3.06 \text{ \AA}$, $c = 3.10 \text{ \AA}$, and $c/a = 1.01$.⁽⁵⁹⁾ Mo₂B₅ is rhombohedral with the hexagonal axis $a = 3.011 \text{ \AA}$, $c = 20.93 \text{ \AA}$, and $c/a = 6.95$.^(58,59) A Chimax Molybdenum Report⁽⁶⁰⁾ gives the eutectic temperature as 2180°C and a composition of 2.75 per cent boron, a value which differs from the results obtained by Steinitz.⁽⁵⁹⁾

MOLYBDENUM-CARBON SYSTEM



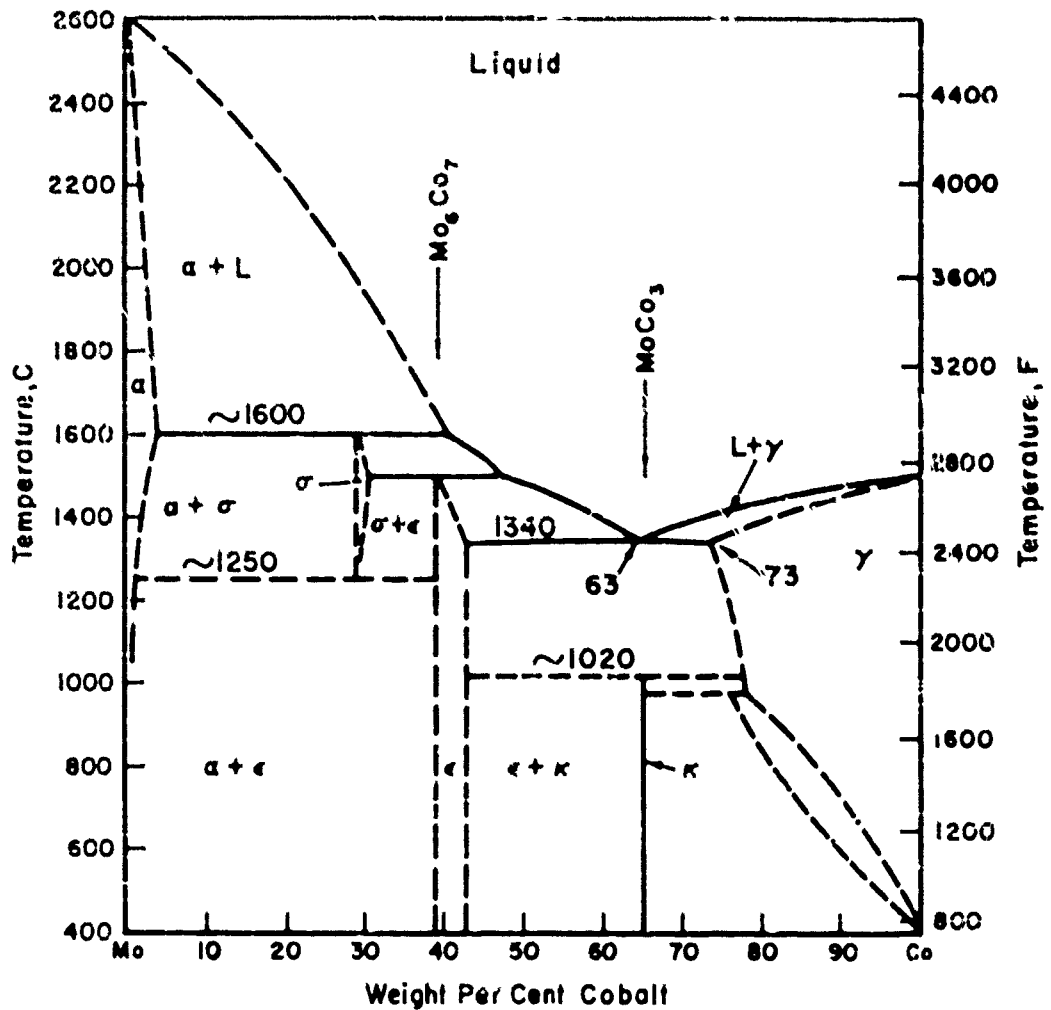
Carbon dissolves interstitially up to 0.018 weight per cent.⁽⁶⁵⁾ Mo₂C is a hexagonal W₂C-type structure with $a = 3.892$ Å, $c = 4.724$ Å, and $c/a = 1.574$.^(66,67) The hexagonal phase MoC is isotypic with WC. There is disagreement on the values for the lattice parameters. Kuo gives the values as $a = 2.898$ Å, $c = 2.809$ Å, and $c/a = 0.969$, with one molybdenum atom per unit cell.⁽⁶⁷⁾ Nowotny reported the lattice constants $a = 3.01$ Å, $c = 14.61$ Å, and $c/a = 4.86$, with 12 atoms of molybdenum per unit cell.⁽⁶⁸⁾

MOLYBDENUM-CHROMIUM SYSTEM



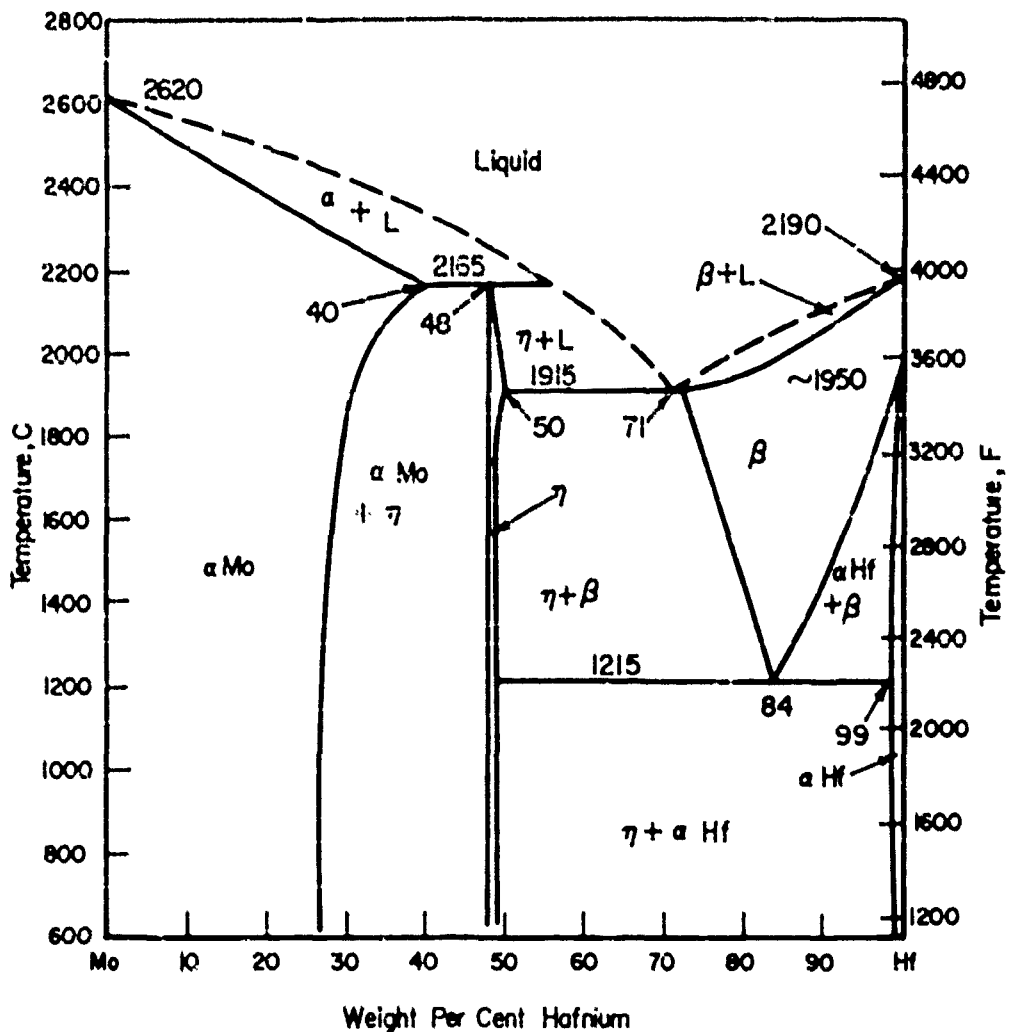
The molybdenum-chromium system forms a continuous series of solid solutions at high temperatures. (15, 64, 71) A minimum in the melting point occurs at approximately 80 weight per cent chromium and 1860 C. (71) Evidence of a phase transformation in alloys up to 40 weight per cent chromium has been found. (71)

MOLYBDENUM-COBALT SYSTEM



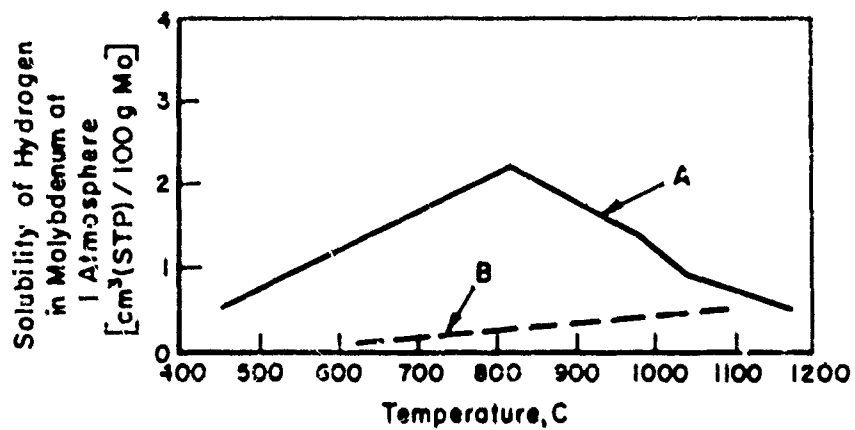
The solid solubility of cobalt in molybdenum was found to be 2.75, 1.75, 1.4, 0.96, and 0.6 weight per cent at 1480, 1375, 1300, 1200, and 1100 C.⁽⁶⁹⁾ Mo₆Co₇ is rhombohedral-hexagonal and isotypic with W₆Fe₇ (D95 type). Its lattice parameters are $a = 8.890 \text{ \AA}$, $\alpha = 30^\circ 45'$ at the ideal composition, and $a = 8.873 \text{ \AA}$, $\alpha = 30^\circ 53'$ if saturated with cobalt.⁽⁷⁰⁾ The structure of MoCo₃ is similar to that of WCo₃. This phase is isotypic with Ni₃Sn (D0₁₉ type).⁽⁷⁰⁾

MOLYBDENUM-HAFNIUM SYSTEM



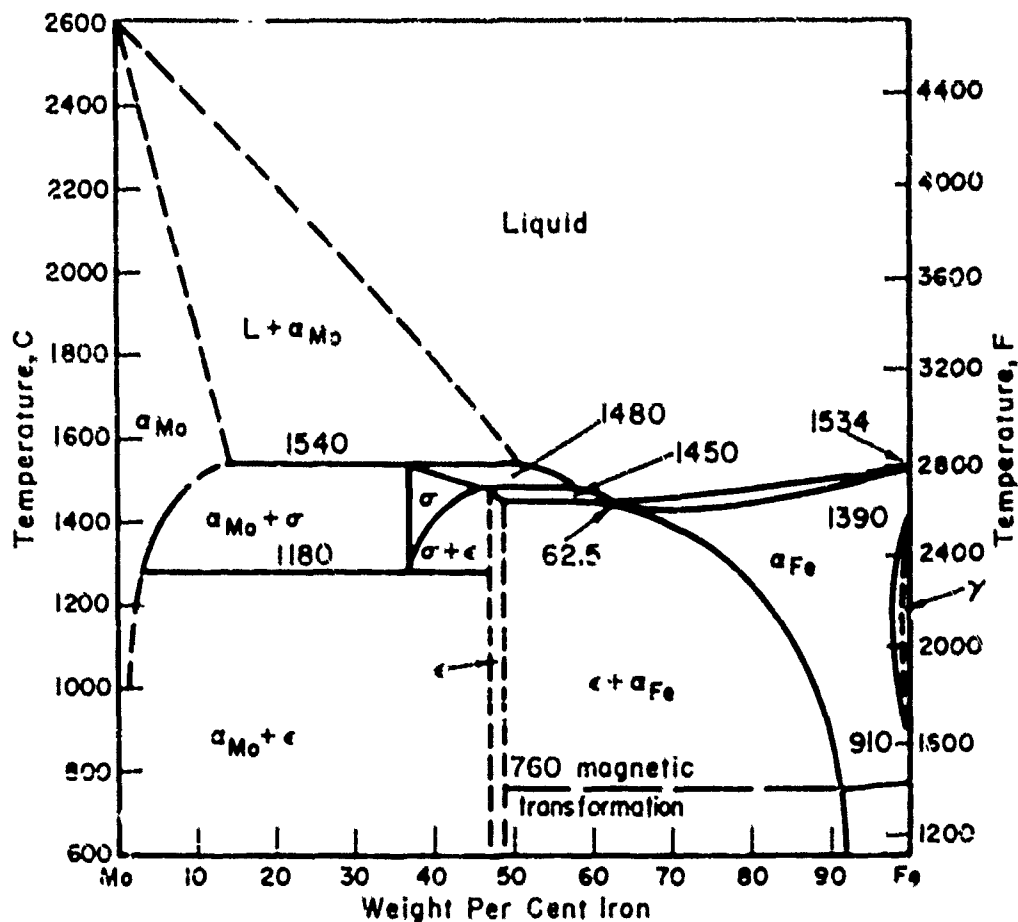
The intermediate Laves η -phase, Mo_2Hf , forms at 2180 C by a peritectic reaction. The crystal structure of this phase is a cubic Cu_2Mg (C15) type, with 8 molecules per unit cell. Its lattice parameter is 7.560 Å. The solubility of hafnium in molybdenum is 40 weight per cent (28 atomic per cent) at 2180 C, decreasing to 28 weight per cent (16.5 atomic per cent) at 900 C. (78)

MOLYBDENUM-HYDROGEN SYSTEM



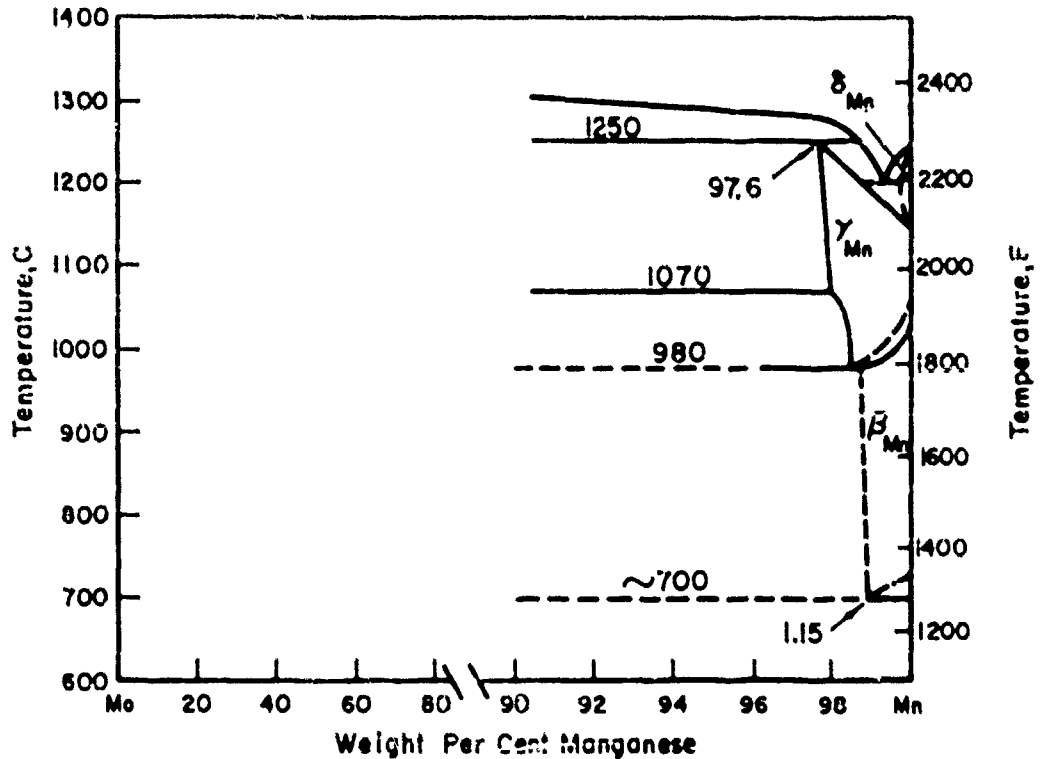
Shown are the results of two determinations of the solubility of hydrogen in solid molybdenum. Curve A was determined by Martin⁽⁷⁶⁾, Curve B by Sieverts and Brüning.⁽⁷⁷⁾

MOLYBDENUM-IRON SYSTEM



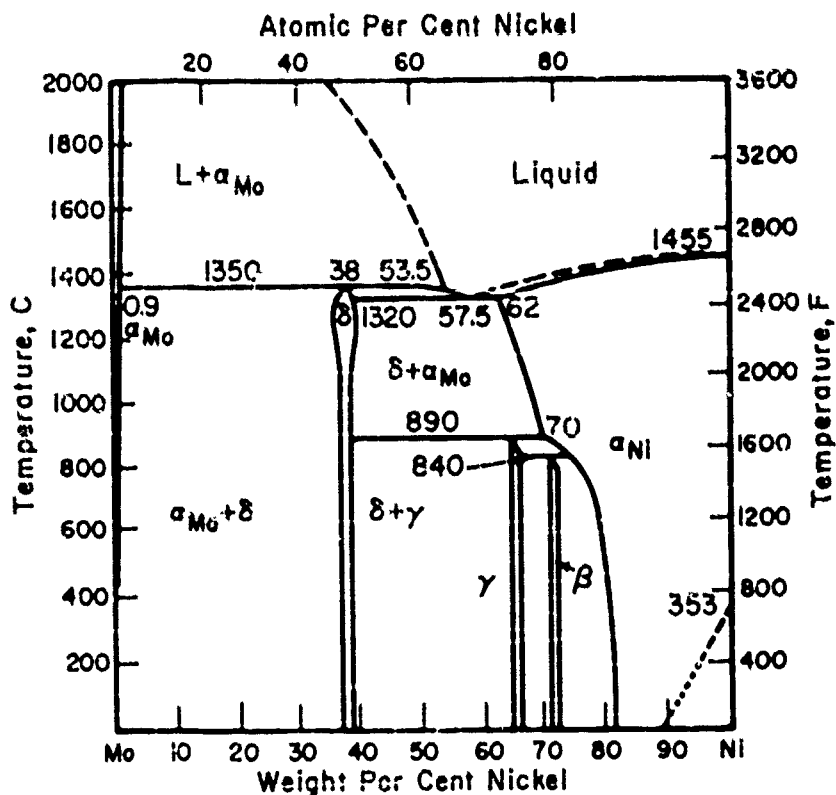
The ϵ -phase is rhombohedral of the W_2Fe_7 (D8₅) type, with $a = 8.99$ Å, $\alpha = 30^\circ 38.8'$. (72, 73) The structure of the α -phase is tetragonal, with $a = 9.186$ Å, $c = 4.812$ Å, and $c/a = 0.5237$ at 36 weight per cent iron (50 atomic per cent). There are 30 atoms per unit cell. (74) The solubility of iron in molybdenum is 10.5, 8.7, 4.8, 3.6, and 2.7 weight per cent at 1480, 1450, 1390, 1200, and 1100 C, respectively. (75)

MOLYBDENUM-MANGANESE SYSTEM



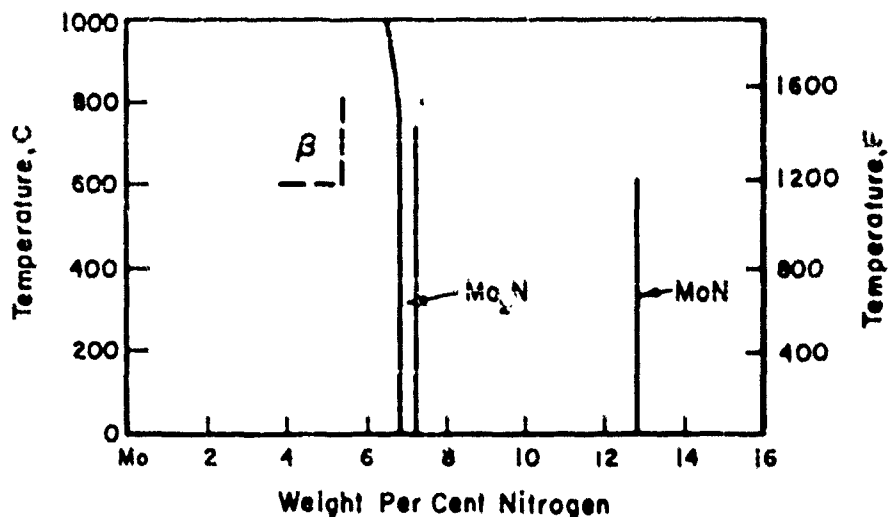
A sigma phase of 50.1 weight per cent (63.7 atomic per cent) is stable above 1115 C. It has a tetragonal structure with $a = 9.10 \text{ \AA}$, $c = 4.74 \text{ \AA}$, and $c/a = 0.52$, and ordered atomic arrangement. (79, 80) Twenty weight per cent manganese was found dissolved in alloys fast-cooled (600 C per minute) from 1800 C. Only about 10 per cent remained in solution after slow cooling to room temperature. (81) Another intermediate phase, possibly stable only above 1100 C, exists between 80 and 88 atomic per cent manganese. (82)

MOLYBDENUM-NICKEL SYSTEM



MoNi (δ) forms by a peritectic reaction at approximately 1350 C.⁽⁸⁵⁾ MoNi₃ (γ) is hexagonal close packed with $a = 2.54$ Å, and $c/a = 1.65$.⁽⁸⁶⁾ MoNi₄ (β) was reported to be a face-centered tetragonal superstructure with $a = 3.62$ Å, $c = 3.57$ Å, and $c/a = 0.986$.⁽⁸⁵⁾ Ham reported β to have an ordered face-centered tetragonal structure with $a = 5.731$ Å, $c = 3.571$ Å, and $c/a = 0.623$.⁽⁸⁷⁾ The solubility of nickel in molybdenum⁽⁸⁸⁾ is 0.8, 0.75, 0.65, and 0.5 weight per cent at 1340, 1315, 1290, and 1200 C, respectively.

MOLYBDENUM-NITROGEN SYSTEM



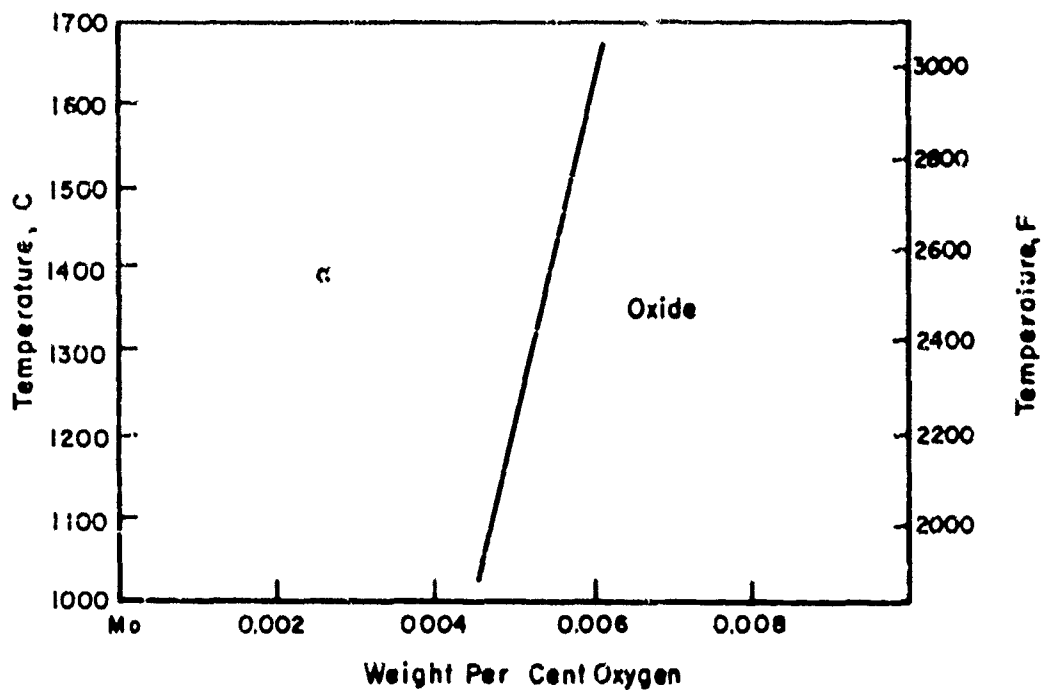
The β -phase, stable only above 600 C, has a face-centered tetragonal lattice of the molybdenum atoms with $a = 4.18$ Å, $c = 4.02$ Å, and $c/a = 0.961$, after quenching from above 850 C. The position of nitrogen atoms is unknown.⁽⁸³⁾ Mo_2N is face-centered cubic with $a = 4.163$ Å on the molybdenum side to $a = 4.168$ Å on the nitrogen side. MoN has a hexagonal superstructure consisting of 16 atoms per unit cell with $a = 5.725$ Å, $c = 5.608$ Å, and $c/a = 0.980$.⁽⁸⁴⁾

MOLYBDENUM-OSMIUM SYSTEM

The molybdenum-osmium system is in its final stages of development by Taylor.⁽¹⁷⁶⁾ He found the solubility of osmium in molybdenum to range from about 10 weight per cent at 1000 C to 30 weight per cent at 2350 C. A β -tungsten-type phase, Mo_3Os , forms around 2200 C. It is stable over a limited composition range at about 40 weight per cent osmium. A sigma phase, Mo_5Os_3 , forms by a peritectic reaction at approximately 2400 C and 45 weight per cent osmium. It is stable over a composition range of about 10 weight per cent at 1000 C. Molybdenum is soluble in osmium up to 25 weight per cent at 1000 C, increasing to about 30 weight per cent at 2400 C.

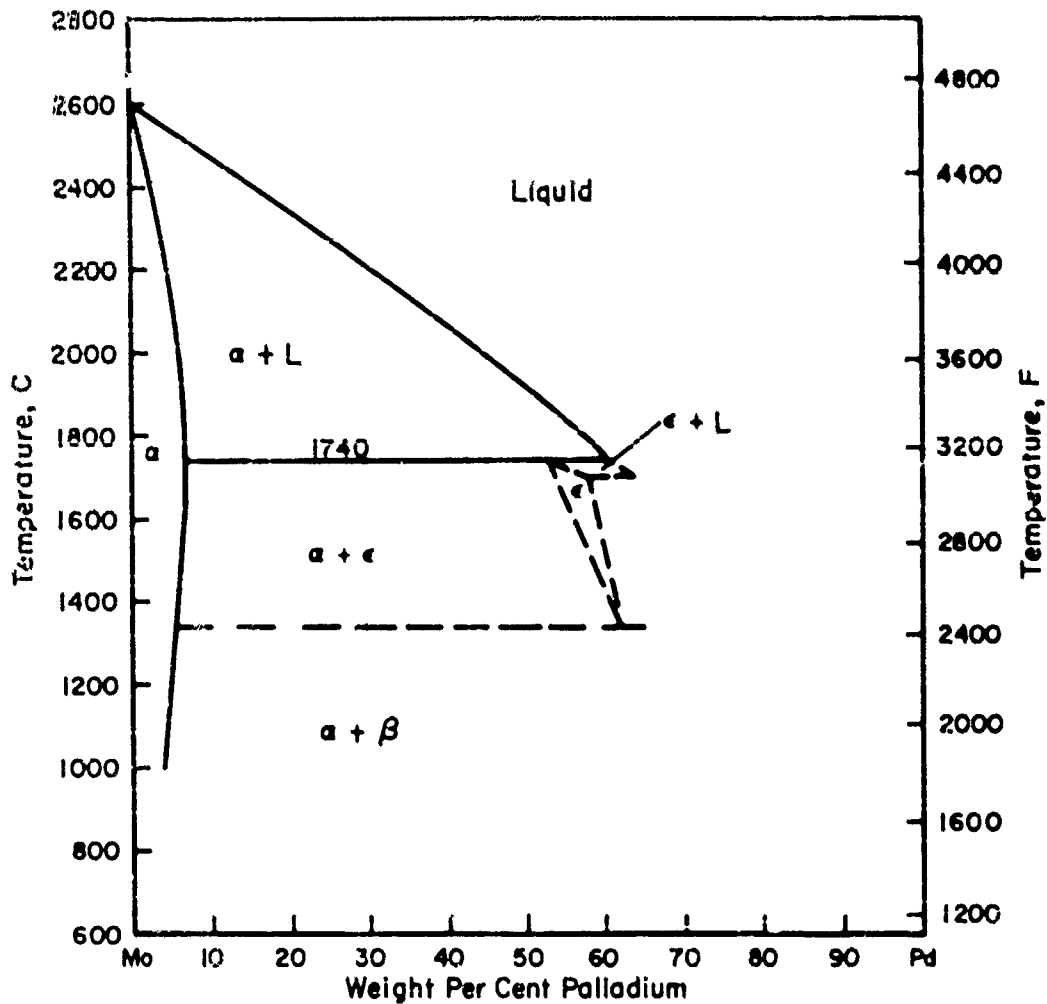
No diagram is available at this time.

MOLYBDENUM-OXYGEN SYSTEM



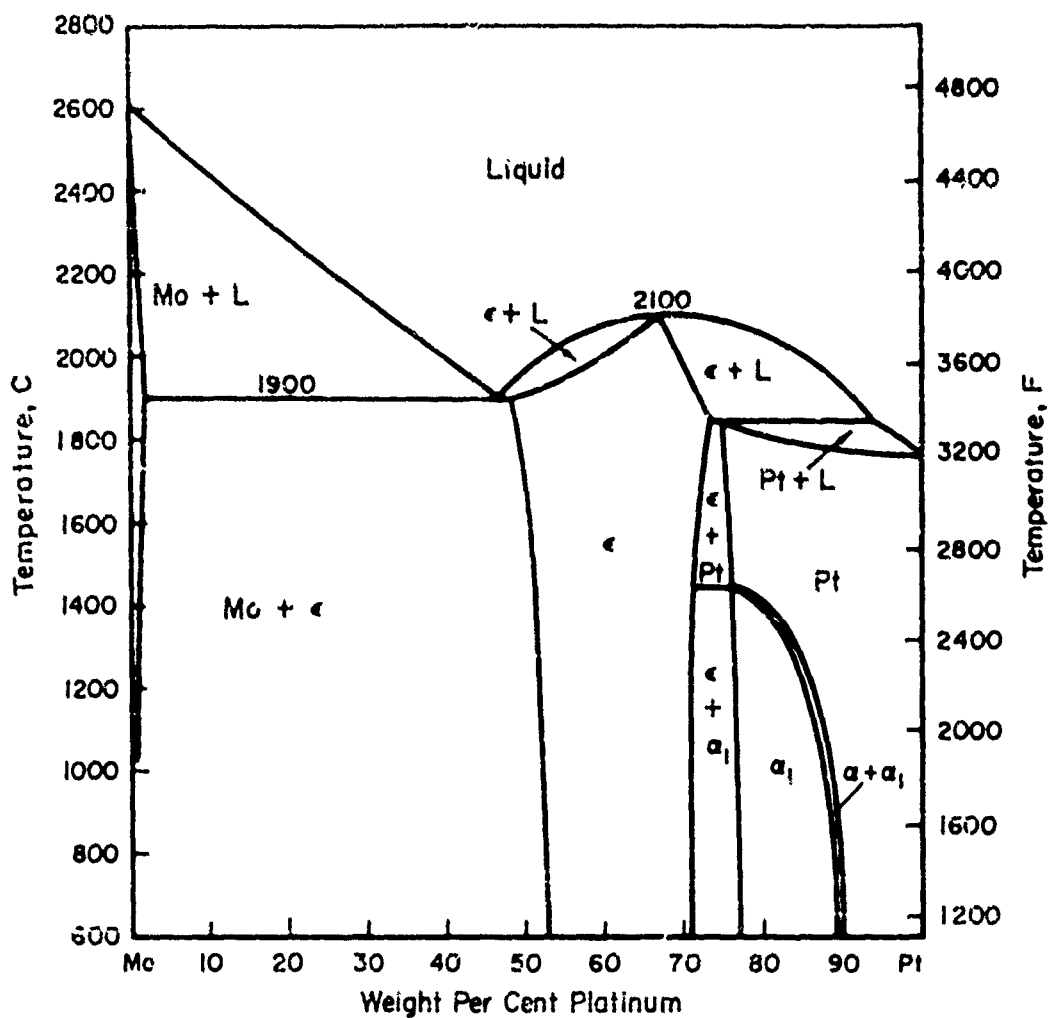
The solubility of oxygen in molybdenum was determined by Few and Manning.⁽⁸⁹⁾ The line represents a three-phase equilibrium between gaseous oxygen, molybdenum oxide, and oxygen dissolved in metallic molybdenum. The composition of the oxide was not determined.

MOLYBDENUM-PALLADIUM SYSTEM



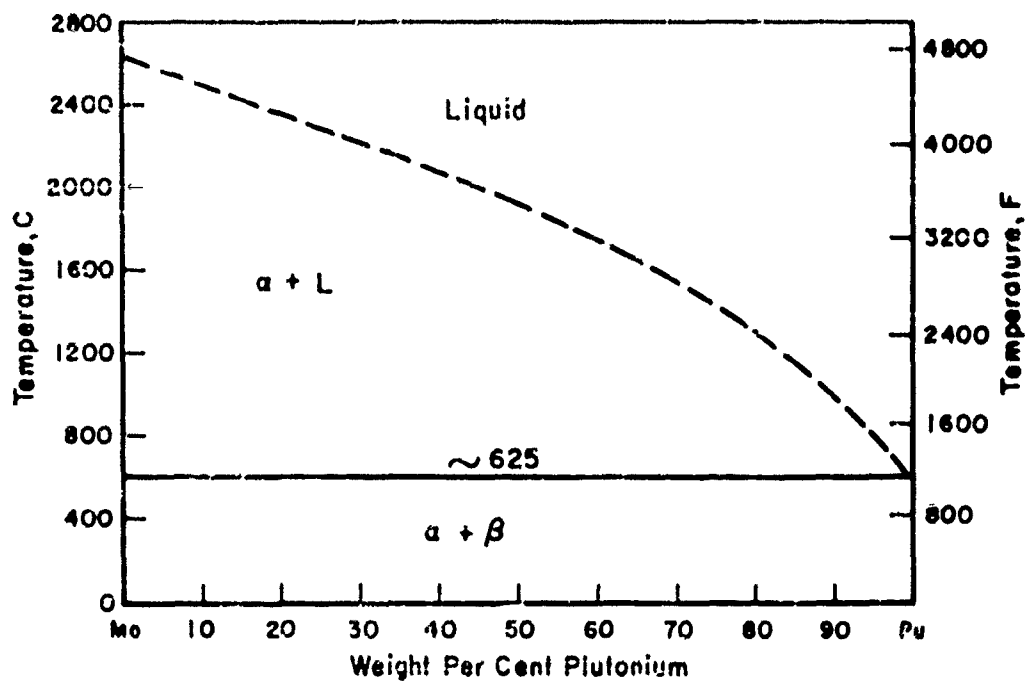
The intermediate phase ϵ is hexagonal close packed, formed by a peritectic reaction at 1740 C. Haworth and Hume-Rothery established the existence of a slight solubility of palladium in molybdenum at high temperatures, 4 to 9 weight per cent palladium.⁽⁹⁰⁾ Their findings disagree with the solubility values obtained by Greenfield and Beck of up to 28 weight per cent palladium.⁽⁹¹⁾ Raub determined that the solubility of molybdenum in palladium is 44.9 weight per cent molybdenum at 1200 C, decreasing to 33.2 per cent at 800 C.

MOLYBDENUM-PLATINUM SYSTEM



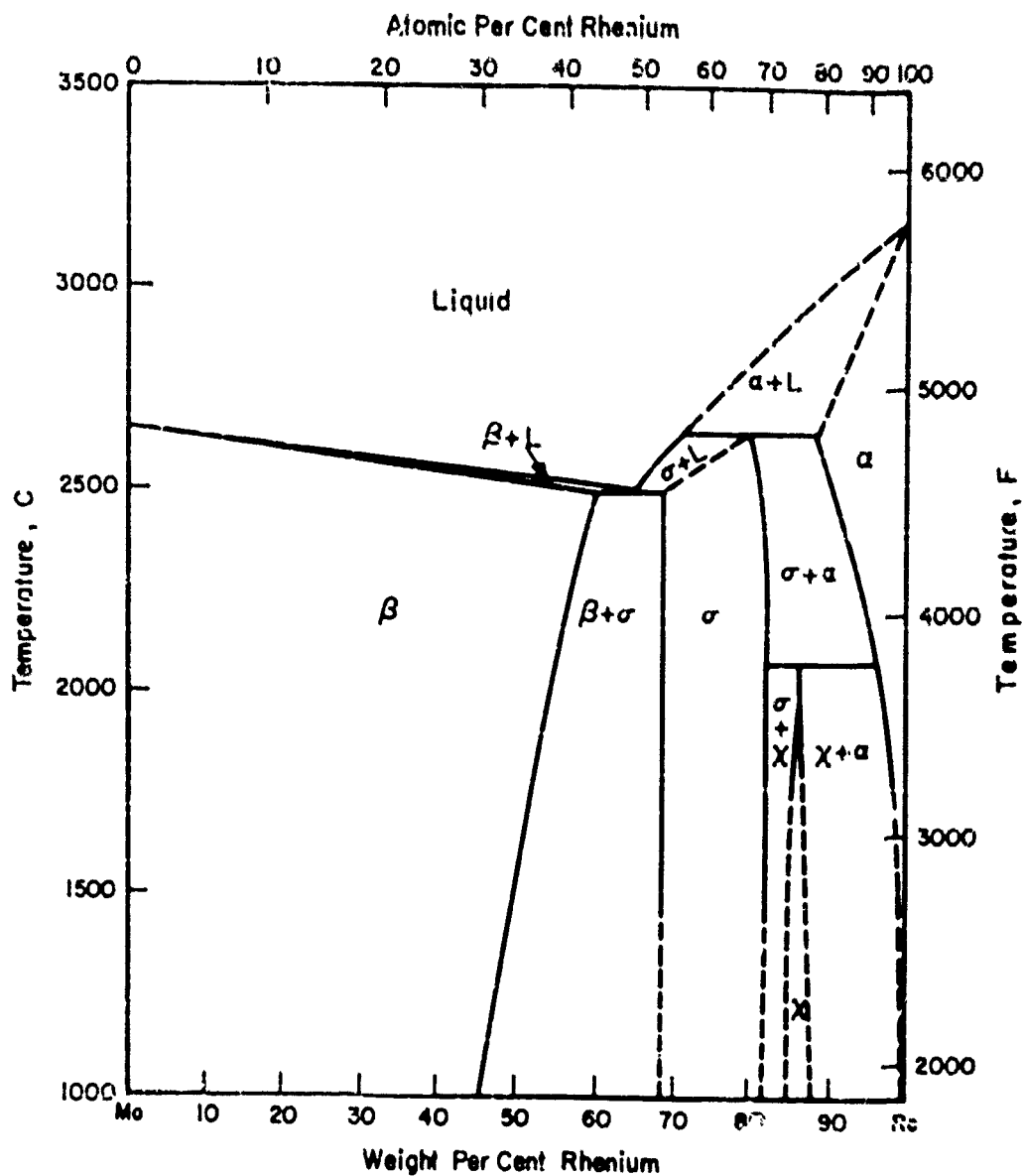
Knapton⁽⁹²⁾ verified Raub's findings⁽⁹²⁾ of an intermediate phase ϵ with a hexagonal-close-packed structure, with $a = 2.80 \text{ \AA}$ and $c/a = 1.603$, at the molybdenum side, and $a = 2.786 \text{ \AA}$ and $c/a = 1.611$, at the platinum side. a_1 is face-centered tetragonal with $a = 3.896 \text{ \AA}$ and $c/a = 1.005$ to 1.009 . The solubility of platinum in molybdenum is very slight.

MOLYBDENUM-PLUTONIUM SYSTEM



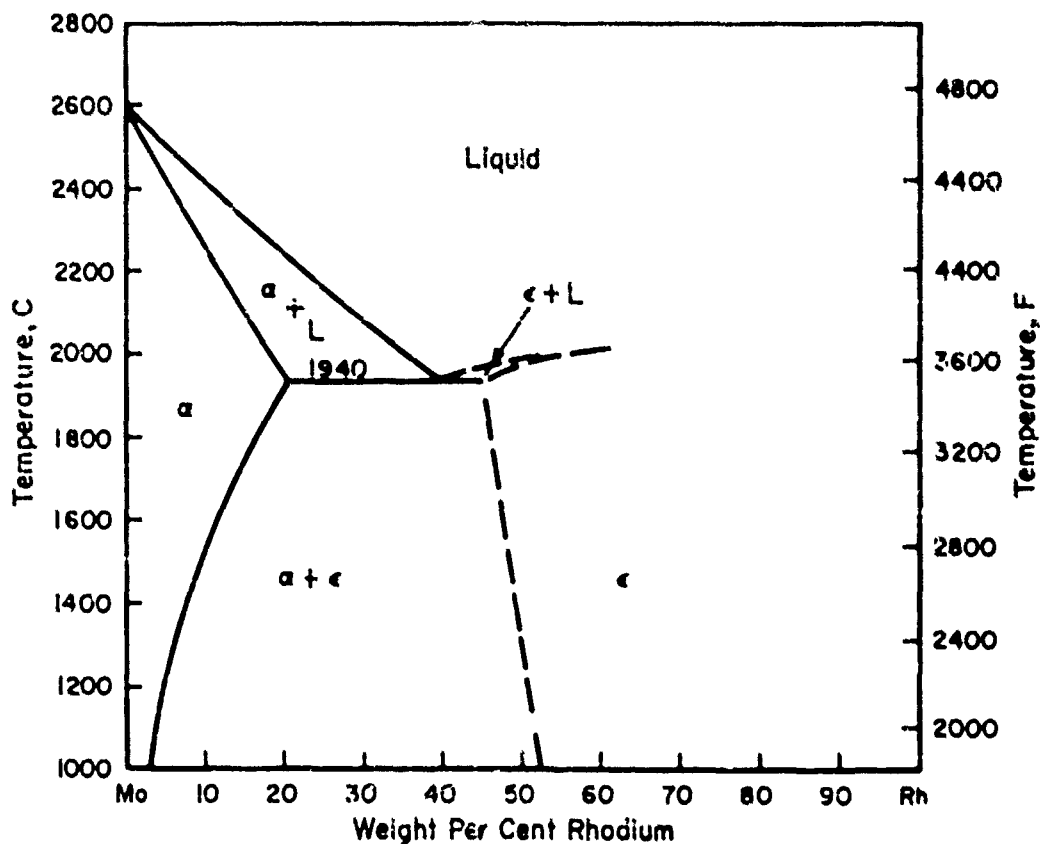
No intermediate phases have been found in this system, (29)

MOLYBDENUM-RHENIUM SYSTEM



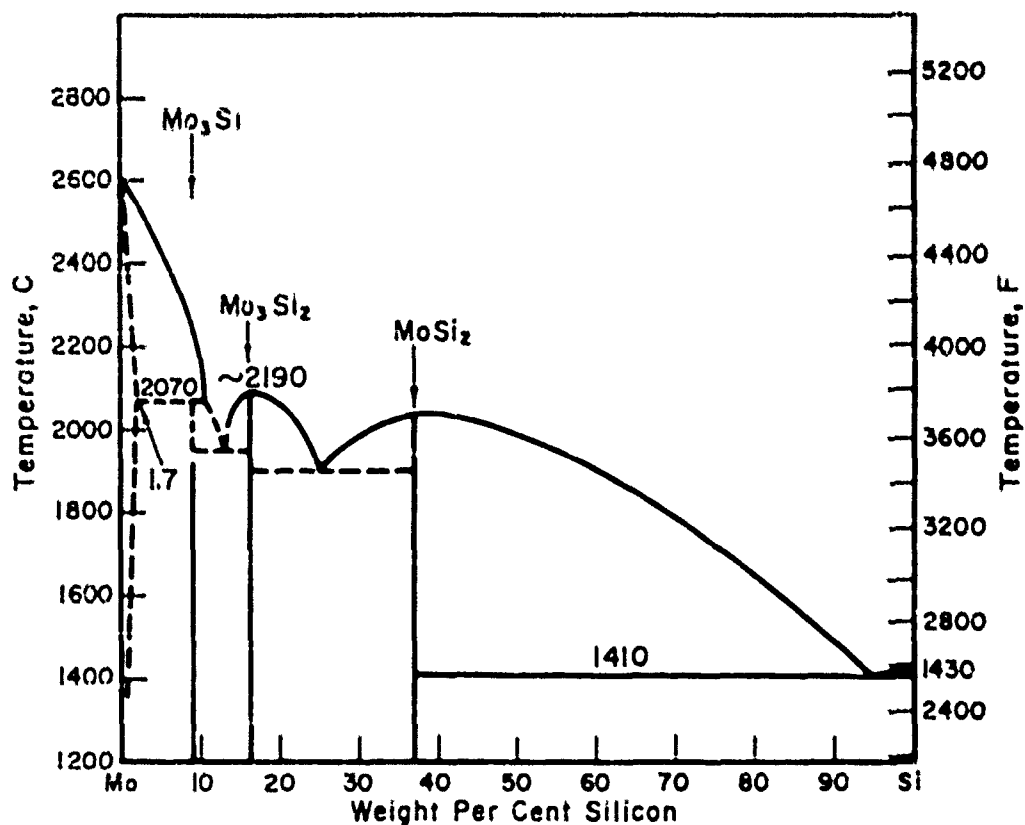
The σ -phase, Mo_2Re_3 , is a tetragonal (D_{2h}^{14}) structure isomorphous with the σ -phase found in iron-chromium alloys. (94-97) The lattice parameters at 60 atomic per cent (73 weight per cent) are $a = 9.588 \text{ \AA}$, $c = 4.983 \text{ \AA}$, and $c/a = 0.5197$. (97) Knapton found the σ -phase to be stable only at 1150°C and above. (96) The body-centered cubic phase, χ , is isomorphous with α -manganese. It corresponds to an approximate composition of MoRe_3 with $a = 9.55 \text{ \AA}$. (91, 94) The solubility of rhenium in molybdenum ranges from 46 weight per cent at 1200°C to 59 weight per cent at the eutectic temperature, 2505°C. (94)

MOLYBDENUM-RHODIUM SYSTEM



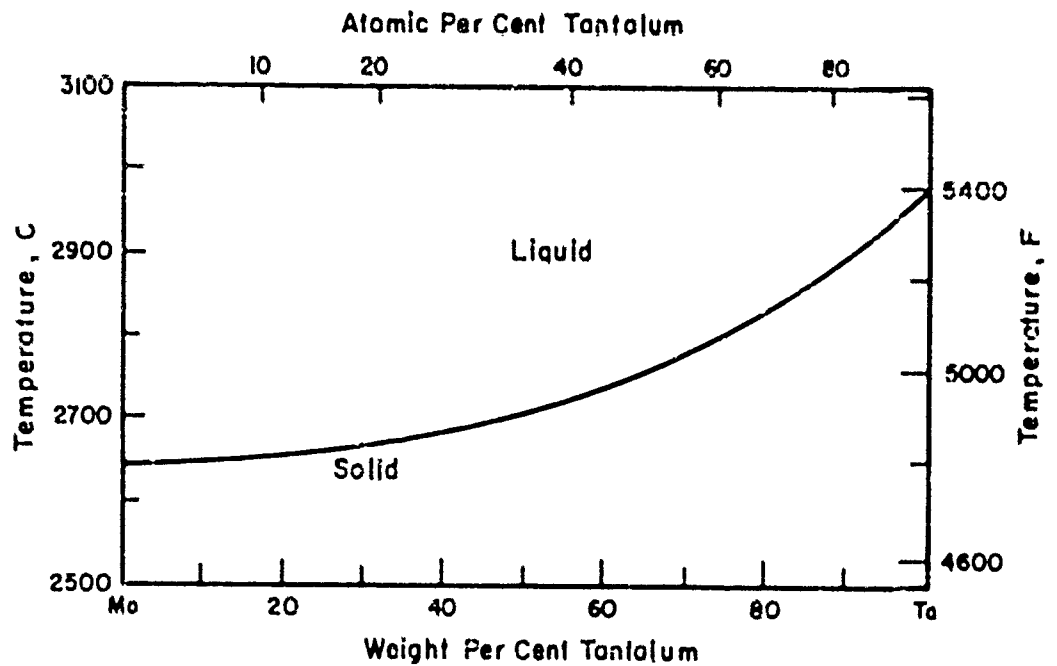
The system contains a eutectic at approximately 41 weight per cent (40 atomic per cent) rhodium. The maximum solubility of rhodium in molybdenum is approximately 21 weight per cent at the eutectic horizontal, diminishing to less than 3 weight per cent at 1100 C.⁽⁹⁰⁾ The ϵ -phase, is hexagonal close packed with $a = 2.740$ kX, $c = 4.350$ kX, and $c/a = 1.599$ at 60 weight per cent rhodium.^(90, 92)

MOLYBDENUM-SILICON SYSTEM



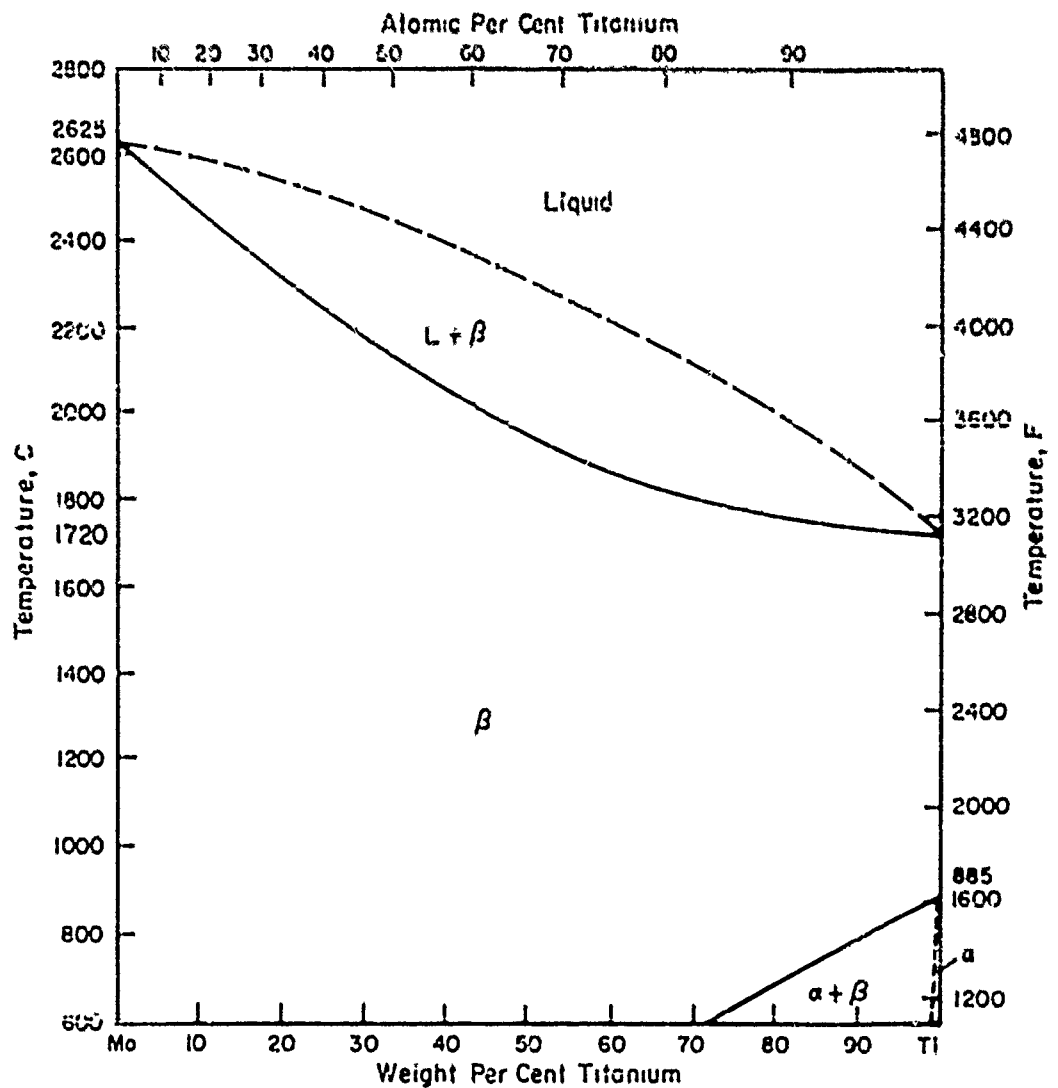
Mo₃Si is isotypic with β -tungsten (A15 type), $a = 4.89$ to 4.90 Å.⁽⁹⁸⁾ Mo₃Si₂ is tetragonal with the dimensions $a = 9.66$ Å, $c = 4.90$ Å, and $c/a = 0.51$. The cell contains 6 Mo₃Si₂.⁽⁹⁹⁾ MoSi₂ is tetragonal, with 6 atoms per unit cell (C116 type), with $a = 3.20$ Å, $c = 7.88$ Å, and $c/a = 2.462$.⁽⁹⁸⁾

MOLYBDENUM-TANTALUM SYSTEM



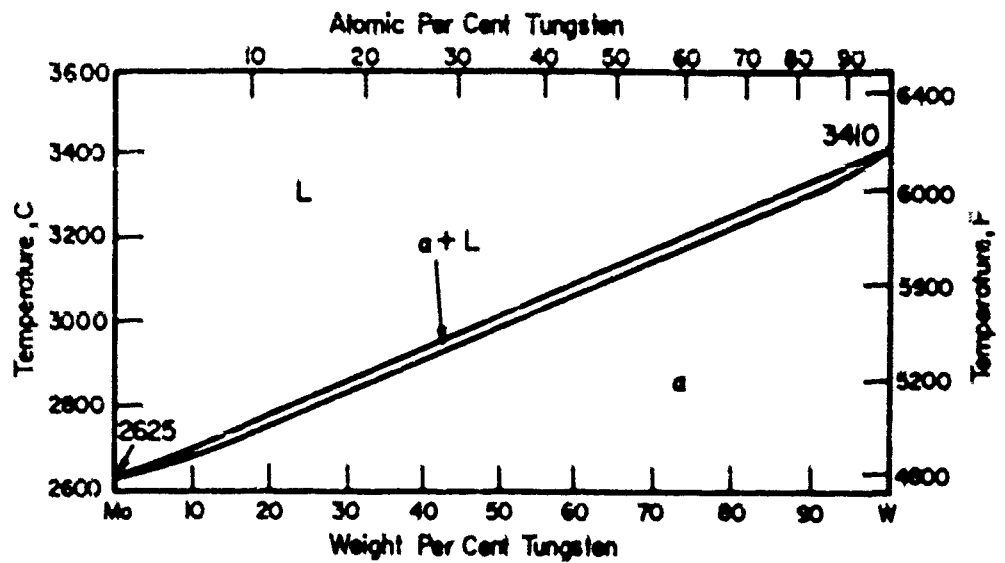
Molybdenum-tantalum alloys exhibit a continuous series of solid solutions. (40, 100, 101) Shown are the results of a melting-point study made by Geach and Summers-Smith. (101)

MOLYBDENUM-TITANIUM SYSTEM



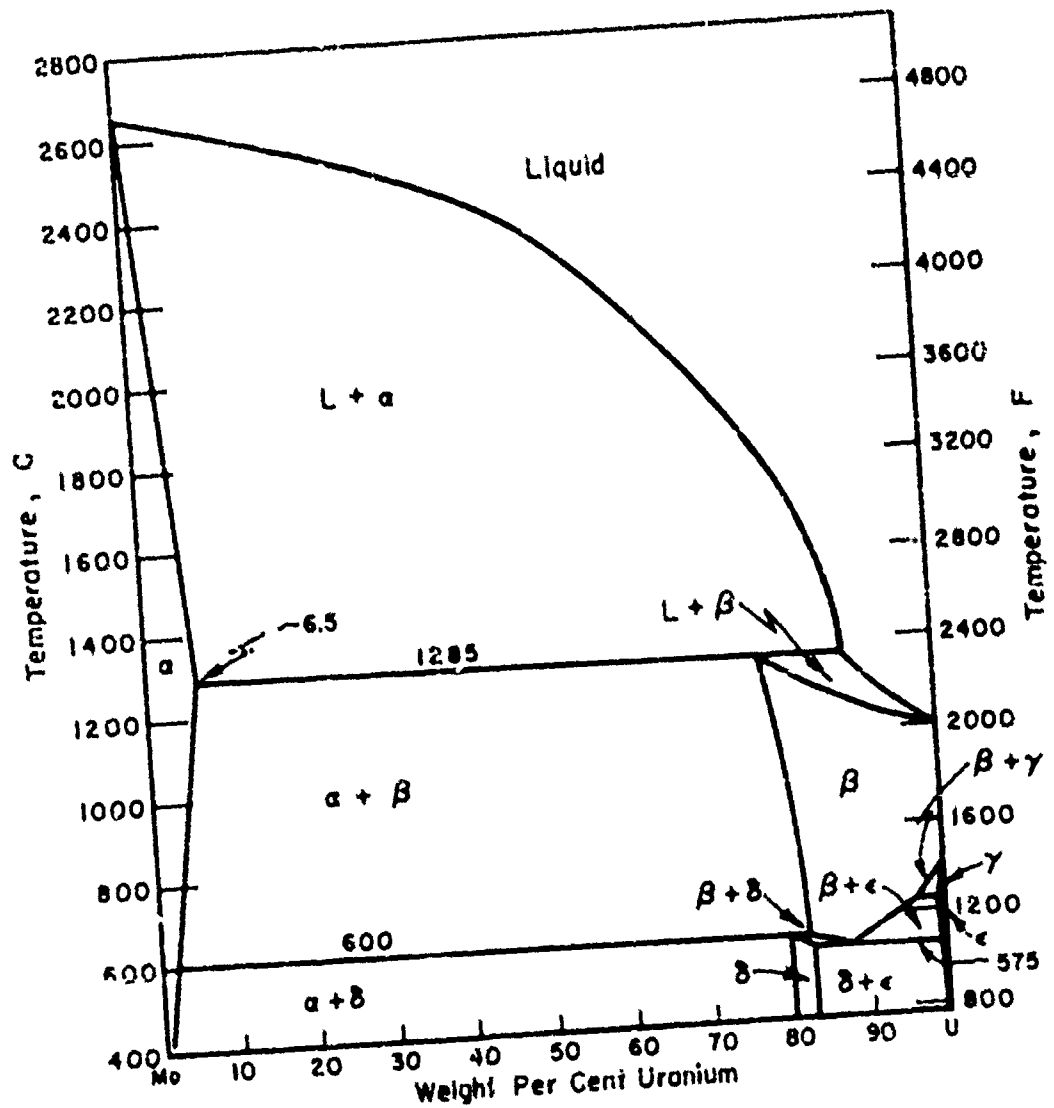
Molybdenum-titanium alloys exhibit a continuous series of solid solutions above 900 C. (102, 103) The body-centered titanium-rich solution transforms to a hexagonal-close-packed structure below 885 C. (103, 104)

MOLYBDENUM-TUNGSTEN SYSTEM



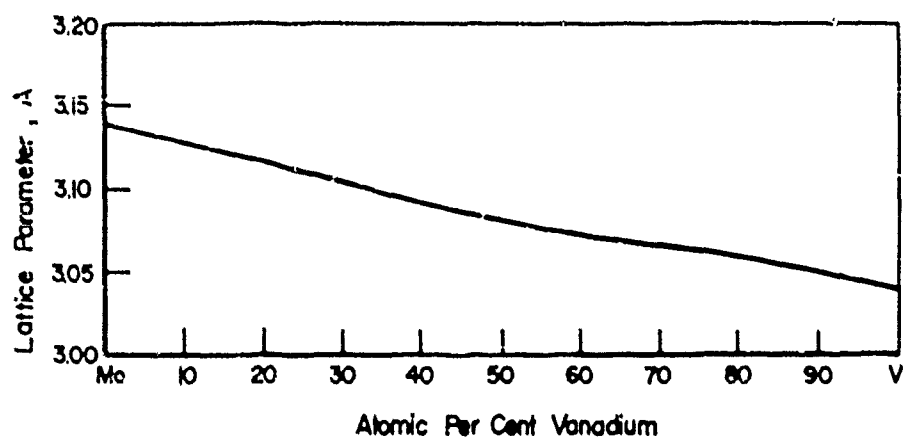
Molybdenum and tungsten form a continuous series of solid solutions. (108, 109, 110)

MOLYBDENUM-URANIUM SYSTEM



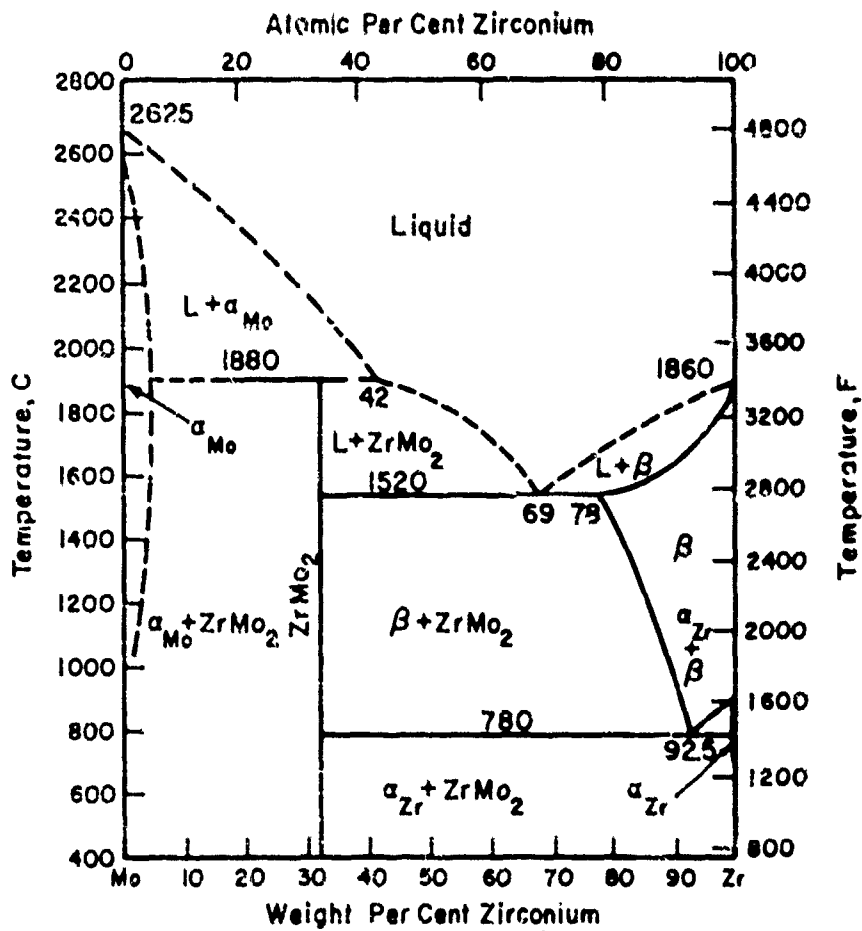
The crystal structure of the δ (MoU_2) phase is of the tetragonal MoSi_2 (C116) type, with $a = 3.427 \text{ \AA}$, $c = 9.834 \text{ \AA}$, and $c/a = 2.871$. (106) The uranium-rich portion of the phase diagram was established by Saller (106) and Halteman. (106) The solubility of uranium in molybdenum is approximately 6.5 weight per cent at 1285°C. (106)

MOLYBDENUM-VANADIUM SYSTEM



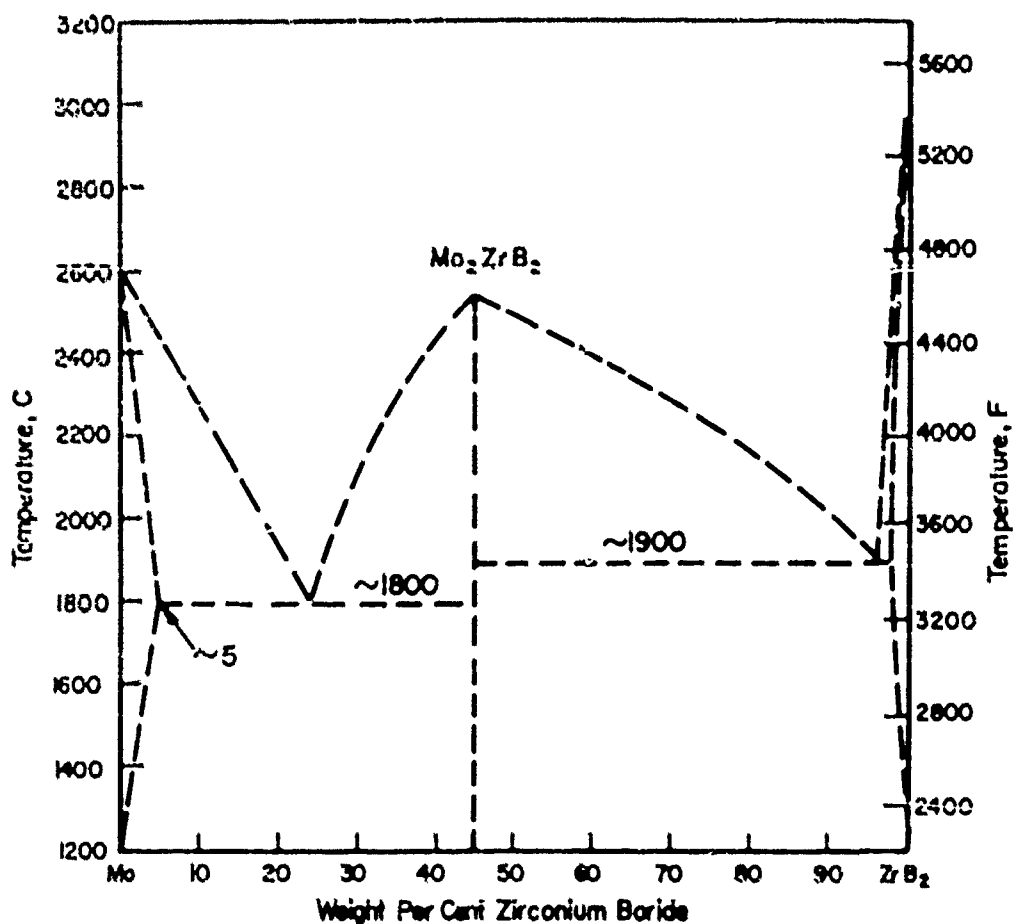
The molybdenum-vanadium system forms a continuous series of solid solutions. The lattice parameters shown were determined by Peplitz and Kleffer.⁽¹⁰⁷⁾

MOLYBDENUM-ZIRCONIUM SYSTEM



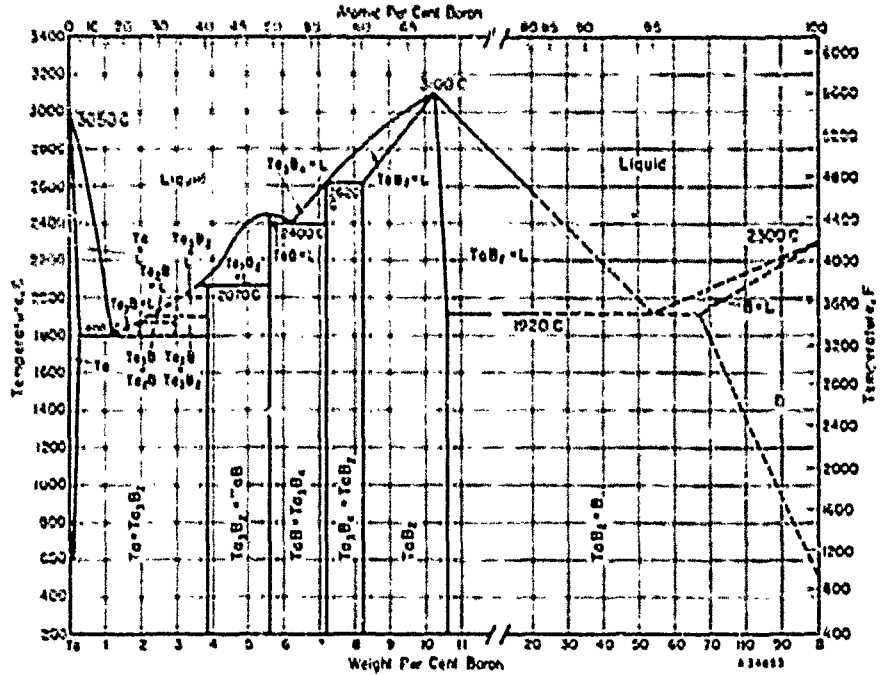
$MoZr_2$ is isotypic with $MgCu_2$ (C15 type), $a = 7.596$, (107, 111) The solid solubility limit of zirconium in slowly cooled alloys was approximately 7 weight per cent zirconium, (107)

MOLYBDENUM-ZIRCONIUM BORIDE SYSTEM



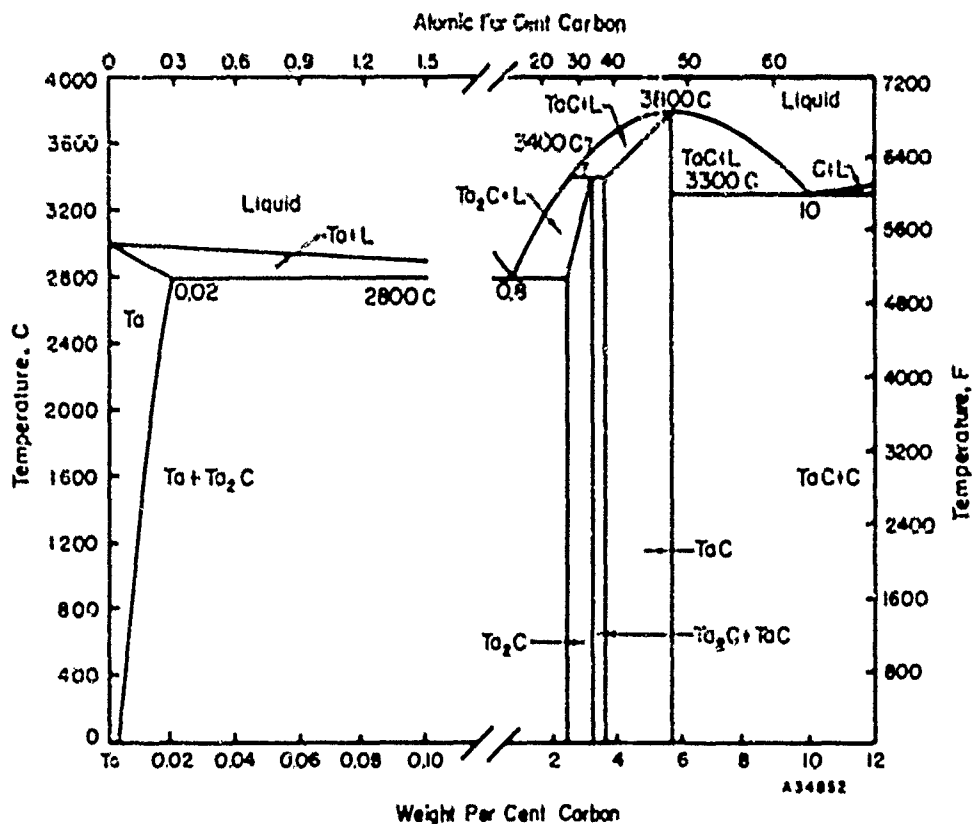
Alloys of 45 weight per cent ZrB₂ (40 atomic per cent) were almost all single phase, Mo₂ZrB₂. The phase has a rhombic structure analogous to Mo₂NiB₂. No other phases were found in the system. At temperatures up to 1800 C, samples containing 24 weight per cent ZrB₂ (20 atomic per cent) melted partially. Alloys with high ZrB₂ content showed signs of melting from 1900 to 2000 C. The maximum solubility of ZrB₂ in molybdenum is about 5 weight per cent. The solubility of molybdenum in ZrB₂ was not determined. (228)

TANTALUM-BORON SYSTEM



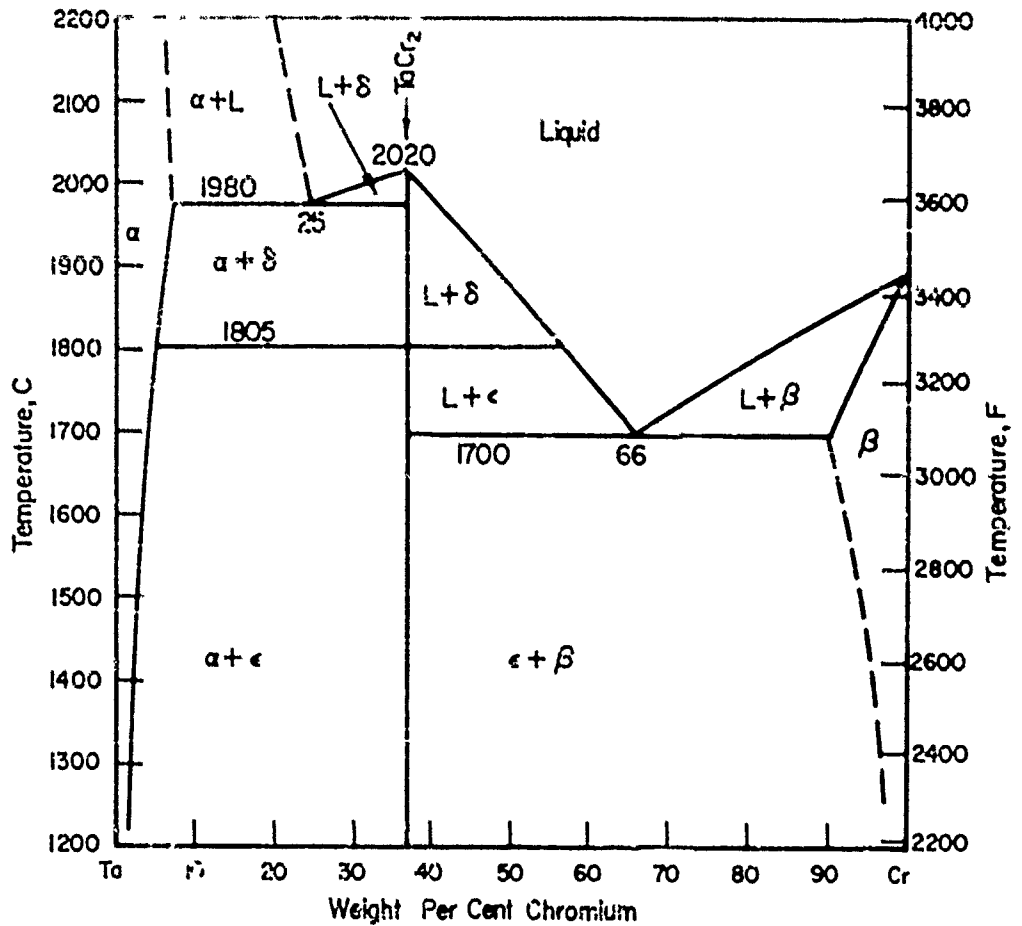
Ta₂B₂ and Ta₂B are stable at high temperatures only.⁽¹¹²⁾ Ta₂B₄ is orthorhombic with $a = 3.29$ Å, $b = 14.0$ Å, and $c = 3.13$ Å.⁽¹¹³⁾ TaB₂ is hexagonal (AlB₂ type) with $a = 3.078$ Å, $c = 3.285$ Å, and $c/a = 1.06$.⁽¹¹³⁾ Ta₂B has a tetragonal CuAl₂-type structure with $a = 5.778$ Å, $c = 4.864$ Å, and $c/a = 0.842$.^(112, 113) TaB is orthorhombic (AB type) with $a = 3.29$ Å, $b = 14.0$ Å, and $c = 3.13$ Å.⁽¹¹³⁾ The phase diagram was developed by Kleffer and Benesovsky.⁽¹¹⁴⁾

TANTALUM-CARBON SYSTEM



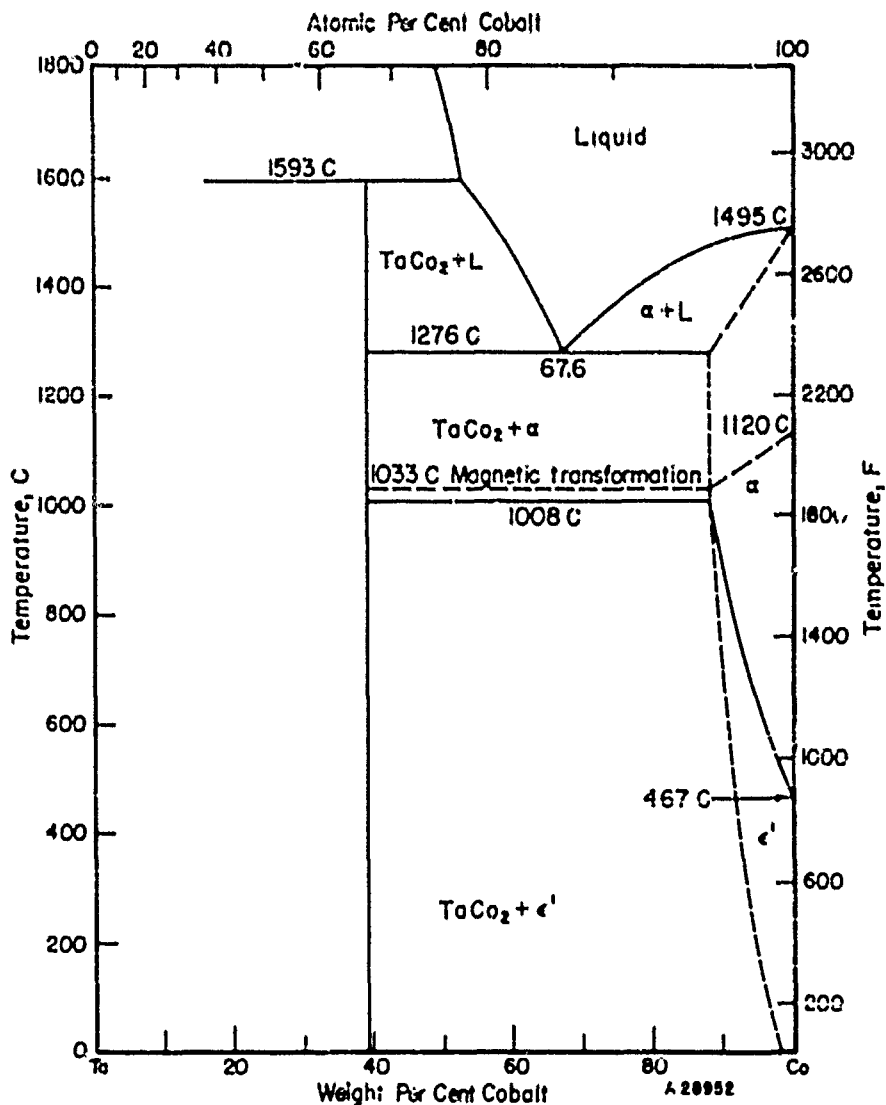
Ta_2C is hexagonal close packed with $a = 3.101$ to 3.104 Å, $c = 4.937$ to 4.941 Å, and $c/a = 1.587$.⁽¹¹⁵⁾ TaC is face-centered cubic (NaCl type) with $a = 4.20$ to 4.67 Å.⁽¹¹⁵⁾ The $Ta-Ta_2C$ eutectic occurs at 0.8 weight per cent carbon and 2800°C, and the $TaC-C$ eutectic occurs at 10 weight per cent carbon and 3300°C.⁽¹¹⁶⁻¹¹⁸⁾

TANTALUM-CHROMIUM SYSTEM



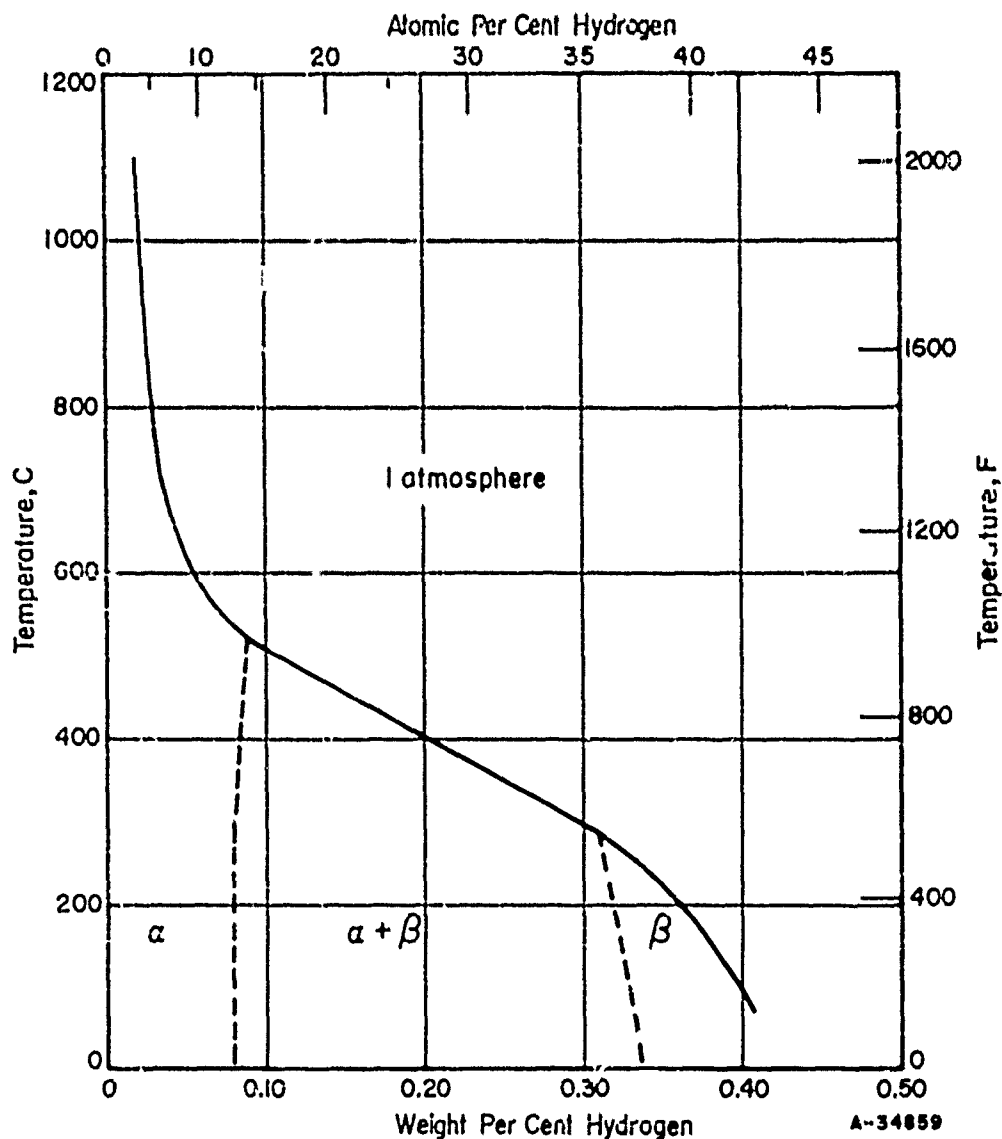
Duwez and Martens⁽¹²³⁾ reported that $TaCr_2$ has a polymorphic transformation between 1375 and 1550 C from the low-temperature cubic structure (MgCu₂-type with $a = 6.661$ Å) to the high-temperature hexagonal structure ($a = 4.925$ Å, $c = 8.062$ Å, $c/a = 1.637$). Elliott considers the compound isomorphous 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.

TANTALUM-COBALT SYSTEM



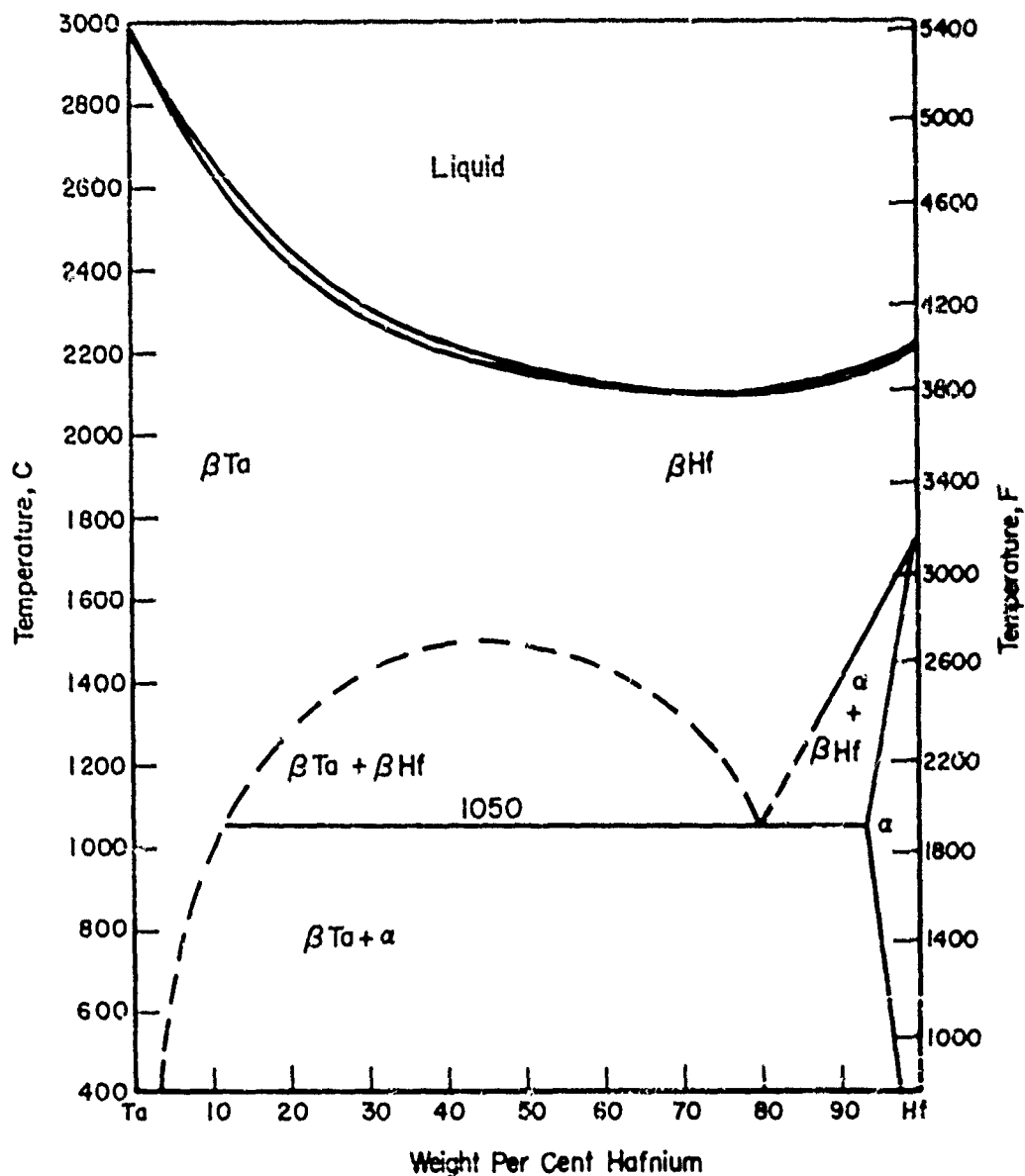
Two modifications of TaCo₂ have been reported: the MgCu₂ type with $a = 6.73$ Å, and the hexagonal MgZn₂ type with $a = 4.79$ Å, $c = 7.83$ Å, and $c/a = 1.63$.⁽¹¹⁹⁾ The compound Ta_{0.8}Co_{2.2} (52.7 weight per cent tantalum) possibly occurs between 1000 and 1300°C. Wallbaum⁽¹²⁰⁾ identified the phase as a hexagonal, MgN₂-type structure with $a = 4.72$ Å, $c = 15.39$ Å, and $c/a = 3.26$. Two modifications of the compound TaCo₃ (50.6 weight per cent tantalum) were studied by Korchynsky and Fountain: the ordered face-centered cubic with $a = 3.65$ Å, and the hexagonal with $a = 3.41$ Å, $c = 15.50$ Å, and $c/a = 1.65$.⁽¹¹⁹⁾ The diagram was determined by Köster and Mulfinger⁽¹²¹⁾ and by Hoschimoto⁽¹²²⁾.

TANTALUM-HYDROGEN SYSTEM



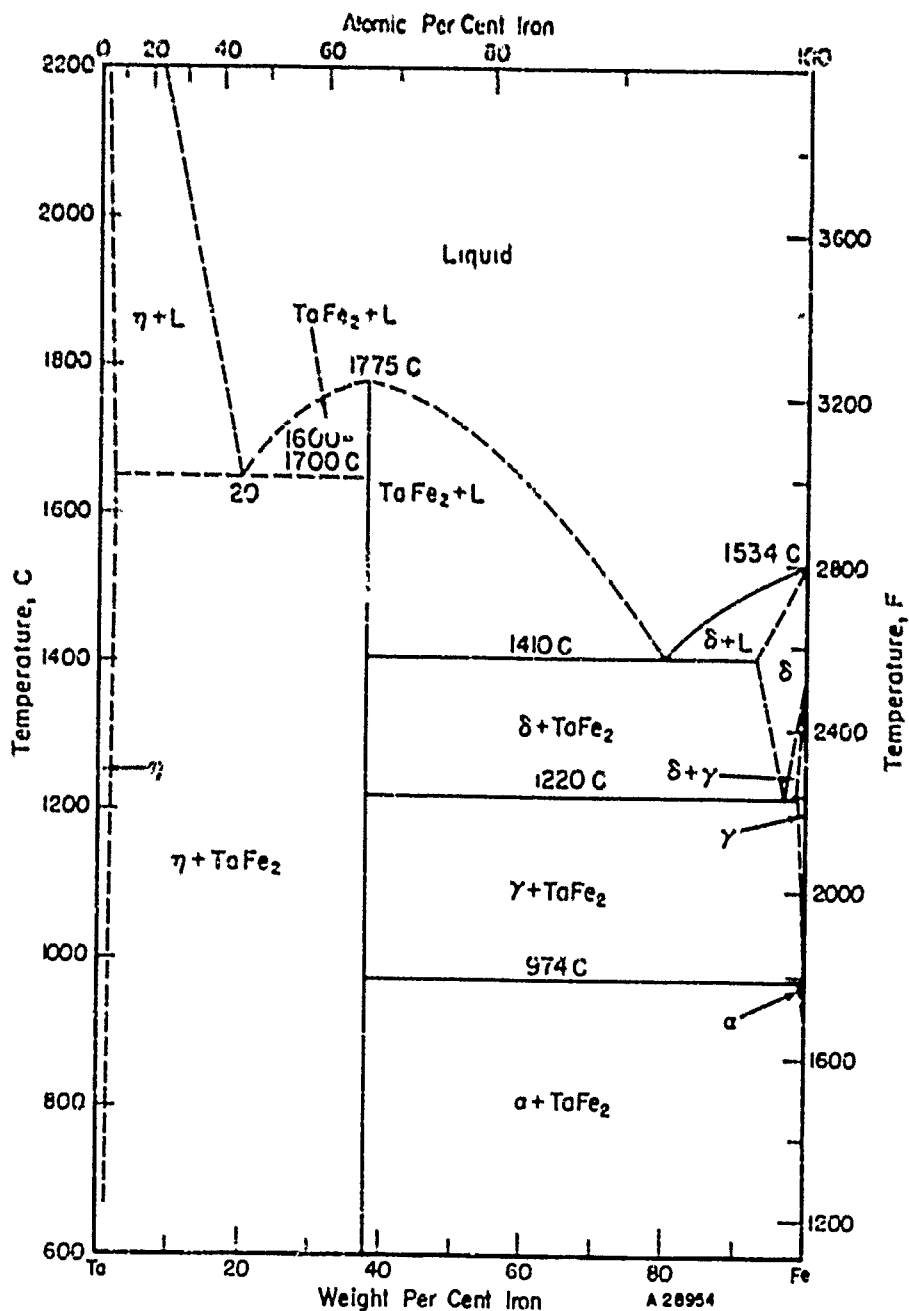
There is poor agreement as to the maximum solubility of hydrogen in tantalum. (126-129) Waite et al. list the solubility of hydrogen as 40 atomic per cent above 50 C, decreasing to 10 and 0 per cent at 0 and -145 C. (130) This strongly temperature-dependent solubility reported by Waite could account for the poor agreement. The second solid solution (β) is body-centered (or slightly distorted body-centered) cubic. (131) The β -phase also has been reported as a hydride of the approximate composition Ta_2H with a body-centered tetragonal structure gradually distorting to a face-centered orthorhombic structure (130)

TANTALUM-HAFNIUM SYSTEM



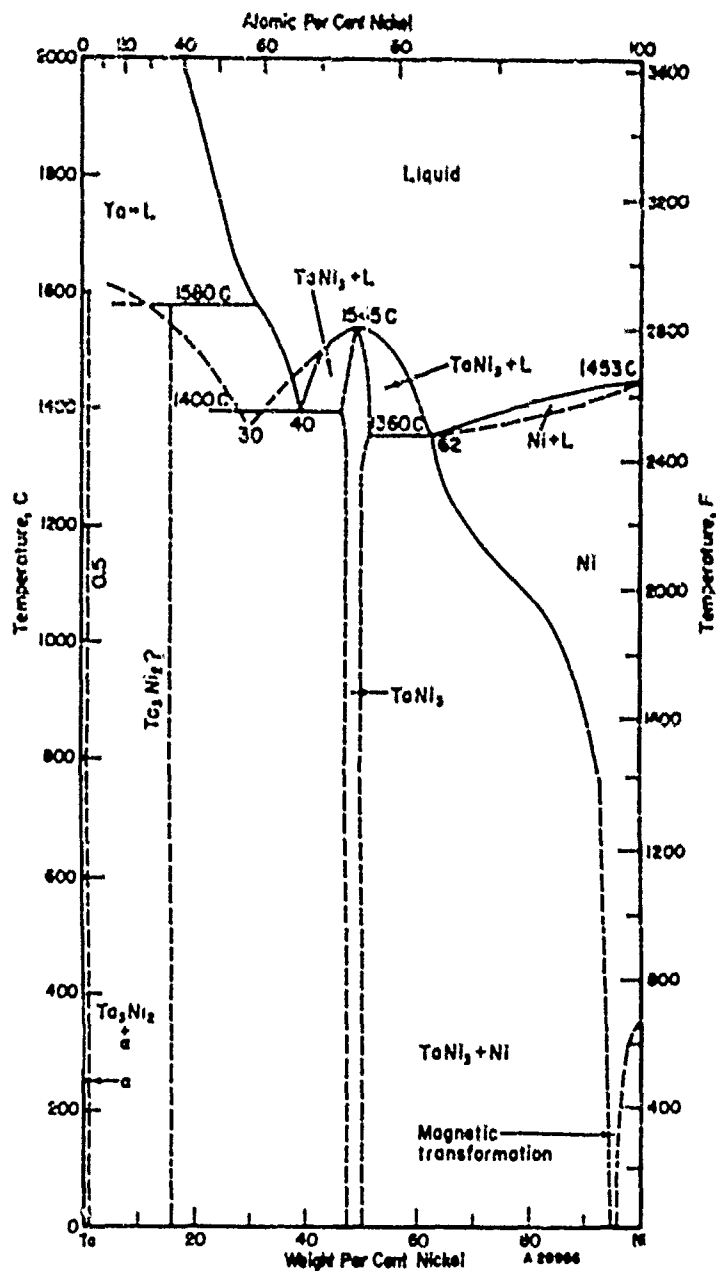
Melting-point determinations for the tentative diagram determined by Deardorff⁽²³²⁾ were made between 50 and 100 weight per cent hafnium. The results indicated a minimum melting point near 80 weight per cent hafnium. The eutectoid temperature is 1050 C with the eutectoid composition about 80 weight per cent hafnium. The solubility of tantalum in hafnium is about 7 weight per cent at 1050 C, possibly decreasing to less than 0.30 weight per cent at 950 C.

TANTALUM-IRON SYSTEM



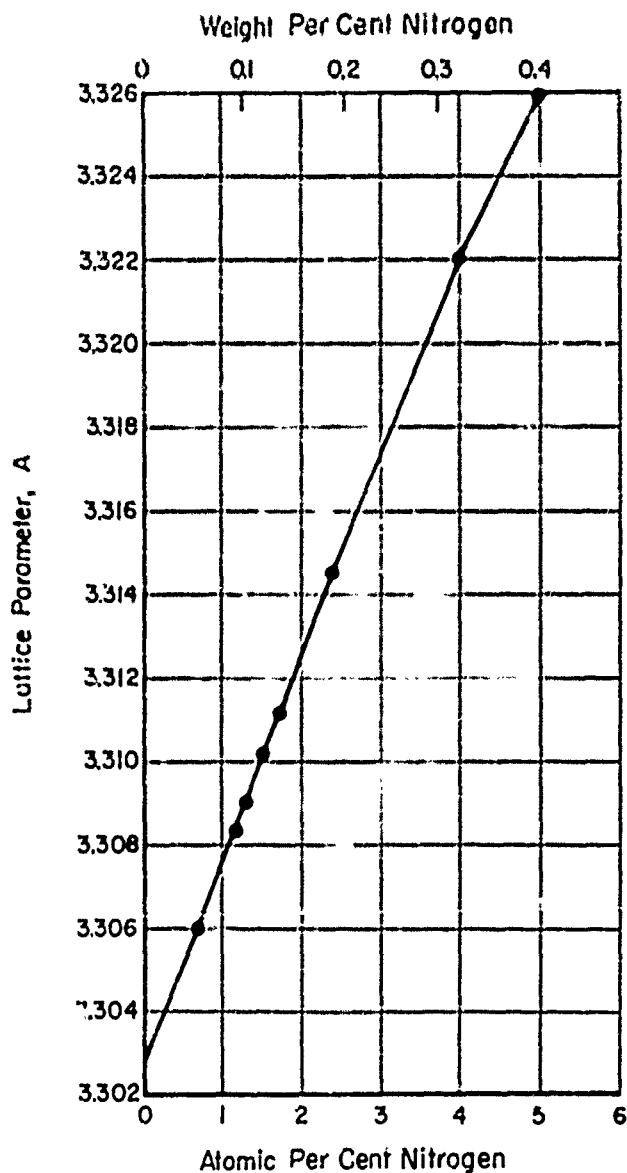
$TaFe_2$ has the $MgZn_2$ (C14) type of structure with $a = 4.81 \text{ \AA}$, $c = 7.85 \text{ \AA}$, and $c/a = 1.63$.⁽¹²⁰⁾
The diagram was developed by Genders and Harrison.⁽¹²⁵⁾

TANTALUM-NICKEL SYSTEM



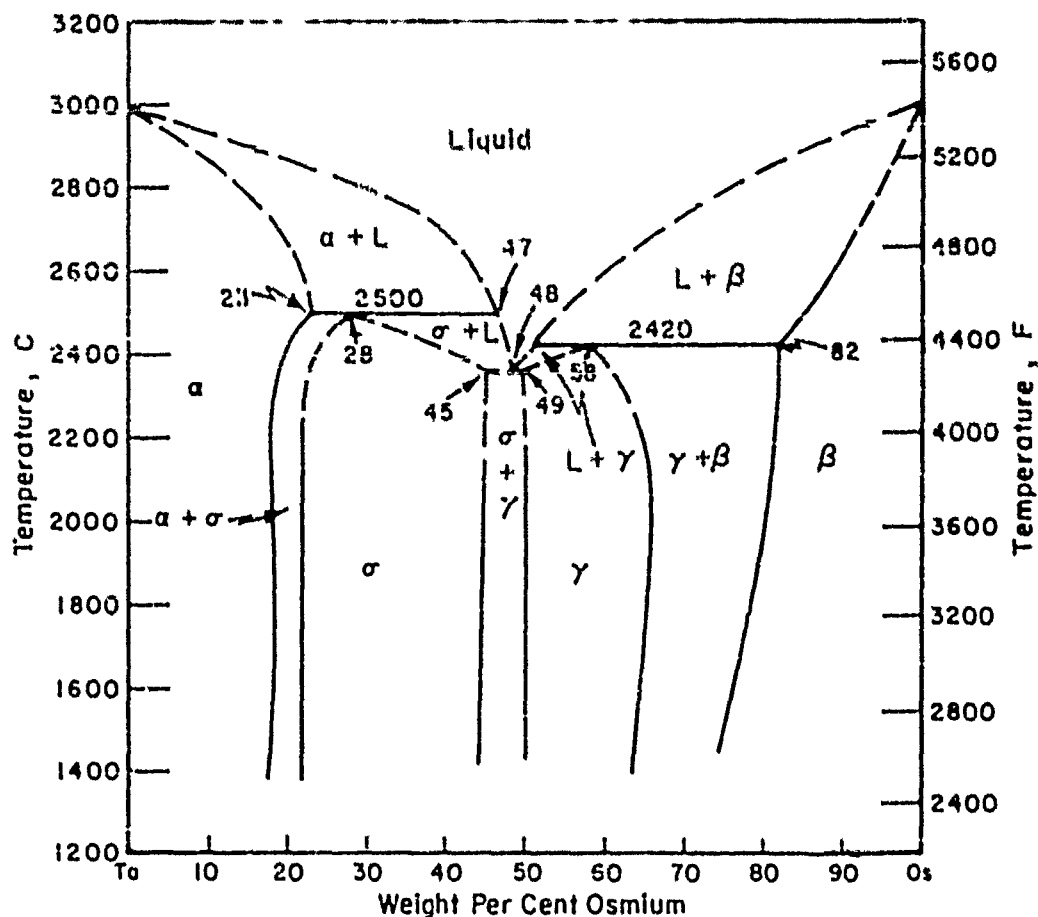
Ta₃Ni₃ is orthorhombic (slightly deformed hcp) with $a = 5.114 \text{ \AA}$, $b = 4.250 \text{ \AA}$, and $c = 4.542 \text{ \AA}$.⁽¹³⁸⁾ The compound Ta₃Ni₂ has been reported but not confirmed.⁽¹³⁹⁾ Alloys between 0 and 5 weight per cent nickel and below 1600°C consist of a tantalum-rich solid solution containing less than 0.05 weight per cent nickel and an intermediate phase.⁽¹⁴⁰⁾

TANTALUM-NITROGEN SYSTEM



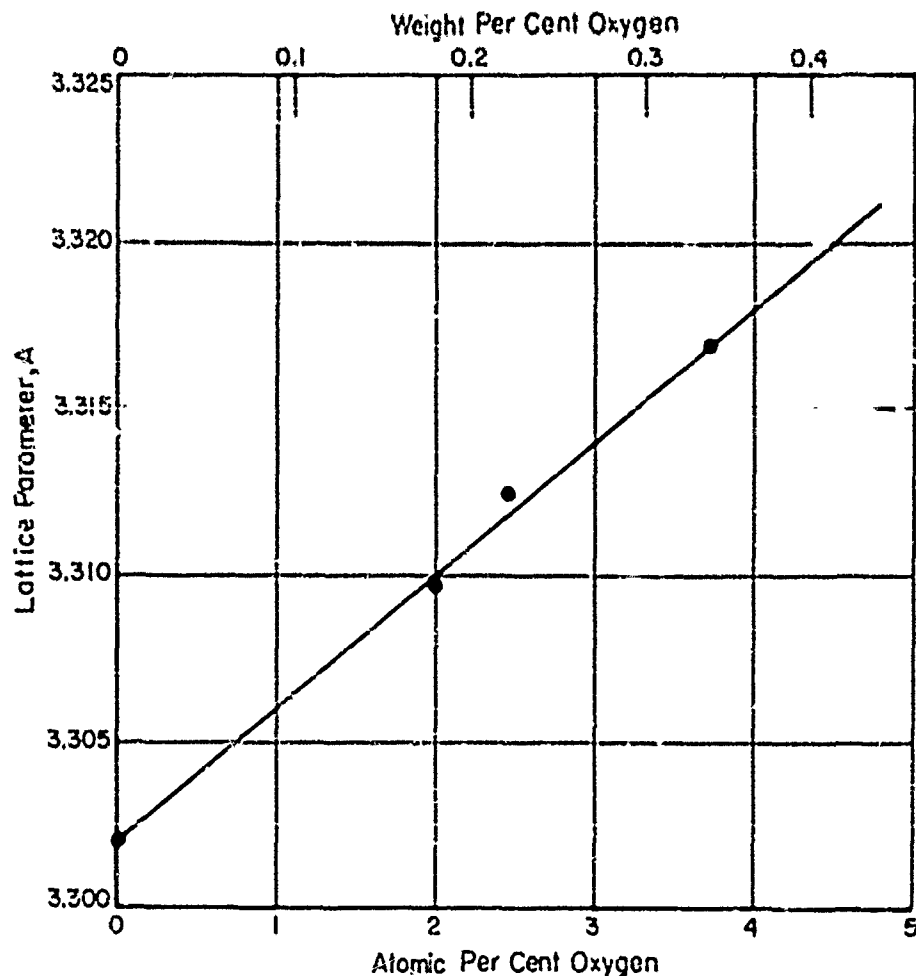
Two intermetallic compounds are definitely established for the tantalum-nitrogen system. TaN is hexagonal close packed with $a = 5.161$ kX, $c = 2.905$ kX, and $c/a = 0.561$.⁽¹³²⁾ Ta_2N is also hexagonal close packed with $a = 3.042$ kX, $c = 4.909$ kX, and $c/a = 1.614$.^(132, 133) The melting point of TaN has been given as 2890 C⁽¹³⁴⁾ and 3090 C⁽¹³⁵⁾. Chloiti has shown that TaN dissociates at high temperatures, forming the lower nitride, Ta_2N , and nitrogen.⁽¹³⁶⁾ Between 1600 and 2000 C, at least 7 atomic per cent nitrogen dissolves in tantalum.⁽¹³⁷⁾

TANTALUM-OSMIUM SYSTEM



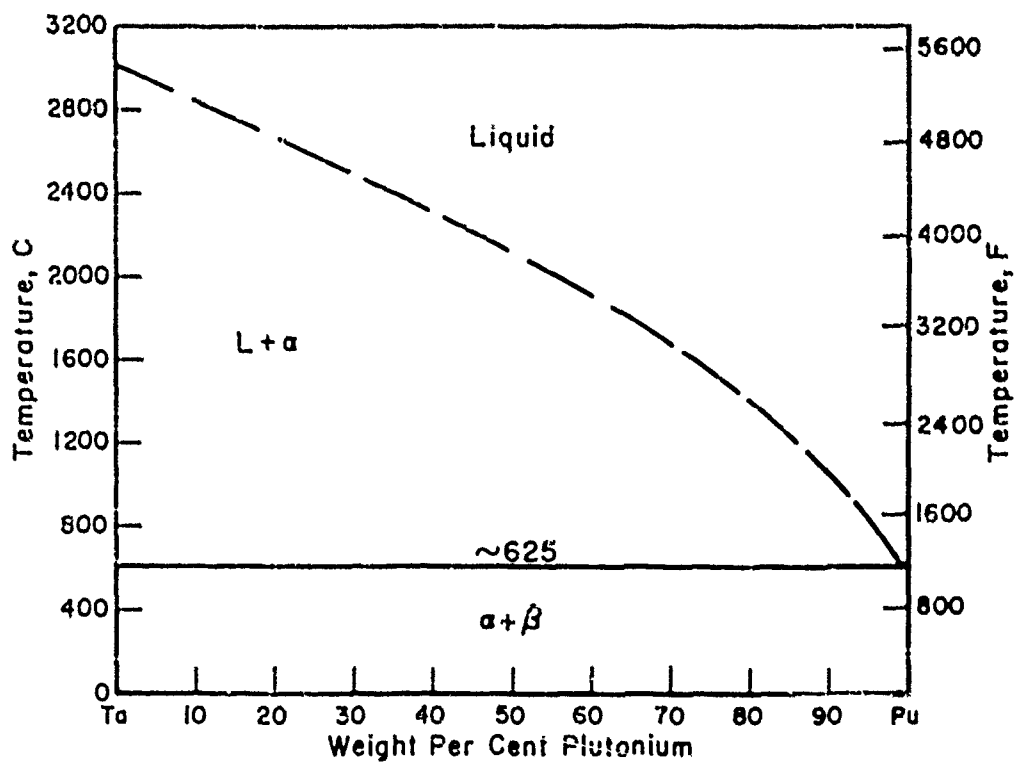
The sigma phase forms by a peritectic reaction at approximately 2500 C.⁽¹⁴⁷⁾ The structure is tetragonal with $a = 9.934 \text{ \AA}$ and $c = 5.189 \text{ \AA}$ at 26 weight per cent (25 atomic per cent) osmium.⁽¹⁴⁸⁾ The gamma phase forms by a peritectic reaction at 2420 C.⁽¹⁴⁷⁾ The structure is probably the cubic α -manganese type observed by Knapp⁽³⁴⁾, with the lattice parameter $a = 3.639 \text{ \AA}$. The solubility of osmium in tantalum is 16 weight per cent (15 atomic per cent) at 1600 C. Increasing to 23 weight per cent (22 atomic per cent) at 2500 C.⁽¹⁴⁷⁾ The solubility of tantalum in osmium is 26 weight per cent (25 atomic per cent) at 1600 C, decreasing to 18 weight per cent (19 atomic per cent) at 2420 C.⁽¹⁴⁷⁾

TANTALUM-OXYGEN SYSTEM



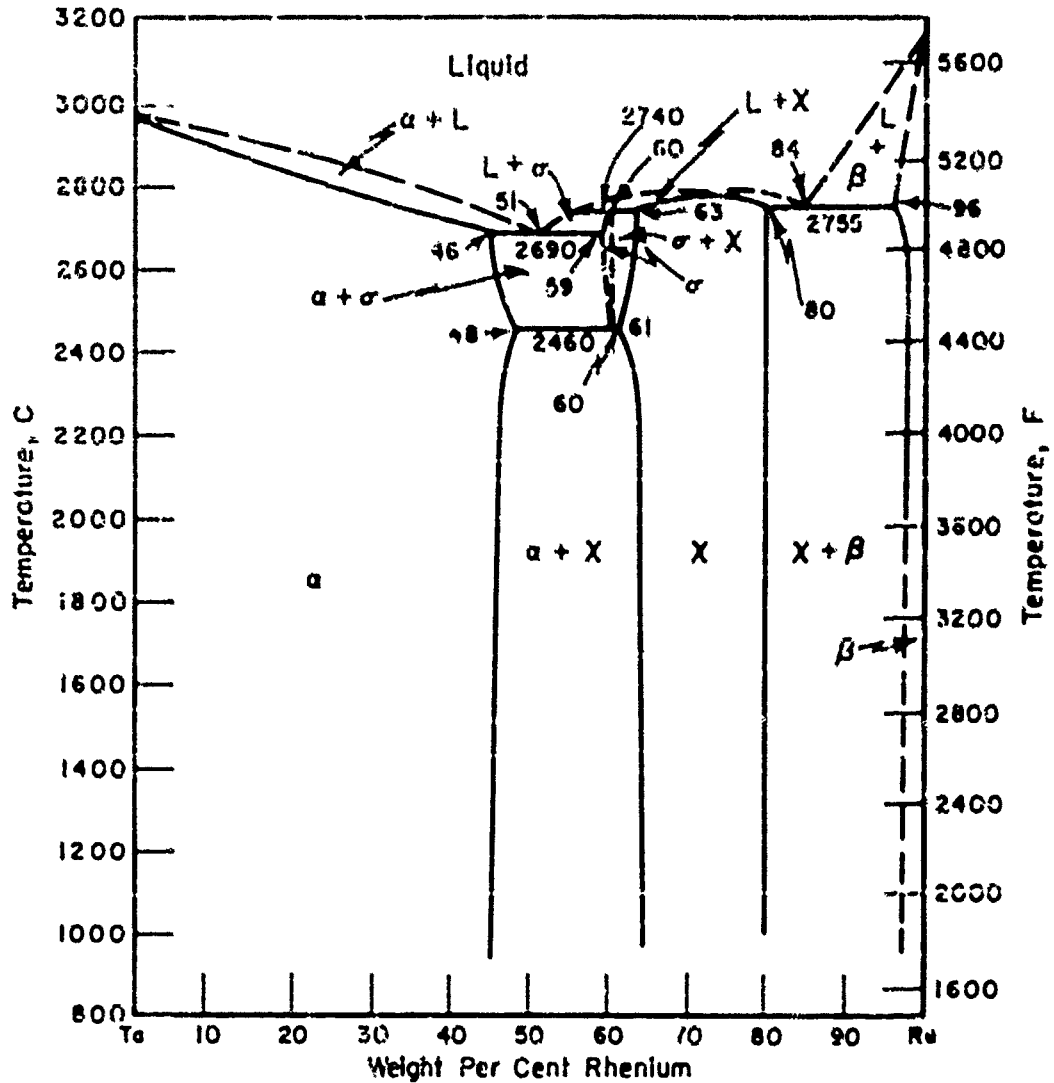
Six oxides of tantalum have been reported. β - Ta_2O_5 is the only oxide that is firmly established. It has an orthorhombic structure with $a = 6.19 \text{ \AA}$, $b = 3.66 \text{ \AA}$, and $c = 3.89 \text{ \AA}$.⁽¹⁴¹⁾ β - Ta_2O_5 transforms to the high-temperature α - Ta_2O_5 at 1320 to 1350 C.^(142, 143) TaO_2 has a tetragonal (T:O_2 type) structure with $a = 4.709 \text{ \AA}$, $c = 3.065 \text{ \AA}$, and $c/a = 0.651$.⁽¹⁴⁴⁾ TaO is cubic (NaCl type) with $a = 4.22$ to $4.39 \text{ \AA}$.⁽¹⁴⁴⁾ Ta_2O is orthorhombic with $a = 5.29 \text{ \AA}$, $b = 4.92 \text{ \AA}$, and $c = 3.05 \text{ \AA}$.⁽¹⁴³⁾ Ta_4O is orthorhombic with $a = 7.194$ to $7.238 \text{ \AA}$, $b = 3.266$ to $3.273 \text{ \AA}$, and $c = 3.204$ to $3.216 \text{ \AA}$.⁽¹⁴⁴⁾ The solid solubility of oxygen in tantalum is 1.5, 2.2, 3.1, and 4.2 atomic per cent at 700, 900, 1100, and 1300 C, respectively.⁽¹⁴⁵⁾ The lattice parameters were determined by Gebhardt.⁽¹⁴⁶⁾

TANTALUM-PLUTONIUM SYSTEM



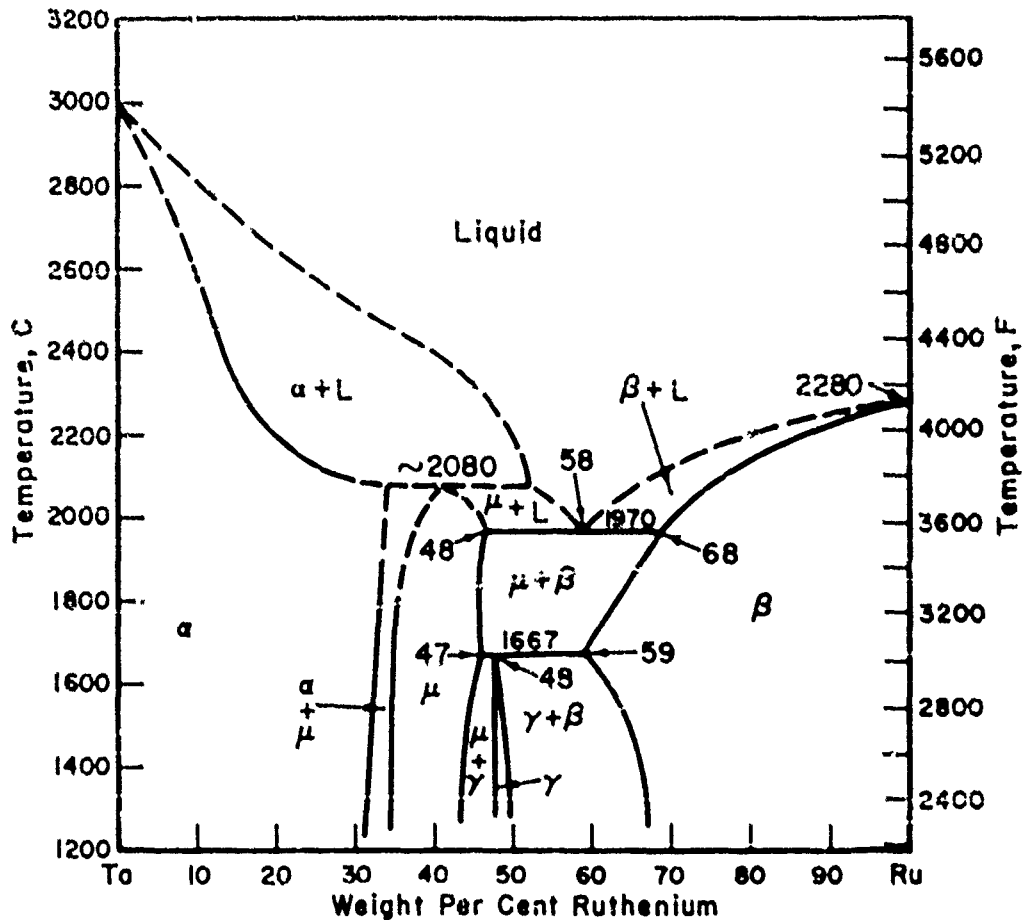
No intermediate phases are known to exist in this system.

TANTALUM-RHENIUM SYSTEM



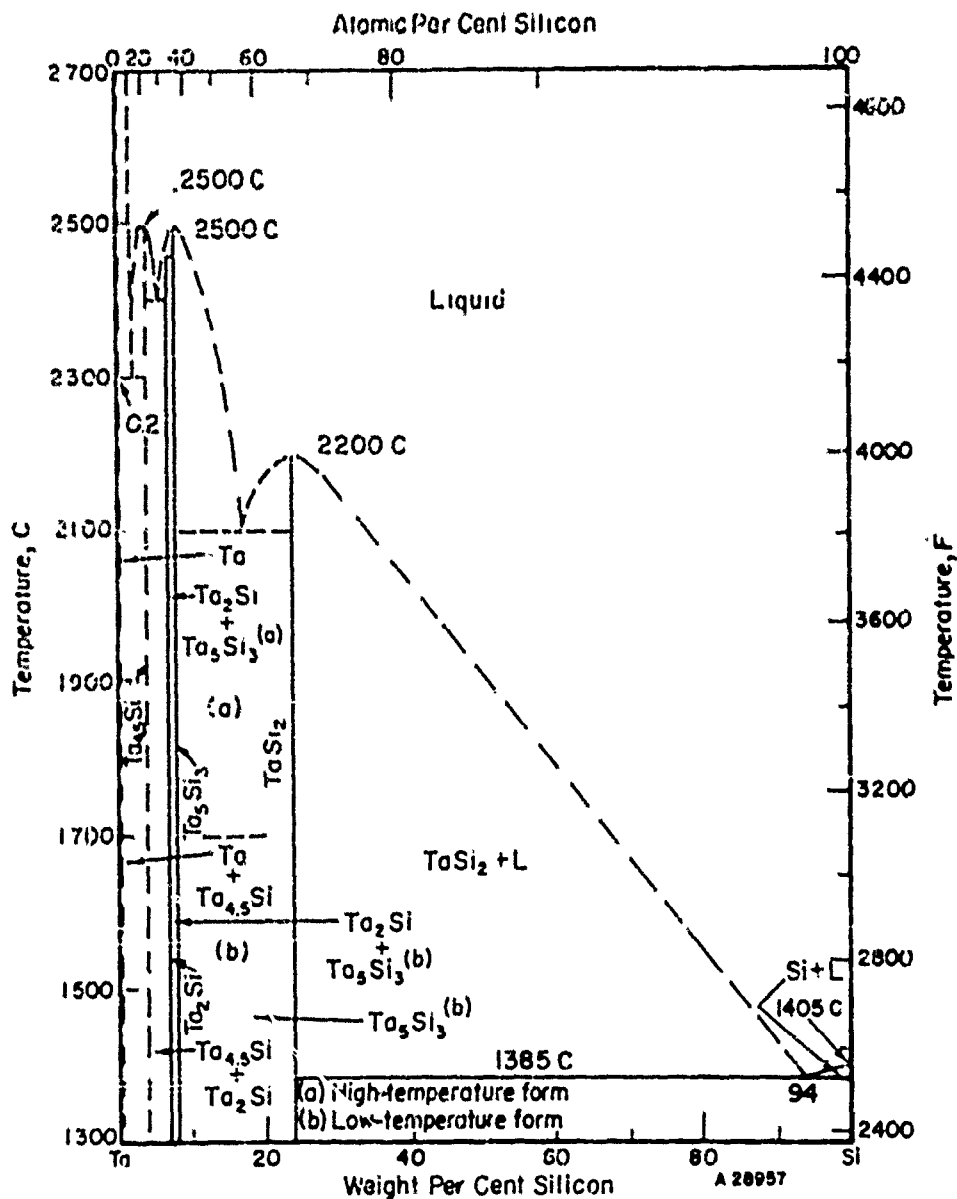
RegTa₂, the sigma phase, has a complex tetrahedral structure, isomorphous with the sigma phase found in the iron-chromium system. The lattice parameter is $a = 9.69 \text{ \AA}$ and $c/a = 0.62$.⁽¹⁴⁹⁾ The chi phase is a complex cubic, isomorphous with α -manganese. The lattice parameter varies from 9.80 $\text{\AA}$ at 60 weight per cent (69 atomic per cent) to 9.63 $\text{\AA}$ at 80 weight per cent (79 atomic per cent).⁽¹⁴⁹⁾

TANTALUM-RUTHENIUM SYSTEM



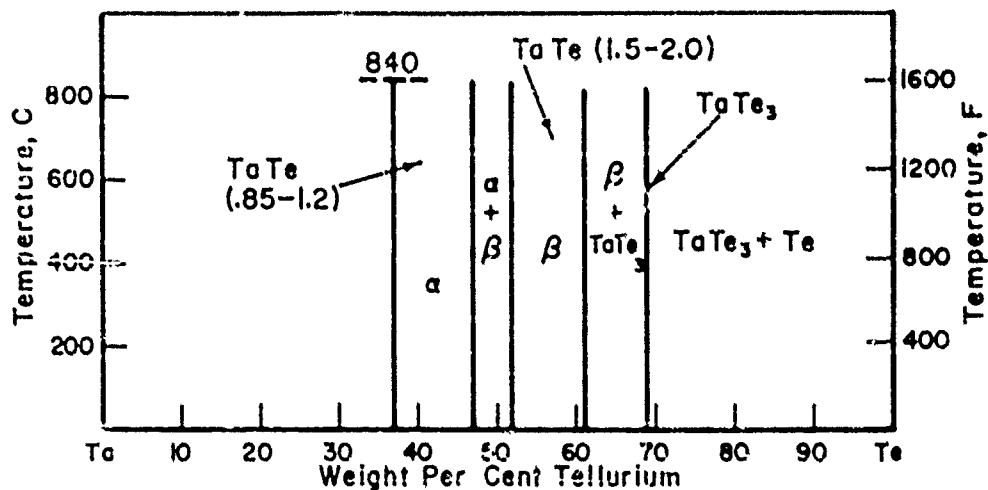
Ruthenium is highly soluble in tantalum, as indicated by the large α field. Detailed X-ray analysis of the α -phase showed that the body-centered cubic structure of tantalum changes to a body-centered tetragonal as the ruthenium content increases. This change begins between 24 and 27 weight per cent ruthenium (35 and 40 atomic per cent). An ordering reaction in the solid solution near 30 weight per cent ruthenium was also indicated. The structures of the intermediate phases μ and γ were not discussed. (147)

TANTALUM-SILICON SYSTEM

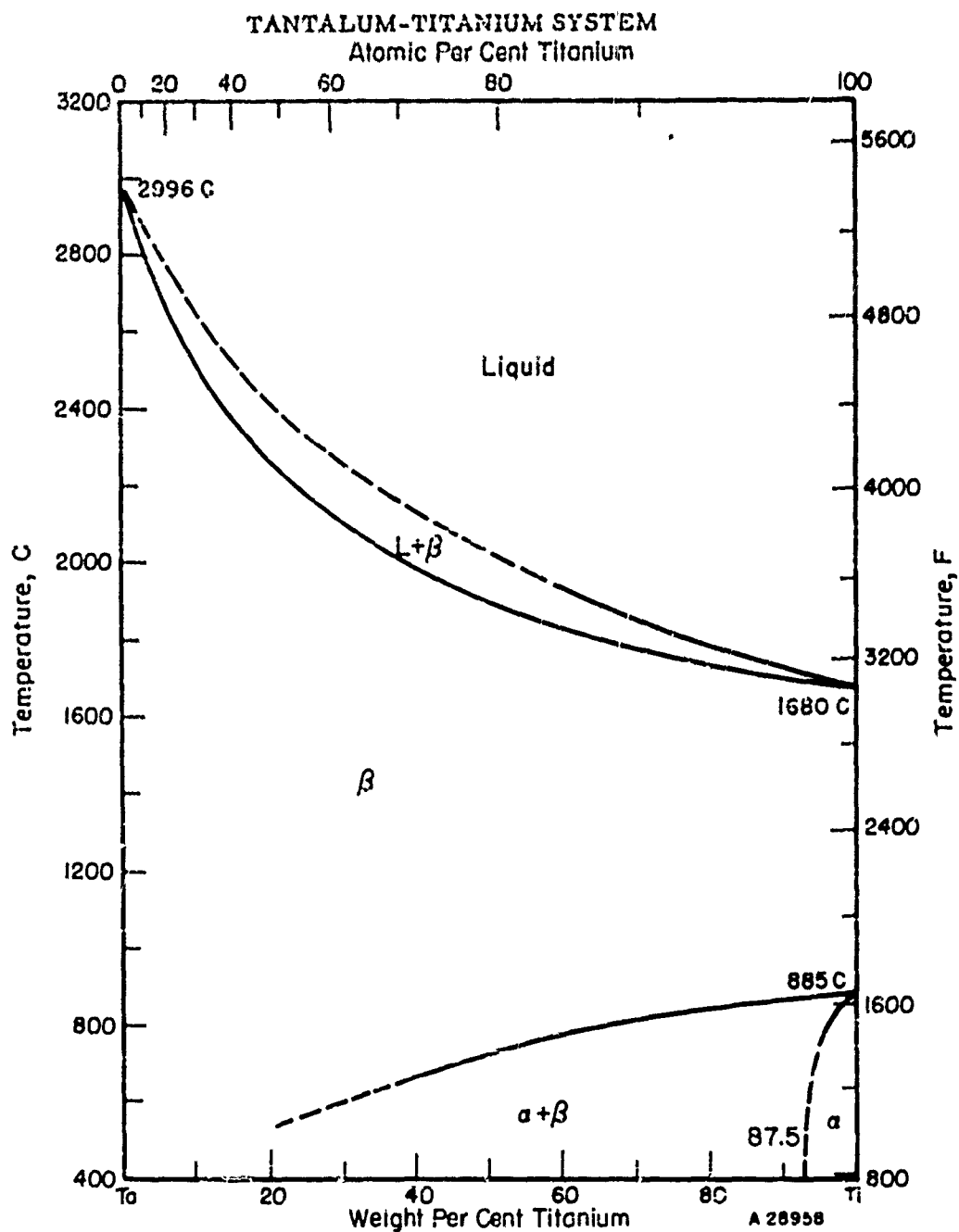


Ta_{4.5}Si is hexagonal (Ni₃Sn type) with $a = 6.093$ kX, $c = 4.909$ kX, and $c/a = 0.807$.⁽¹⁵⁰⁾
 Ta₂Si is tetragonal (CuAl₂ type) with $a = 6.155$ kX, $c = 5.029$ kX, and $c/a = 0.818$.⁽¹⁵⁰⁾ Ta₅Si₃ is hexagonal (Mn₅Si₃ type) with $a = 7.459$ kX, $c = 5.215$ kX, and $c/a = 0.699$.⁽¹⁵⁰⁾ TaSi₂ is hexagonal (CrSi₂ type) with $a = 4.771$ kX, $c = 6.551$ kX, and $c/a = 1.373$.⁽¹⁵⁰⁾ Parthe' et al.⁽¹⁵¹⁾ found a high- and low-temperature modification for Ta₅Si₃ with a tetragonal structure and lattice parameters $a = 9.96$ kX, $c = 5.05$ kX, $c/a = 0.51$ and $a = 6.503$ kX, $c = 11.849$ kX, and $c/a = 1.822$, respectively. Hansen⁽¹⁵⁾ proposed the phase diagram shown.

TANTALUM-TELLURIUM SYSTEM

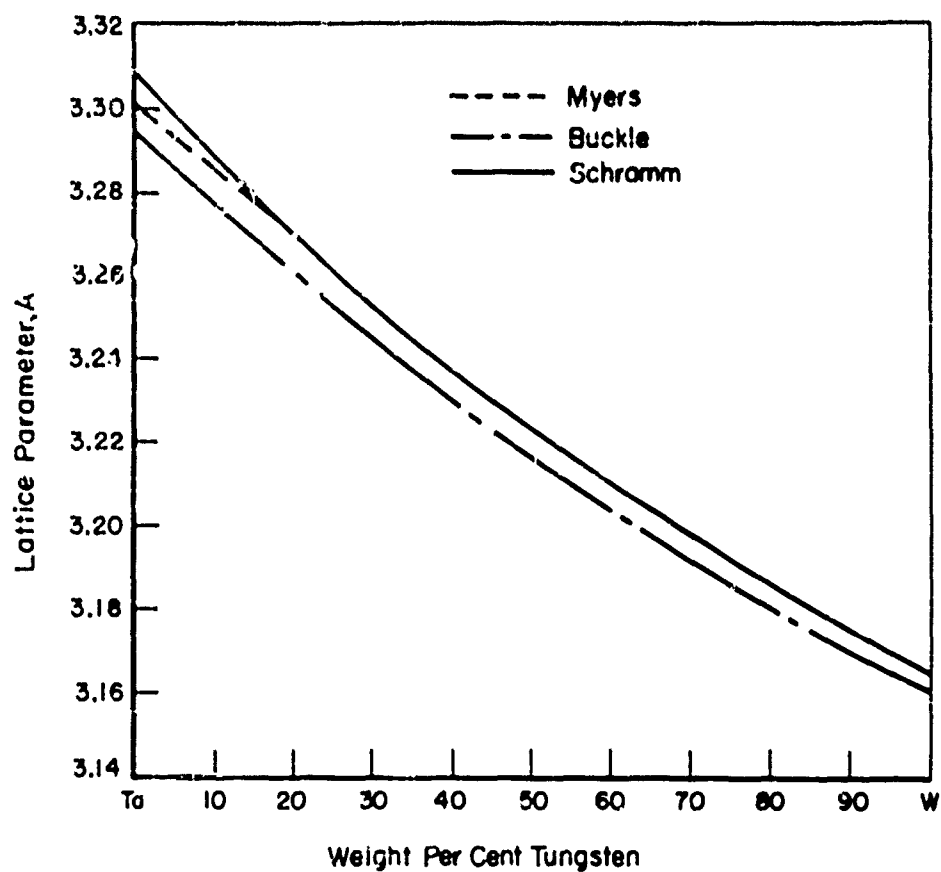


The compound TaTe_3 has a tetragonal lattice with $a = 6.5 \text{ \AA}$ and $c = 11.8 \text{ \AA}$. The α -phase, $\text{TaTe}_{0.85-1.2}$, shows a polymorphic change at 840 C. There is also evidence for the existence of a lower telluride of tantalum.⁽¹⁵²⁾



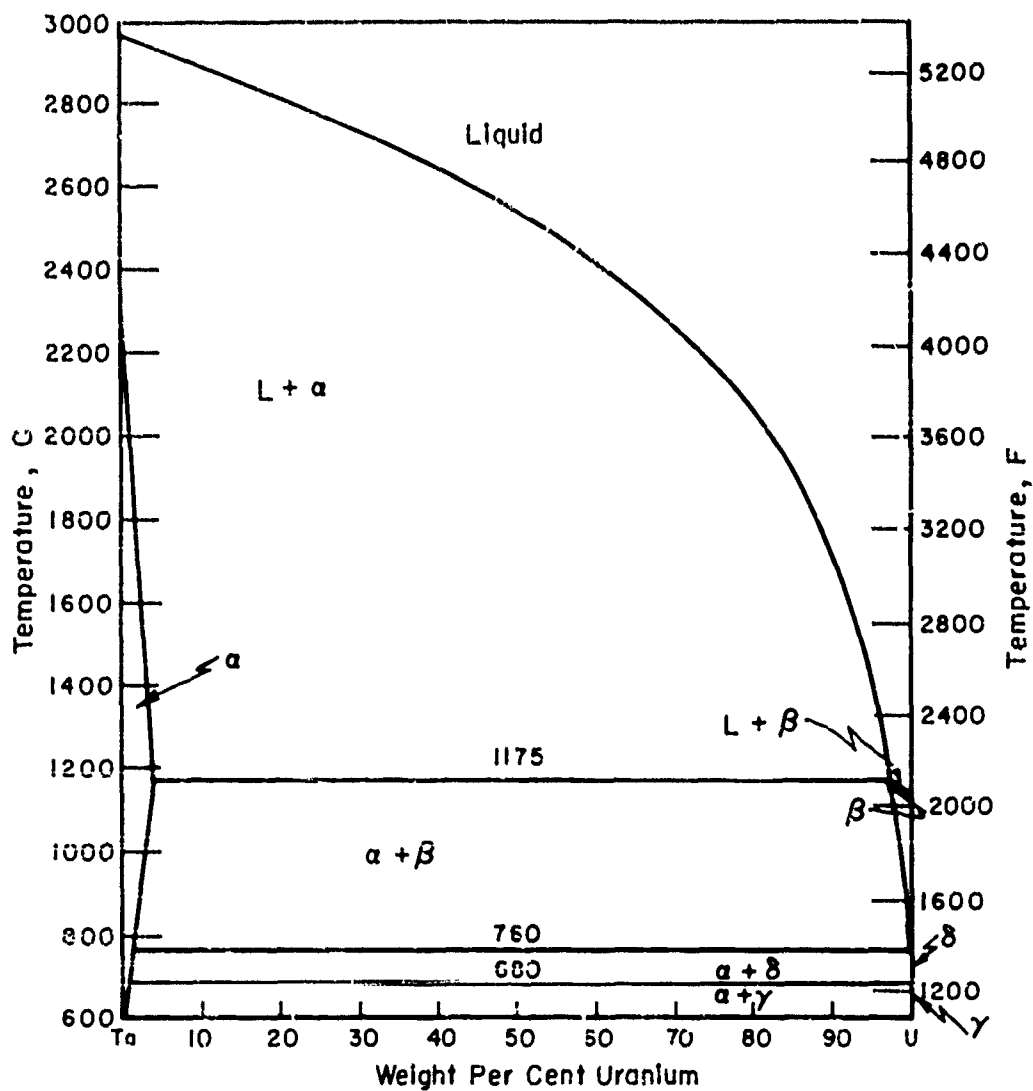
Tantalum and β -titanium form a continuous series of solid solutions. The beta solid solution can be retained on quenching for titanium contents up to 50 to 60 weight per cent. (153, 154)

TANTALUM-TUNGSTEN SYSTEM



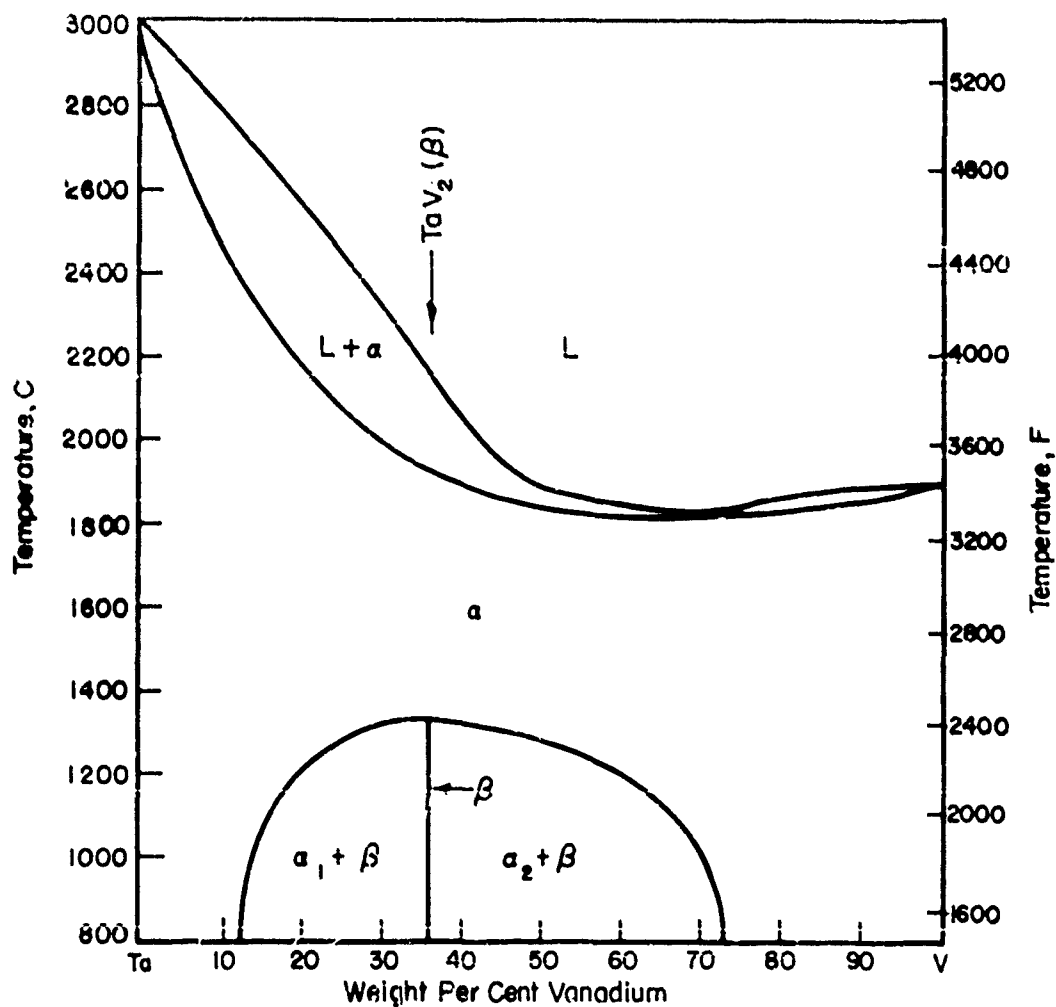
Tantalum and tungsten form a complete series of solid solutions. (40, 155, 158, 159)

TANTALUM-URANIUM SYSTEM



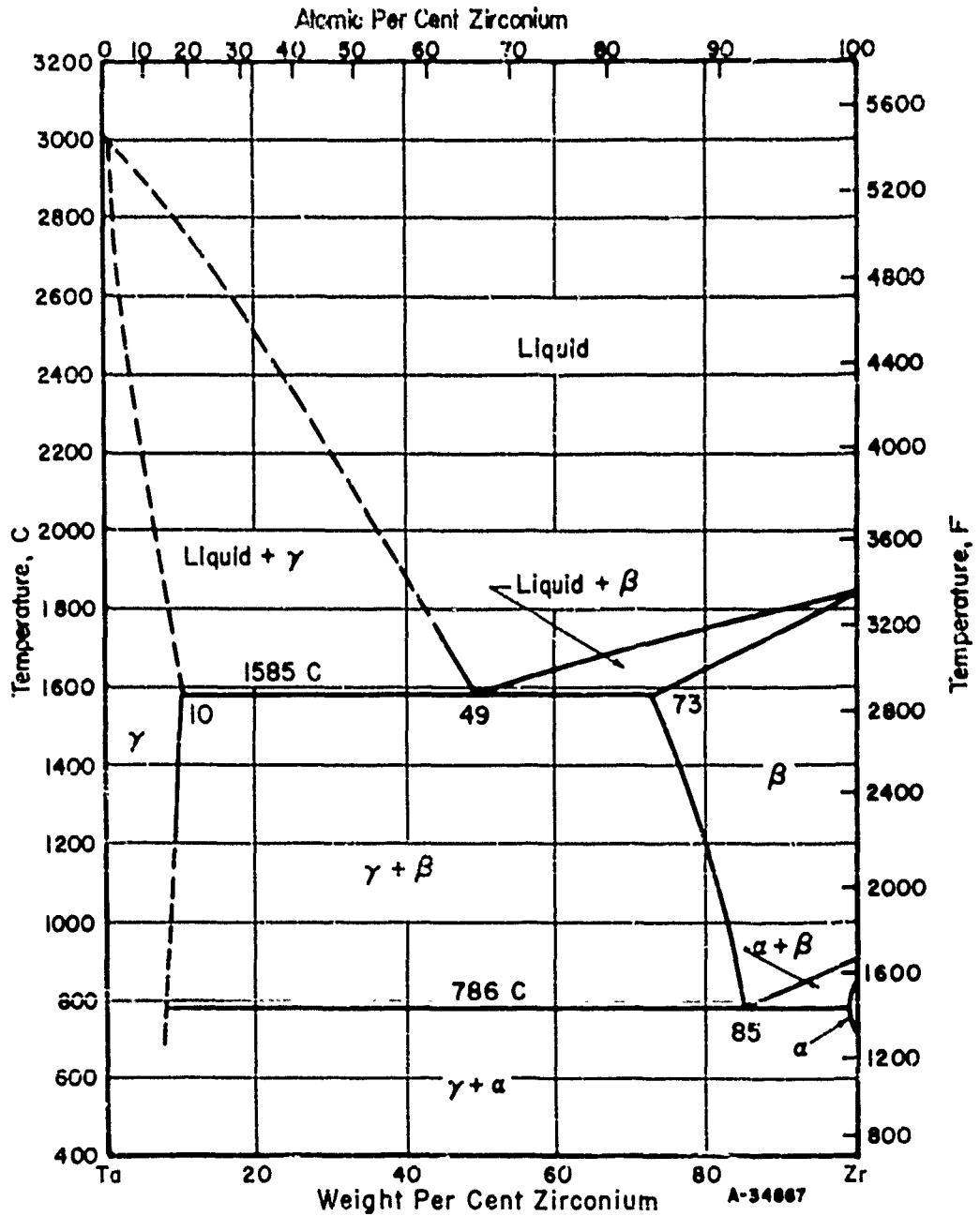
The high-temperature solid solubility of tantalum in uranium and uranium in tantalum is less than 2 atomic per cent. A peritectic reaction occurs at 1175 C near the uranium-rich side. No intermediate compounds were observed. (155)

TANTALUM-VANADIUM SYSTEM



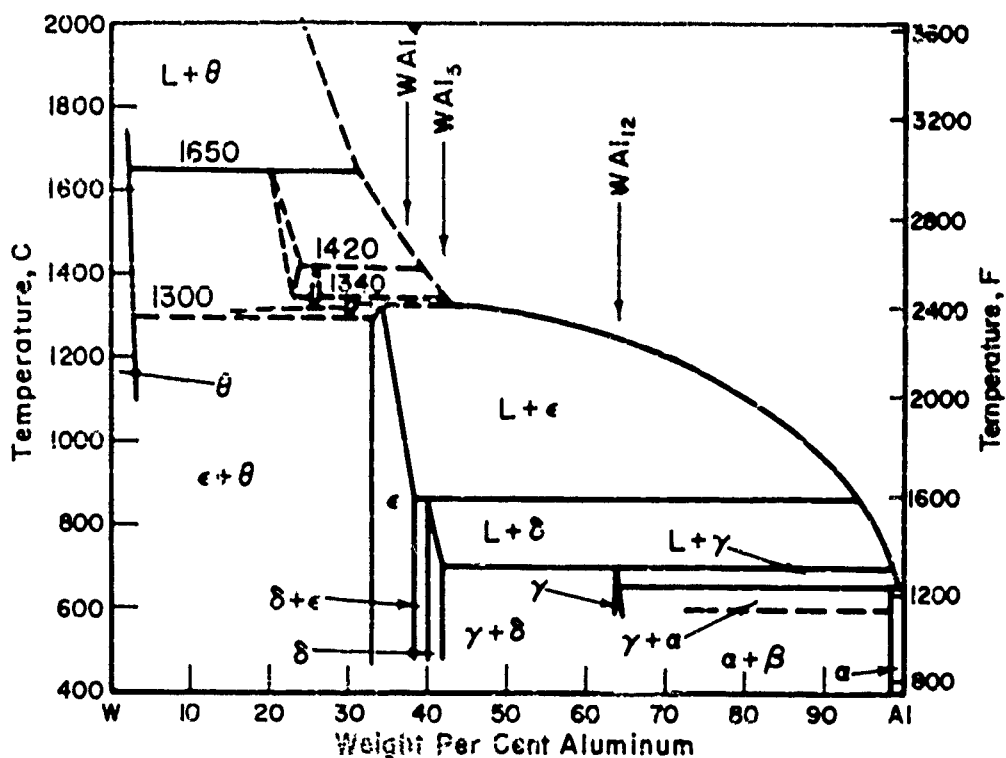
Complete miscibility exists above 1920 C. Below this temperature TaV₂ precipitates. The structure was shown to be face-centered cubic isomorphous with MgCu₂.^(156, 157)

TANTALUM-ZIRCONIUM SYSTEM



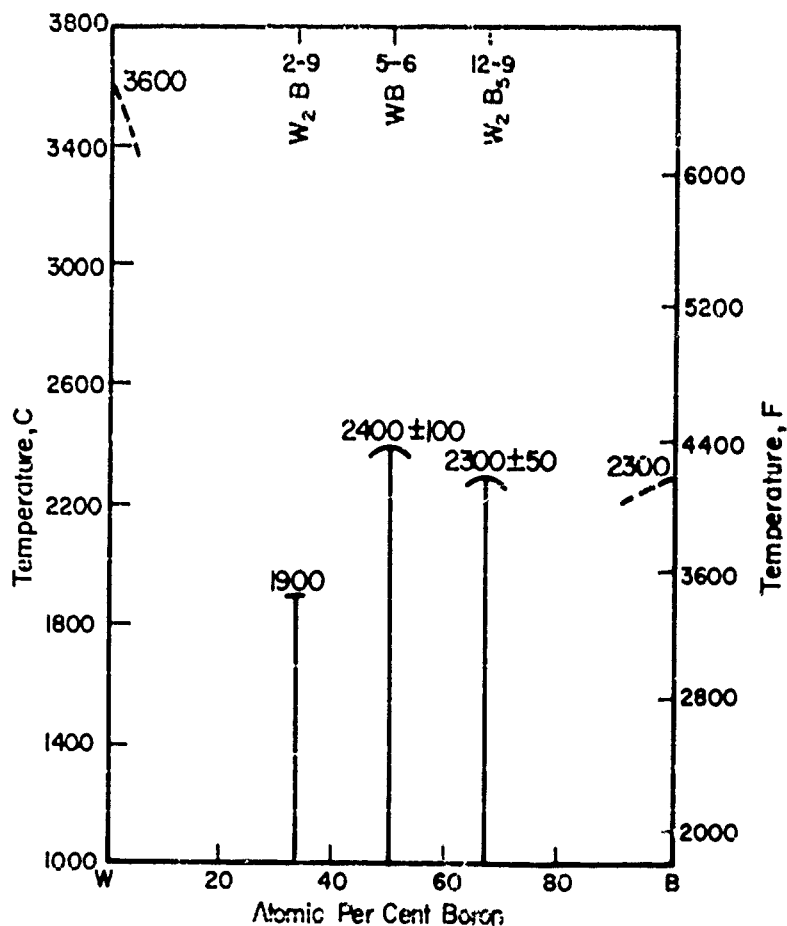
The maximum solubility of zirconium in tantalum is approximately 10 weight per cent. The maximum solubility of tantalum in β -zirconium is approximately 27 weight per cent. The solubility of tantalum in α -zirconium is less than 0.22 atomic per cent. No intermediate phases were found. (160)

TUNGSTEN-ALUMINUM SYSTEM



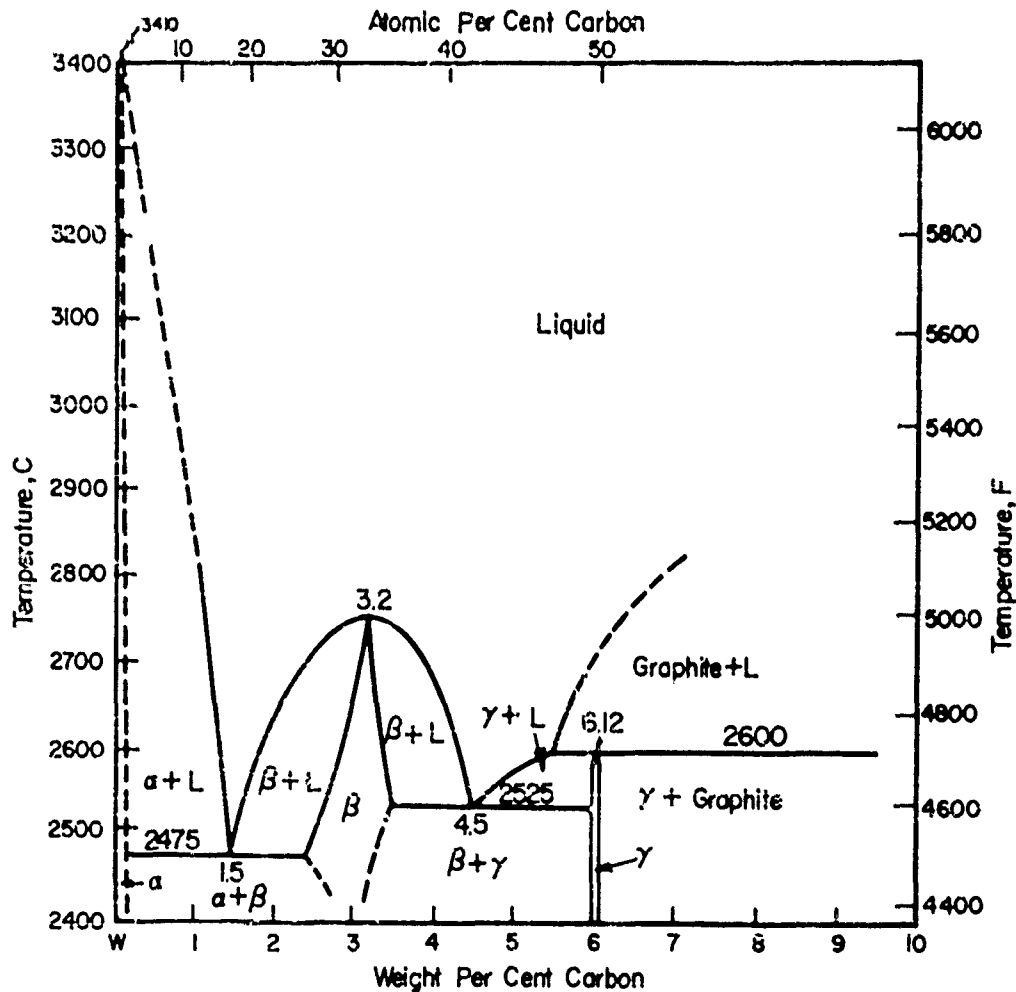
$WAl_4(\epsilon)$ has a monoclinic structure with $a = 5.272 \text{ \AA}$, $b = 17.771 \text{ \AA}$, $c = 5.215 \text{ \AA}$, and $\beta = 100^\circ 12'$. The cell contains 30 atoms mostly confined to 8 well-defined layers.⁽¹⁶¹⁾ $WAl_{12}(\gamma)$ has a body-centered cubic structure with two WAl_{12} units per cell.⁽¹⁶³⁾ The third intermediate phase is $WAl_5(\delta)$. The solubility of aluminum in tungsten is 2.4 weight per cent at 1300 C; the solubility of tungsten in aluminum is 1.5 weight per cent at 850 C.⁽¹⁶²⁾

TUNGSTEN-BORON SYSTEM



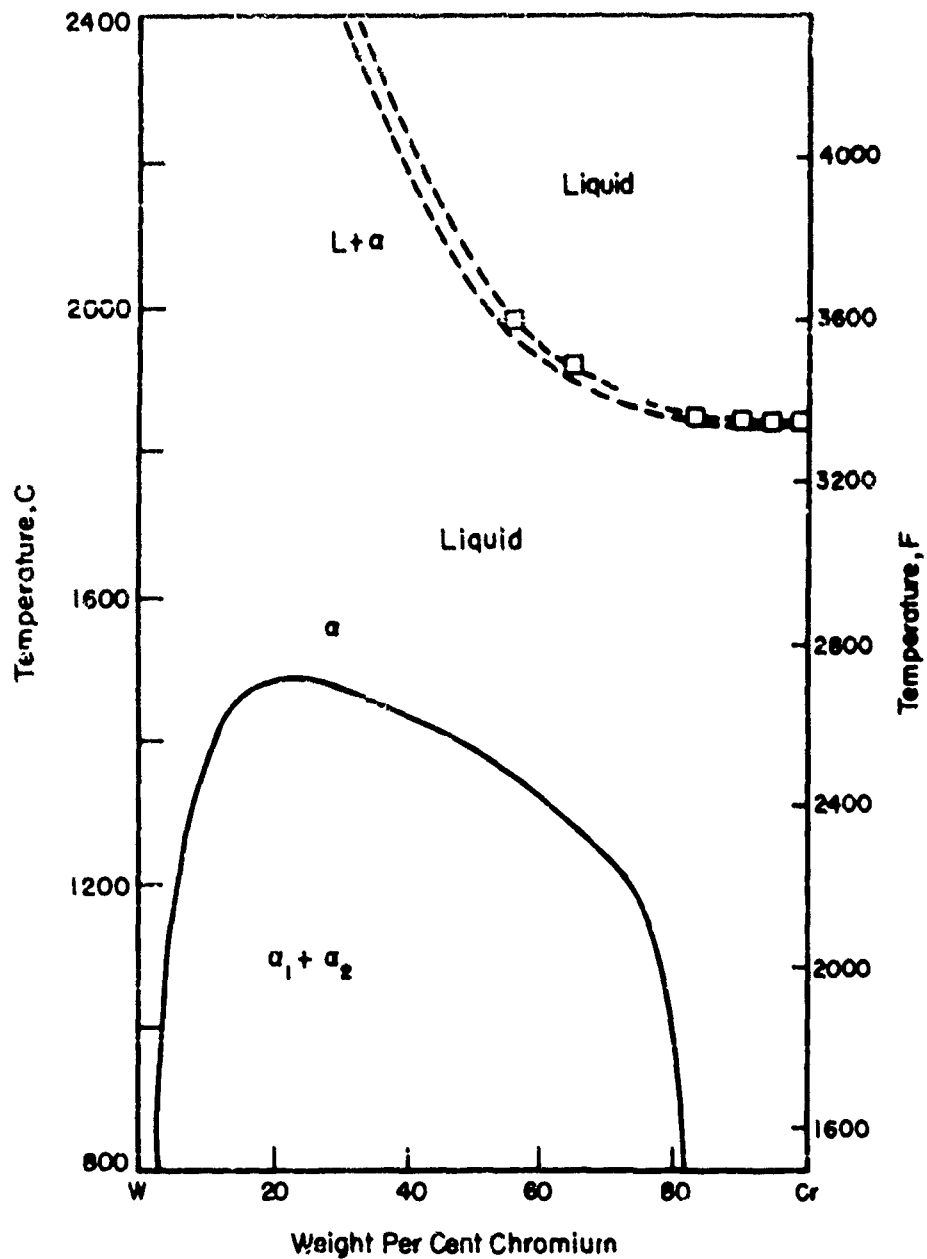
W_2B is tetragonal of the $CuAl_2$ (C16) type with $a = 5.564$ Å, $c = 4.740$ Å, and $c/a = 0.852$.⁽⁵⁸⁾ A low-temperature form of WB , stable below $1850^\circ C$, is tetragonal (MoB type) with $a = 3.115$ Å, $c = 19.33$ Å, and $c/a = 5.44$.⁽⁶⁸⁾ The high-temperature modification, corresponding to β -MoB, is orthorhombic (CrB type) with $a = 3.07$ Å.⁽¹⁶⁴⁾ W_2B_5 has a hexagonal defect structure with $a = 2.982$ Å, $c = 13.87$ Å, and $c/a = 4.65$.⁽¹⁶⁴⁾ The phase diagram was obtained from Reference 108.

TUNGSTEN-CARBON SYSTEM



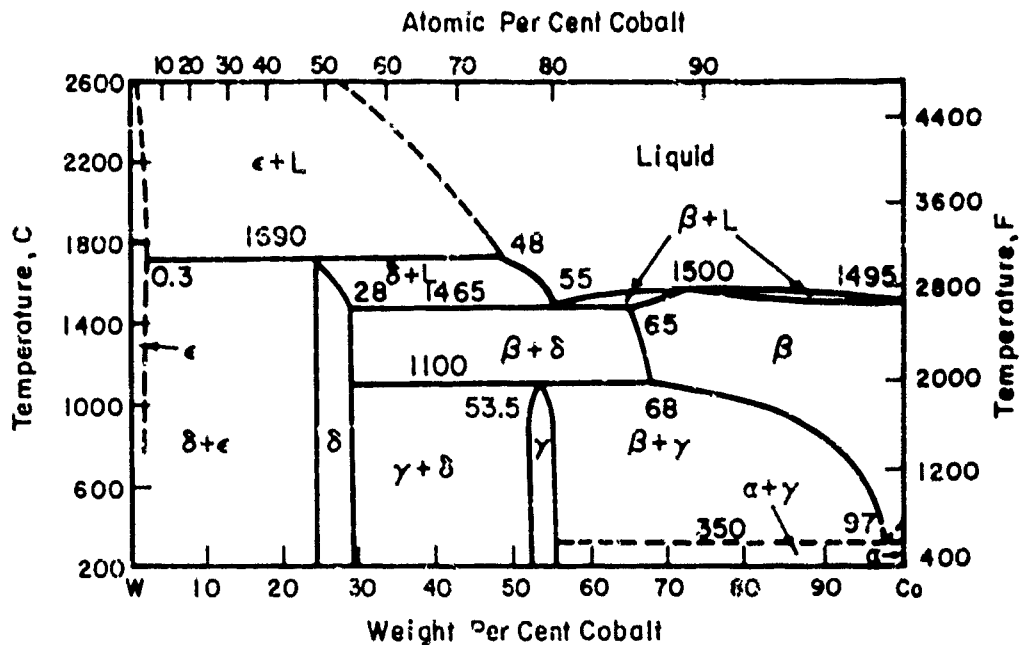
The low-temperature modification of W₂C is hexagonal with $a = 2.994 \text{ \AA}$, $c = 4.724 \text{ \AA}$, and $c/a = 1.578$.⁽¹⁶⁵⁾ The high-temperature modification β -W₂C is possibly a face-centered cubic structure with $a = 4.16 \text{ \AA}$.⁽¹⁶⁶⁾ WC has a simple hexagonal structure with $a = 2.906 \text{ \AA}$, $c = 2.83 \text{ \AA}$, and $c/a = 0.976$.⁽¹⁶⁵⁾

TUNGSTEN-CHROMIUM SYSTEM



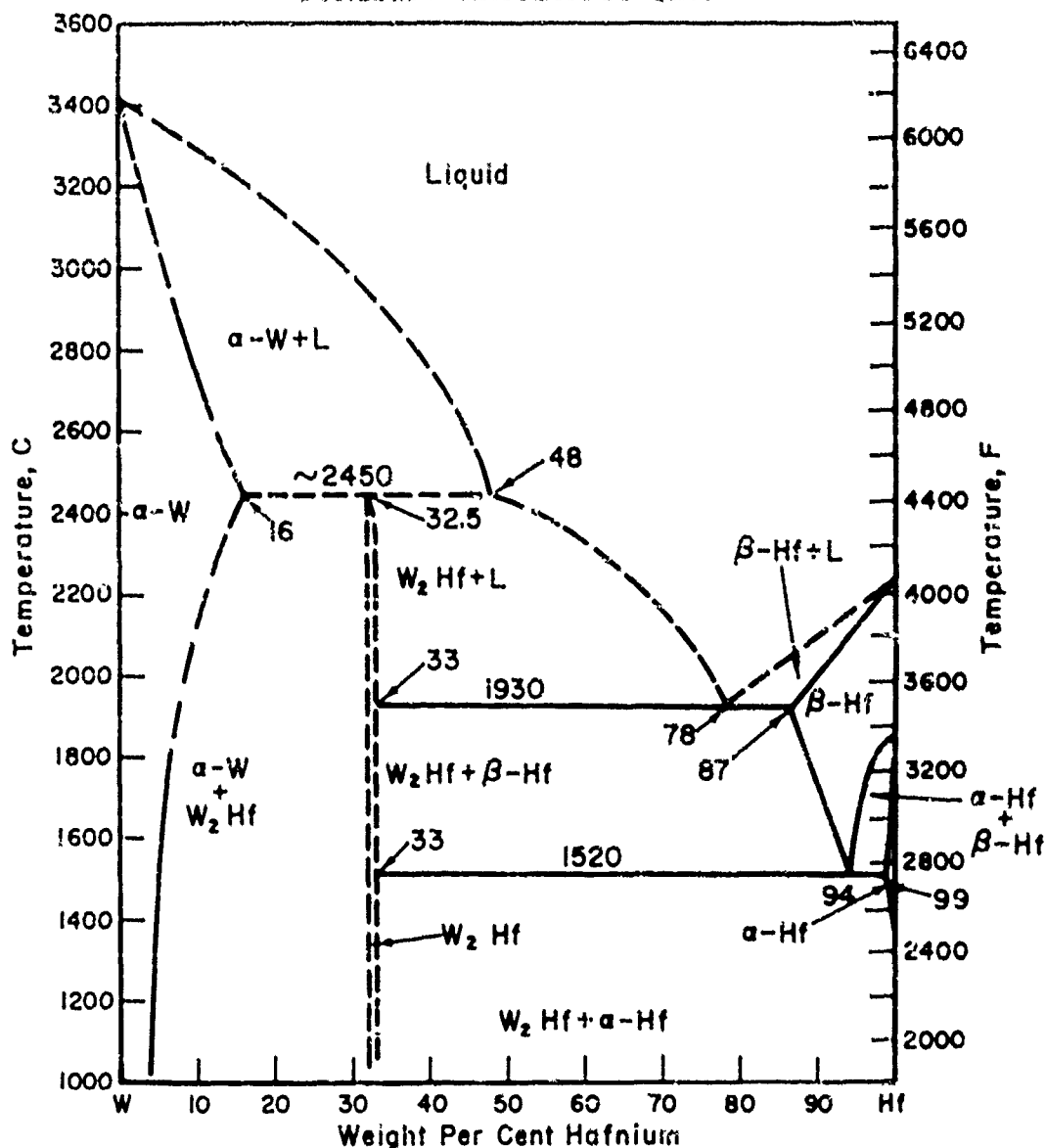
Tungsten and chromium form a continuous series of solid solutions above 1800° C. A solid-state immiscibility field exists below this temperature.⁽¹⁷¹⁾

TUNGSTEN-COBALT SYSTEM



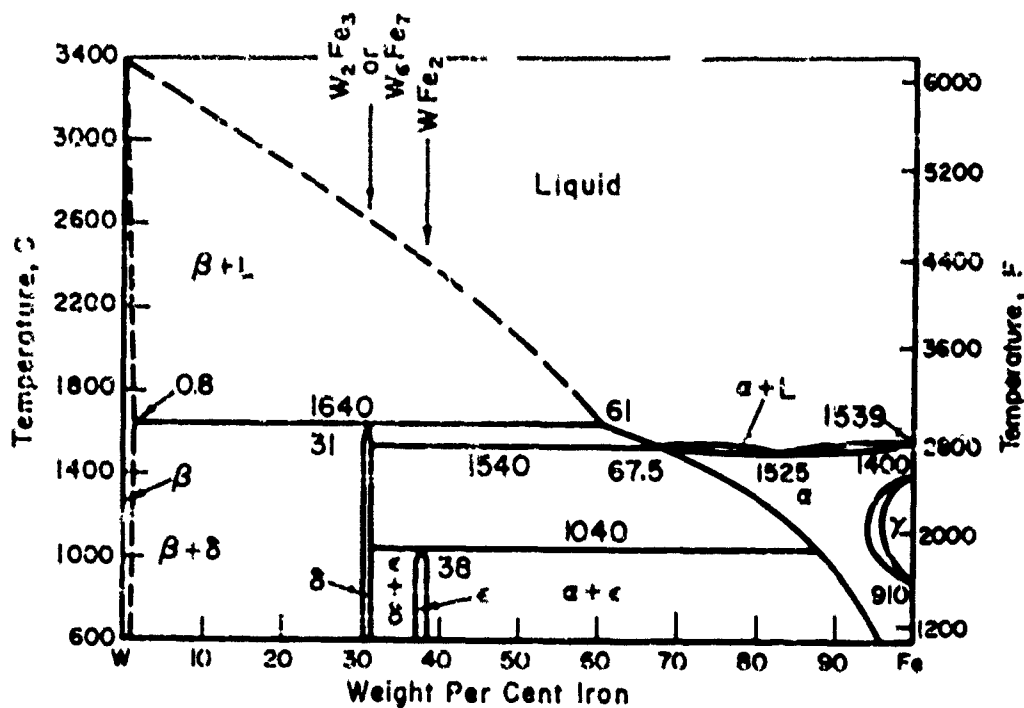
WCo₃(γ) is hexagonal of the Ni₃Sn (DO₁₉) type with $a = 5.13 \text{ \AA}$, $c = 4.13 \text{ \AA}$, and $c/a = 0.805$.⁽¹⁶⁷⁾ W₅Co(δ) is rhombohedral-hexagonal and isotypic with W₅Fe₇ (D8₅ type).⁽¹⁶⁷⁾ Its lattice parameters are: $a = 4.732 \text{ \AA}$, $c = 25.53 \text{ \AA}$ at the cobalt-rich limit, and $a = 4.761$, $c = 25.72 \text{ \AA}$ at the tungsten-rich limit.⁽¹⁶⁷⁾

TUNGSTEN-HAFNIUM SYSTEM



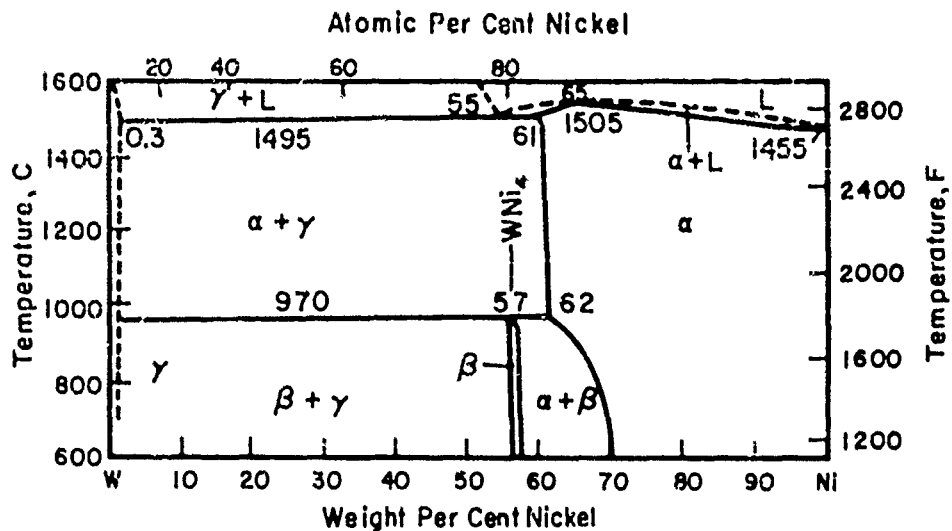
W_2Hf has the $MgCu_2$ -type structure (C15) with $a = 7.584$ kX. (32) Elliot reports the lattice parameter as $a = 7.556$ kX. (176) The solubility of tungsten in β -hafnium is approximately 13 weight per cent at 1930 C. It is about 0.9 weight per cent in α -hafnium at 1520 C. (32) Braum and Rudy determined the peritectic temperature as 2540 ± 50 C, the eutectic temperature as 1930 ± 30 C, and the eutectoid temperature as approximately 1730 C. (196) They (196) show an α -tungsten solubility field smaller (6 weight per cent maximum solubility) than that shown by Grant and Gleason (32).

TUNGSTEN-IRON SYSTEM



WFe_2 is isomorphous with the hexagonal $MgZn_2$ (C14) structure, with $a = 4.735$ kX, $c = 7.700$ kX, $c/a = 1.627$.⁽¹⁷²⁾ Sykes reports the δ -phase as W_2Fe_3 with $a = 4.731$ kX, $c = 25.78$ kX, and $c/a = 5.440$. The structure has trigonal Laue symmetry with 39 to 40 atoms per unit cell.⁽¹⁷³⁾ Amfelt reported the δ -phase as W_6Fe_7 (DB5 type) with 13 atoms per unit cell. The structure is rhombohedral with $a = 9.04$ Å and $\alpha = 30^\circ 39.5'$.⁽¹⁷⁴⁾ The solubility of iron in tungsten is 0.8 weight per cent at 1640 C with little change in solubility with temperature.⁽¹⁷⁵⁾

TUNGSTEN-NICKEL SYSTEM



WNi_4 is body-centered tetragonal with $a = 5.730 \pm 1 \text{ \AA}$, $c = 3.553 \pm 1 \text{ \AA}$, and $c/a = 0.620$, with 10 atoms per unit cell in ordered positions.⁽¹⁷⁷⁾ The solubility of nickel in tungsten is about 0.3 weight per cent at 1495°C.⁽¹⁷⁸⁾

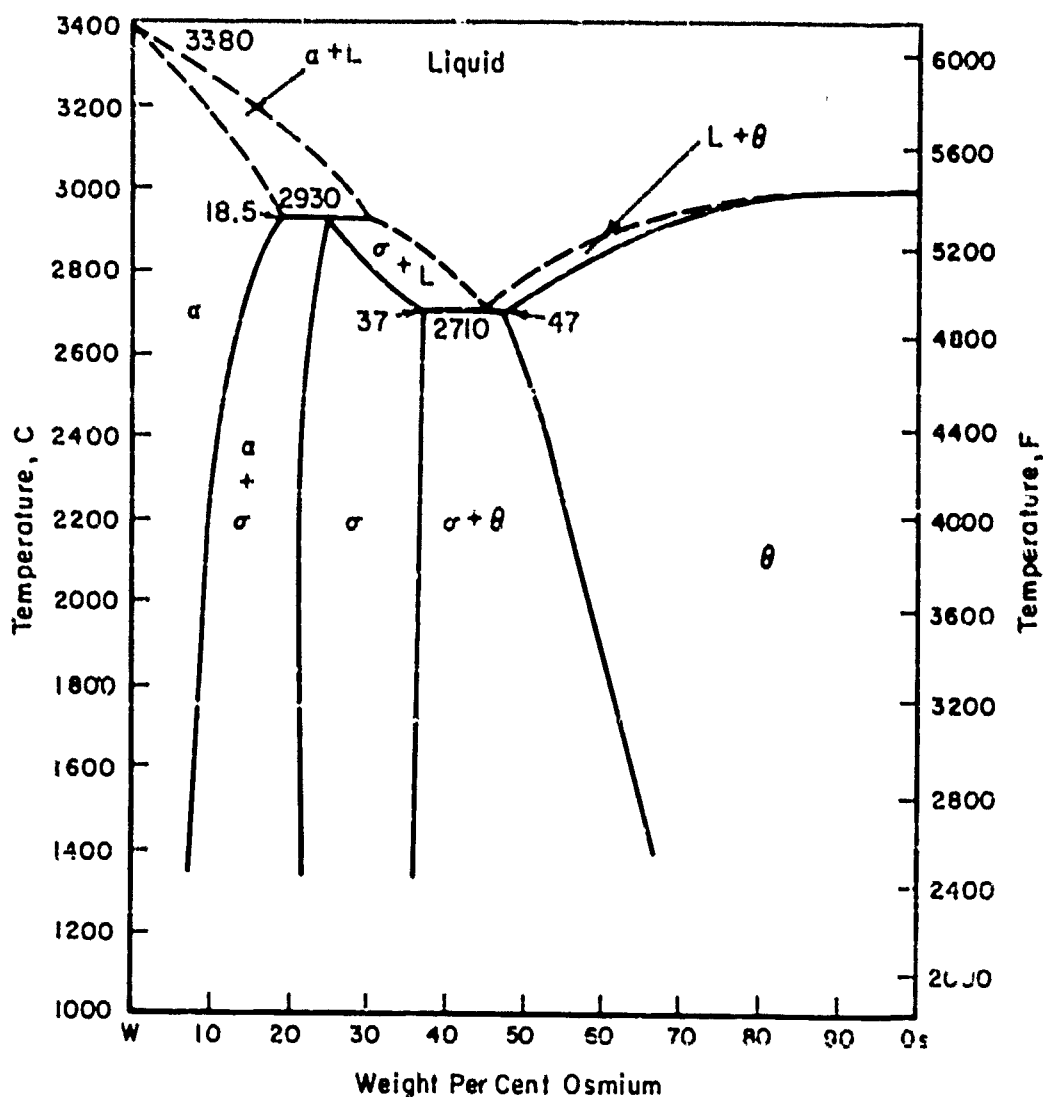
TUNGSTEN-NITROGEN SYSTEM

SOLUBILITY OF NITROGEN IN TUNGSTEN⁽¹⁹⁷⁾ (1 Atm Pressure)

<u>Temperature, C</u>	<u>Weight Per Cent Nitrogen</u>	<u>Atomic Per Cent Nitrogen</u>
2400	0.38×10^{-3}	0.50×10^{-2}
2000	0.11×10^{-3}	0.14×10^{-2}
1600	0.19×10^{-4}	0.25×10^{-3}
1200	0.13×10^{-5}	0.17×10^{-4}

A nitride of the approximate composition W_2N has a face-centered cubic lattice of tungsten atoms with interstitial nitrogen atoms, $a = 4.126 \text{ \AA}$.⁽¹⁹³⁾ Schönberg observed a hexagonal phase of the approximate composition WN . This phase is isomorphous with WC and has the lattice constants $a = 2.893 \text{ \AA}$, $c = 2.826 \text{ \AA}$, and $c/a = 0.977$.

TUNGSTEN-OSMIUM SYSTEM



The σ -phase, W_3Os has the tetragonal β -uranium type of structure with $a = 9.62$ Å, $c = 4.93$ Å, and $c/a = 0.518$. These lattice parameters were measured at a composition of 33.3 atomic per cent (34 weight per cent) osmium. The solubility of osmium in tungsten is approximately 18.5 weight per cent at 2930 C, decreasing to 9.5 weight per cent at 2200 C. The solubility of tungsten in osmium is 53 weight per cent at 2710 C, decreasing to 35 weight per cent at 1500 C, (78)

OXIDES OF TUNGSTEN

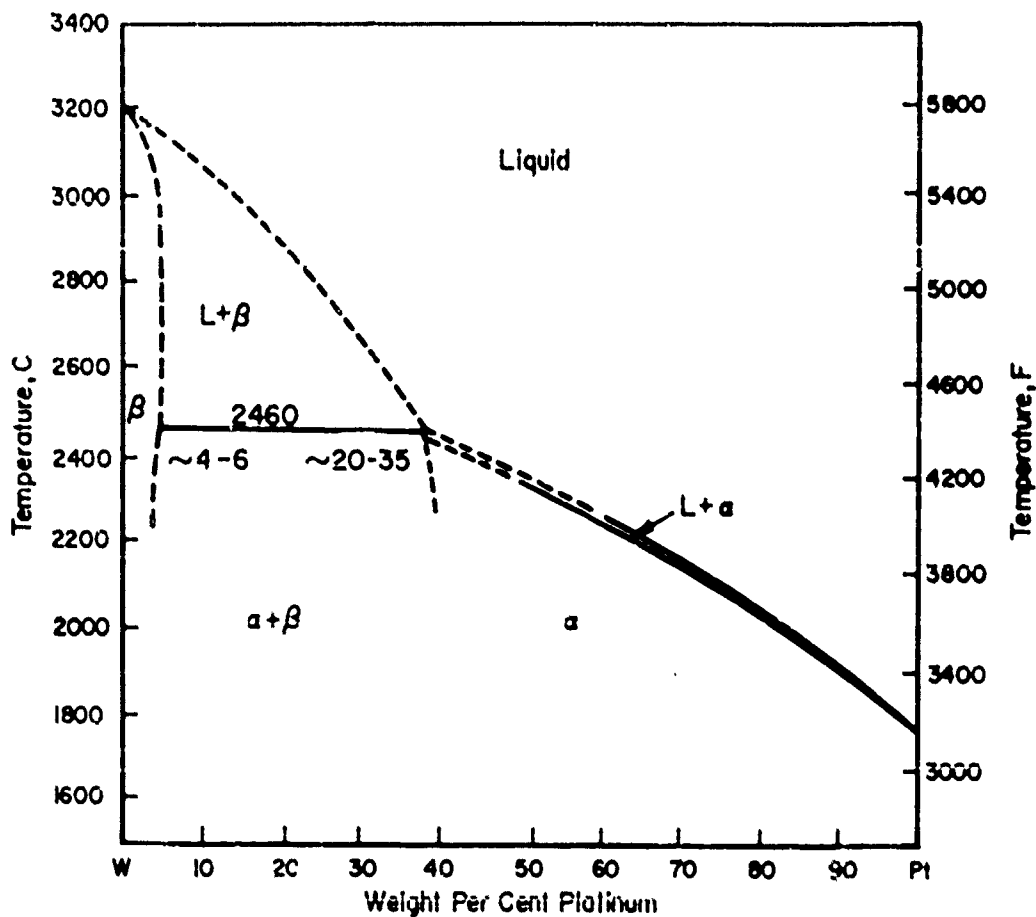
WO_3 has a very narrow range of homogeneity. The structure is monoclinic, isomorphous with MoO_3 with $a = 6.560 \text{ \AA}$, $b = 4.884 \text{ \AA}$, $c = 5.546 \text{ \AA}$, $\beta = 118.93^\circ$, and 12 atoms per unit cell.⁽¹⁹⁹⁾

A one-phase region exists between the composition $\text{WO}_{2.65}$ and $\text{WO}_{2.75}$. The structure is monoclinic with the lattice parameters $a = 18.32 \text{ \AA}$, $b = 3.79 \text{ \AA}$, $c = 11.04 \text{ \AA}$, $\beta = 115^\circ 2'$, and 67 atoms per unit cell ($\text{W}_{16}\text{O}_{117} = \text{WO}_{2.72}$).⁽²⁰⁰⁾

Another one-phase field occurs between the composition $\text{WO}_{2.88}$ and $\text{WO}_{2.92}$. The structure is monoclinic with the lattice parameters $a = 12.1 \text{ \AA}$, $b = 3.75 \text{ \AA}$, $c = 23.4 \text{ \AA}$, and $\beta = 98^\circ$ for the composition $\text{WO}_{2.90}$ ($= \text{W}_{20}\text{O}_{186}$). The structure is closely related to that of ReO_3 (DO_3 type).⁽²⁰⁰⁾

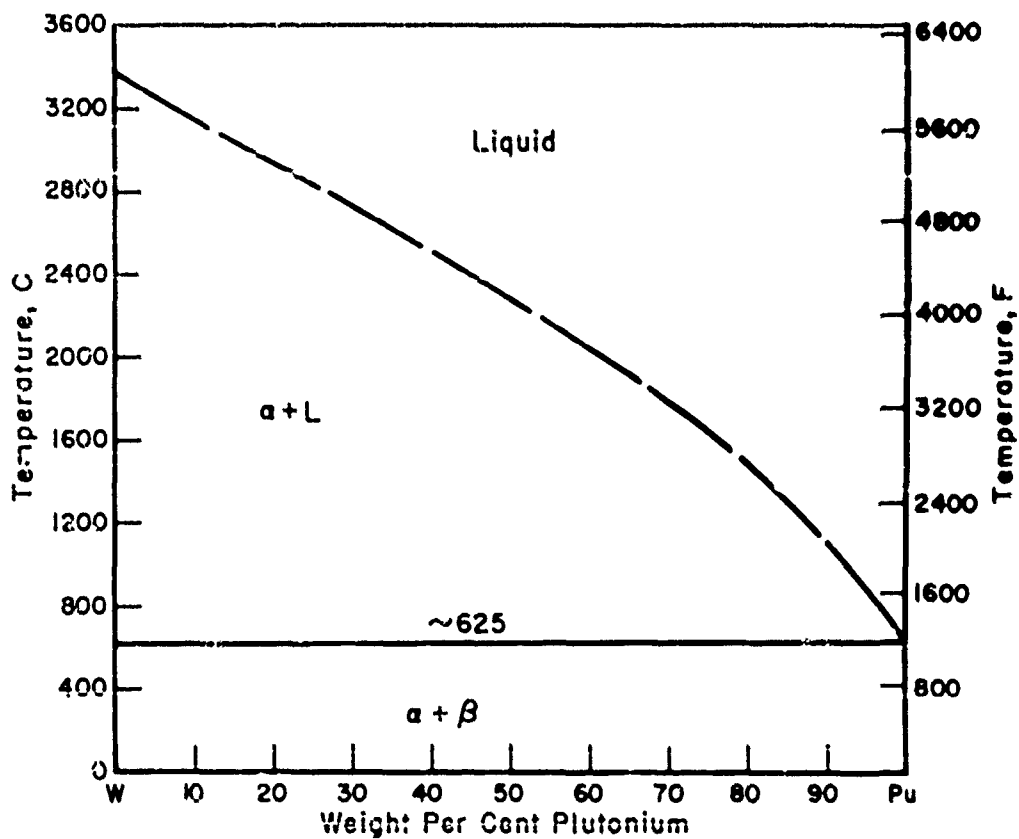
WO_3 is reported to have three structural modifications. The room temperature form is monoclinic with $a = 7.285 \text{ \AA}$, $b = 7.517 \text{ \AA}$, $c = 3.835 \text{ \AA}$, and $\beta = 90.90^\circ$.⁽²⁰¹⁾ At -60°C , a polymorphic transformation occurs, resulting in a structure of higher symmetry than the room-temperature modification.⁽²⁰²⁾ Between 700 and 750°C , a polymorphic transformation occurs, resulting in a tetragonal structure with $a = 5.25 \pm 2 \text{ \AA}$, $c = 3.92 \pm 2 \text{ \AA}$, $c/a = 0.746$, and 8 atoms per unit cell.⁽²⁰³⁾

TUNGSTEN-PLATINUM SYSTEM



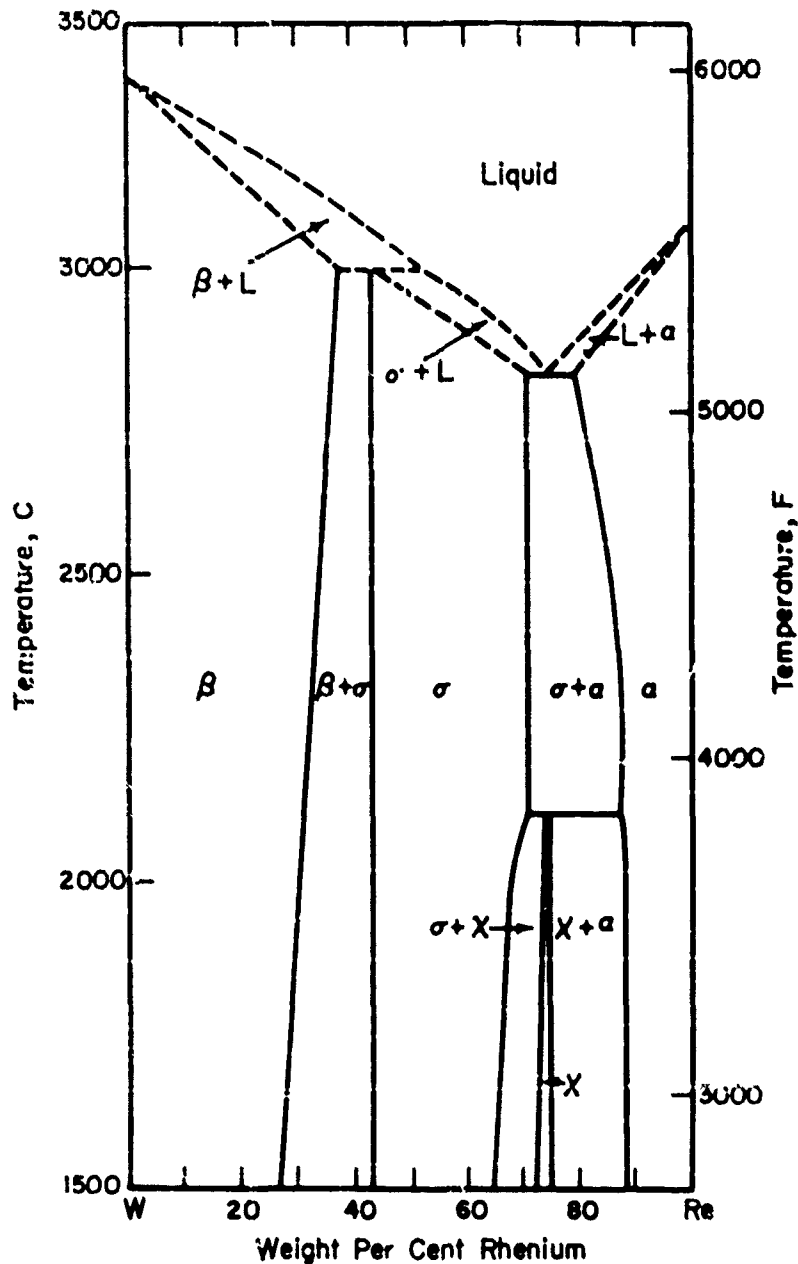
The maximum solubility of platinum in tungsten at the solidus temperature lies between 4 and 6 weight per cent platinum.⁽¹⁷⁸⁾ Platinum and tungsten form a series of solid solutions up to a maximum of 62 weight per cent tungsten.⁽¹⁷⁹⁾ Nemilov found evidence of an order-disorder transformation in the range of 75 atomic per cent tungsten (76 weight per cent).⁽¹⁸⁰⁾

TUNGSTEN-PLUTONIUM SYSTEM



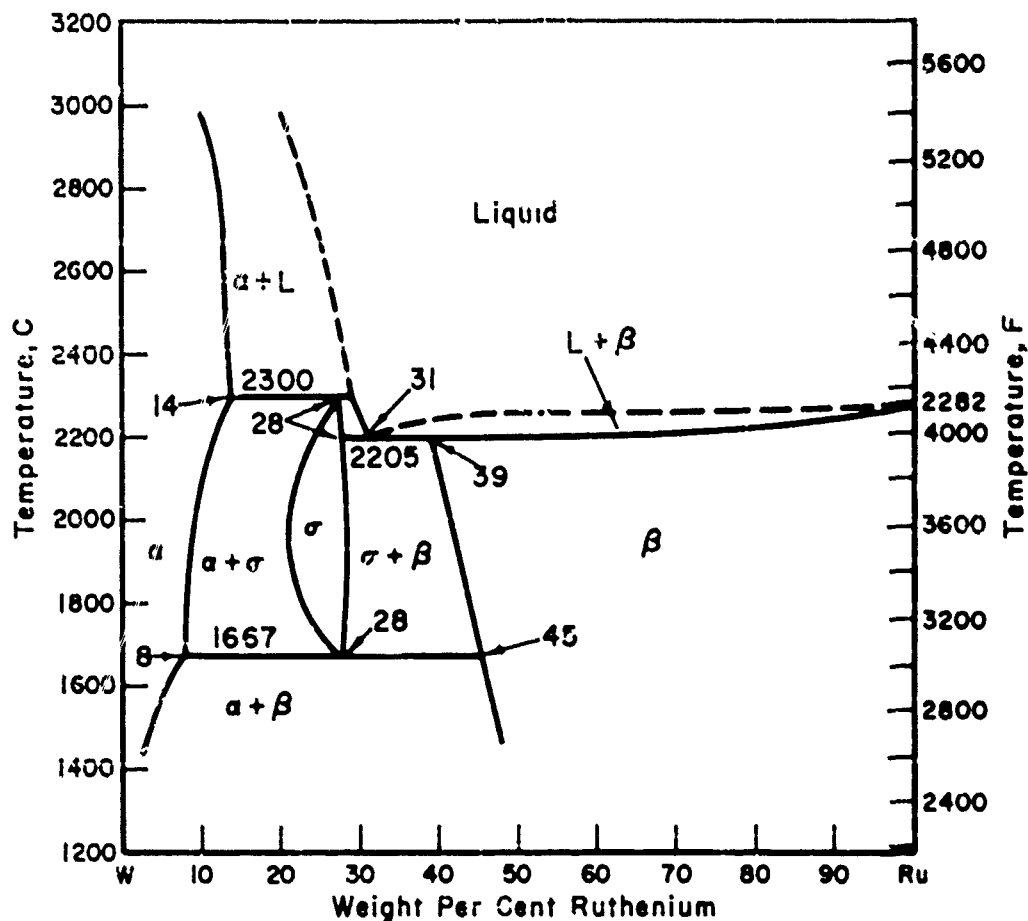
No intermediate phases have been found for this system. (20)

TUNGSTEN-RHENIUM SYSTEM



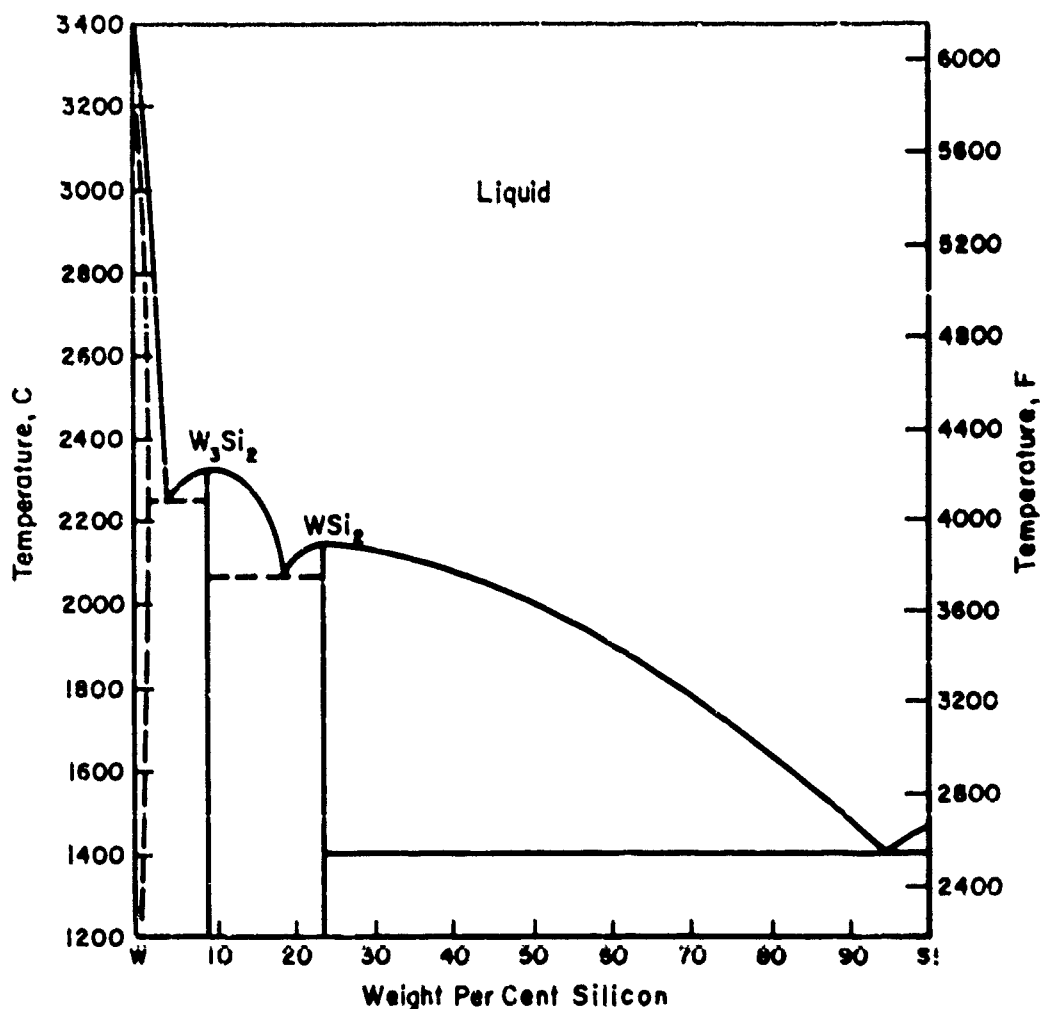
The α -phase is a tetragonal (D_{2h}^{14}) structure isomorphous with the σ -phase found in iron-chromium alloys.⁽¹⁸¹⁾ Knapton reported the lattice parameters as $a = 9.645 \text{ \AA}$ and $c = 5.038 \text{ \AA}$ at 60 weight per cent rhenium.⁽¹⁸²⁾ The X -phase is isomorphous with α -manganese with an approximate composition of Re_3W .⁽¹⁸¹⁾ The solubility of rhenium in tungsten ranges from 28 weight per cent at 1600 C to 37 weight per cent at 3000 C. The terminal solubility of tungsten in rhenium ranges from approximately 11 weight per cent at 1600 C to 20 weight per cent at 2800 C.⁽¹⁸¹⁾

TUNGSTEN-RUTHENIUM SYSTEM



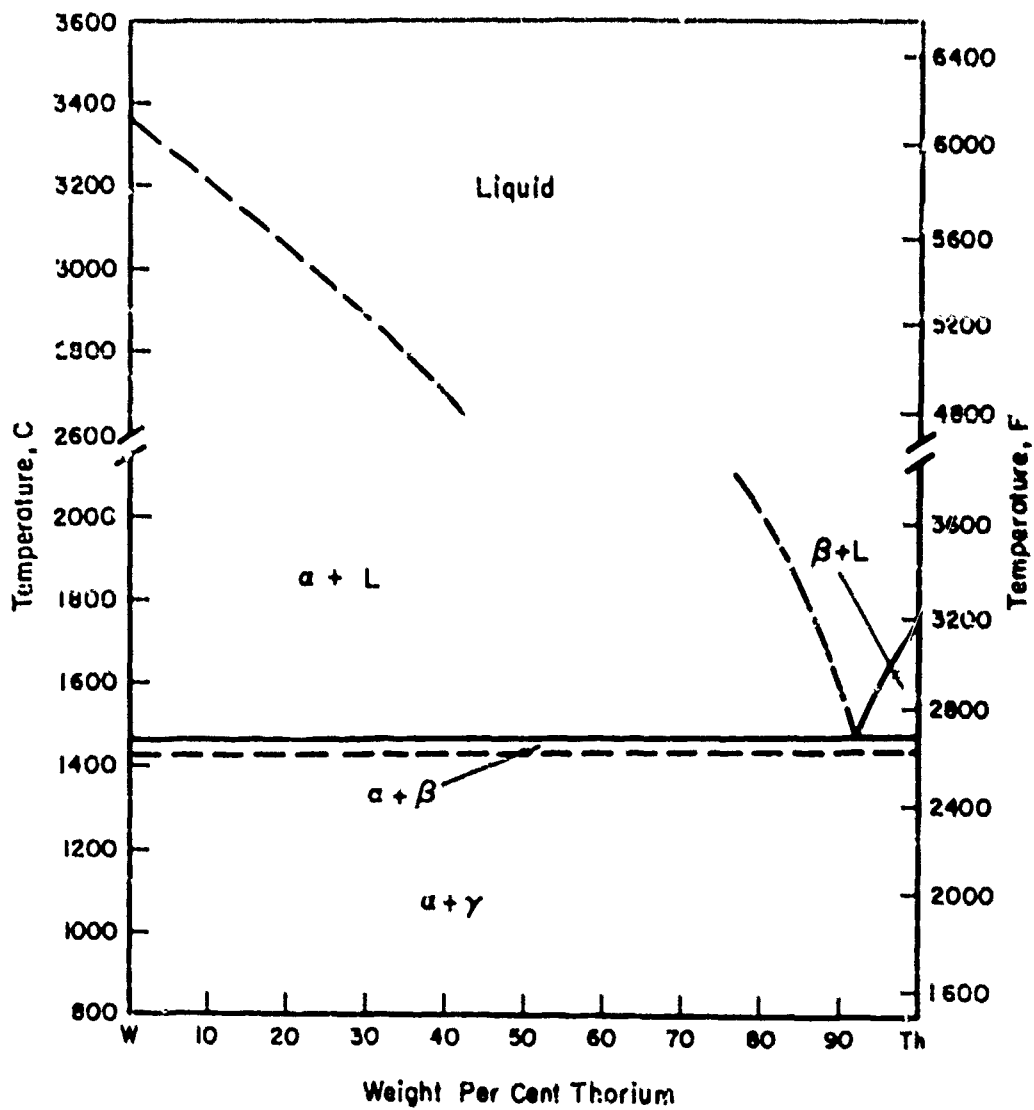
The σ -phase has the stoichiometric composition W_3Ru_2 .^(147, 183) The lattice parameters are $a = 9.55 \text{ \AA}$ and $c/a = 0.52$.⁽¹⁸³⁾ Ruthenium is soluble in tungsten up to 10 atomic per cent (8 weight per cent) ruthenium at 1600 C, increasing to about 23 atomic per cent (14 weight per cent) at 2300 C.⁽¹⁴⁷⁾ The solubility of tungsten in ruthenium is approximately 41 atomic per cent (56 weight per cent) tungsten at 1600 C, increasing to 45 atomic per cent (61 weight per cent) at 2205 C.⁽¹⁴⁷⁾

TUNGSTEN-SILICON SYSTEM



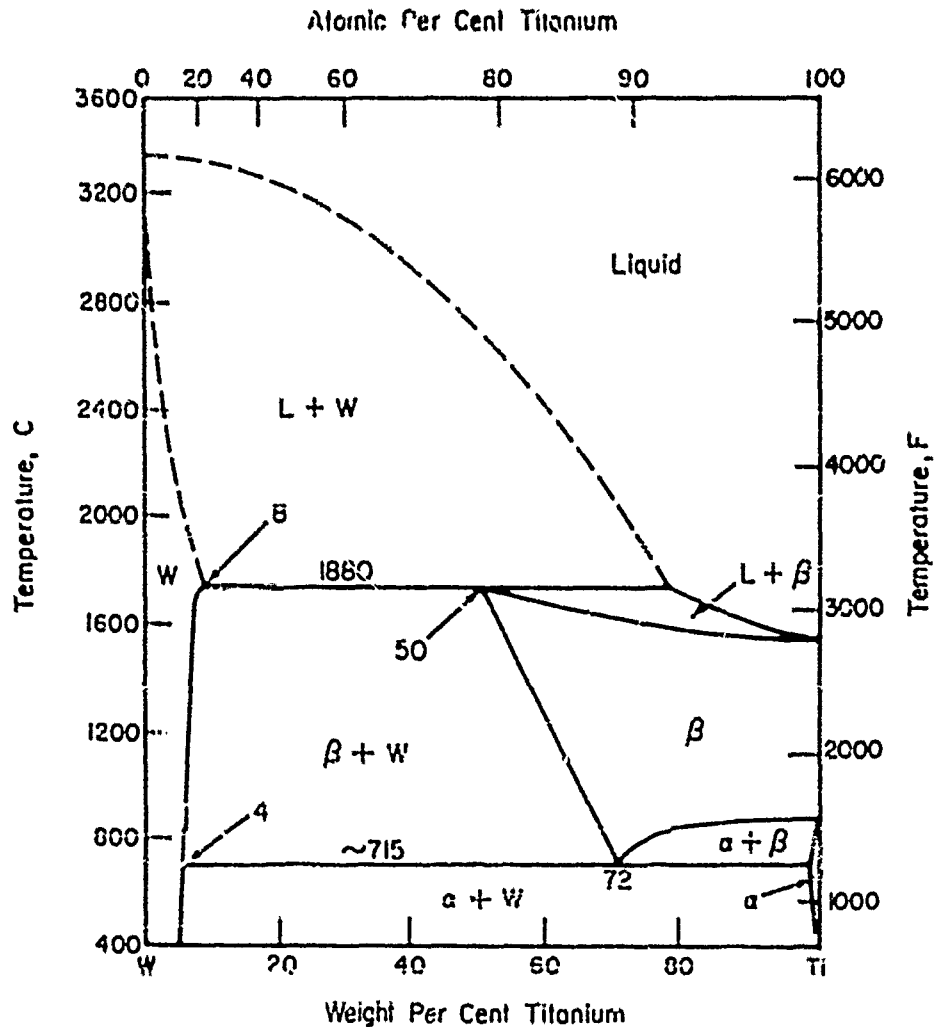
W_3Si_2 (or possibly W_5Si_3) has a tetragonal structure with $a = 3.56$ Å, $c = 4.94$ Å, $c/a = 0.52$, and four formula units " W_3Si_2 " per unit cell. (184) WSi_2 has a tetragonal $MoSi_2$ (C11) type of structure with $a = 3.21$ Å, $c = 7.83$ Å, and $c/a = 2.44$. (185) The solubility of silicon in tungsten is about 0.9 weight per cent at 1800°C. (186)

TUNGSTEN-THORIUM SYSTEM



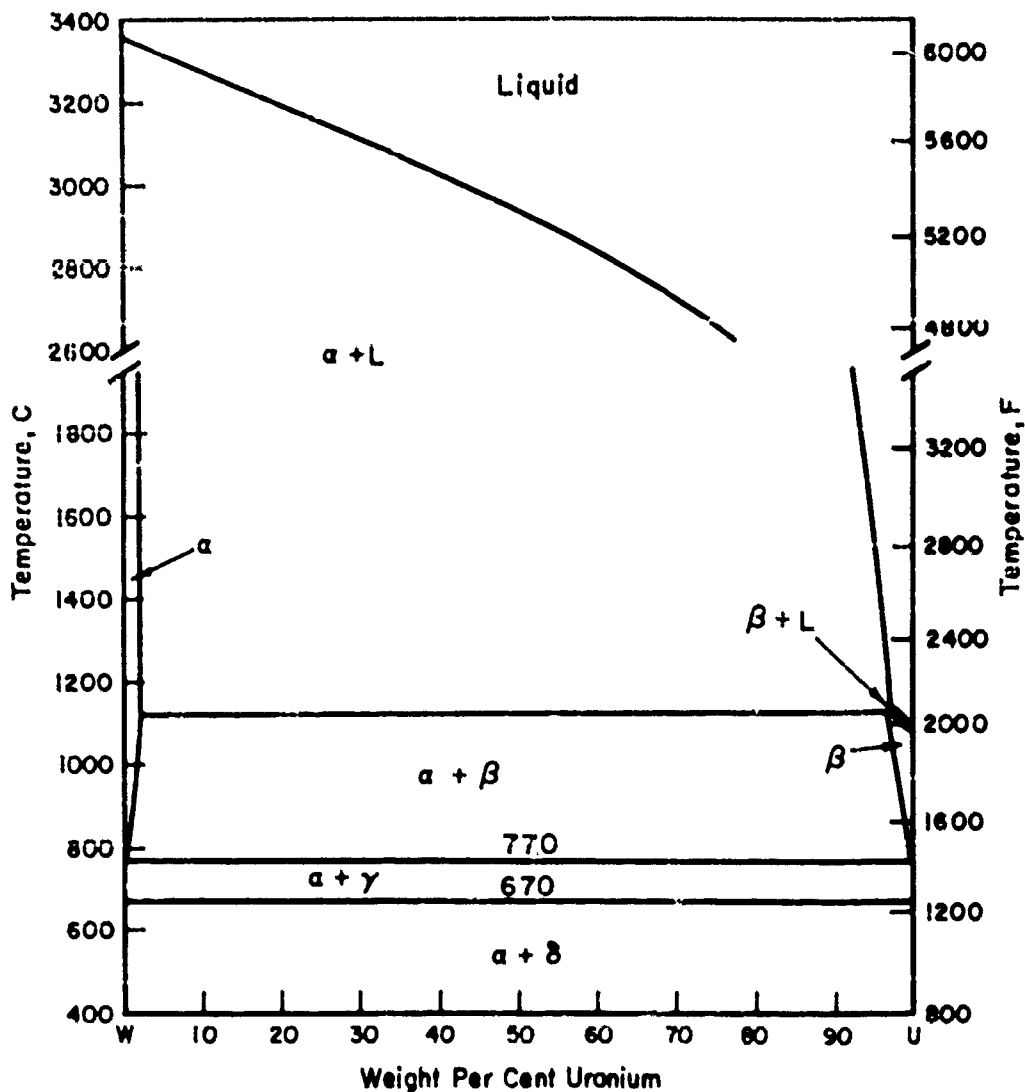
There are no intermetallic compounds in the system. The eutectic temperature is 1475 C. Very little solubility occurs in any of the terminal phases, (187, 188)

TUNGSTEN-TITANIUM SYSTEM



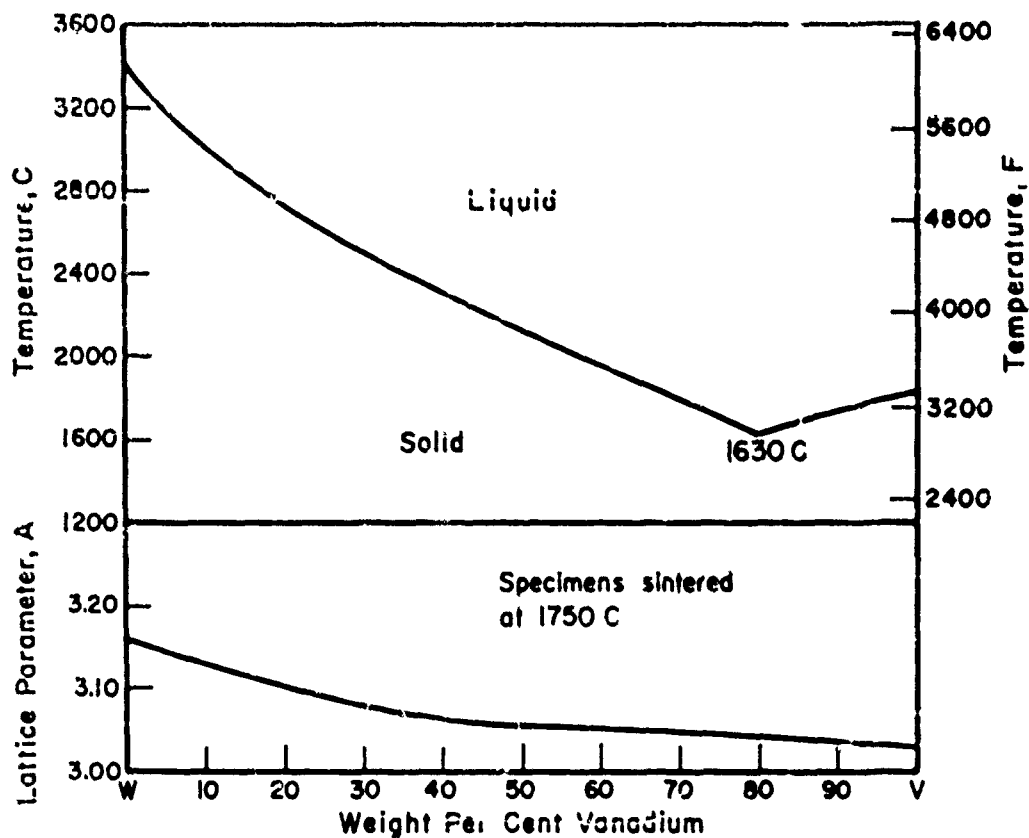
The solubility of titanium in tungsten is approximately 8 weight per cent at 1880 C, decreasing to 4 weight per cent at 715 C.⁽¹⁸⁹⁾ The solubility of tungsten in titanium is approximately 0.8 weight per cent at 715 C.⁽¹⁸⁹⁾

TUNGSTEN-URANIUM SYSTEM



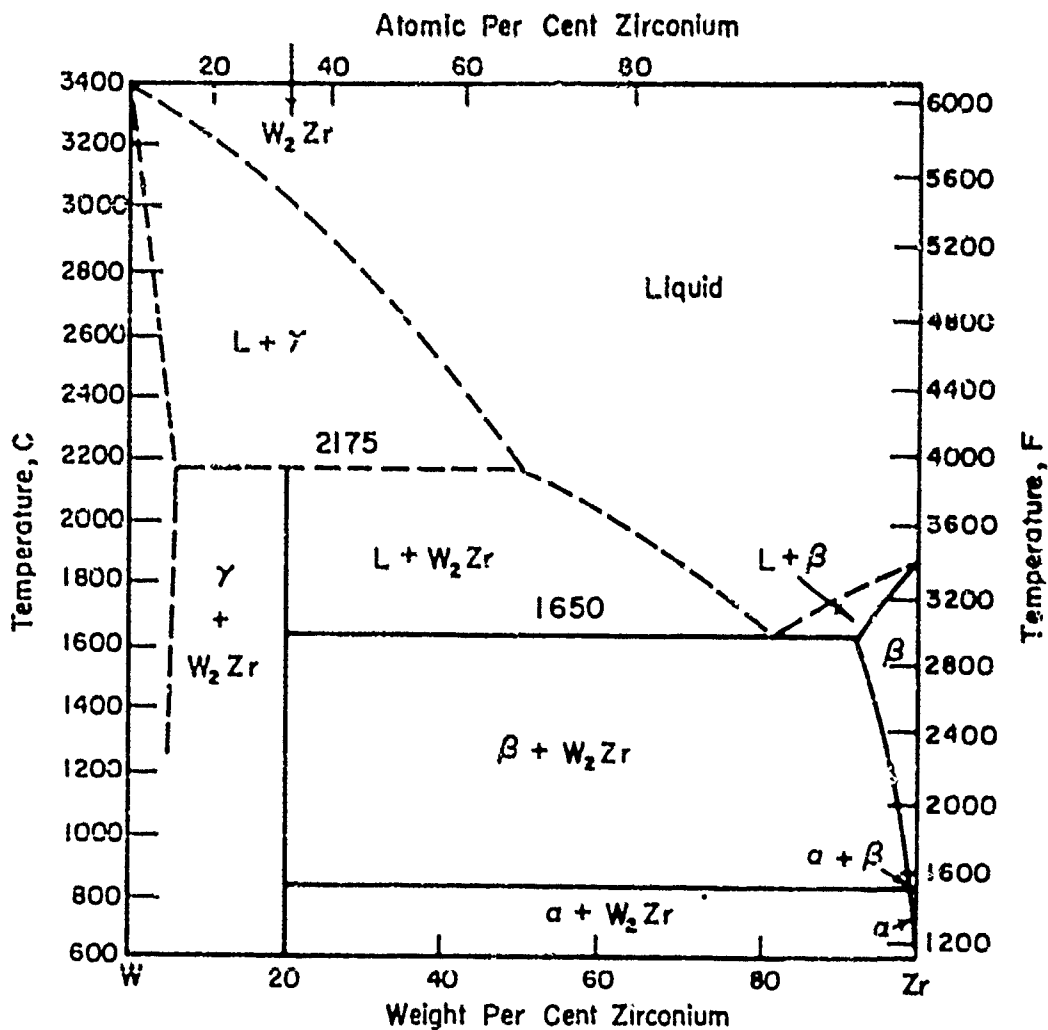
The solubility of uranium in tungsten is about 0.1 atomic per cent at 1000 C. ⁽¹⁹⁰⁾ The solubility of tungsten in uranium is 0.2 to 0.7 atomic per cent tungsten. ⁽¹⁹¹⁾ There are no intermetallic compounds in the system.

TUNGSTEN-VANADIUM SYSTEM



Lattice-parameter measurements indicate a continuous series of solid solutions at 1750 C.⁽¹⁹²⁾ The system is similar to the Mo-Cr system in that a two-phase region possibly exists at lower temperatures.^(192, 193)

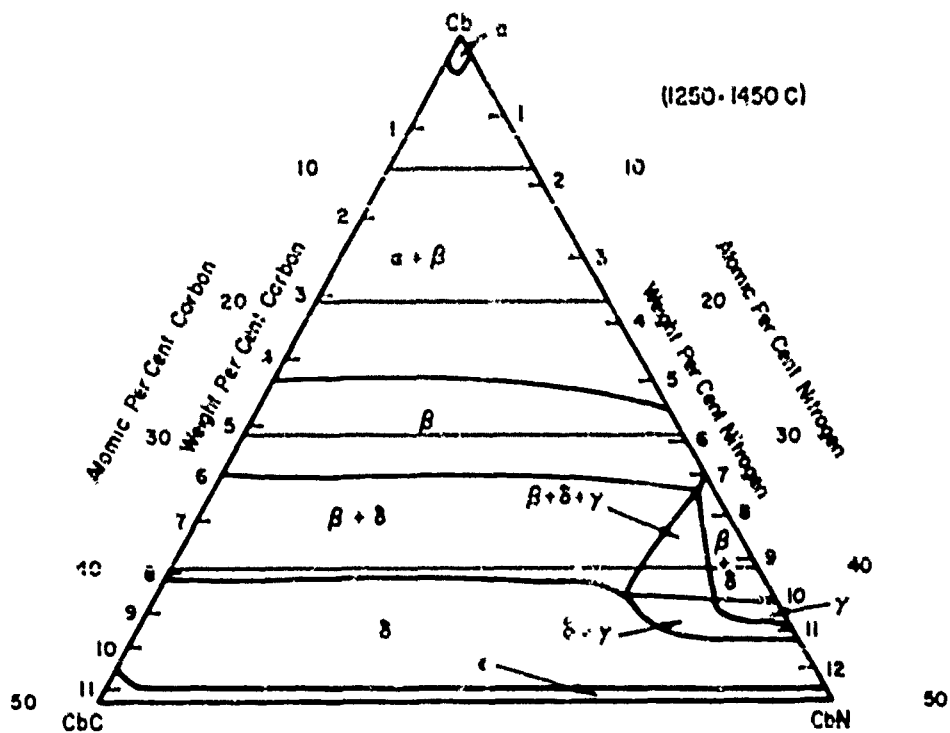
TUNGSTEN-ZIRCONIUM SYSTEM



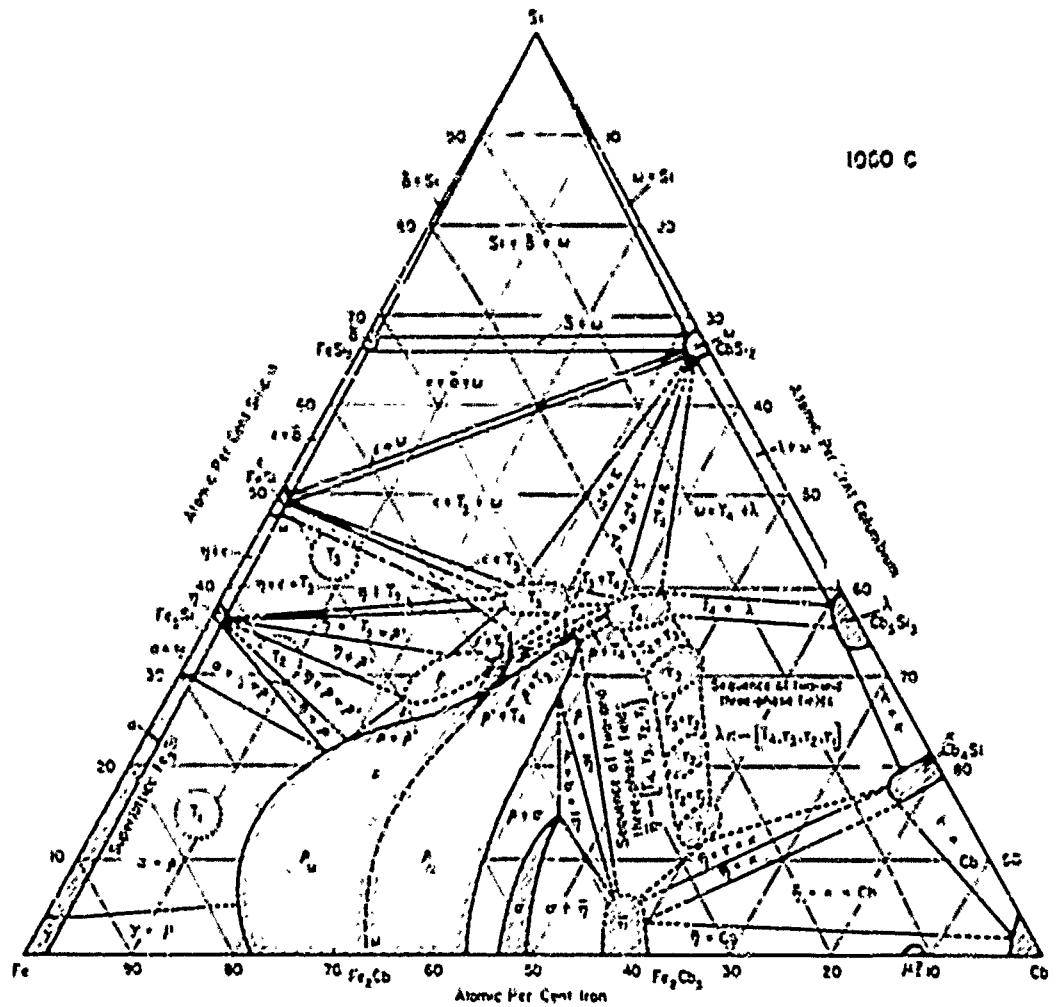
W_2Zr has the cubic $MgCu_2$ (C15) type of structure with $a = 7.615 \text{ \AA}$.⁽¹⁷⁸⁾ The solubility of zirconium in tungsten is about 3 weight per cent at 2150°C.⁽¹⁹⁴⁾ The solubility of tungsten in α -zirconium is less than 0.5 weight per cent tungsten.⁽¹⁹⁵⁾

TERNARY PHASE
DIAGRAMS

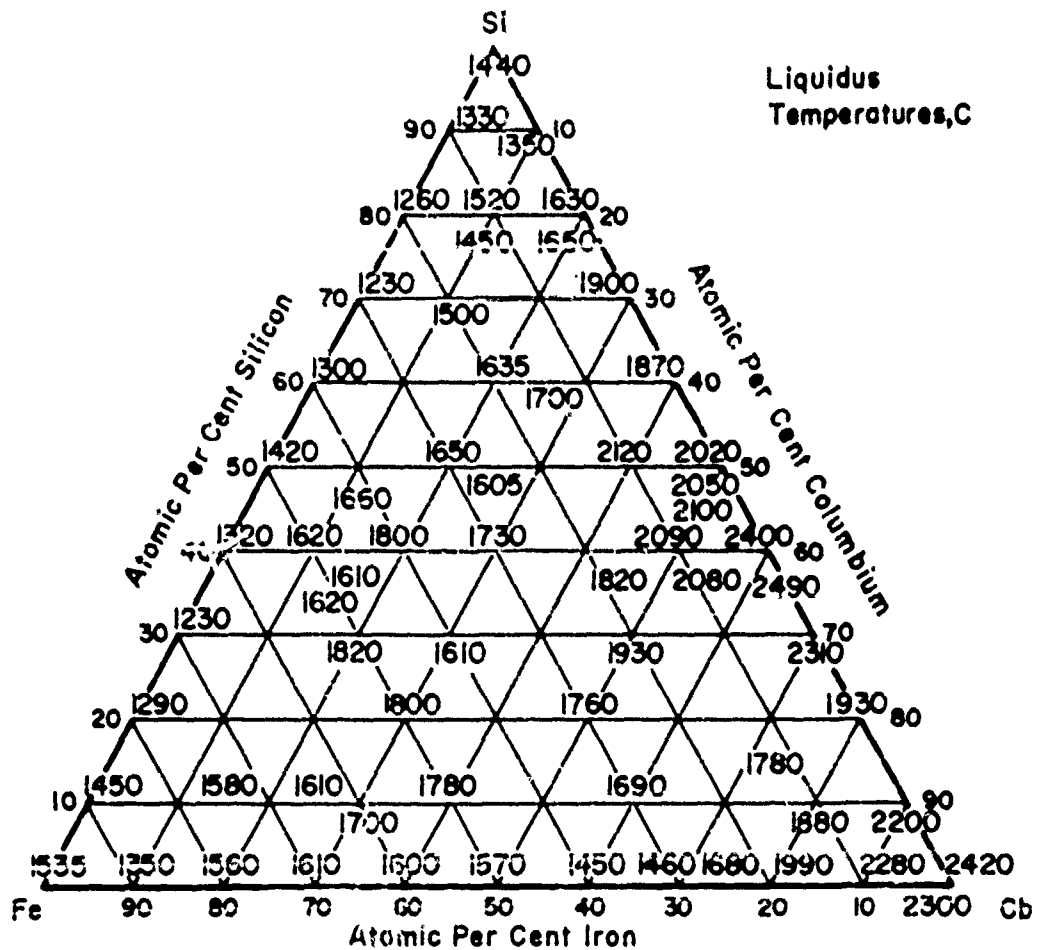
COLUMBIUM-COLUMBIUM CARBIDE-COLUMBIUM NITRIDE SYSTEM (204)



COLUMBIUM-IRON-SILICON SYSTEM(205)

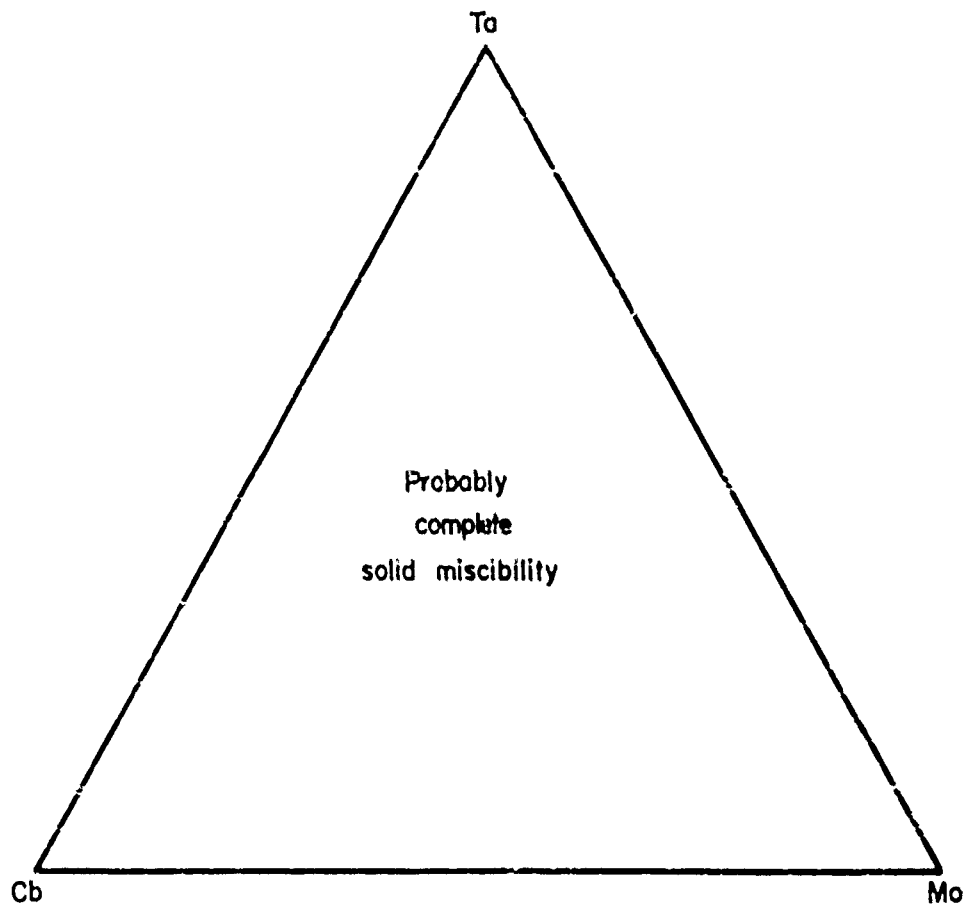


COLUMBIUM-IRON-SILICON SYSTEM(205)

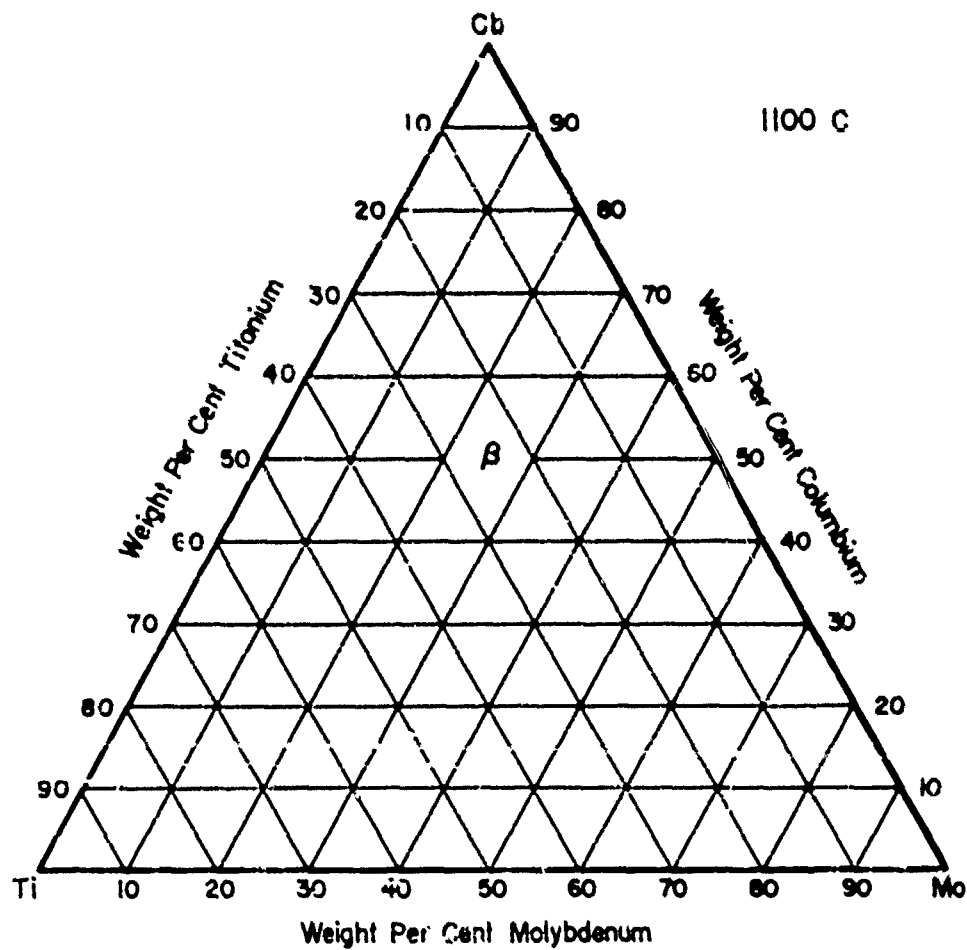


Melting temperatures in the Cb-Fe-Si system (liquidus approximate values only).

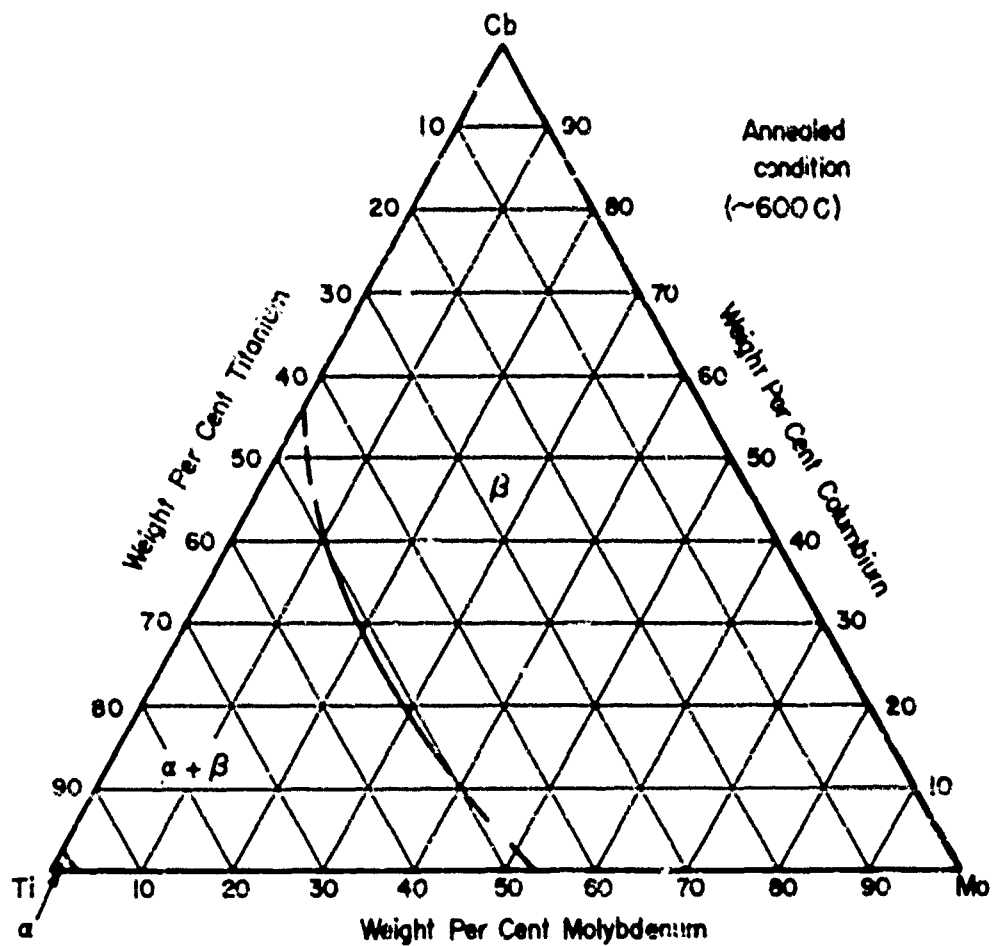
COLUMBIUM-MOLYBDENUM-TANTALUM SYSTEM⁽²⁰⁶⁾



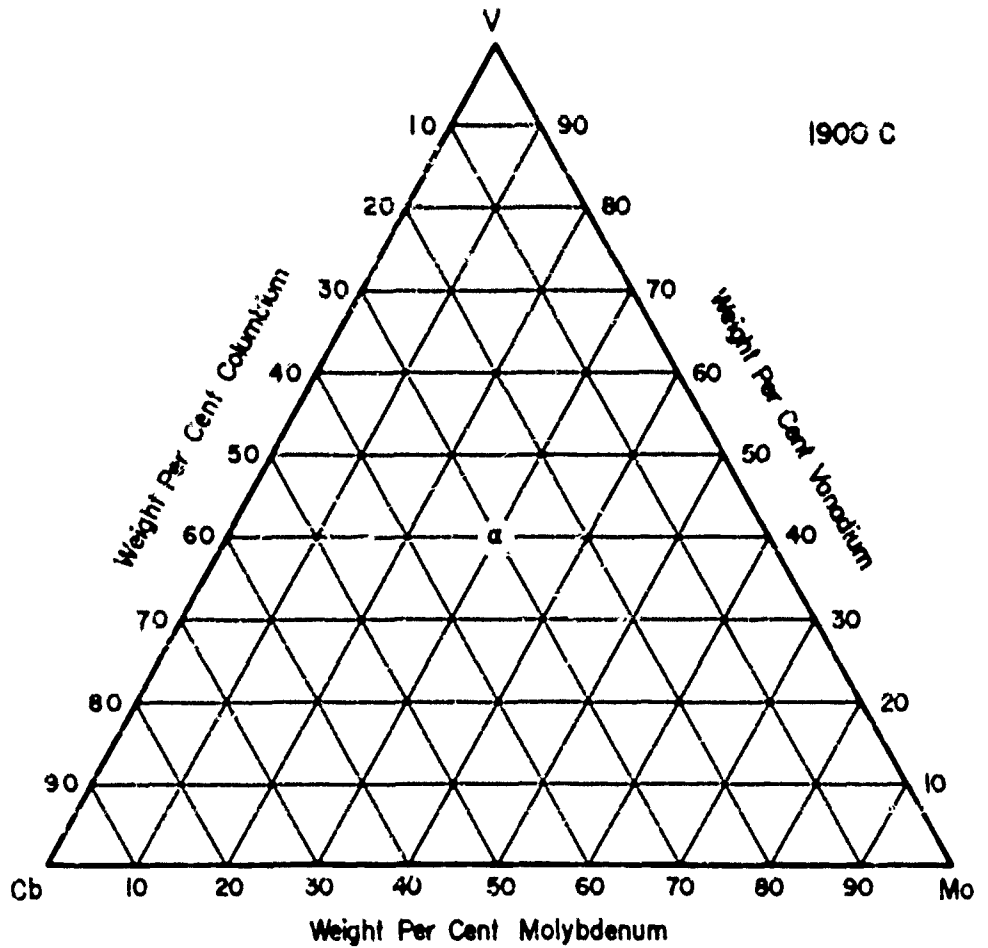
COLUMBIUM-MOLYBDENUM-TITANIUM SYSTEM⁽²⁰⁷⁾



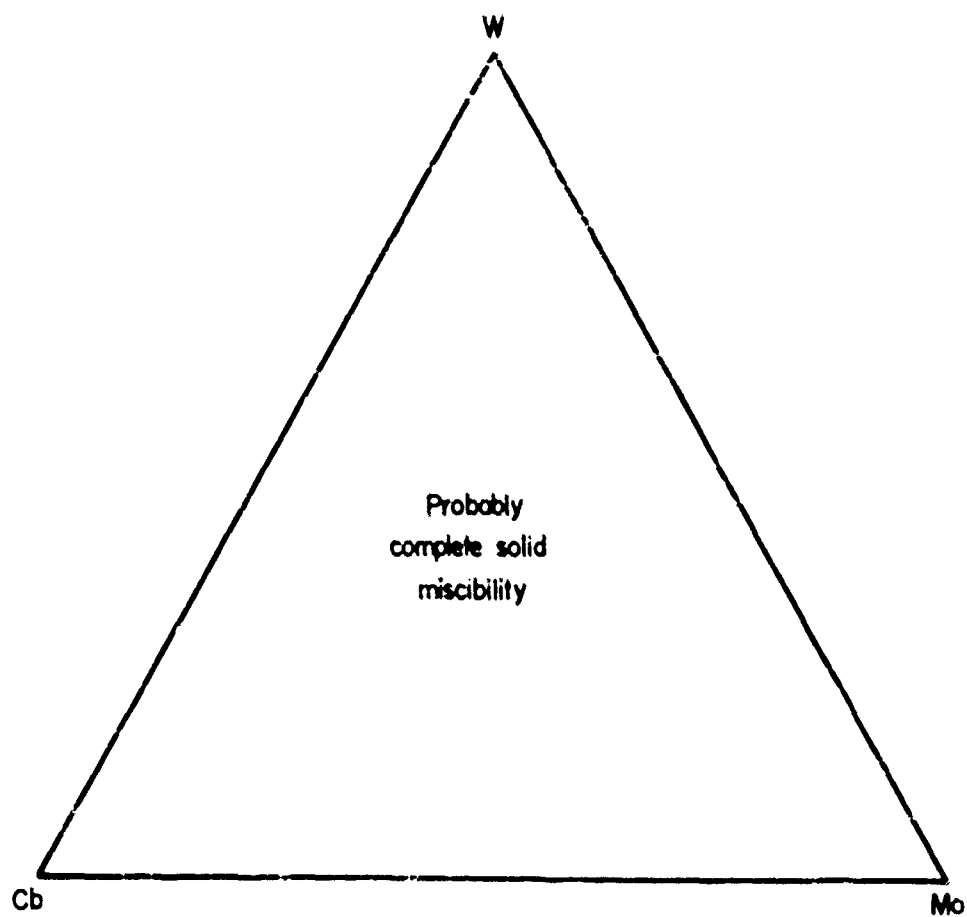
COLUMBIUM-MOLYBDENUM-TITANIUM SYSTEM(207)



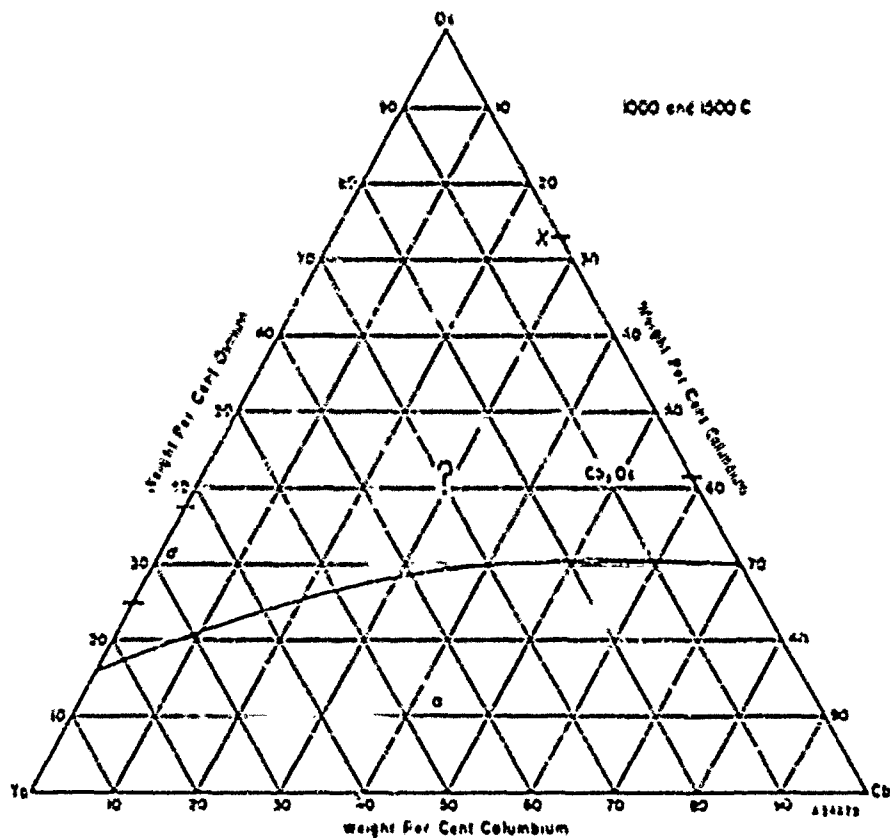
COLUMBIUM-MOLYBDENUM-VANADIUM SYSTEM⁽²⁰⁸⁾



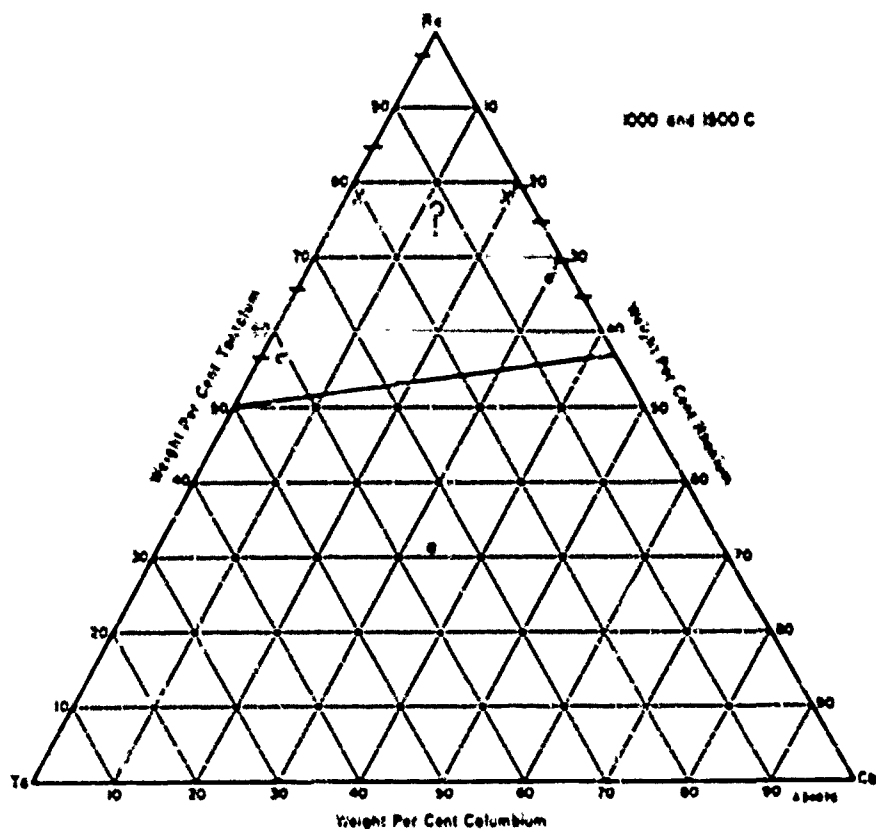
COLUMBIUM-MOLYBDENUM-TUNGSTEN SYSTEM (206)



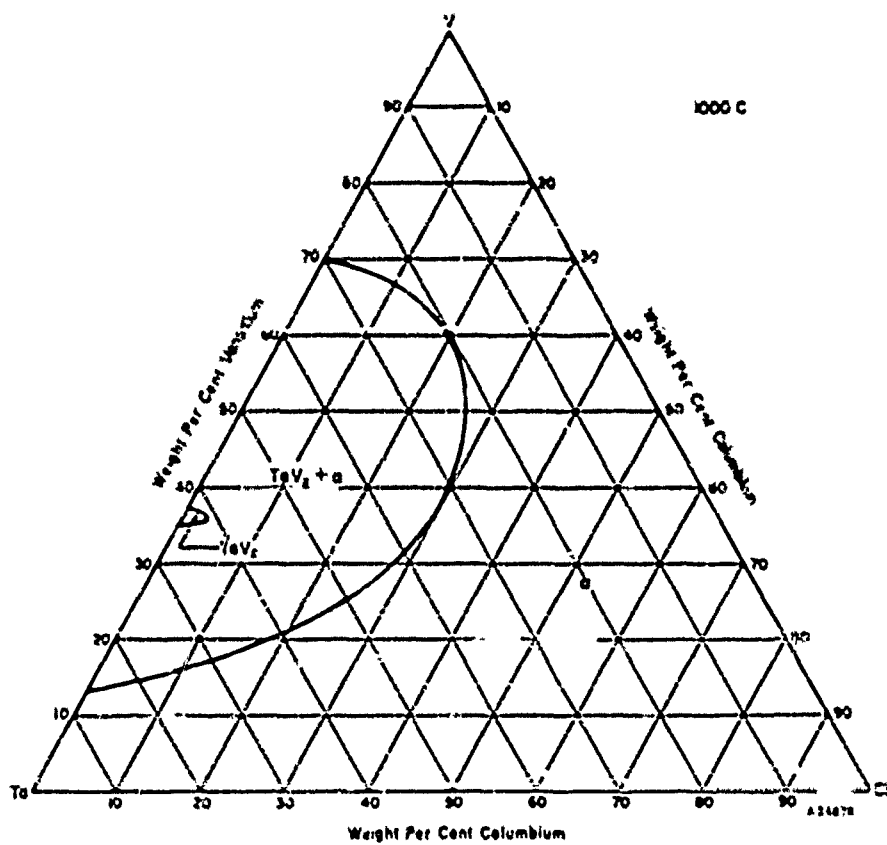
COLUMBIUM-TANTALUM-OSMIUM SYSTEM (406)



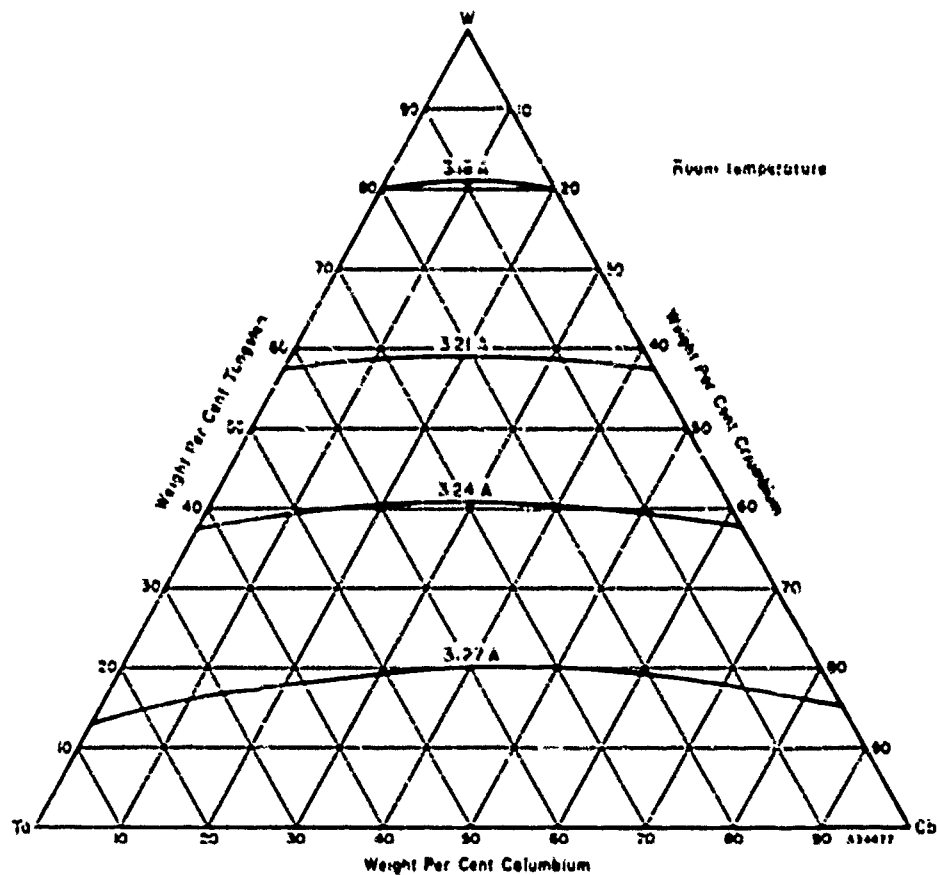
COLUMBIUM-TANTALUM-RHENIUM SYSTEM (206)



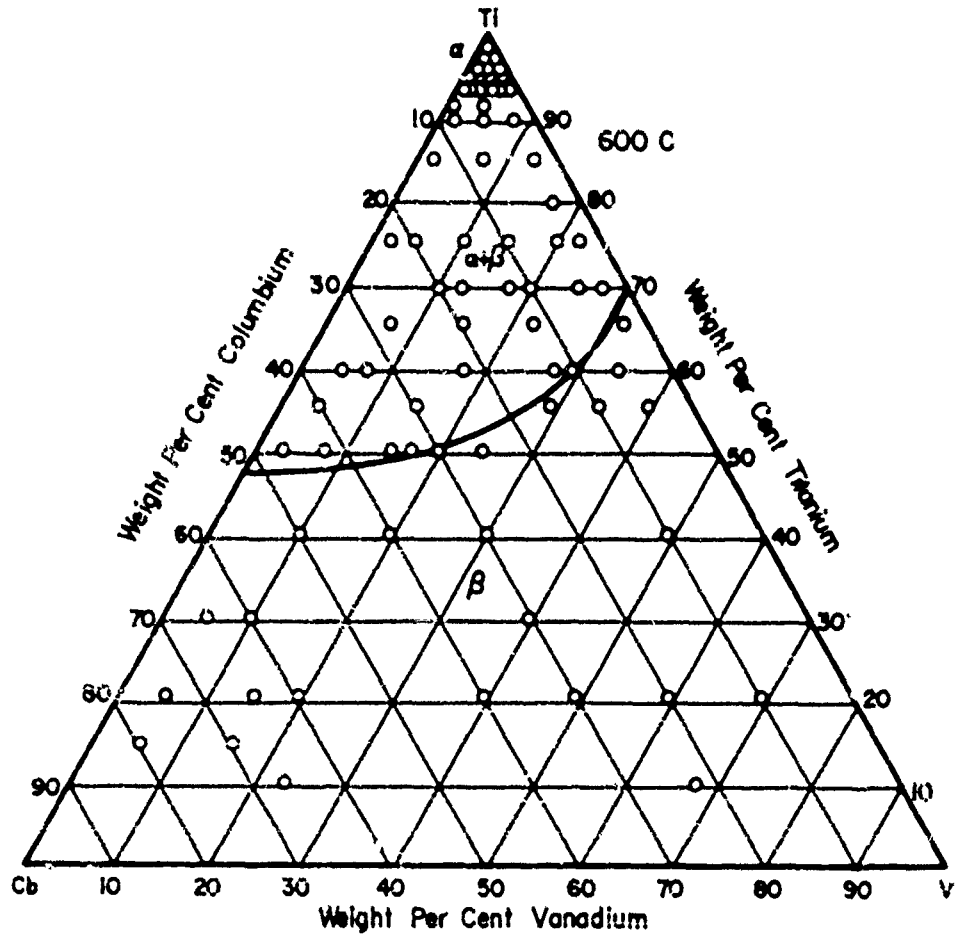
COLUMBIUM-TANTALUM-VANADIUM SYSTEM(206)



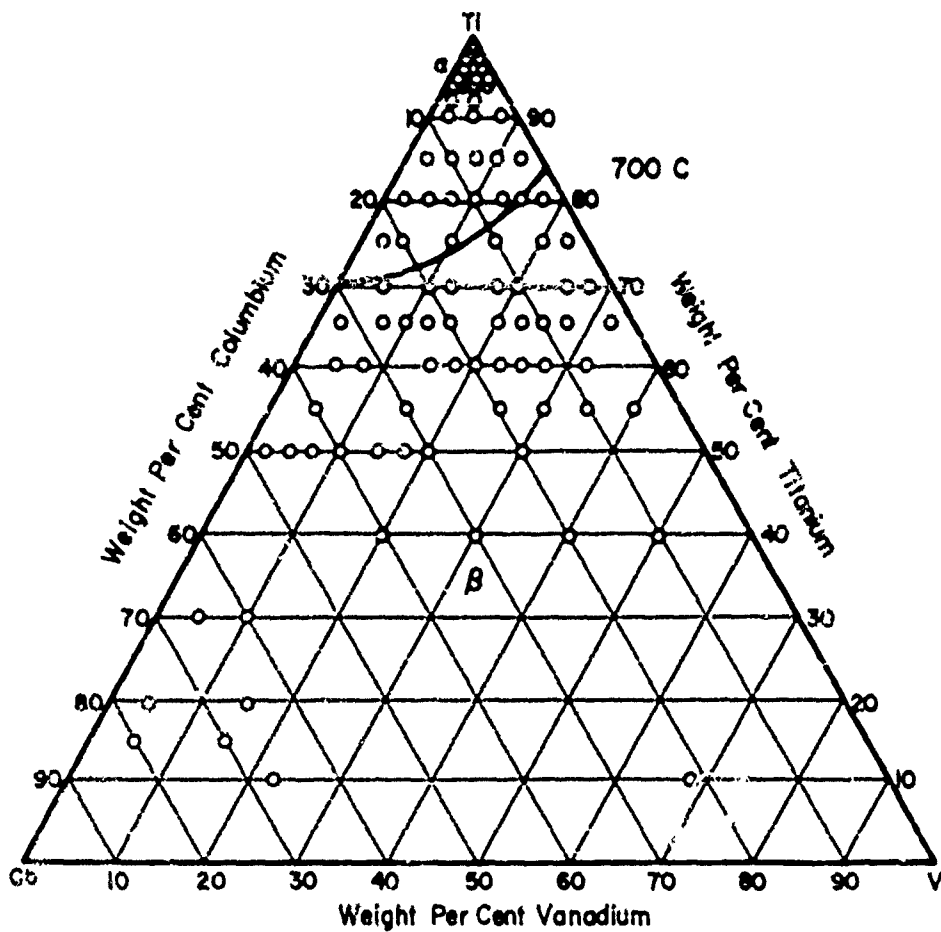
COLUMBIUM-TANTALUM-TUNGSTEN SYSTEM(206)



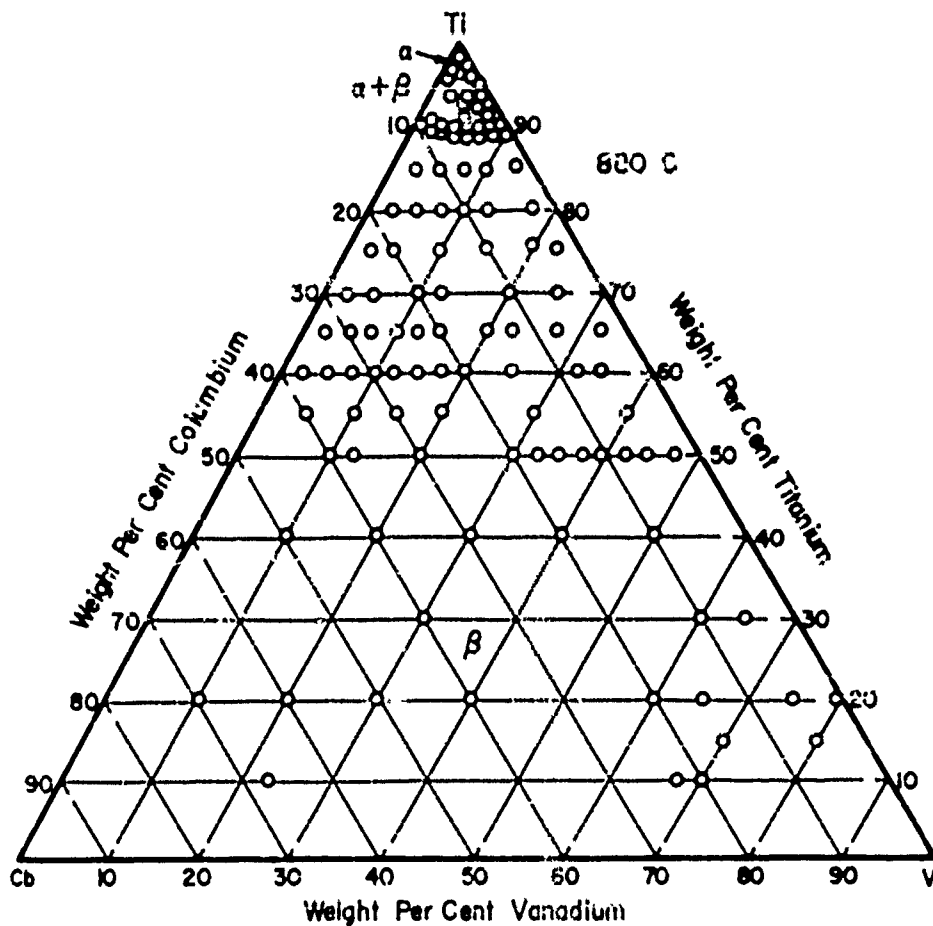
COLUMBIUM-TITANIUM-VANADIUM SYSTEM



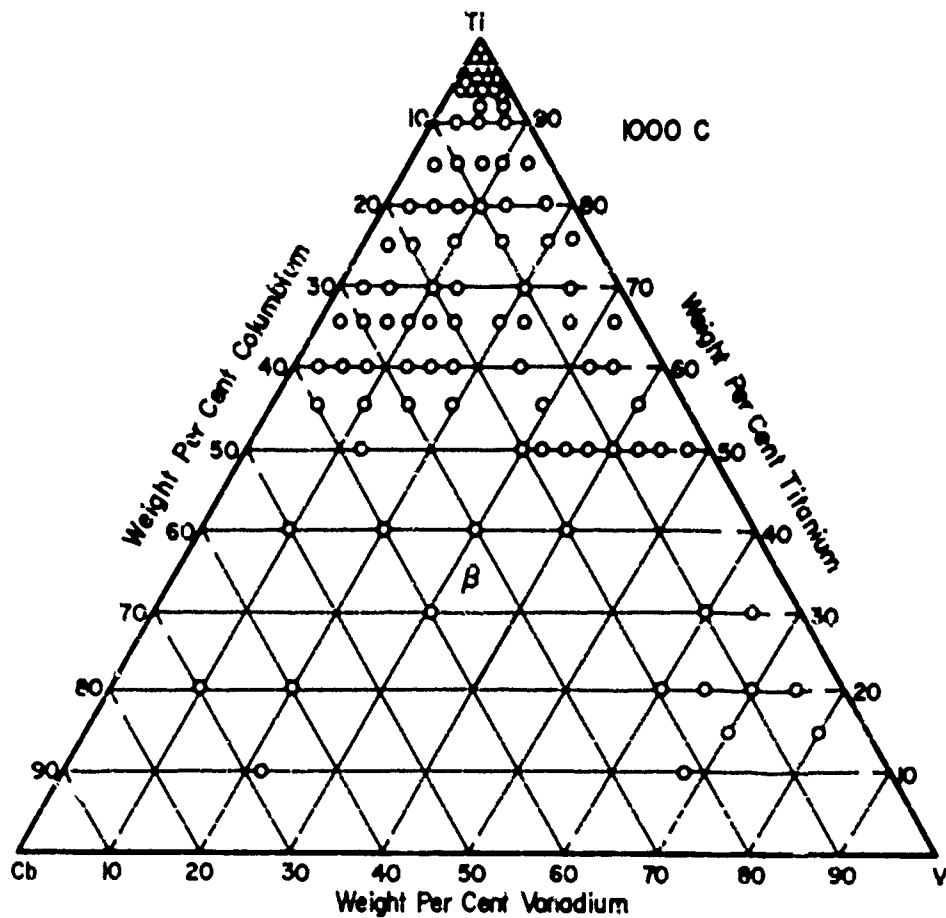
COLUMBIUM-TITANIUM-VANADIUM SYSTEM



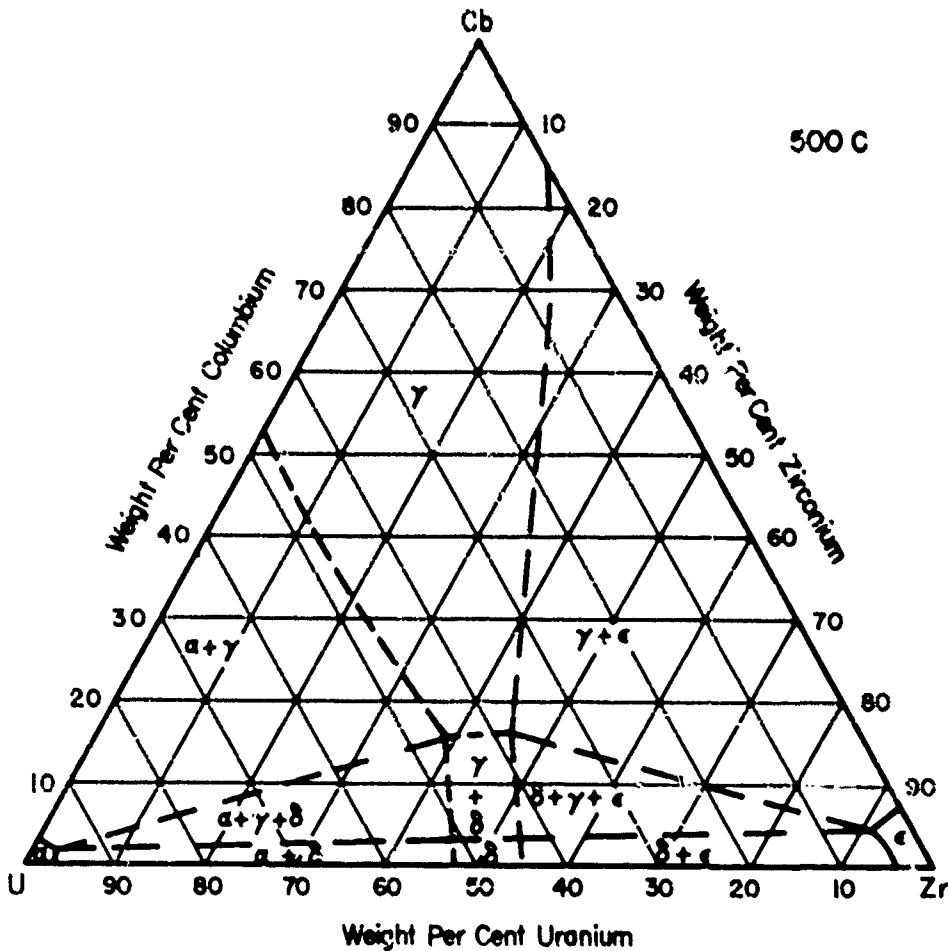
COLUMBIUM-TITANIUM-VANADIUM SYSTEM



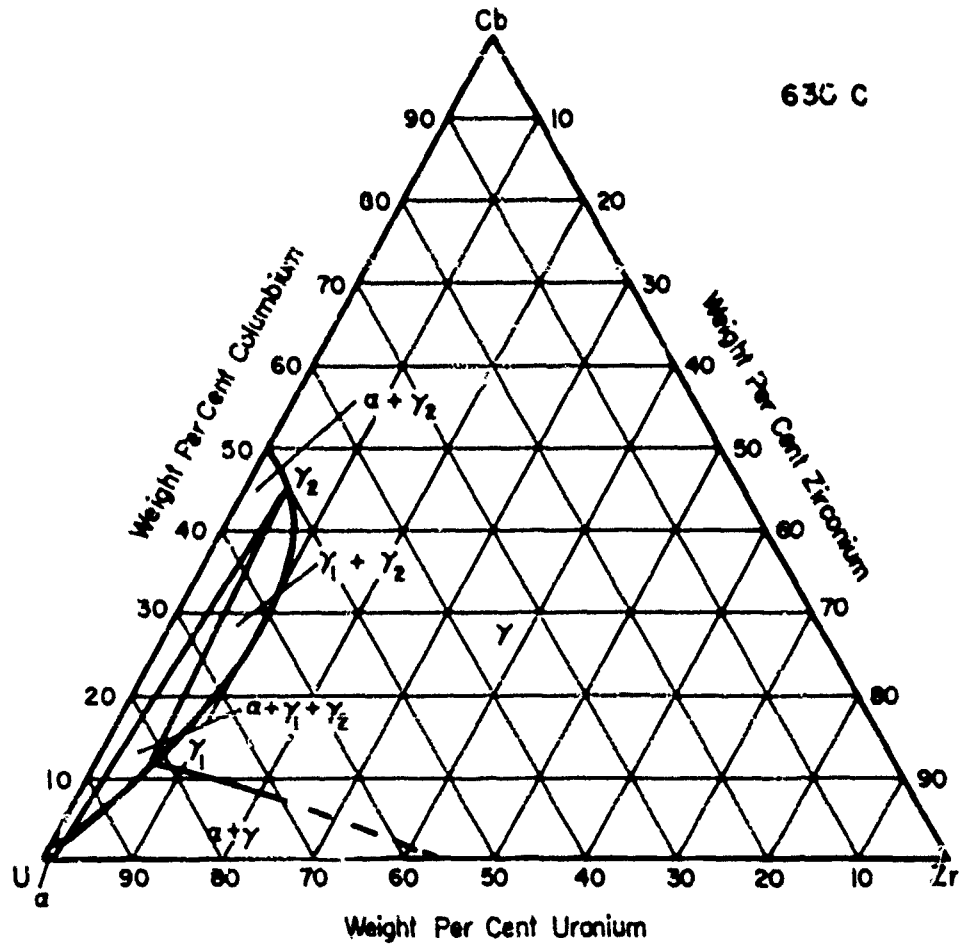
COLUMBIUM-TITANIUM-VANADIUM SYSTEM



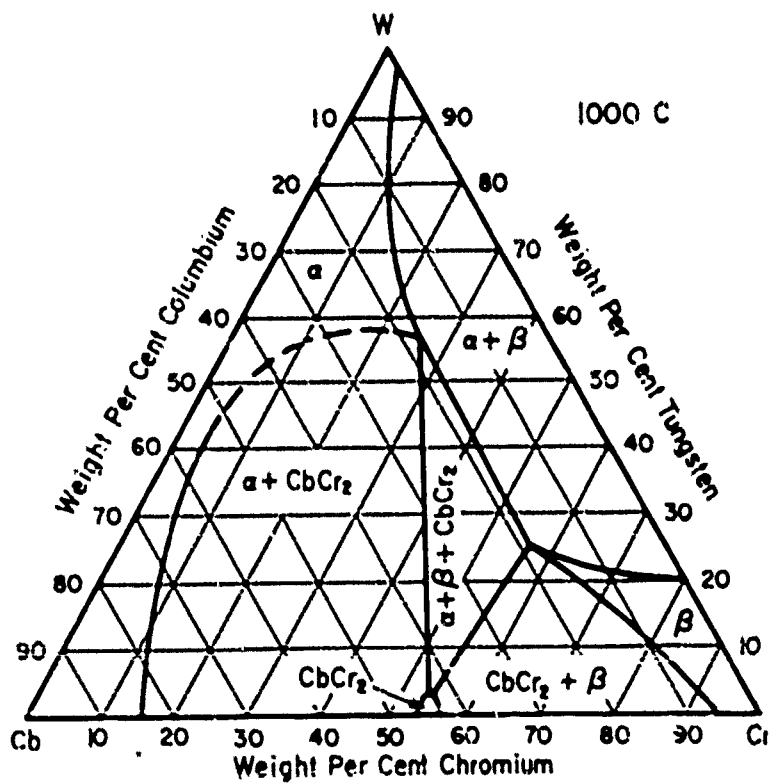
COLUMBIUM-URANIUM-ZIRCONIUM SYSTEM(210)



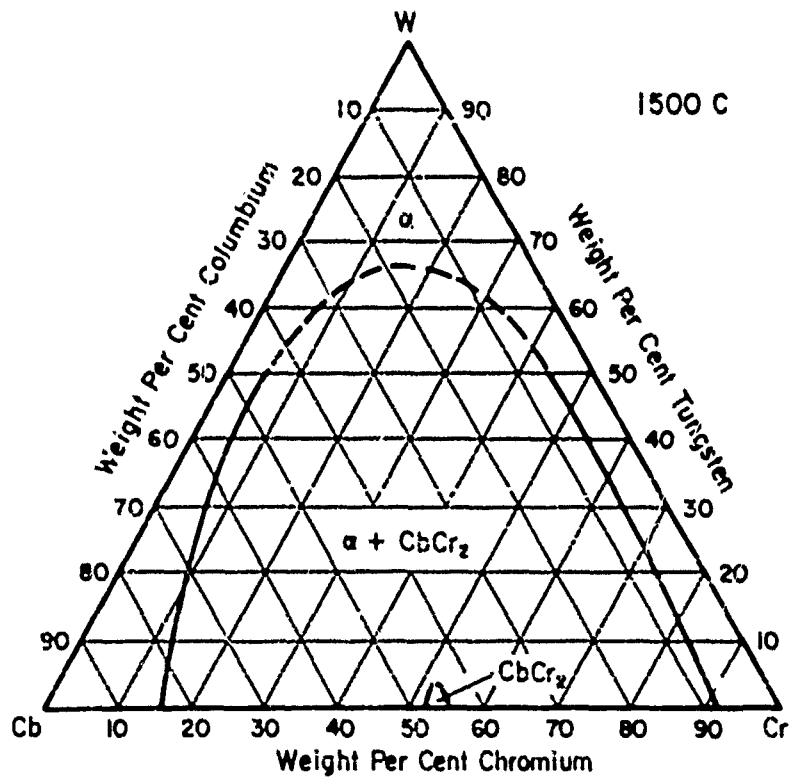
COLUMBIUM-URANIUM-ZIRCONIUM SYSTEM (210)



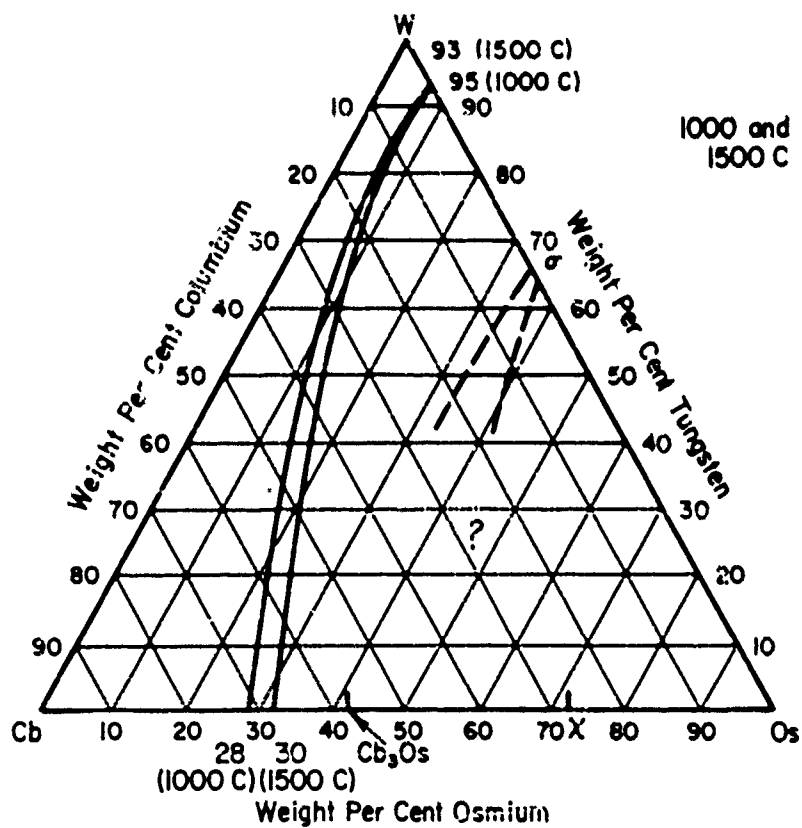
COLUMBIUM-TUNGSTEN-CHROMIUM SYSTEM(206)



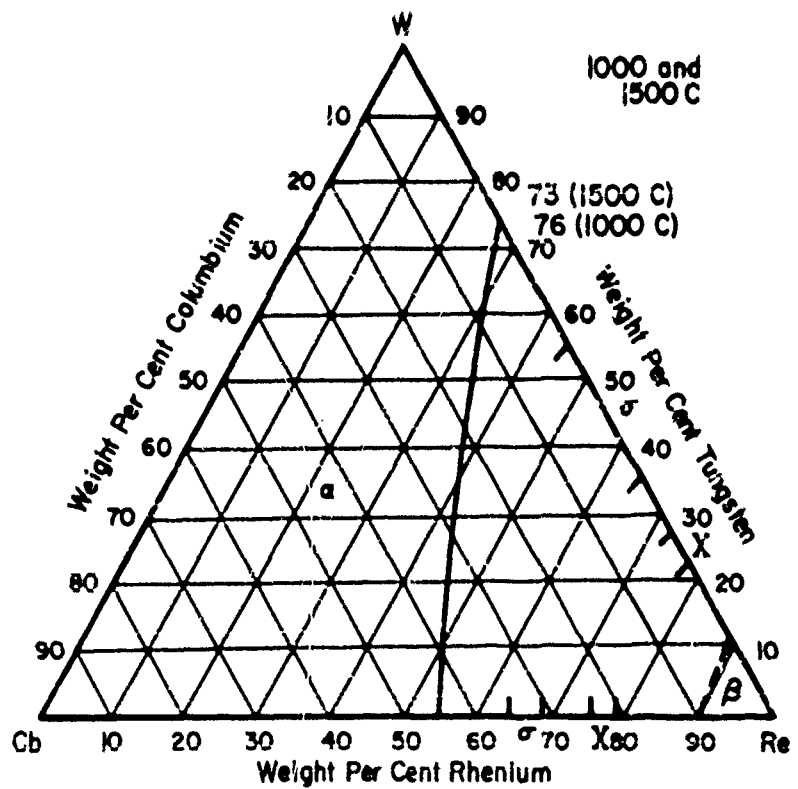
COLUMBIUM-TUNGSTEN-CHROMIUM SYSTEM (206)



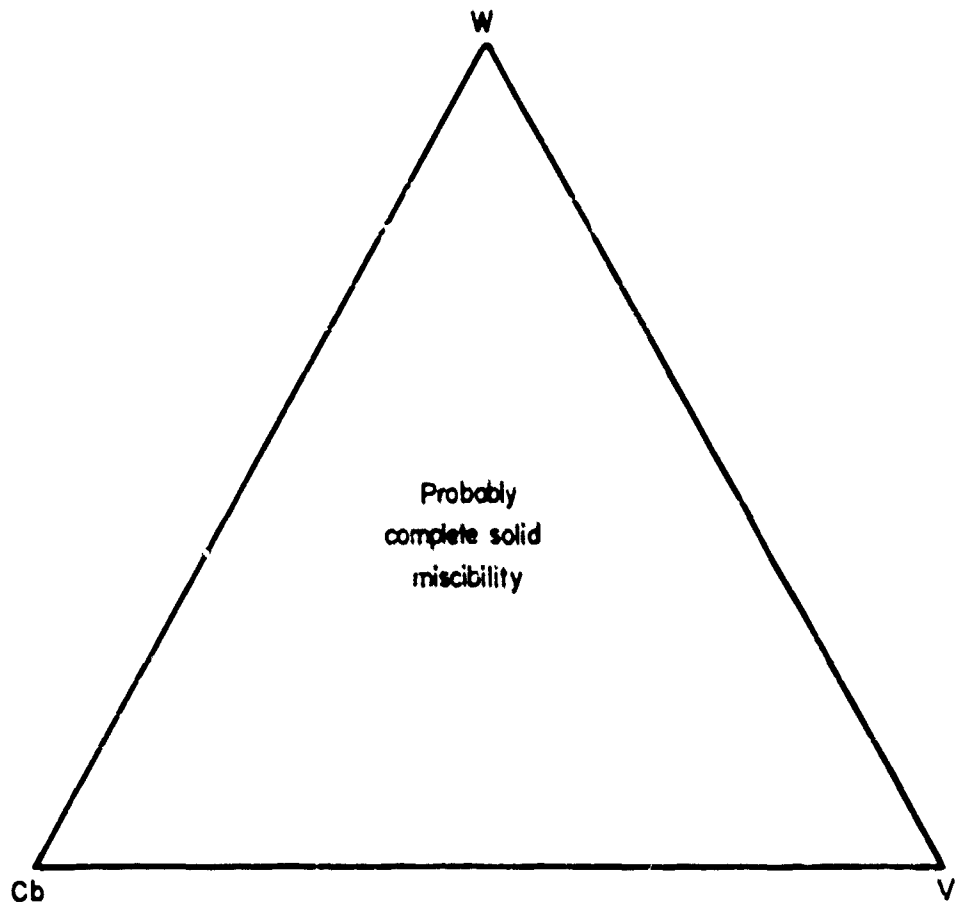
COLUMBIUM-TUNGSTEN-OSMIUM SYSTEM (206)



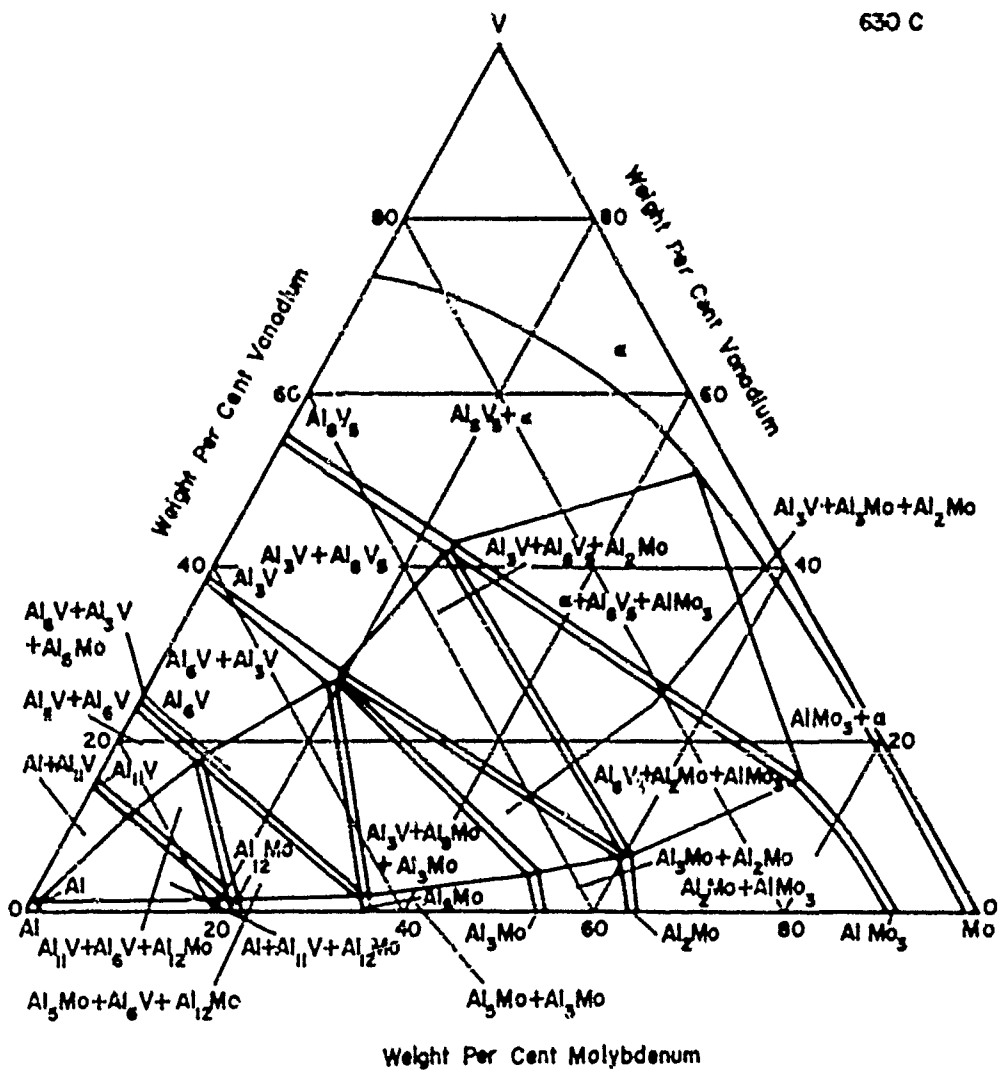
COLUMBIUM-TUNGSTEN-RHENIUM SYSTEM (206)



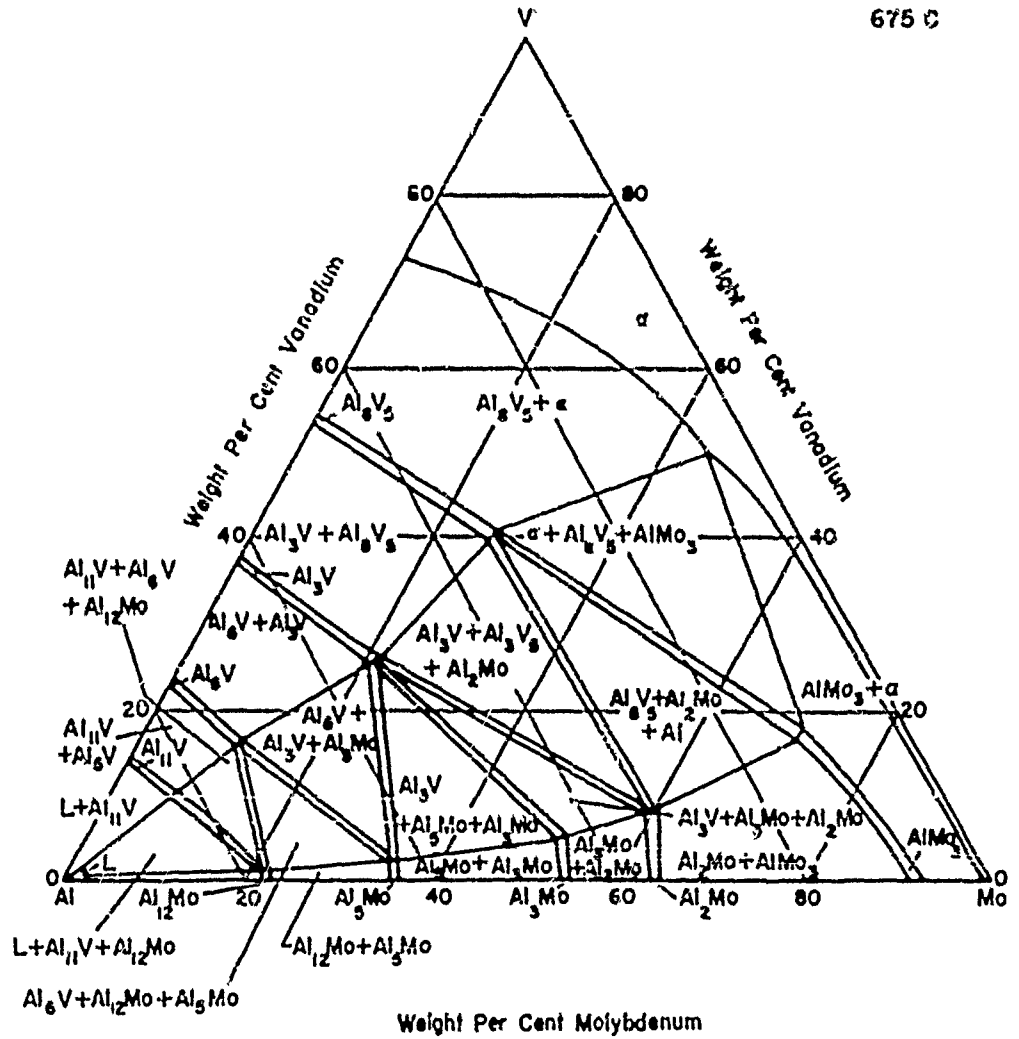
COLUMBIUM-TUNGSTEN-VANADIUM SYSTEM(206)



MOLYBDENUM-ALUMINUM-VANADIUM SYSTEM(211)

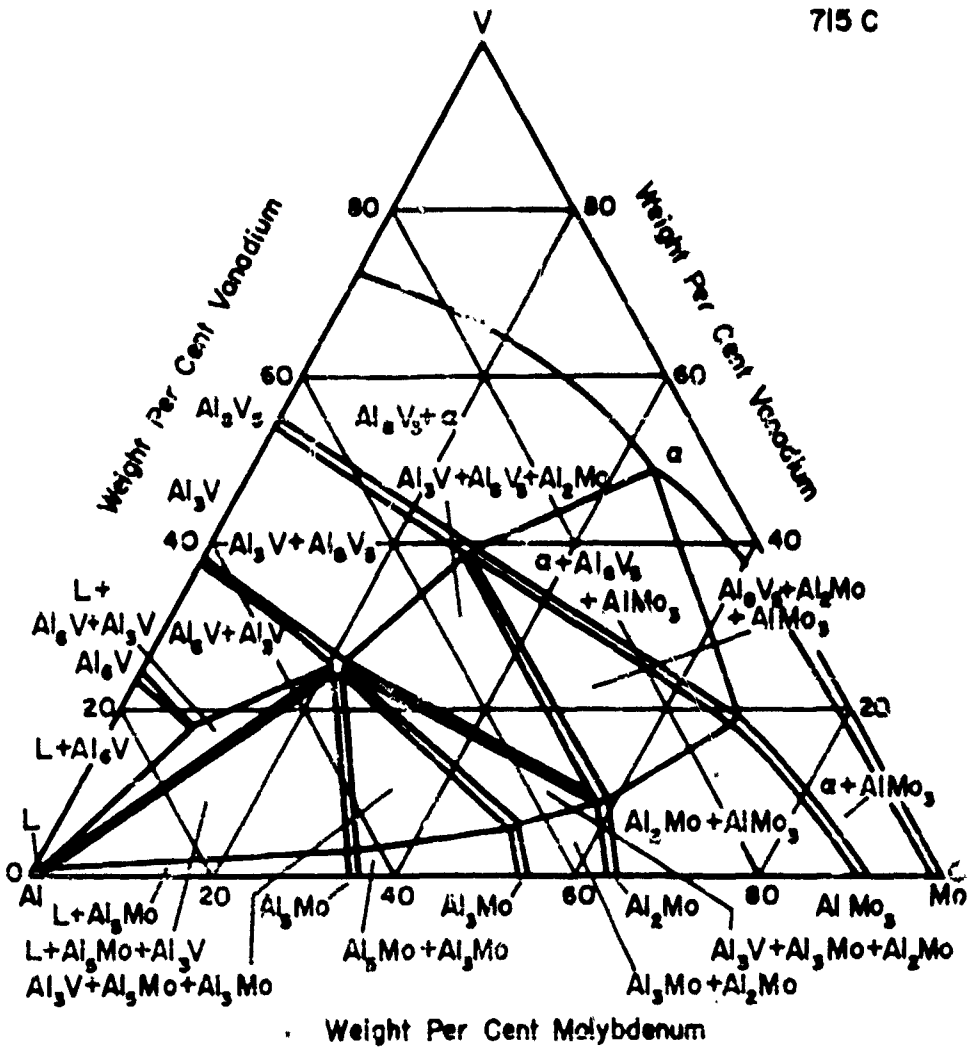


MOLYBDENUM-ALUMINUM-VANADIUM SYSTEM(211)

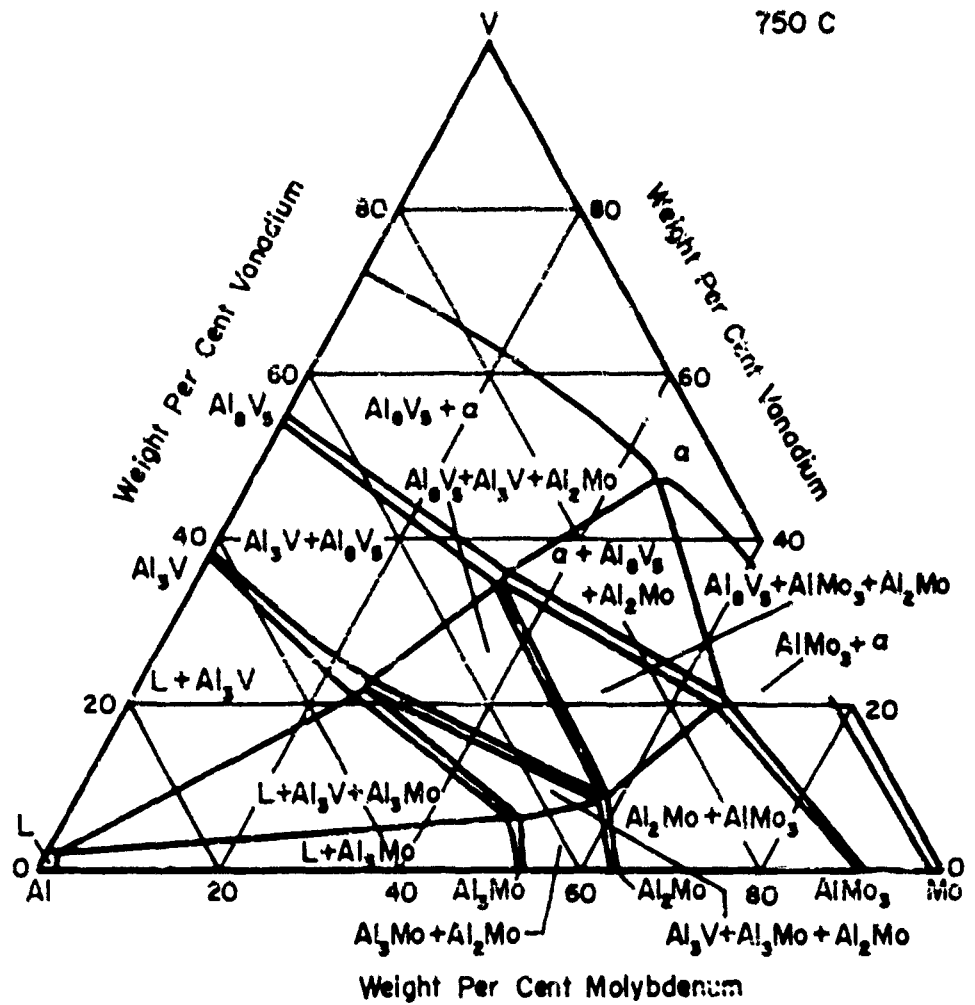


MOLYBDENUM-ALUMINUM-VANADIUM SYSTEM(211)

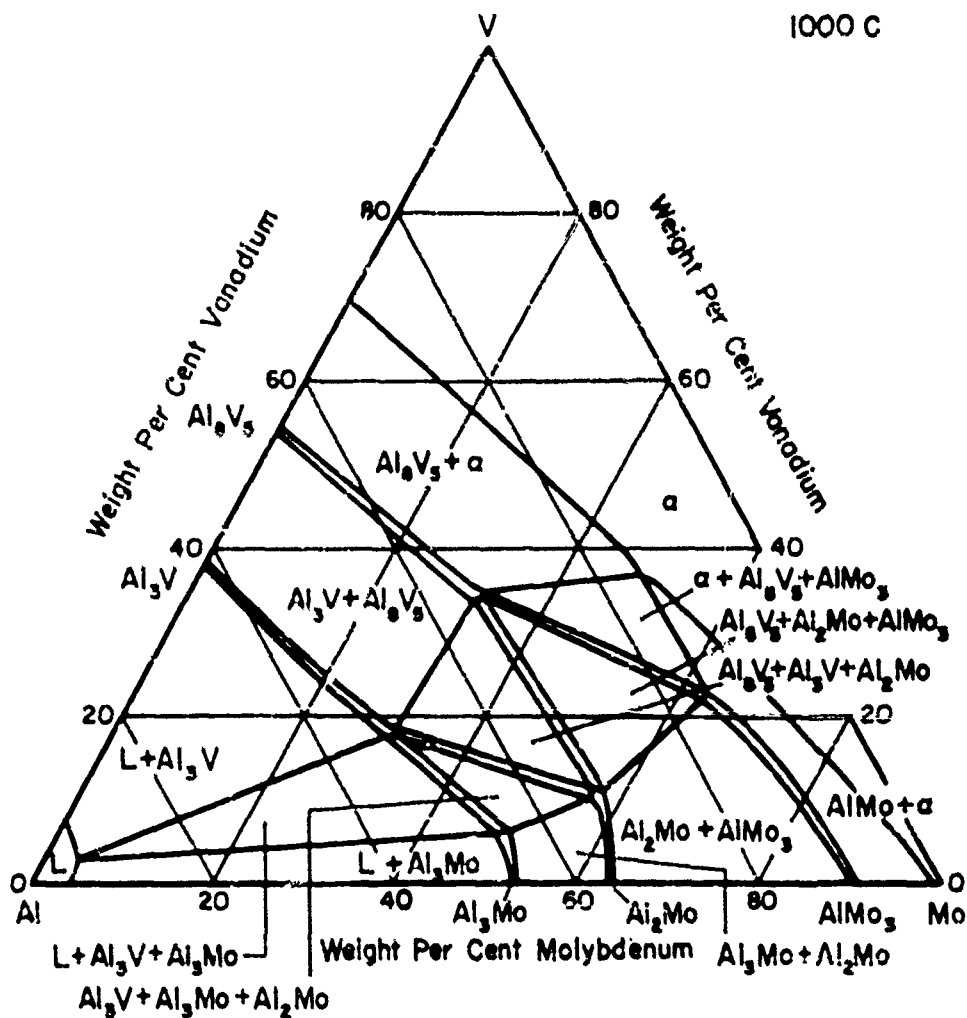
715 C



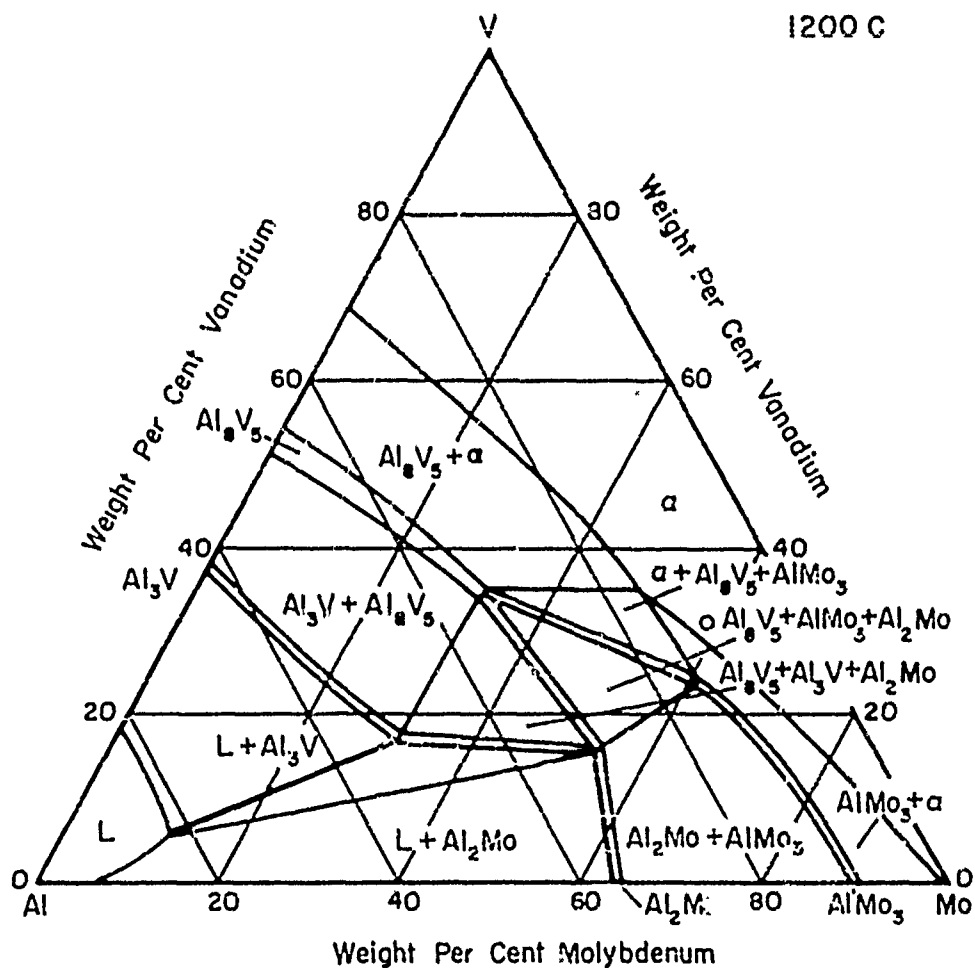
MOLYBDENUM-ALUMINUM-VANADIUM SYSTEM(211)



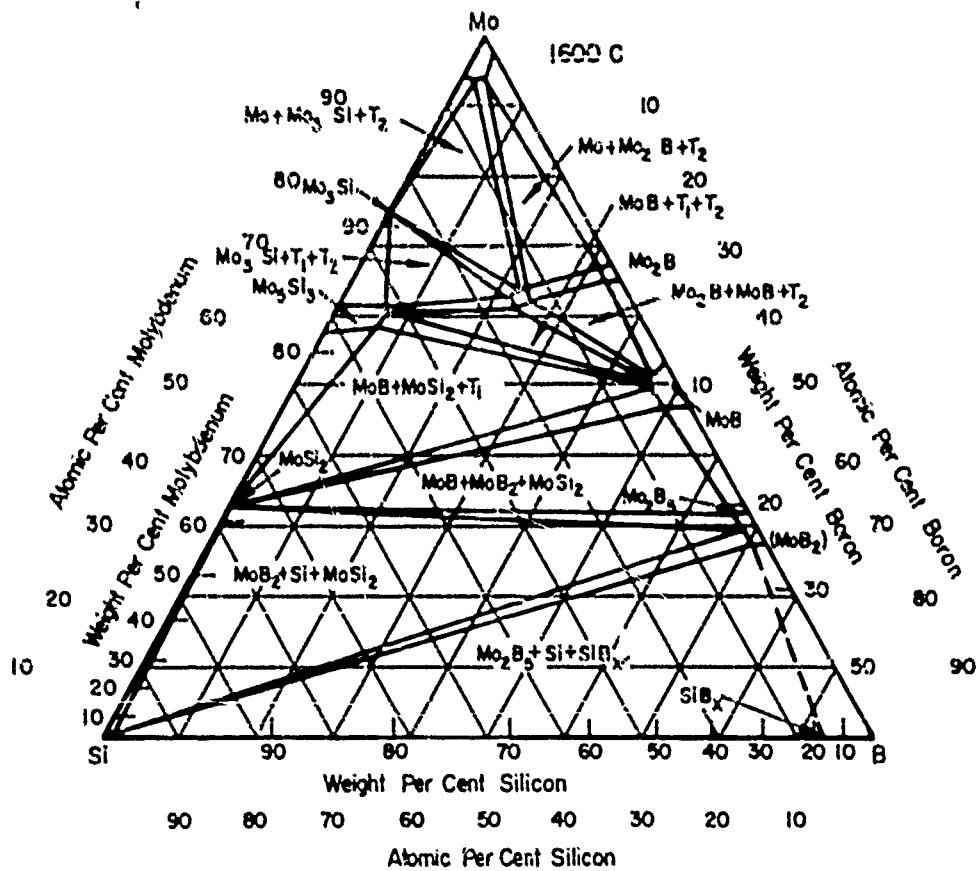
MOLYBDENUM-ALUMINUM-VANADIUM SYSTEM(211)



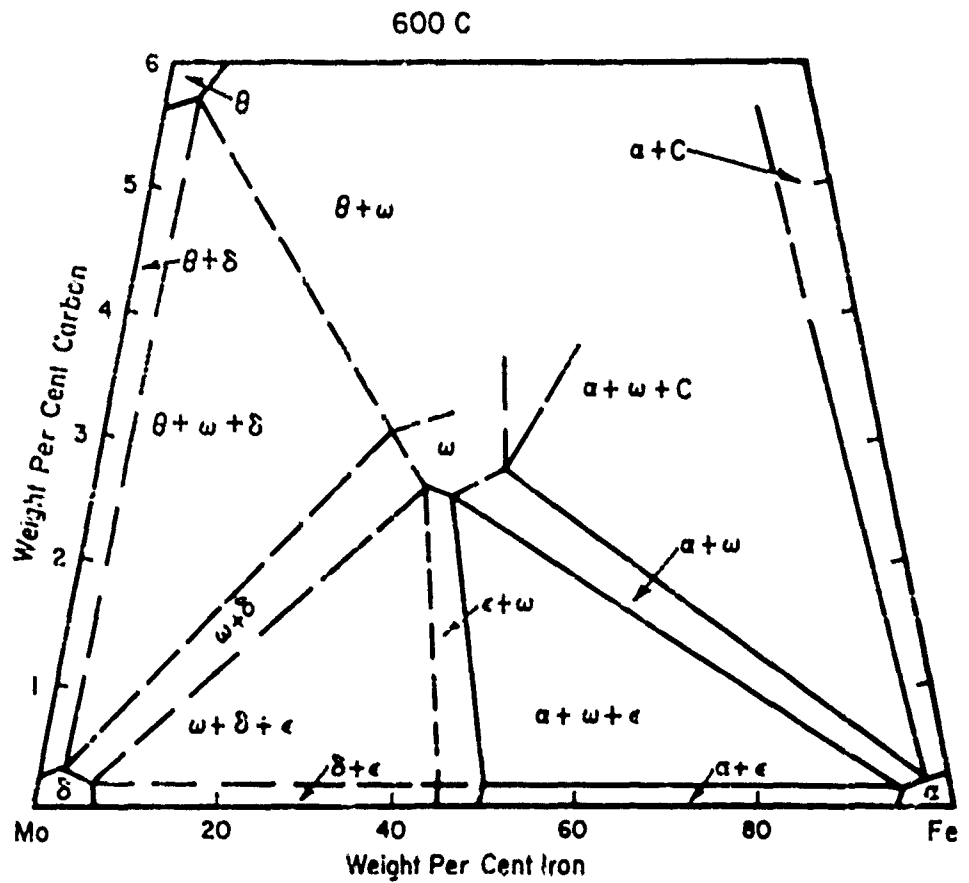
MOLYBDENUM-ALUMINUM-VANADIUM SYSTEM (211)



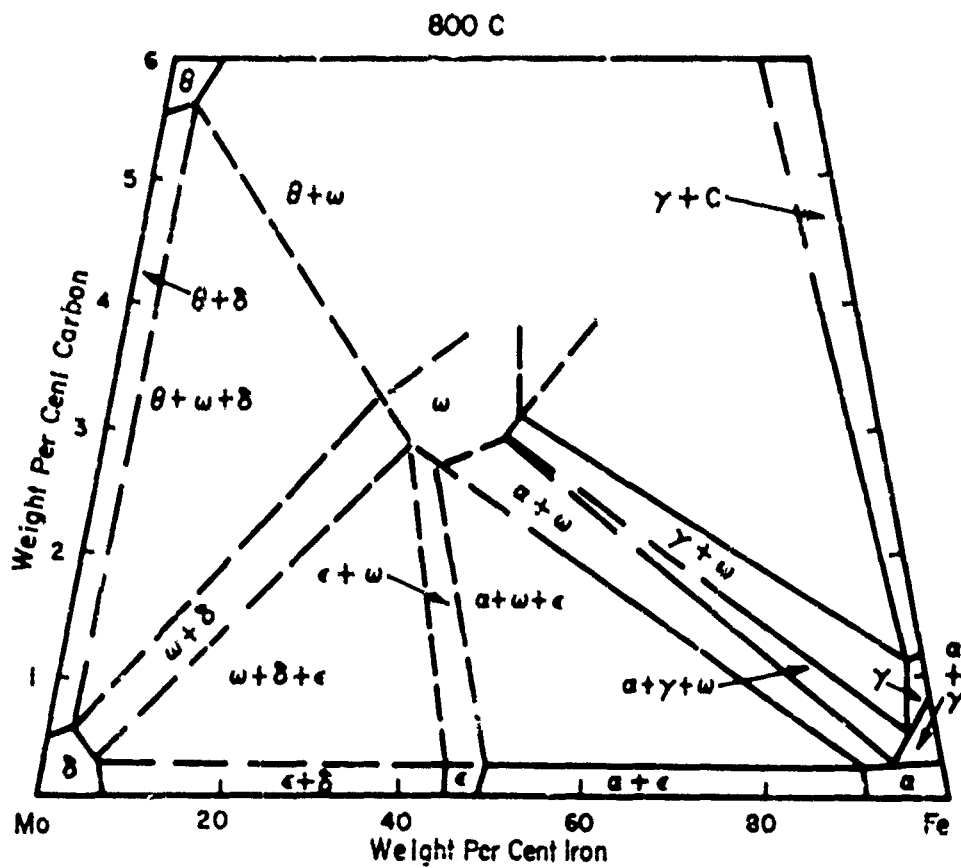
MOLYBDENUM-BORON-SILICON SYSTEM⁽²¹²⁾



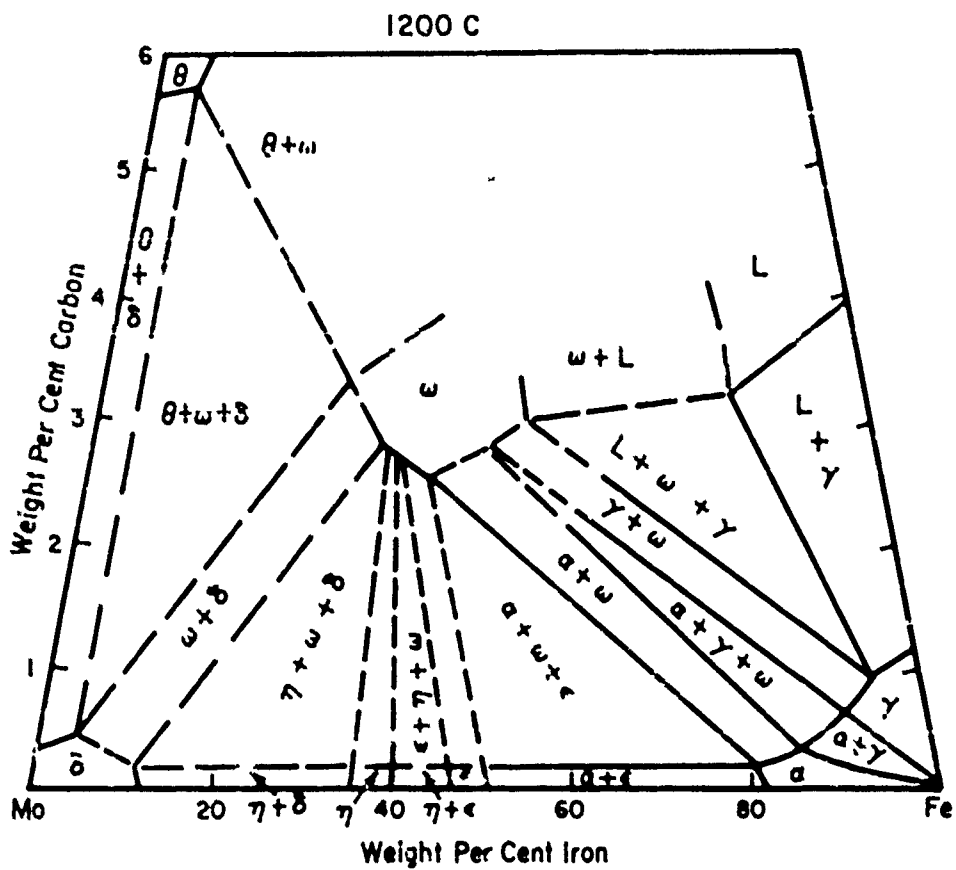
MOLYBDENUM-CARBON-IRON SYSTEM⁽²¹³⁾



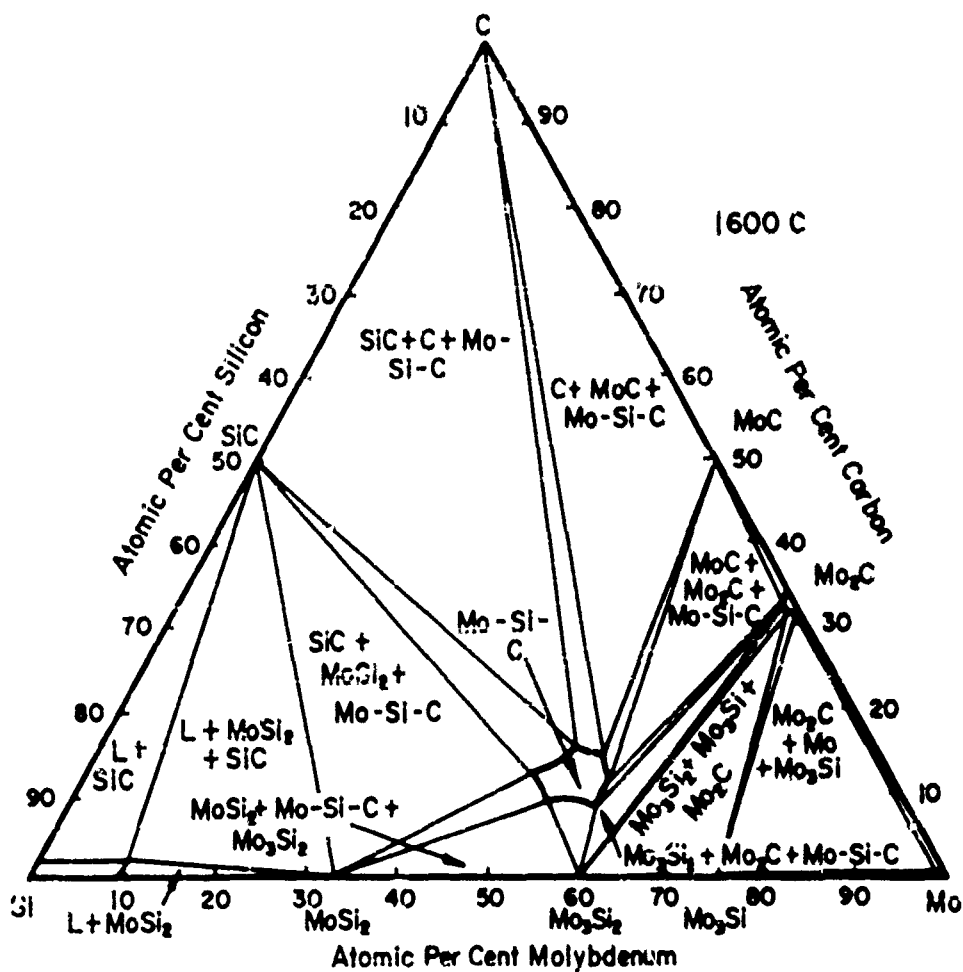
MOLYBDENUM-CARBON-IRON SYSTEM(213)



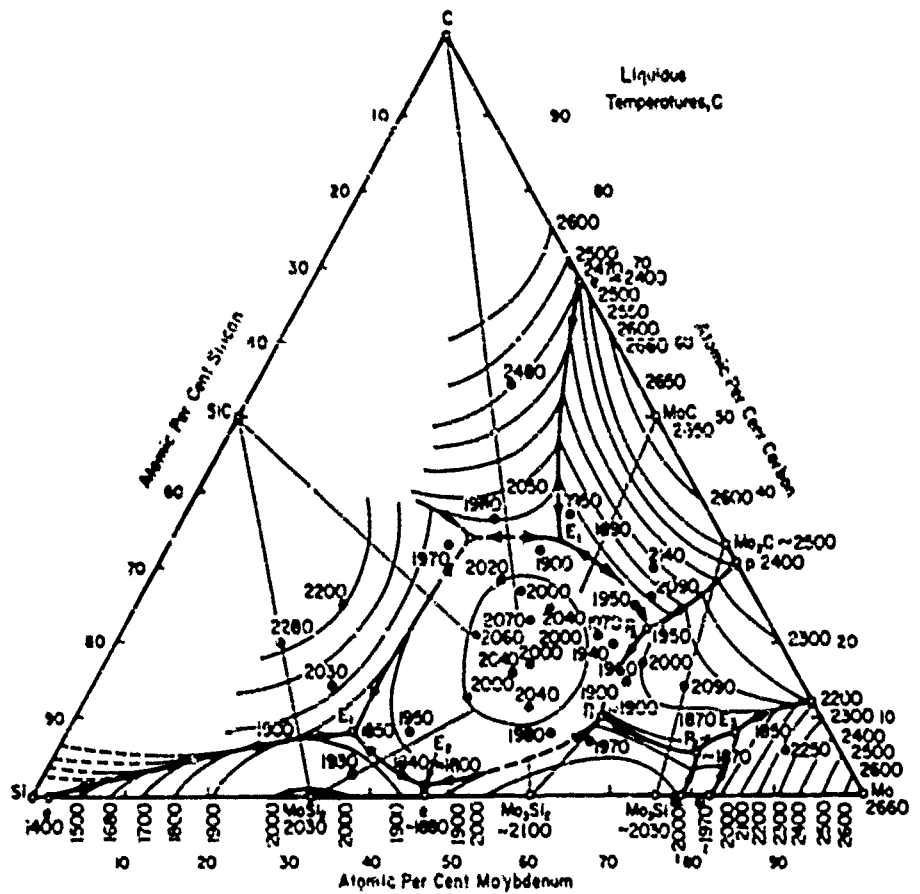
MOLYBDENUM-CARBON-IRON SYSTEM (213)



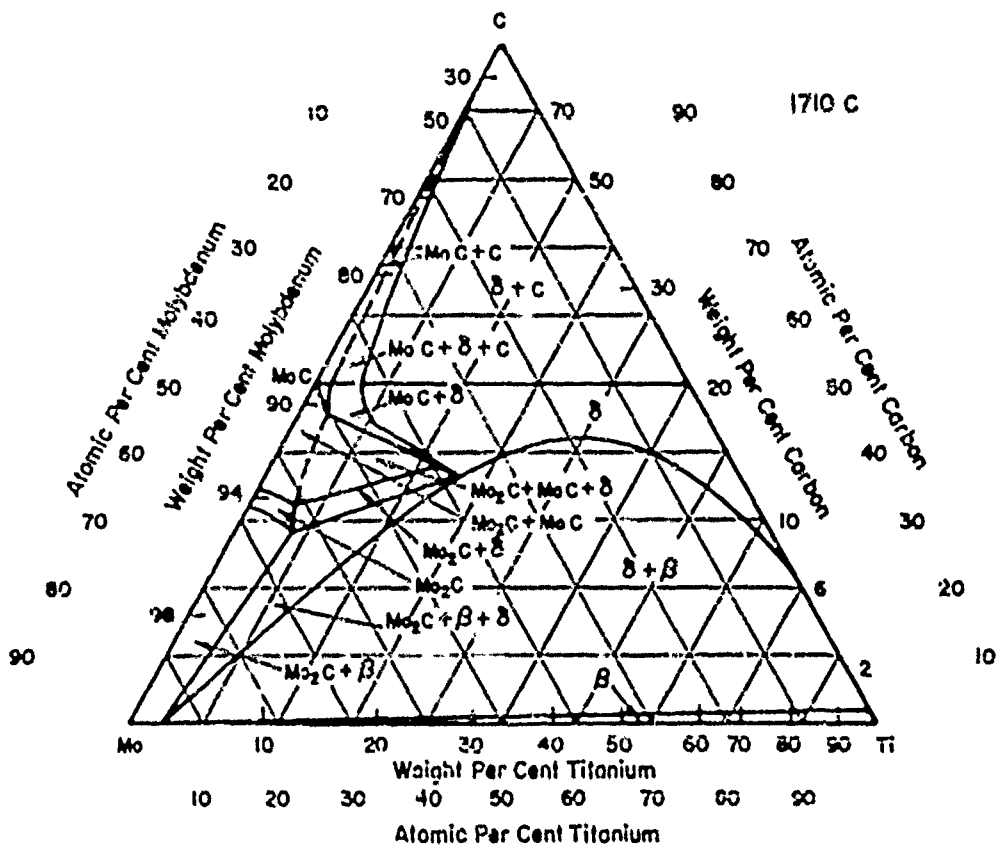
MOLYBDENUM-CARBON-SILICON SYSTEM (214)



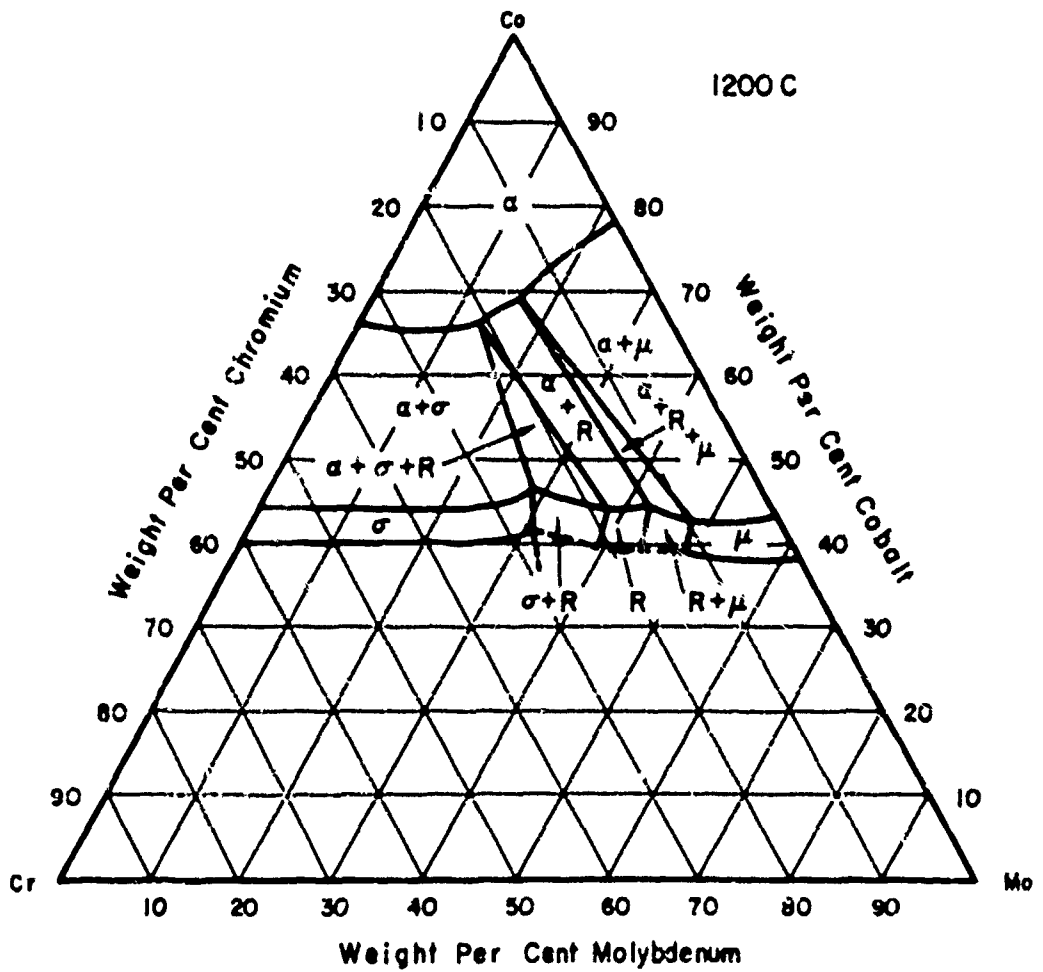
MOLYBDENUM-CARBON-SILICON SYSTEM⁽²¹⁴⁾



MOLYBDENUM-CARBON-TITANIUM SYSTEM(215)



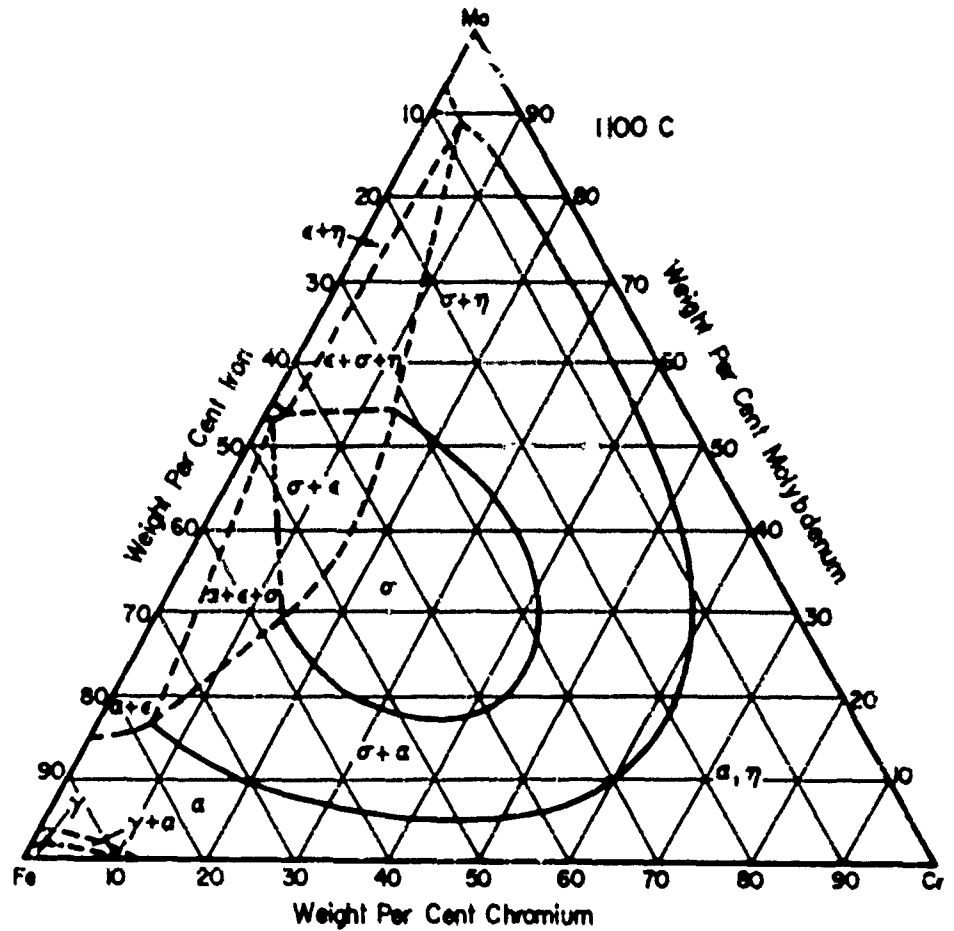
MOLYBDENUM-CHROMIUM-COBALT SYSTEM(226)



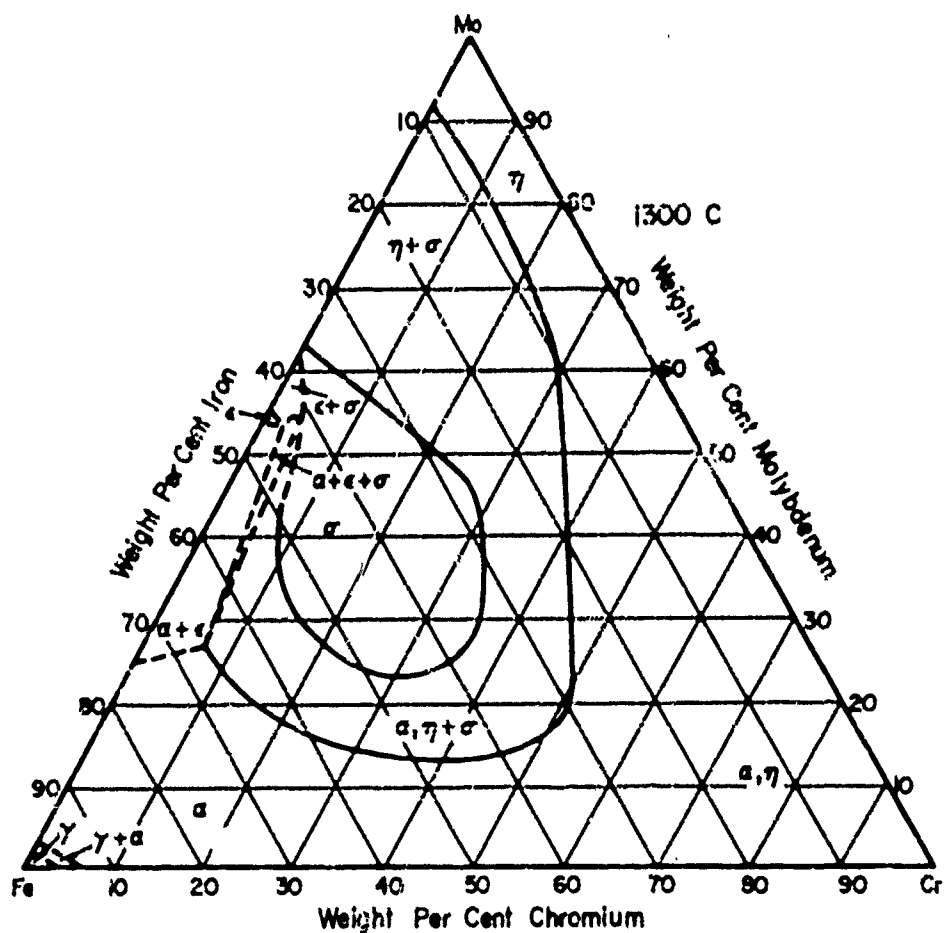
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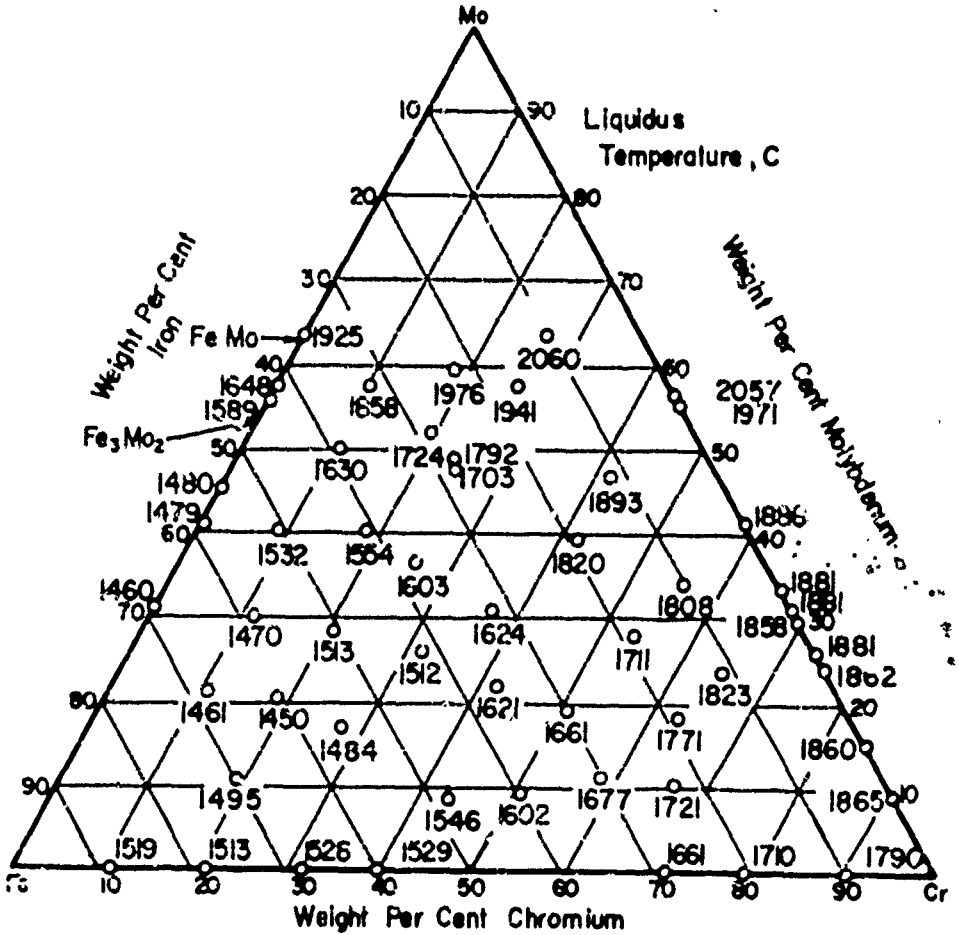
MOLYBDENUM-CHROMIUM-IRON SYSTEM(216)



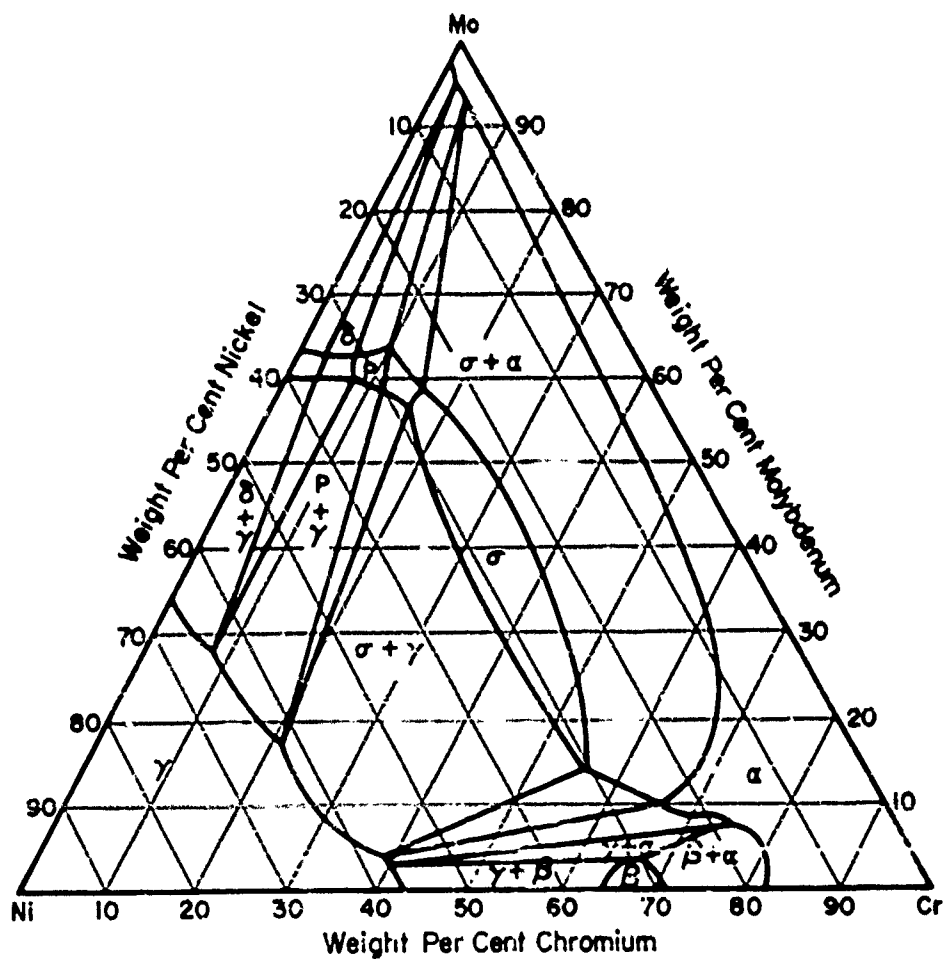
MOLYBDENUM-CHROMIUM-IRON SYSTEM(216)



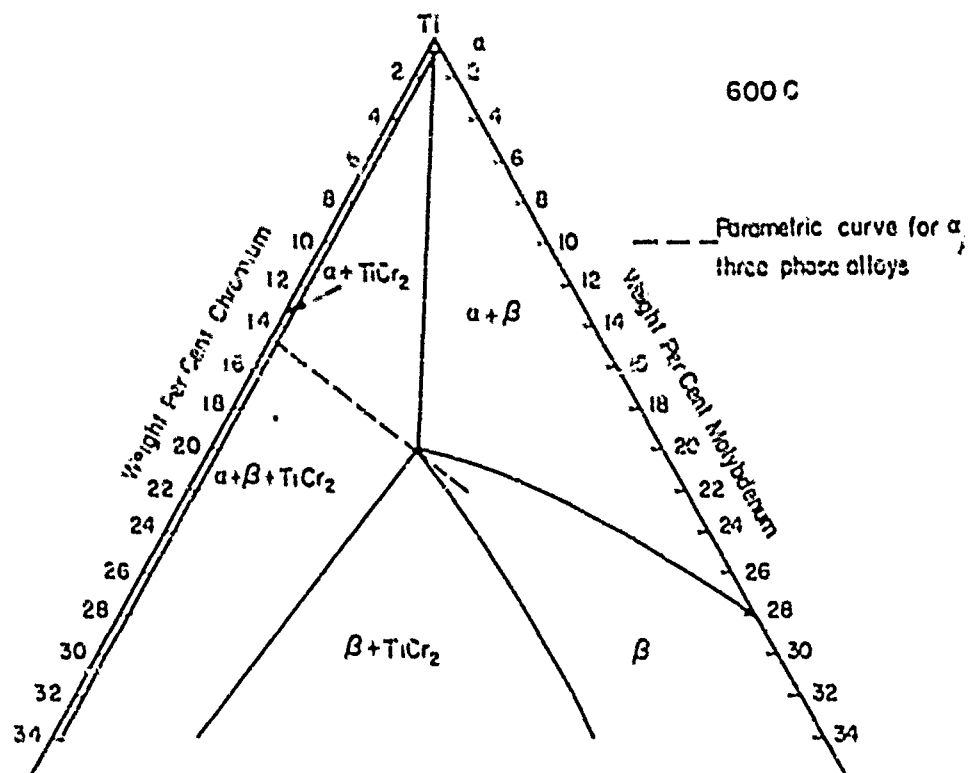
MOLYBDENUM-CHROMIUM-IRON SYSTEM⁽²¹⁶⁾



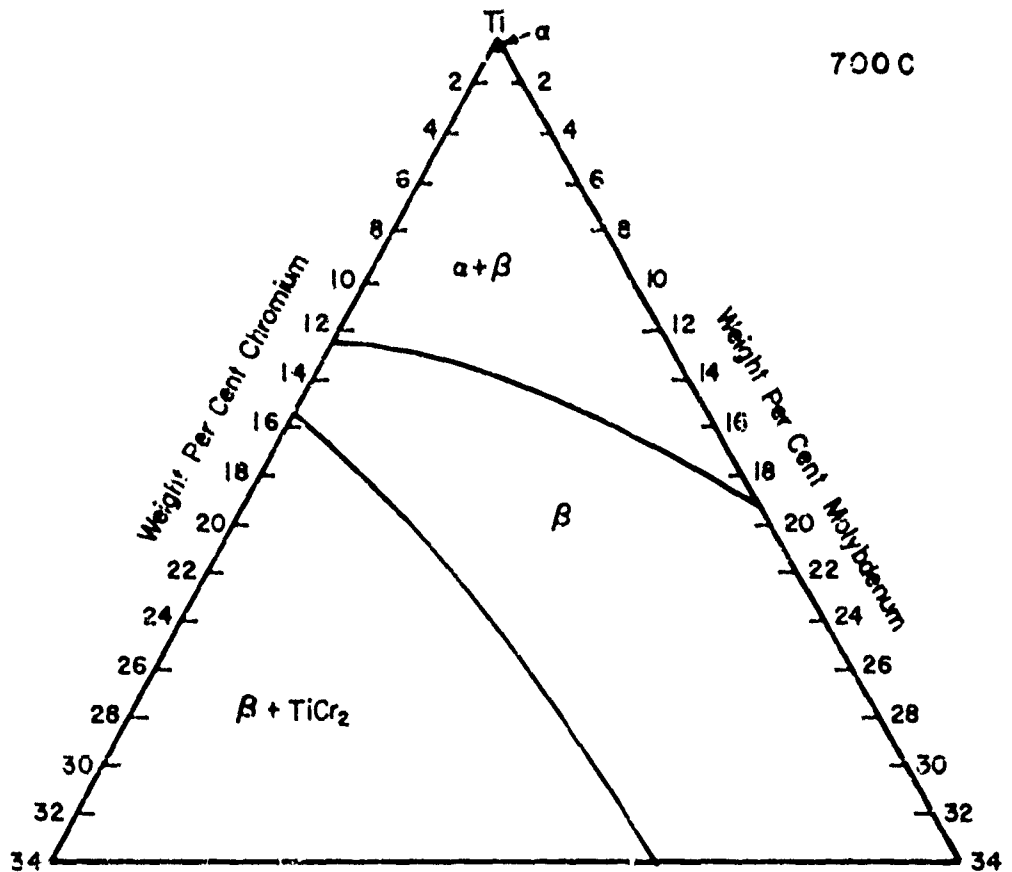
MOLYBDENUM-CHROMIUM-NICKEL SYSTEM⁽⁶⁴⁾



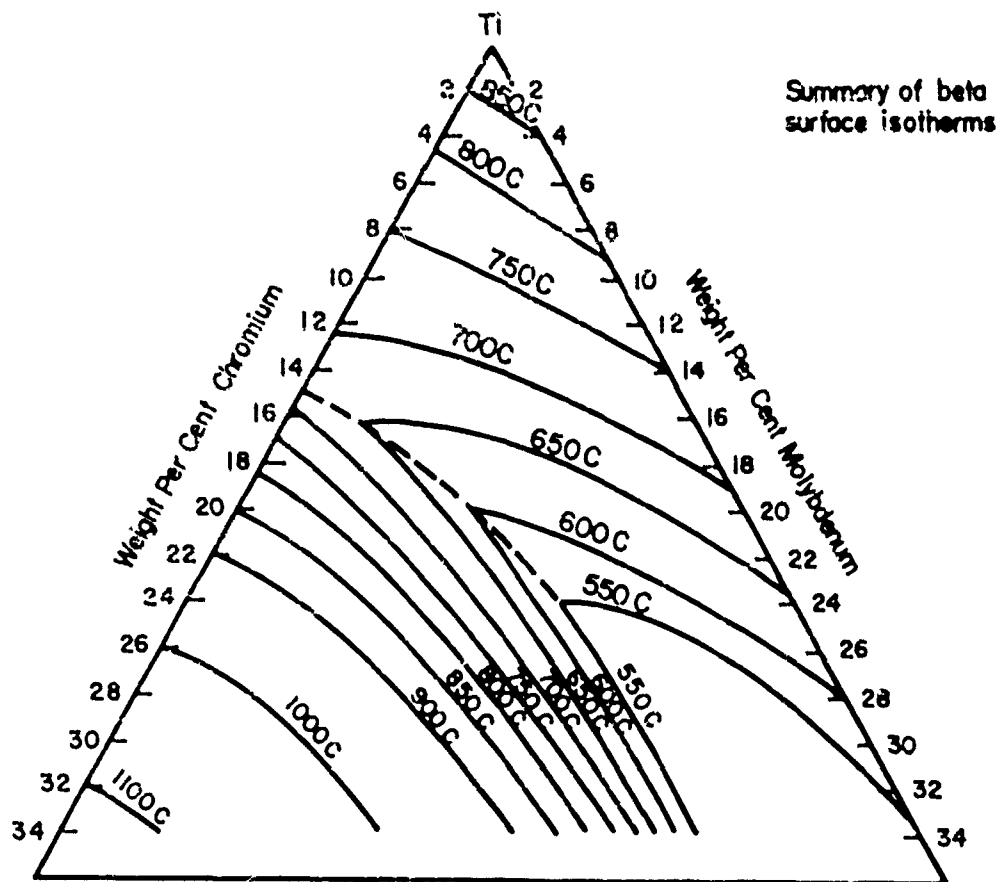
MOLYBDENUM-CHROMIUM-TITANIUM SYSTEM (217)



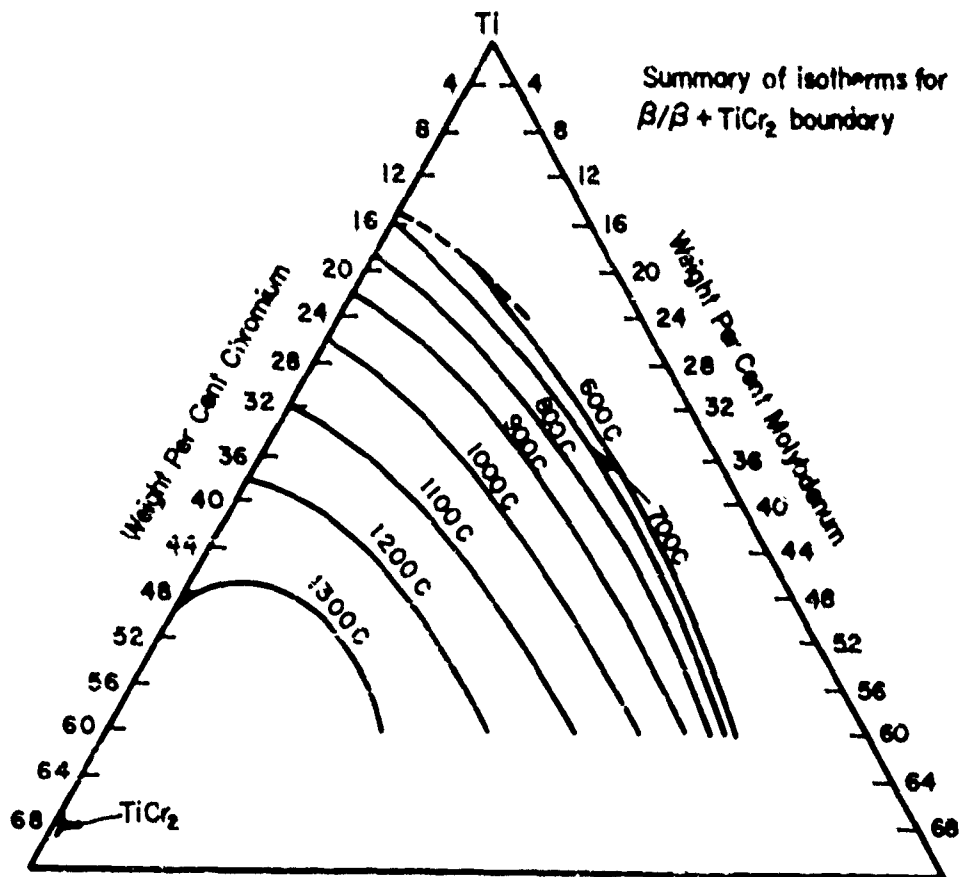
MOLYBDENUM-CHROMIUM-TITANIUM SYSTEM(217)



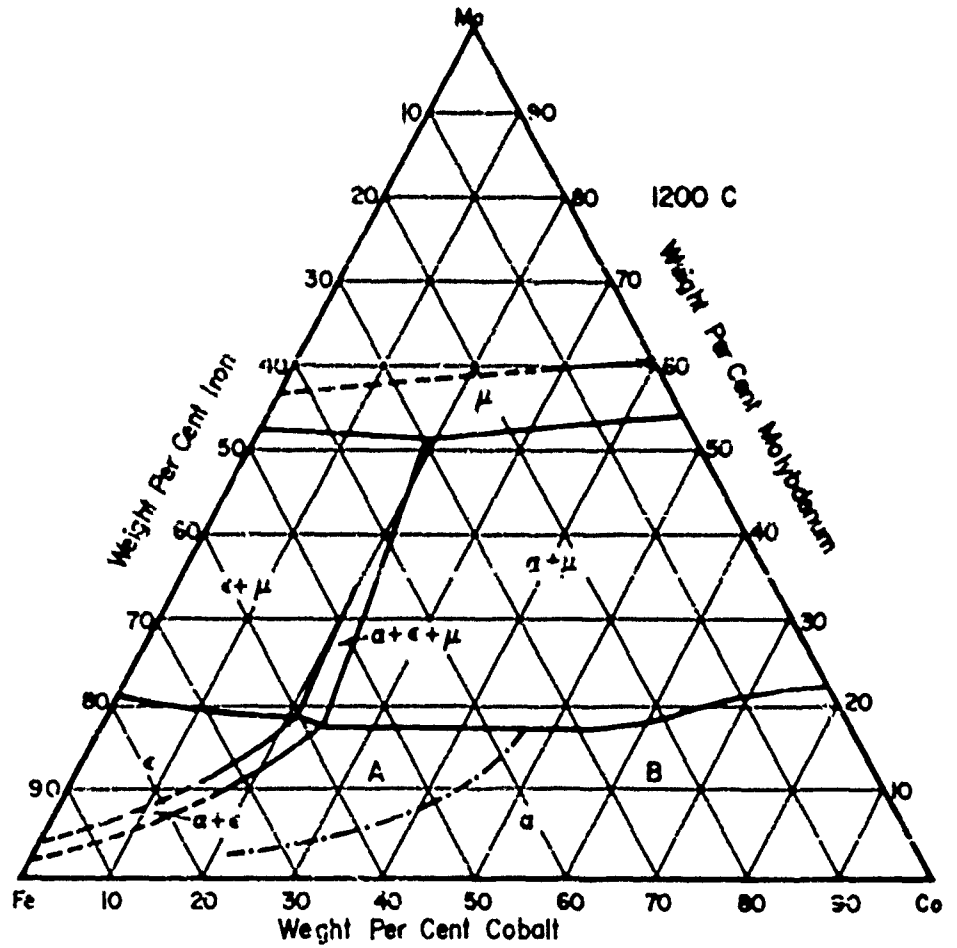
MOLYBDENUM-CHROMIUM-TITANIUM SYSTEM(217)



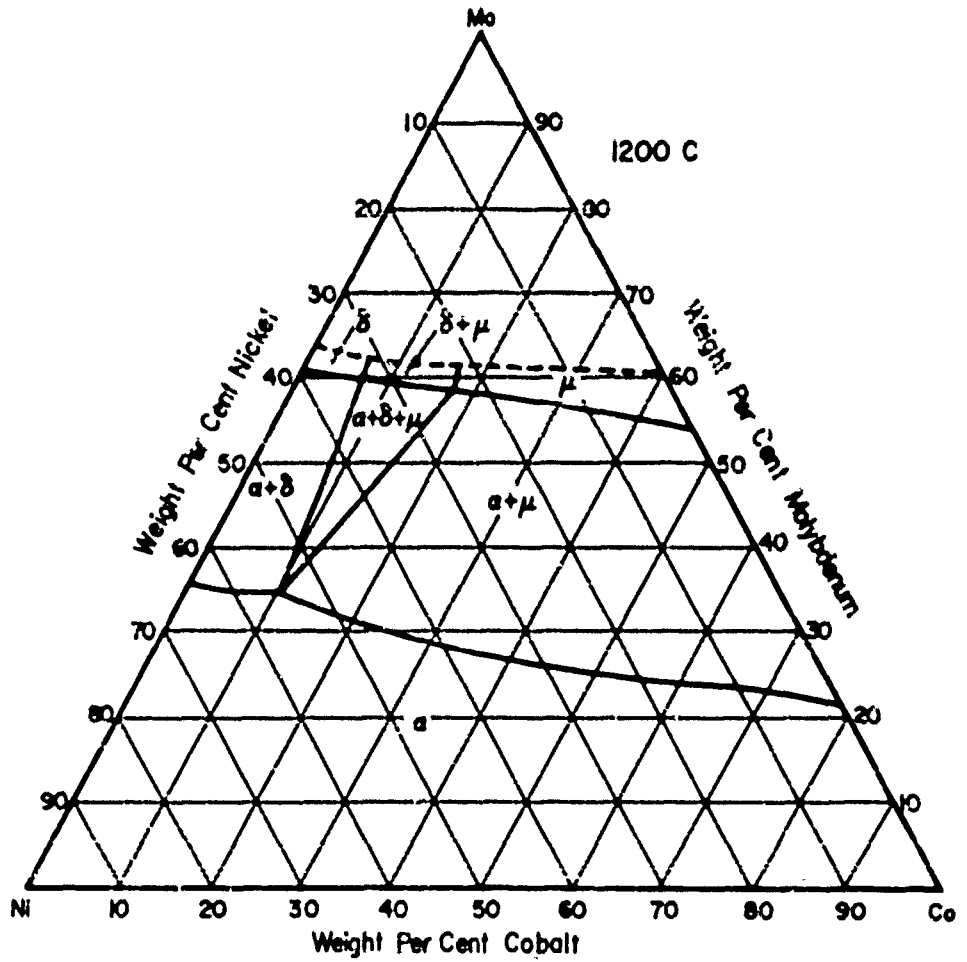
MOLYBDENUM-CHROMIUM-TITANIUM SYSTEM(217)



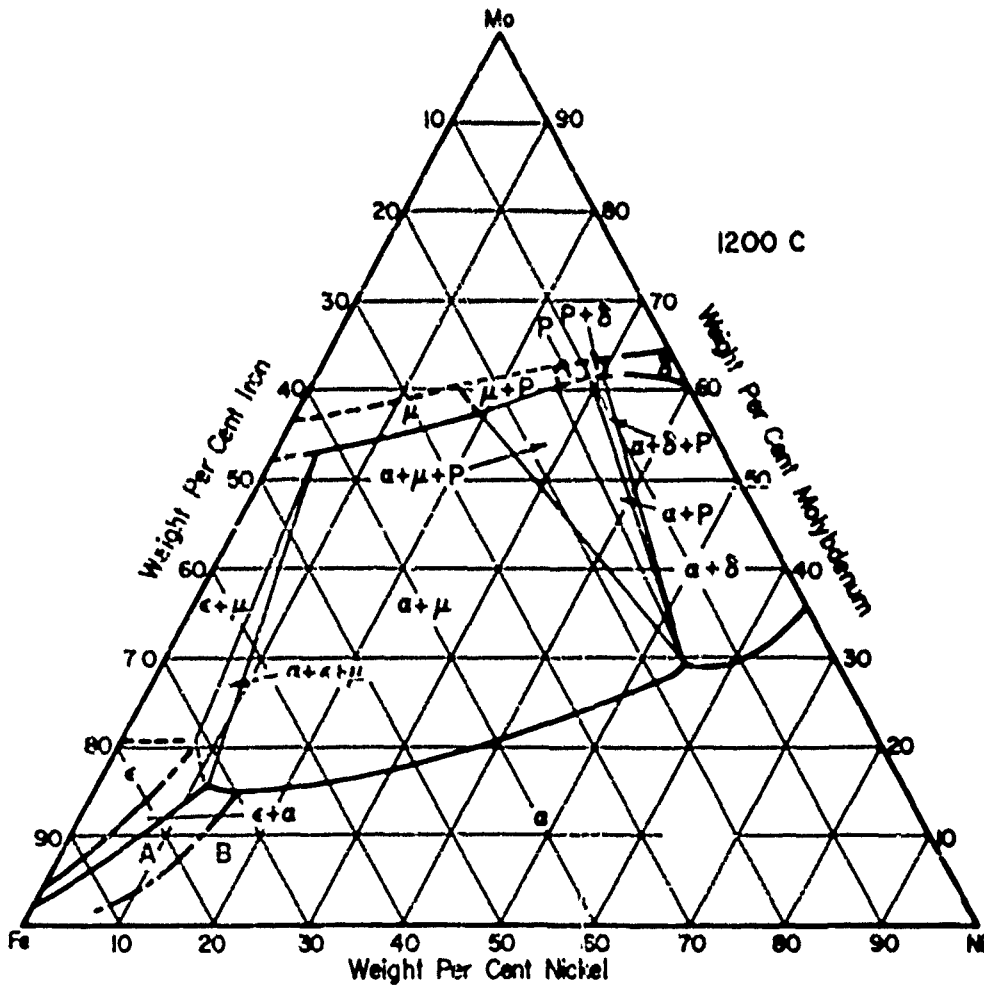
MOLYBDENUM-COBALT-IRON SYSTEM(227)



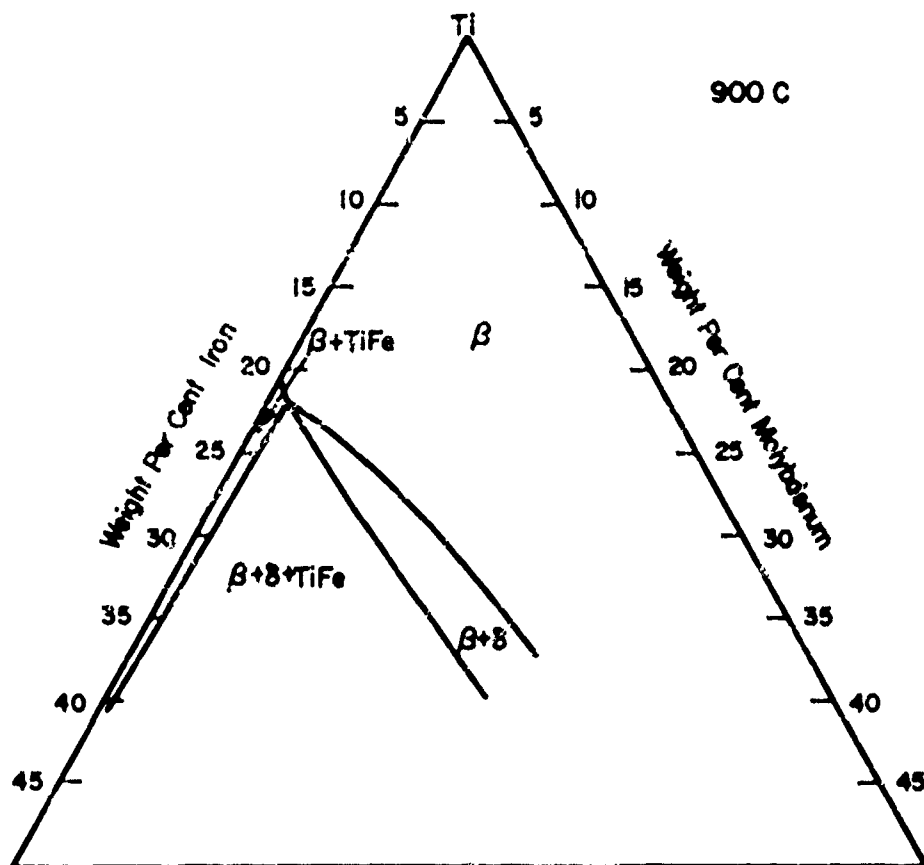
MOLYBDENUM-COBALT-NICKEL SYSTEM(227)



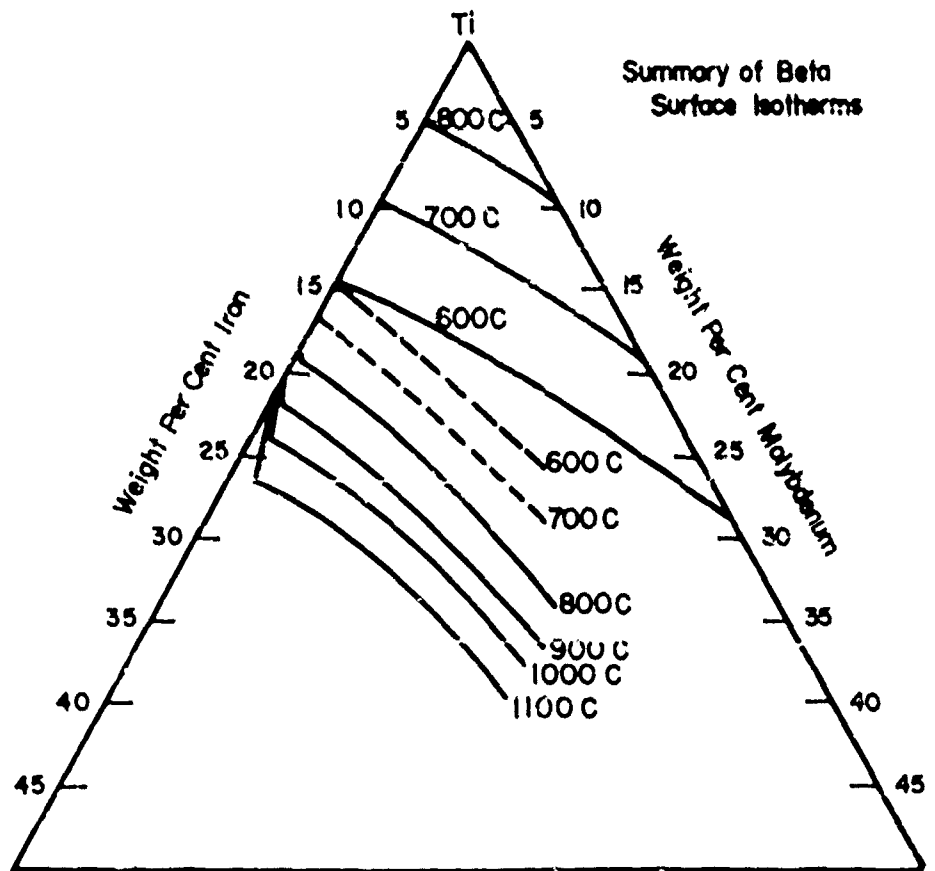
MOLYBDENUM-IRON-NICKEL SYSTEM⁽²²⁷⁾



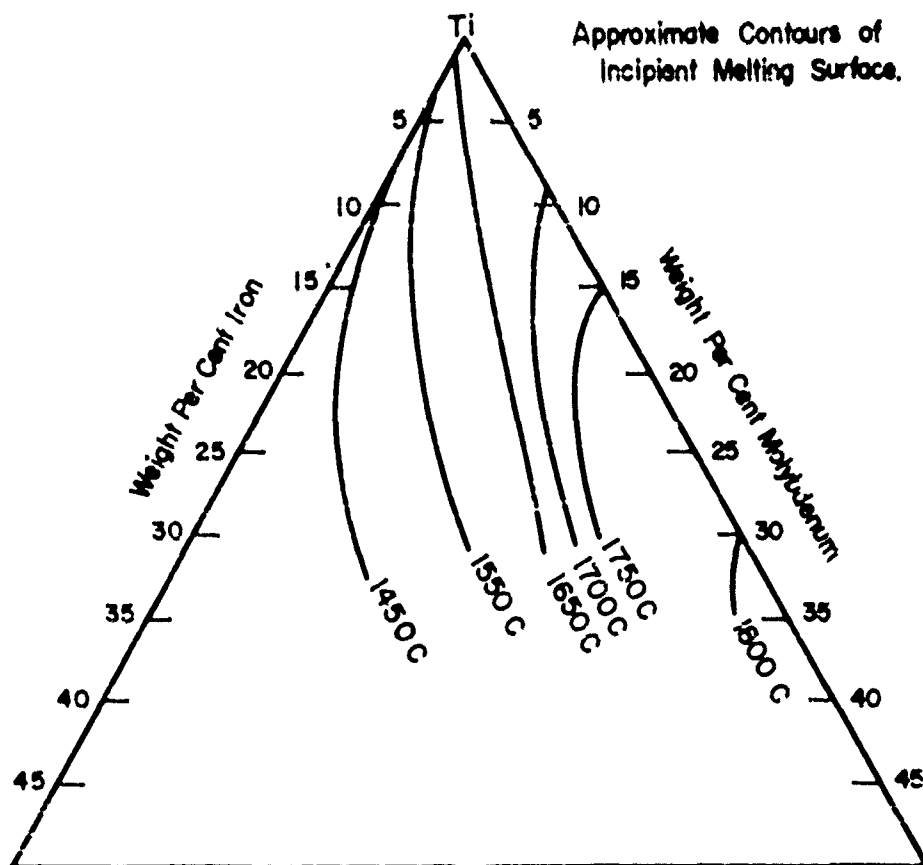
MOLYBDENUM-IRON-TITANIUM SYSTEM(217)



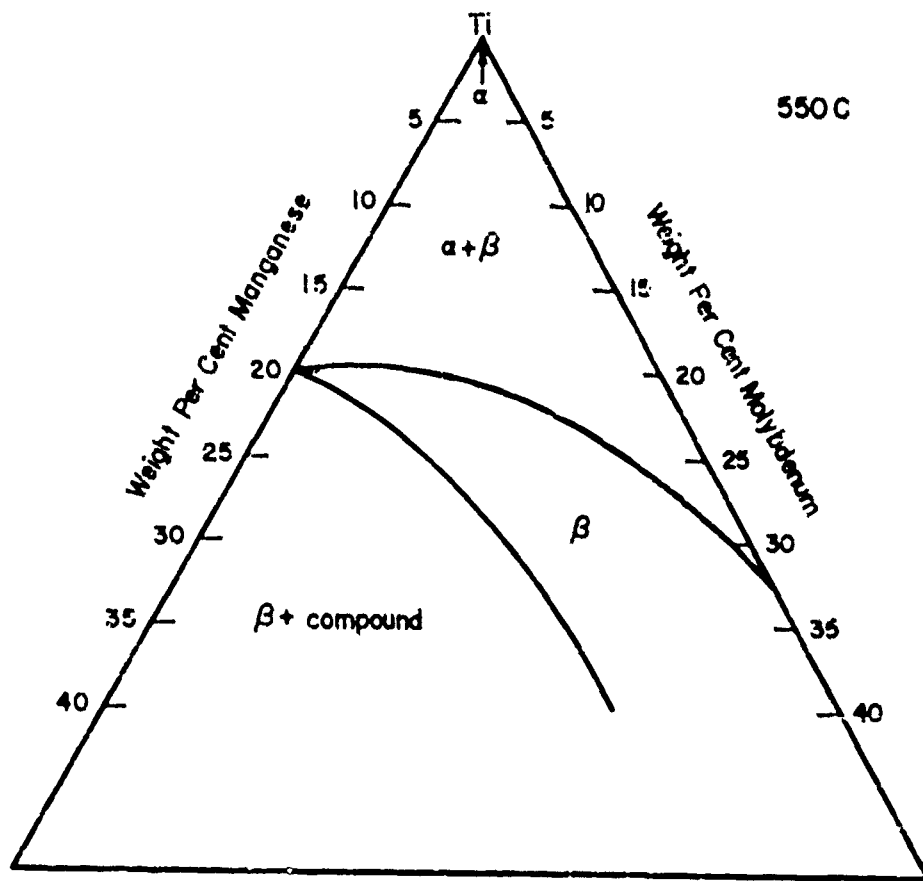
MOLYBDENUM-IRON-TITANIUM SYSTEM(217)



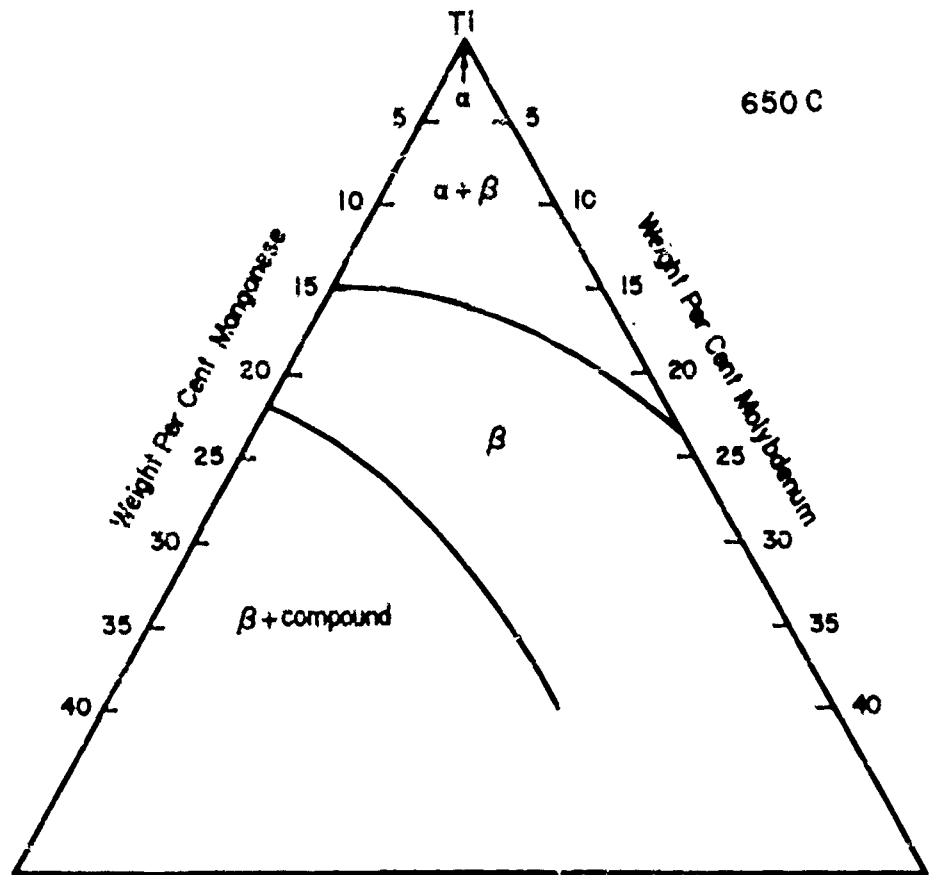
MOLYBDENUM-IRON-TITANIUM SYSTEM⁽²¹⁷⁾



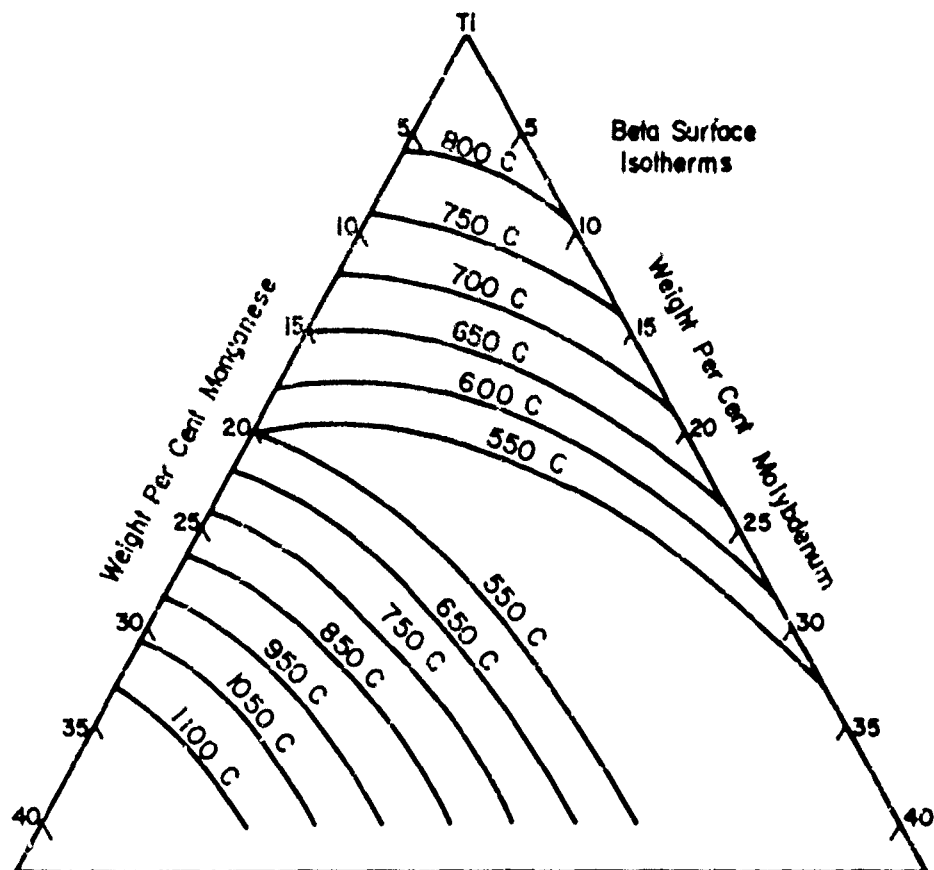
MOLYBDENUM-MANGANESE-TITANIUM SYSTEM(217)



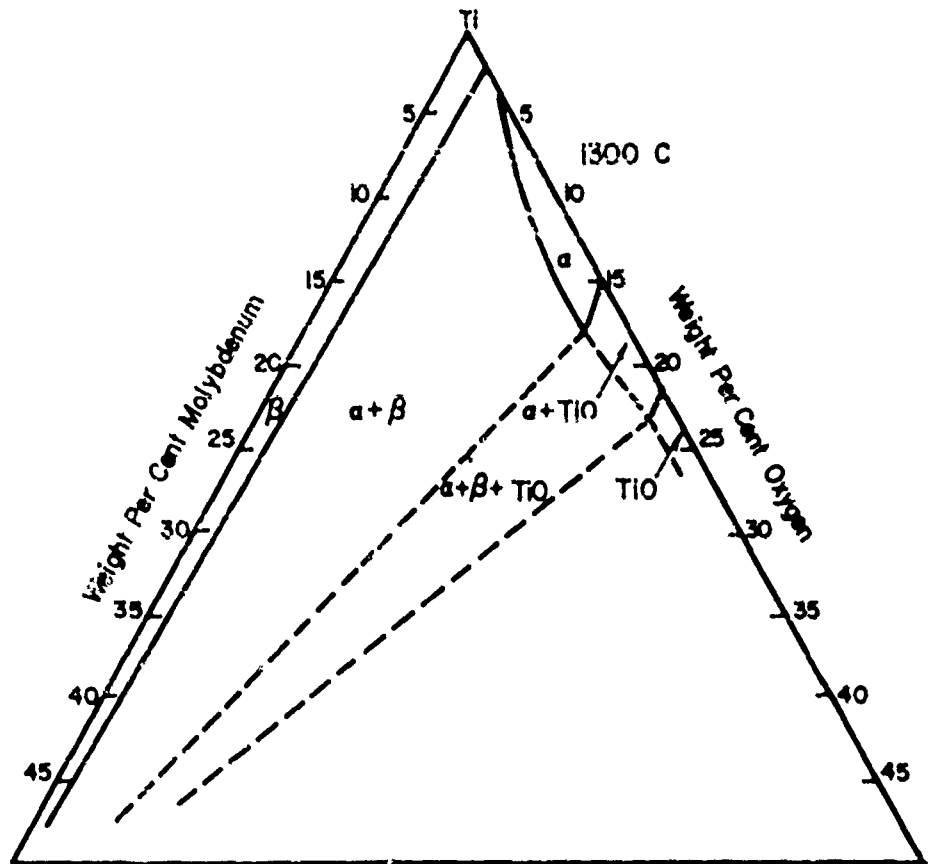
MOLYBDENUM-MANGANESE-TITANIUM SYSTEM(217)



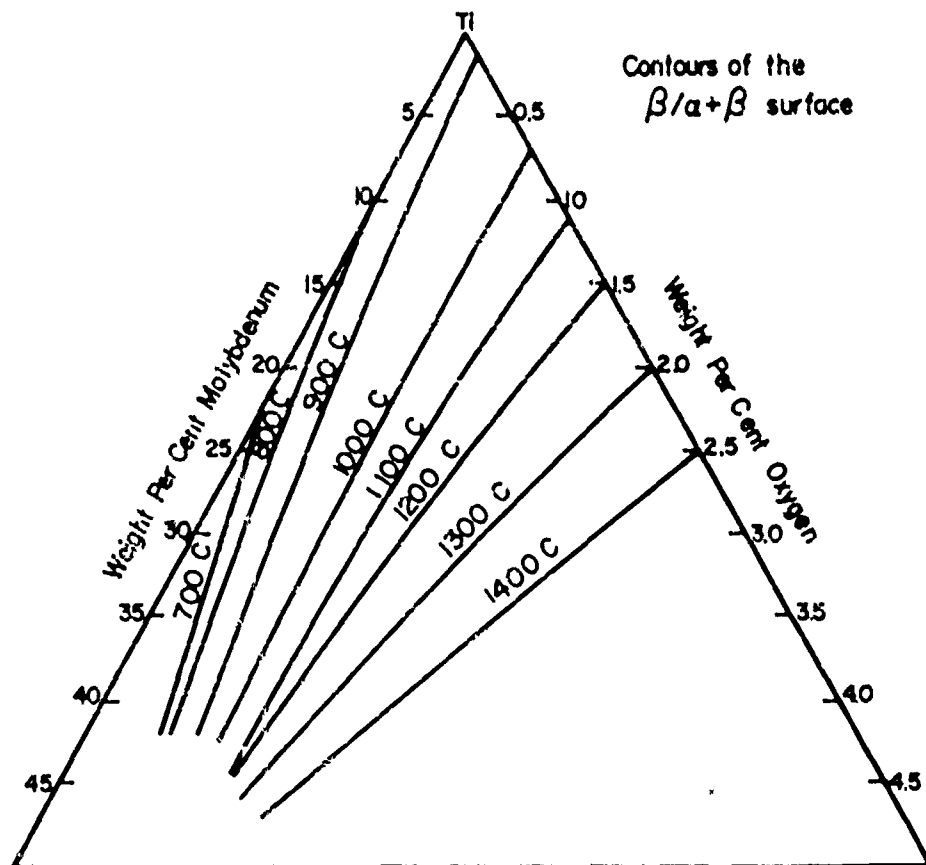
MOLYBDENUM-MANGANESE-TITANIUM SYSTEM(217)



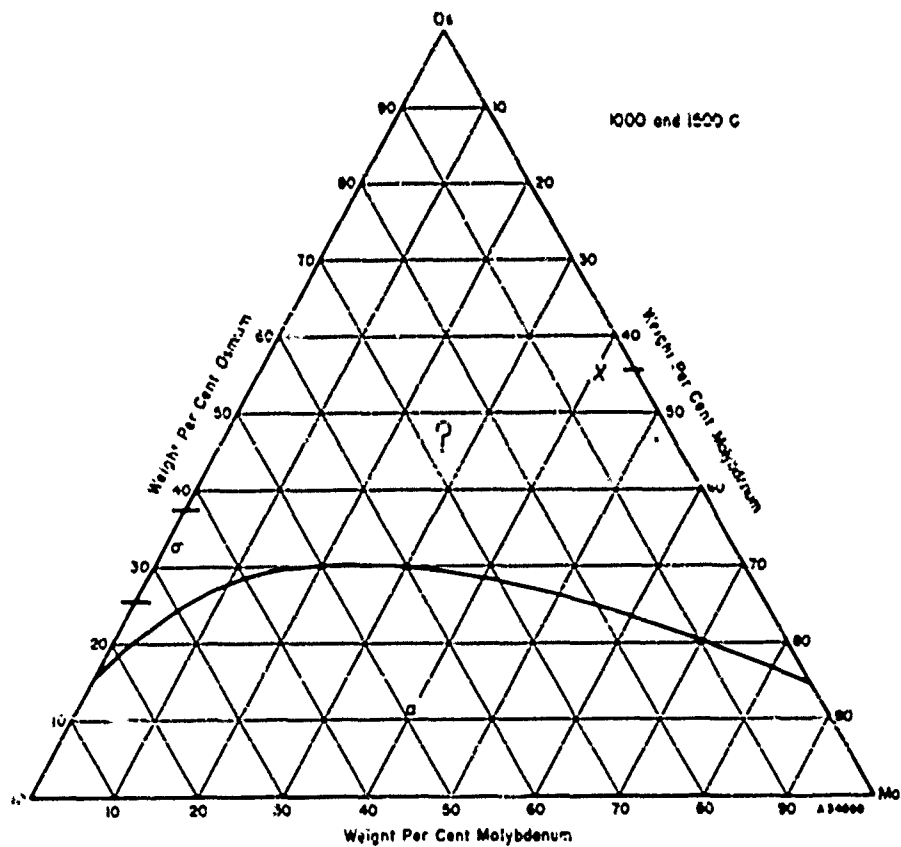
MOLYBDENUM-OXYGEN-TITANIUM SYSTEM(217)



MOLYBDENUM-OXYGEN-TITANIUM SYSTEM(217)



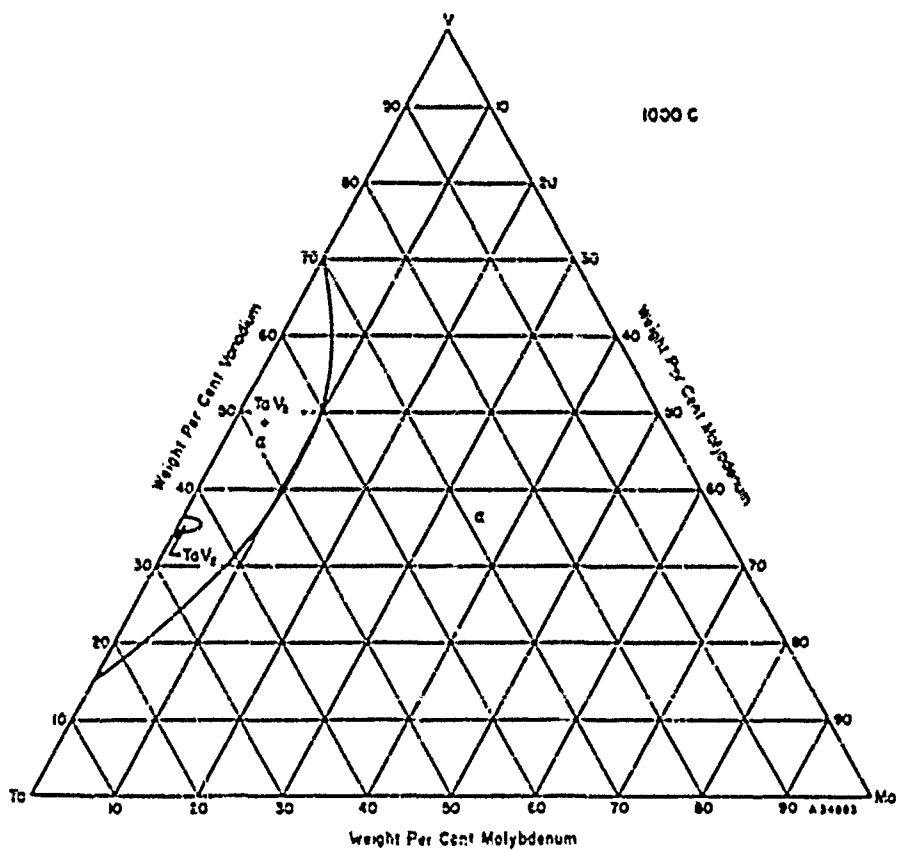
MOLYBDENUM-TANTALUM-OSMIUM SYSTEM(206)



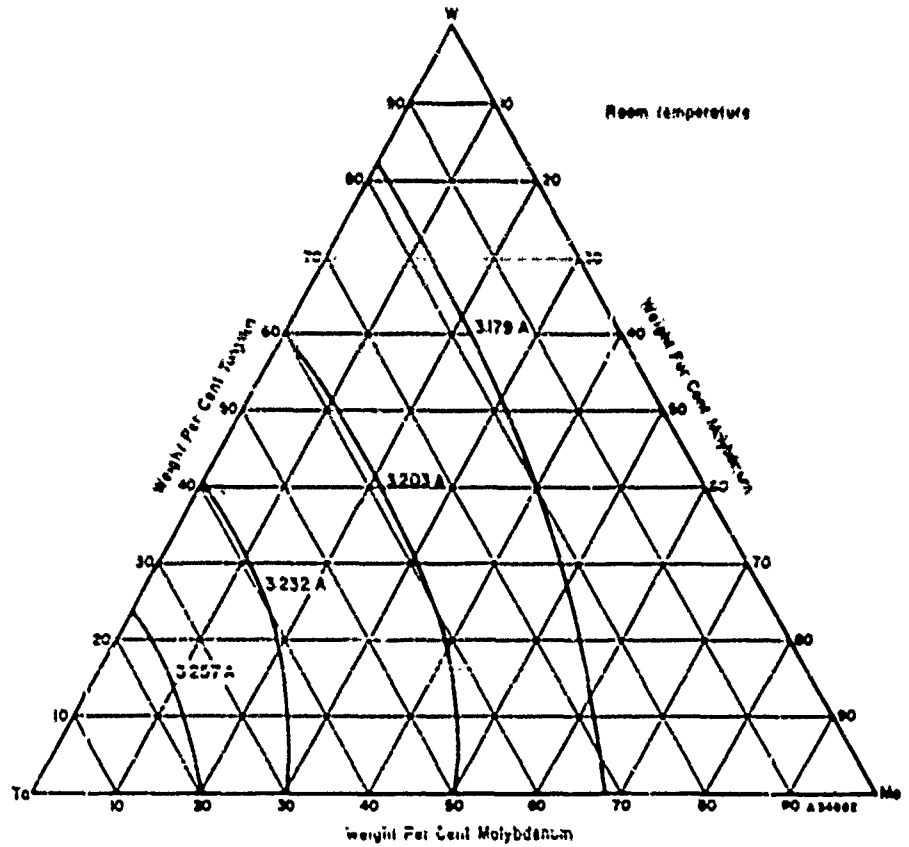
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MOLYBDENUM-TANTALUM-VANADIUM SYSTEM(206)



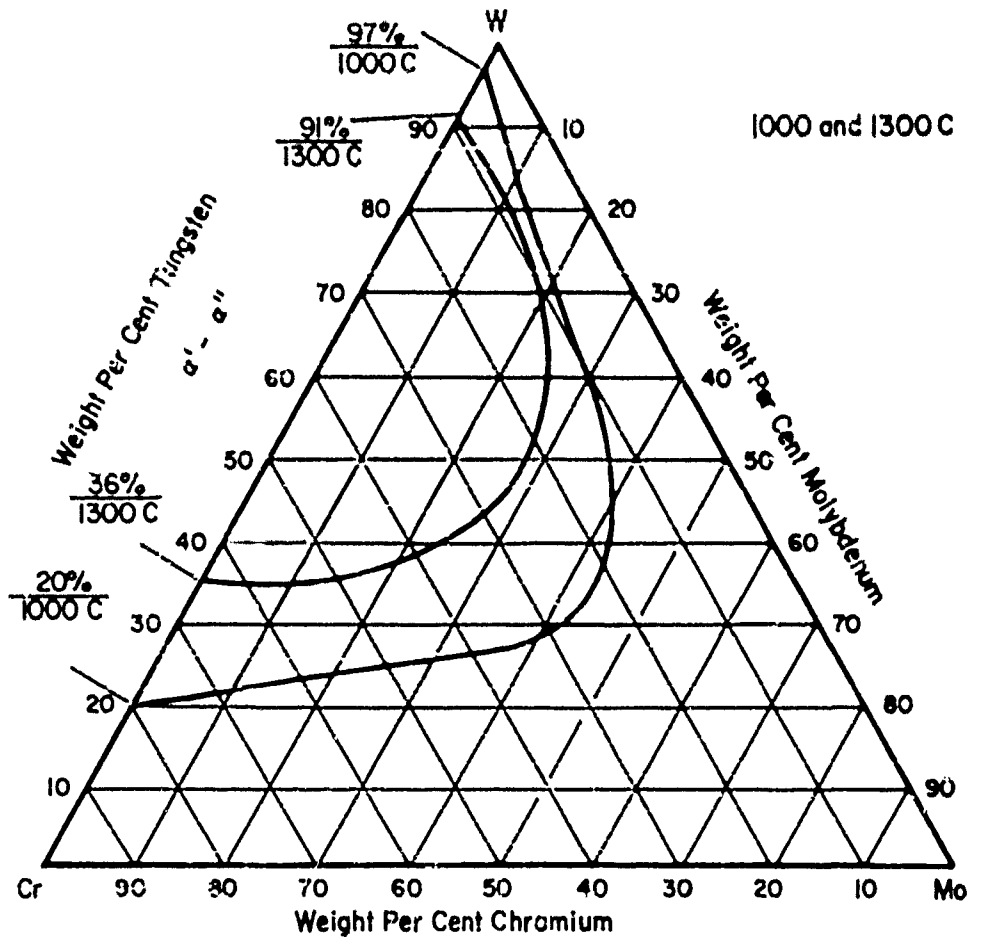
MOLYBDENUM-TANTALUM-TUNGSTEN SYSTEM⁽²⁰⁶⁾



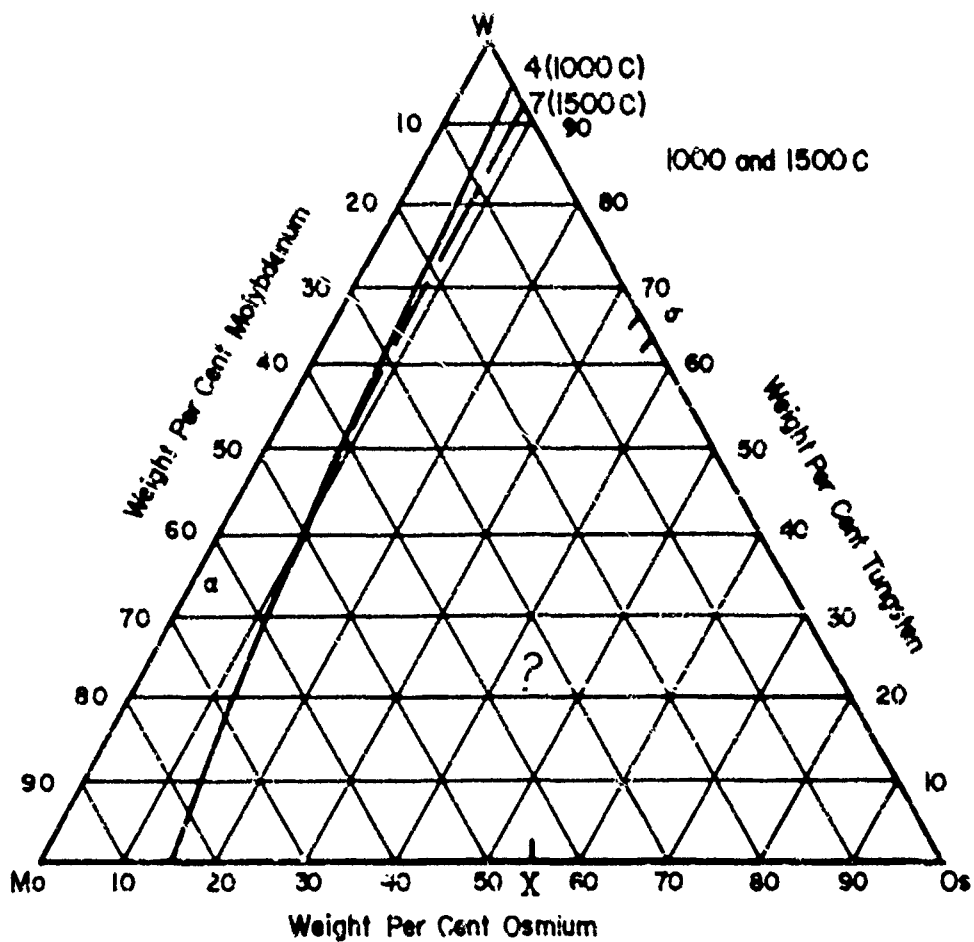
1. The first part of the document is a list of names and titles, including "The Hon. Mr. Justice" and "The Hon. Mr. Justice".



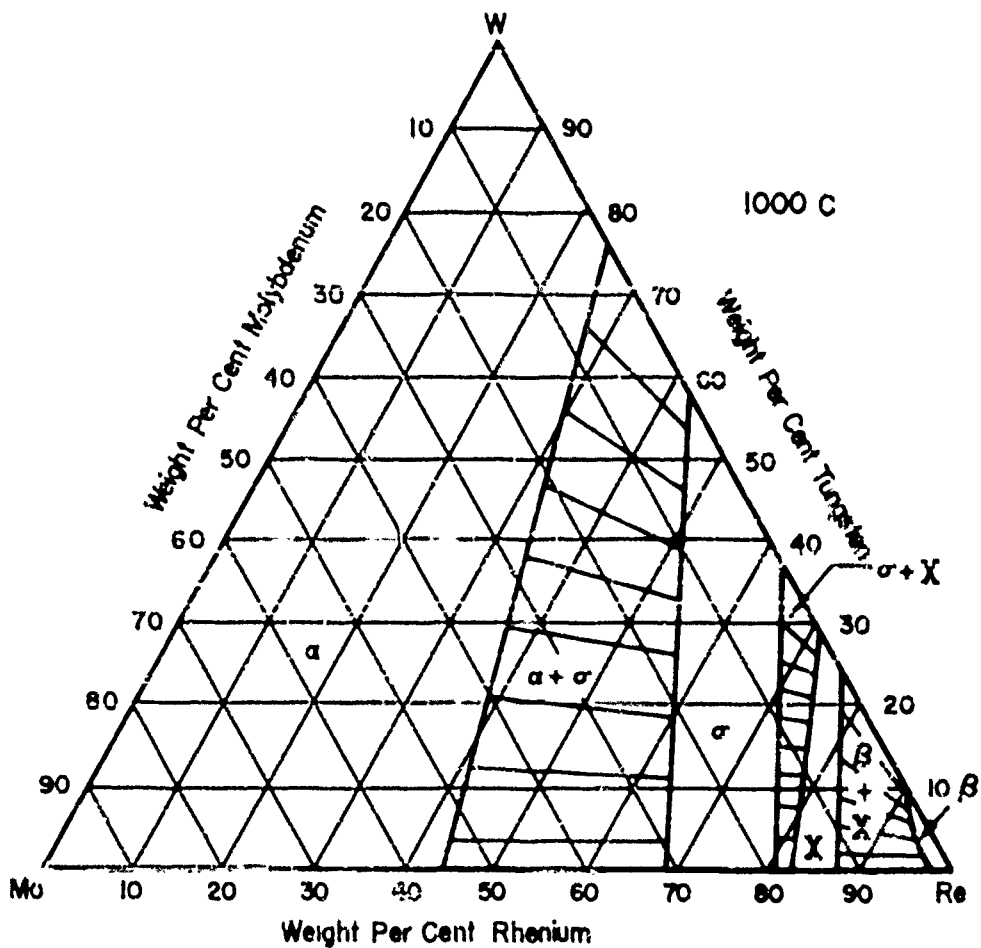
MOLYBDENUM-TUNGSTEN-CHROMIUM SYSTEM(218)



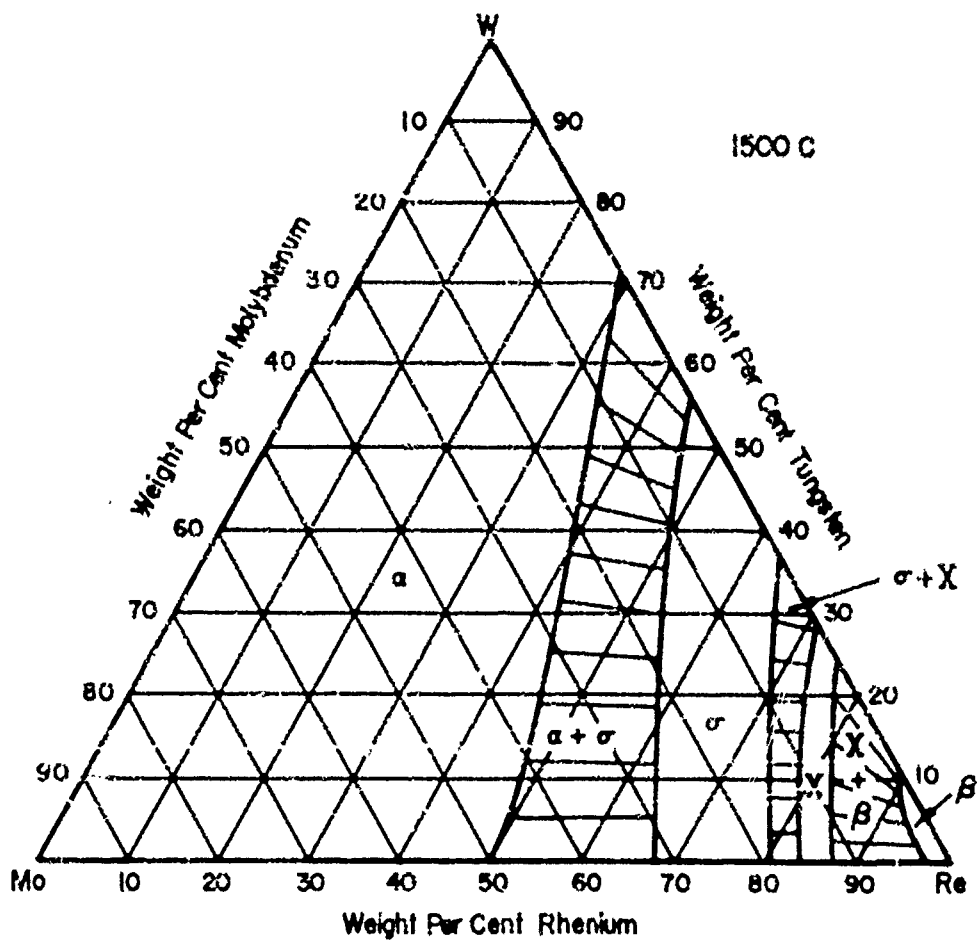
MOLYBDENUM-TUNGSTEN-OSMIUM SYSTEM(206)



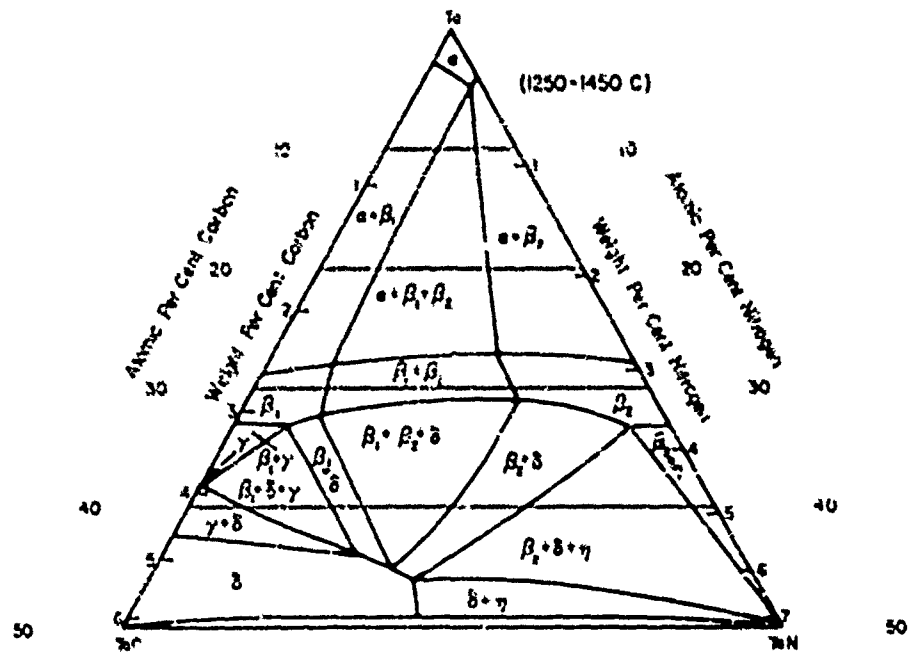
MOLYBDENUM-TUNGSTEN-RHENIUM SYSTEM(206)



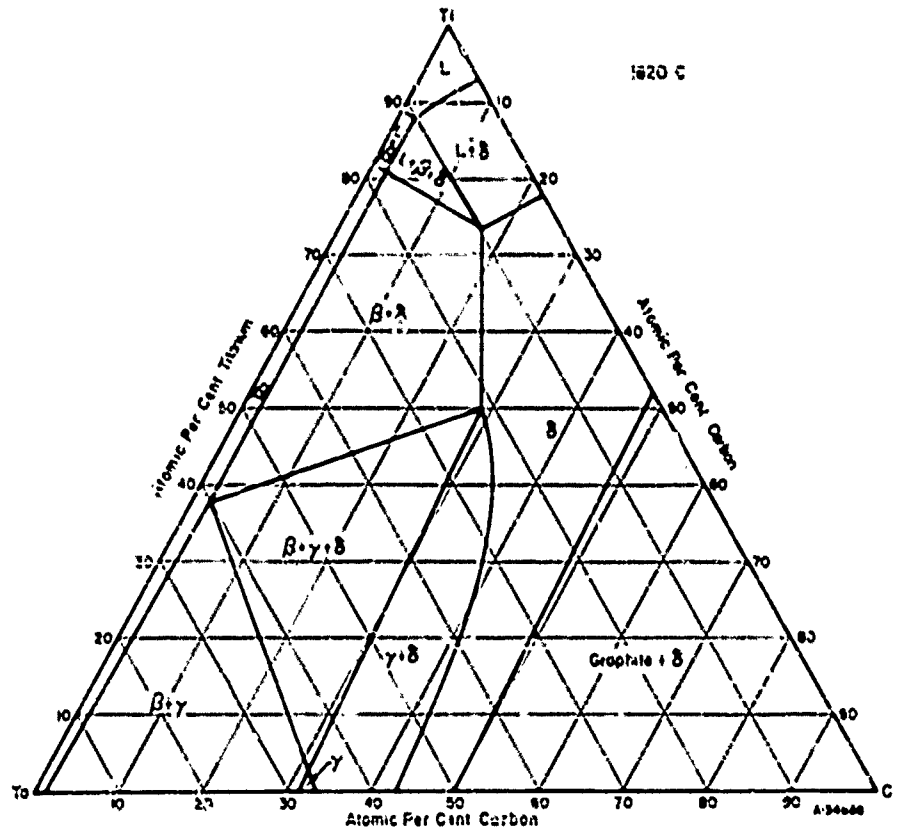
MOLYBDENUM-TUNGSTEN-RHENIUM SYSTEM(206)



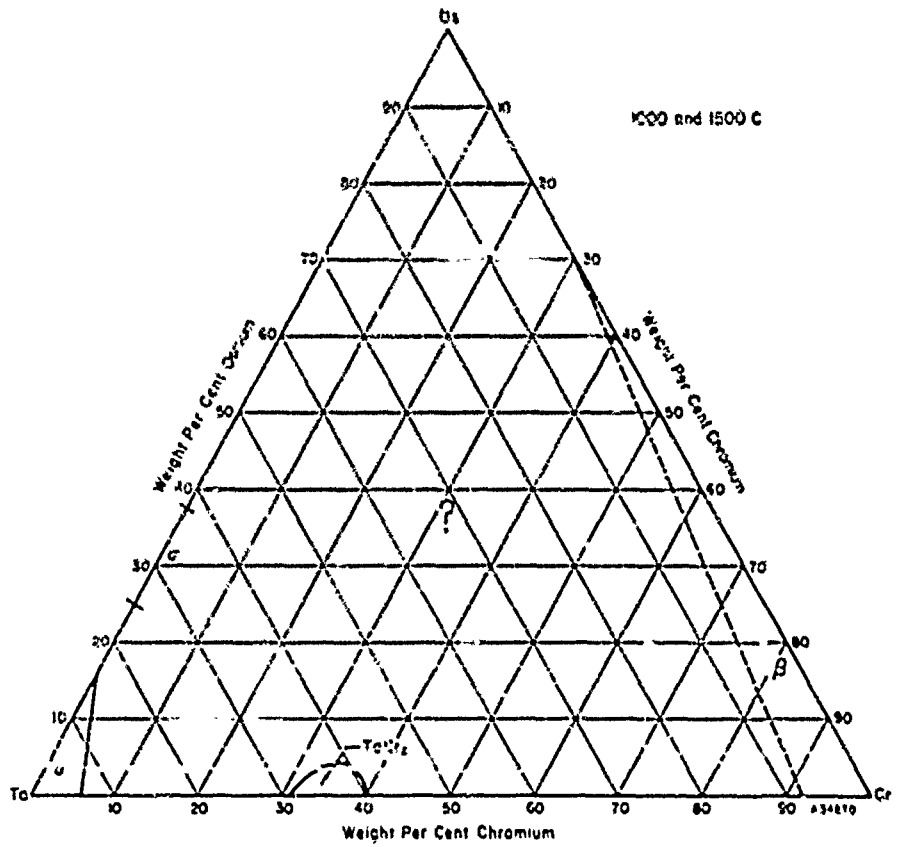
TANTALUM-TANTALUM CARBIDE-TANTALUM NITRIDE SYSTEM(219)



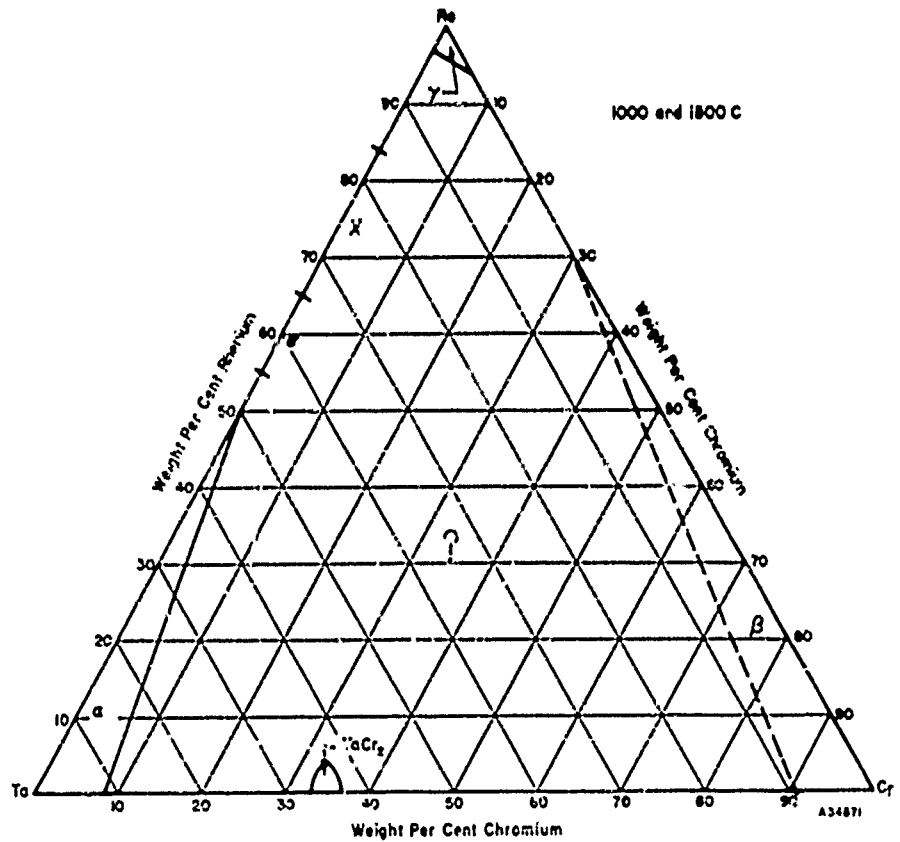
TANTALUM-CARBON-TITANIUM SYSTEM(220)



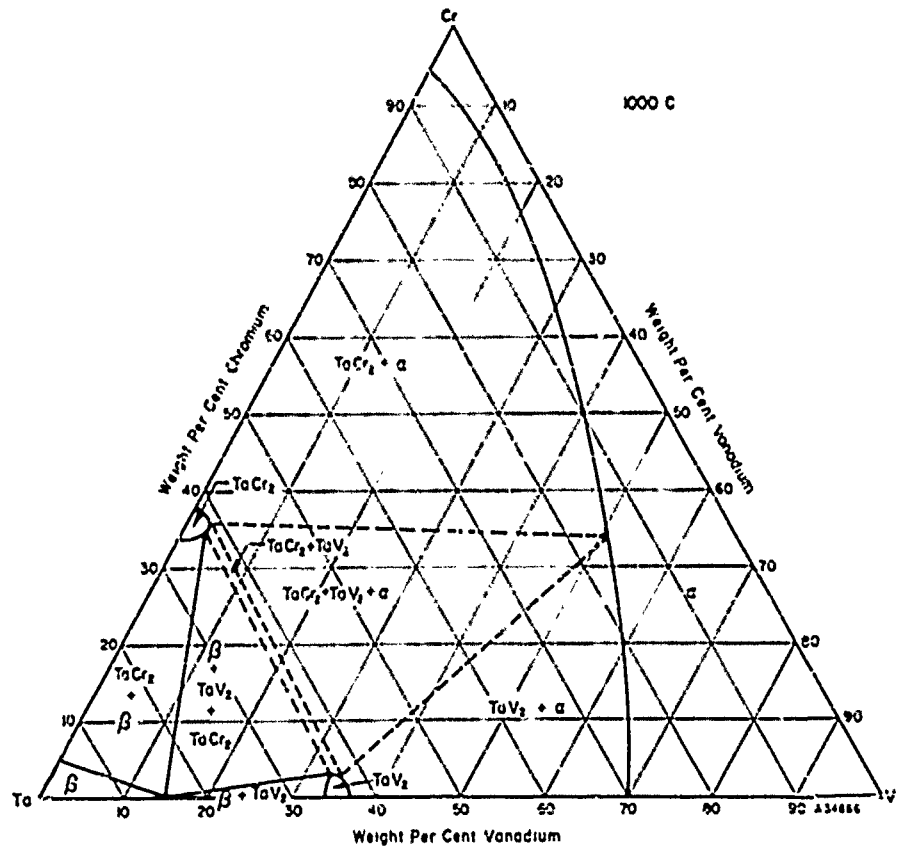
TANTALUM-CHROMIUM-OSMIUM SYSTEM (206)



TANTALUM-CHROMIUM-RHENIUM SYSTEM(206)



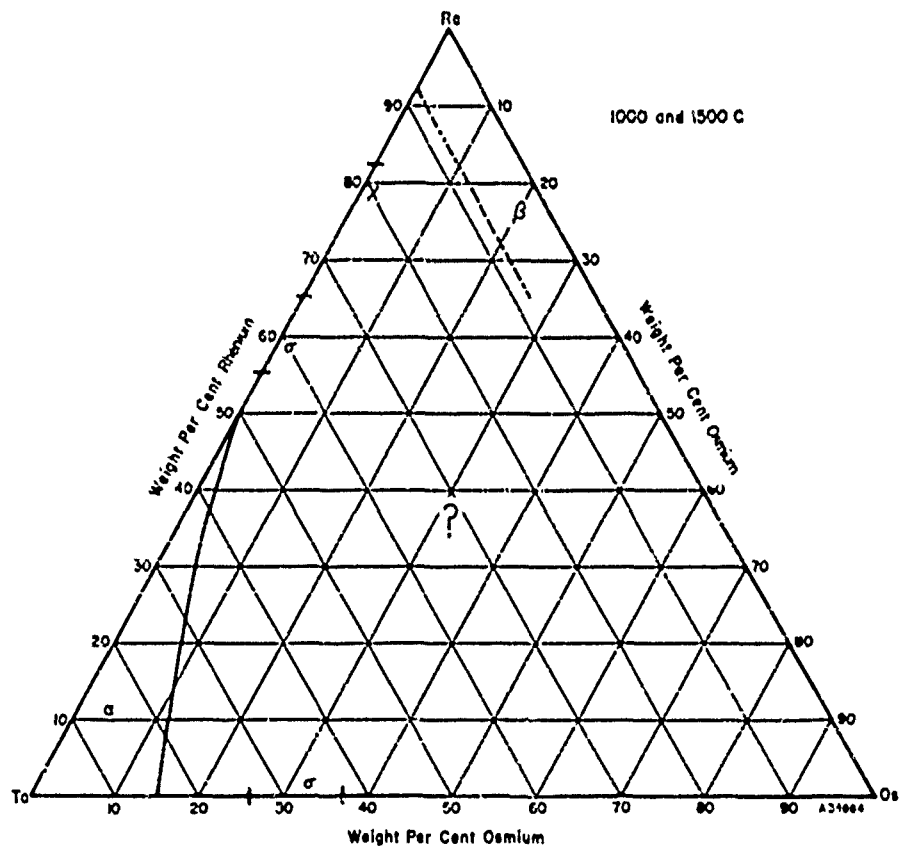
TANTALUM-CHROMIUM-VANADIUM SYSTEM(206)



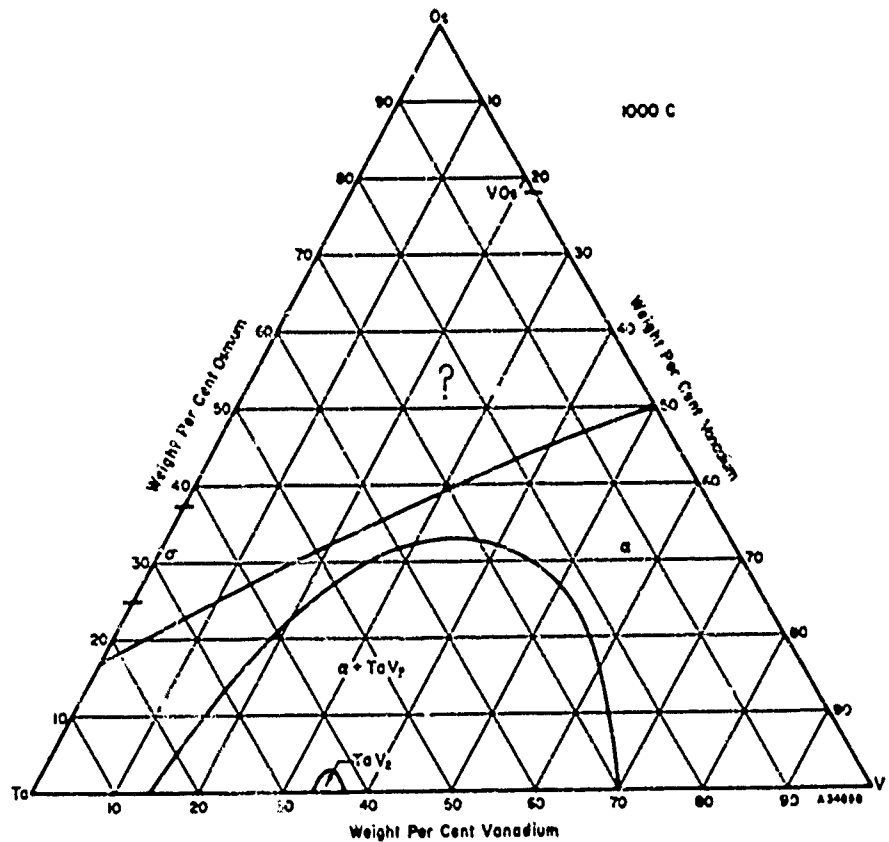
THE UNIVERSITY OF CHICAGO



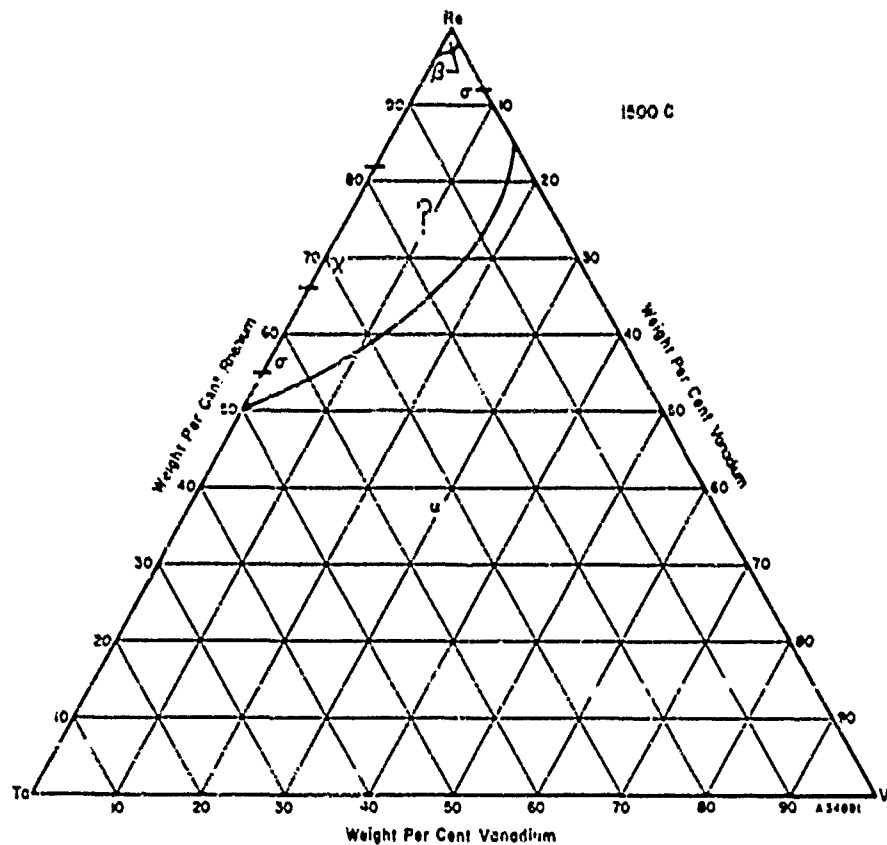
TANTALUM-OSMIUM-RHENIUM SYSTEM(206)



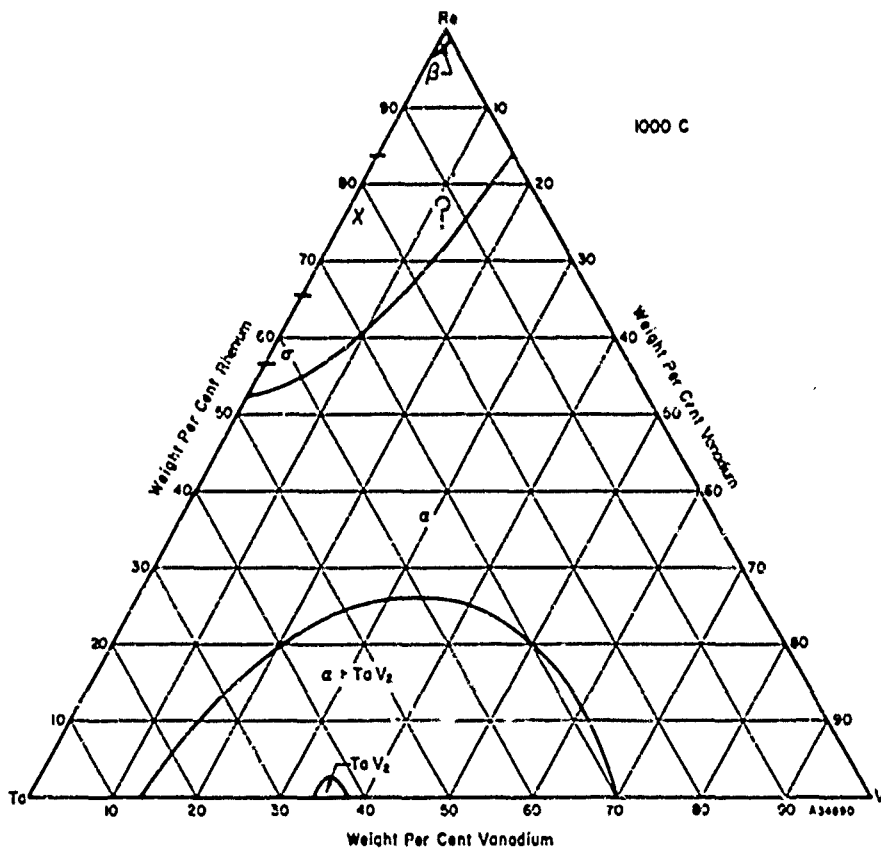
TANTALUM-OSMIUM-VANADIUM SYSTEM(206)



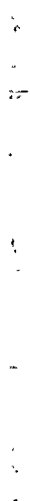
TANTALUM-OSMIUM-VANADIUM SYSTEM⁽²⁰⁶⁾



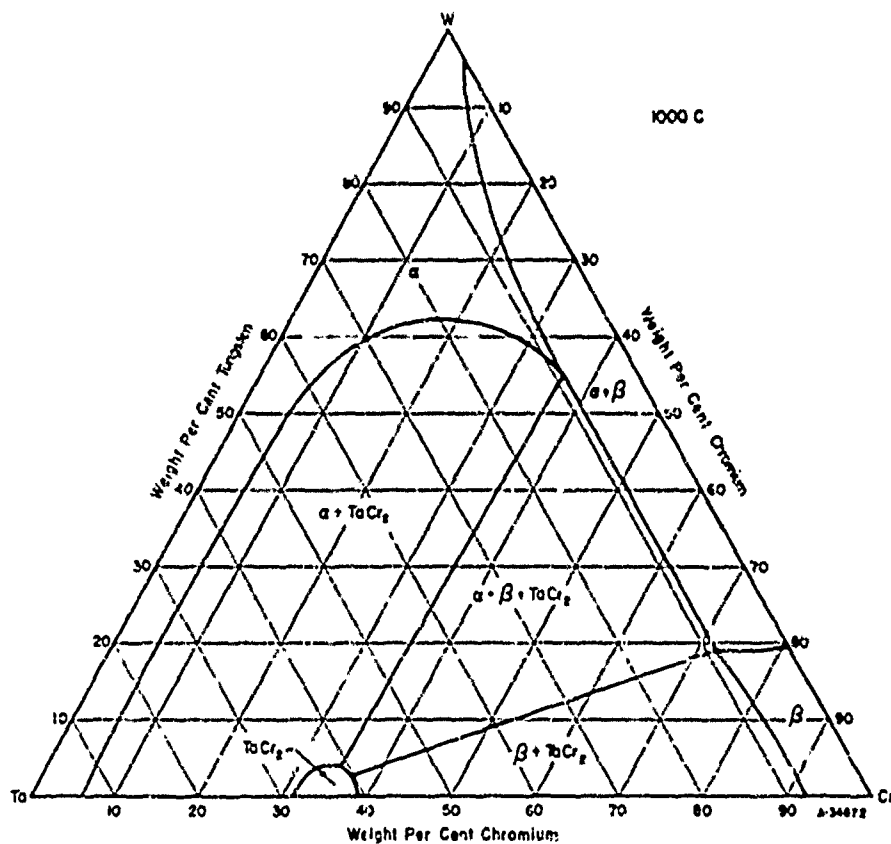
TANTALUM-RHENIUM-VANADIUM SYSTEM(206)



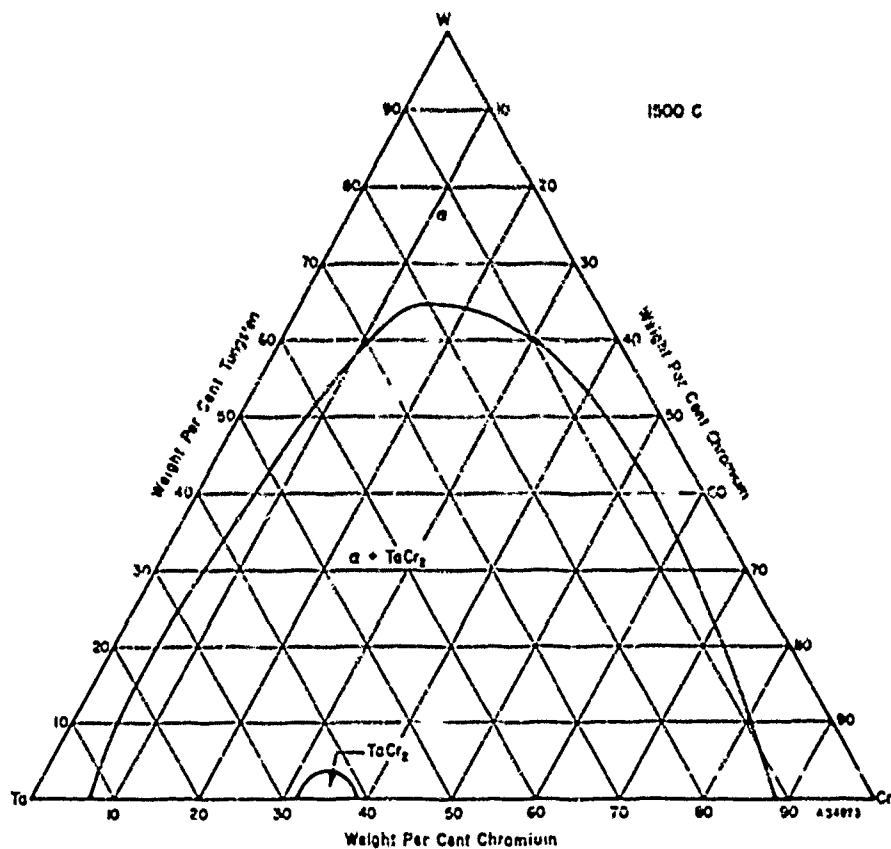
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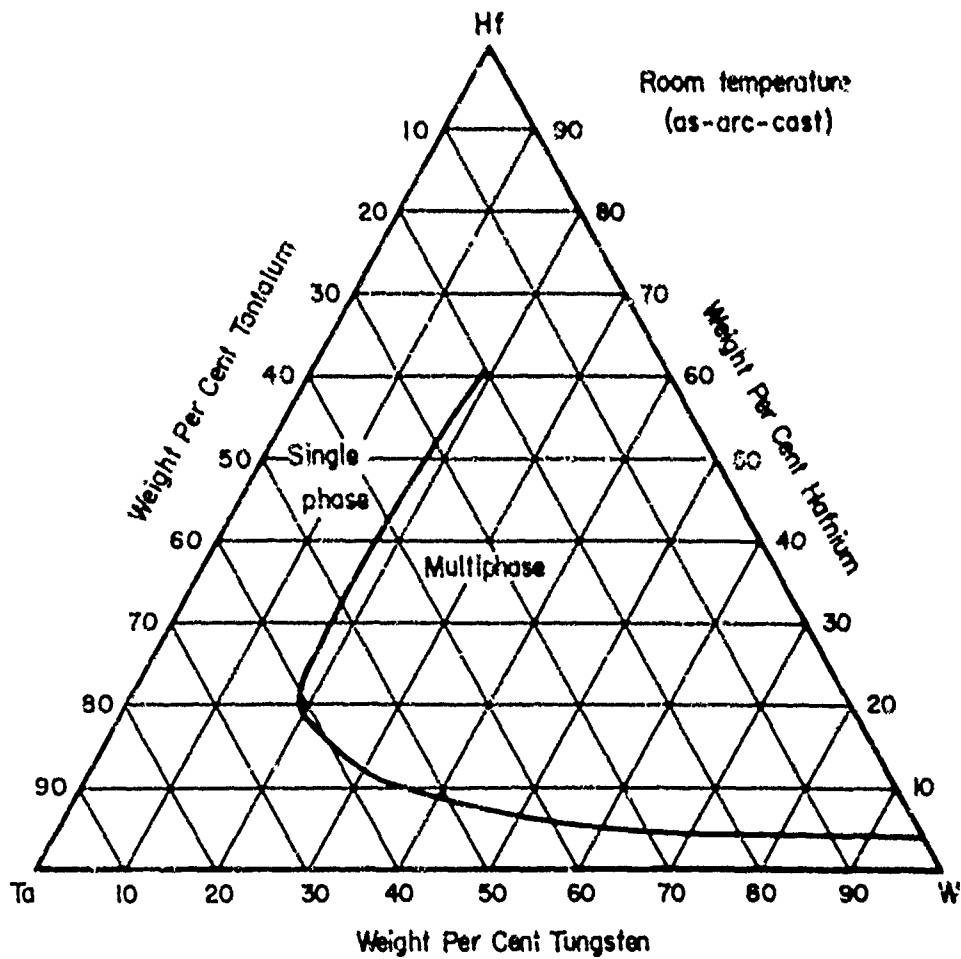
TANTALUM-TUNGSTEN-CHROMIUM SYSTEM(206)



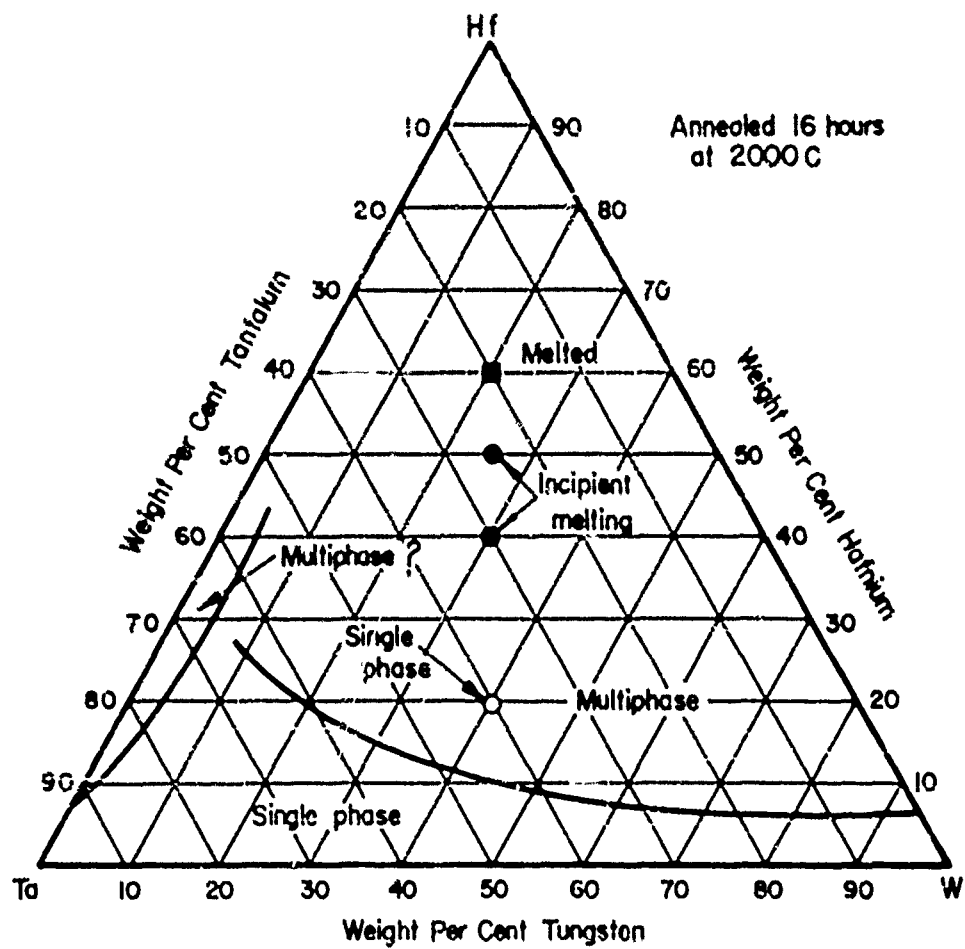
TANTALUM-TUNGSTEN-CHROMIUM SYSTEM(206)



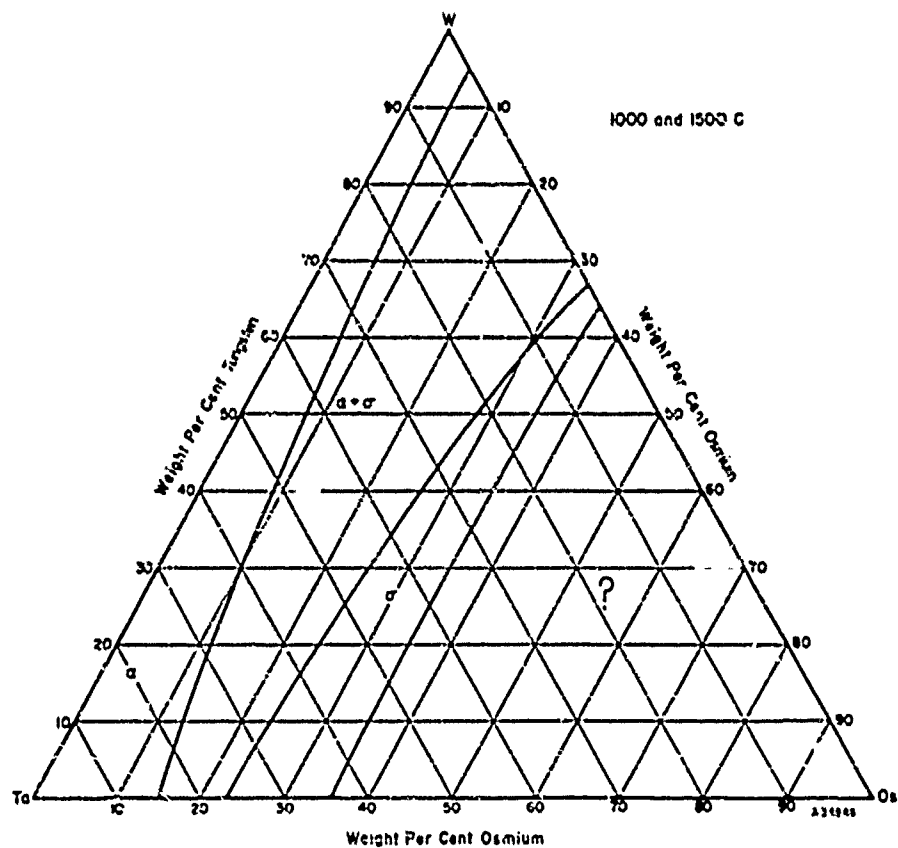
TANTALUM-TUNGSTEN-HAFNIUM SYSTEM(225)



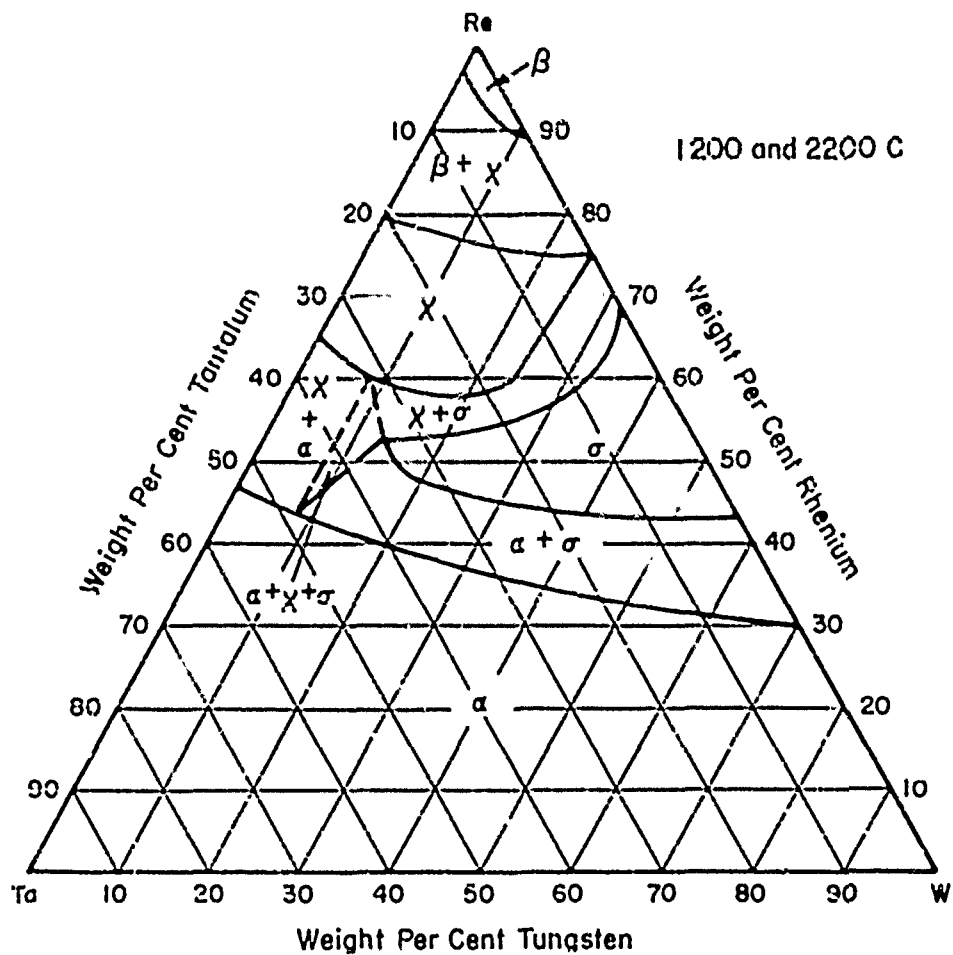
TANTALUM-TUNGSTEN-HAFNIUM SYSTEM(225)



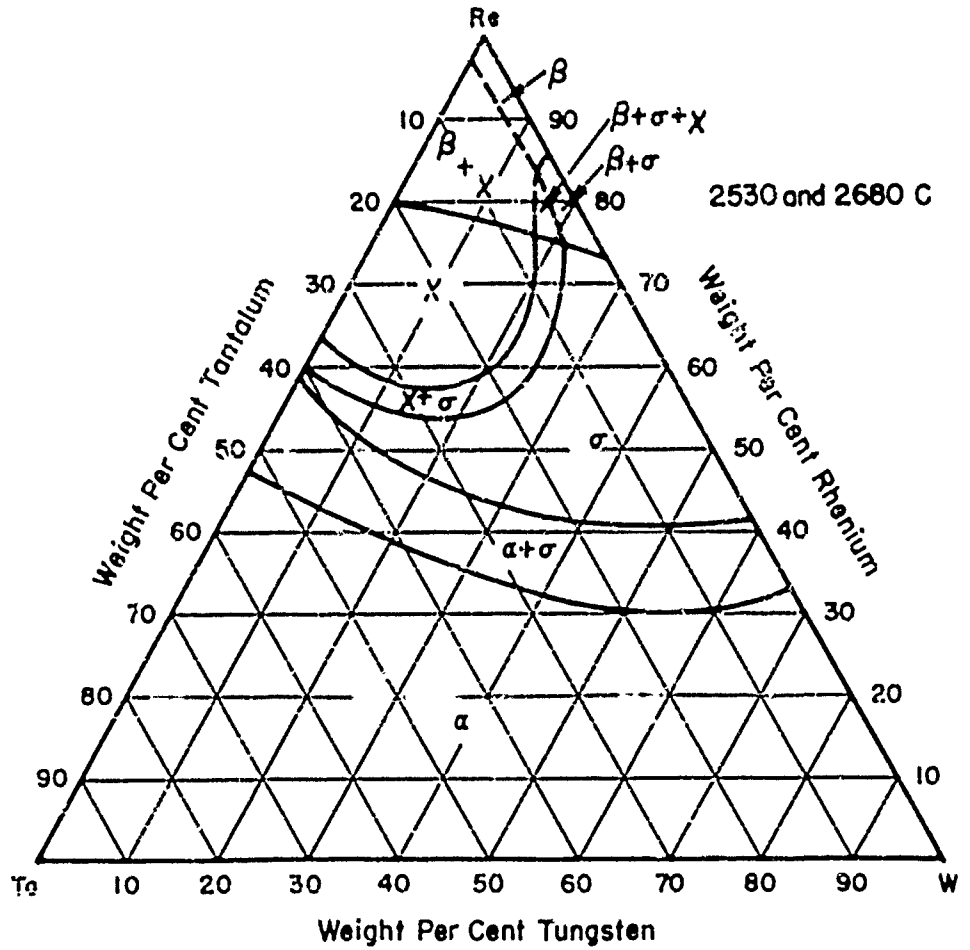
TANTALUM-TUNGSTEN-OSMIUM SYSTEM(206)



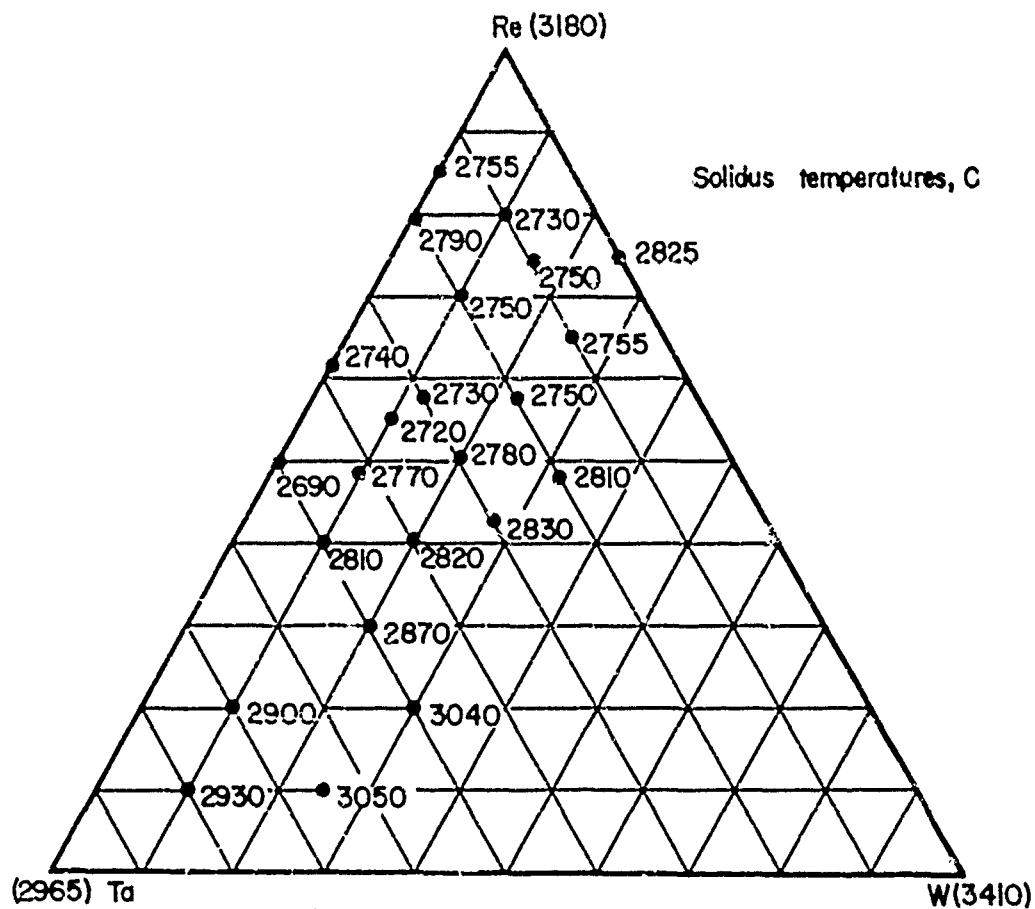
TANTALUM-TUNGSTEN-RHENIUM SYSTEM(149)



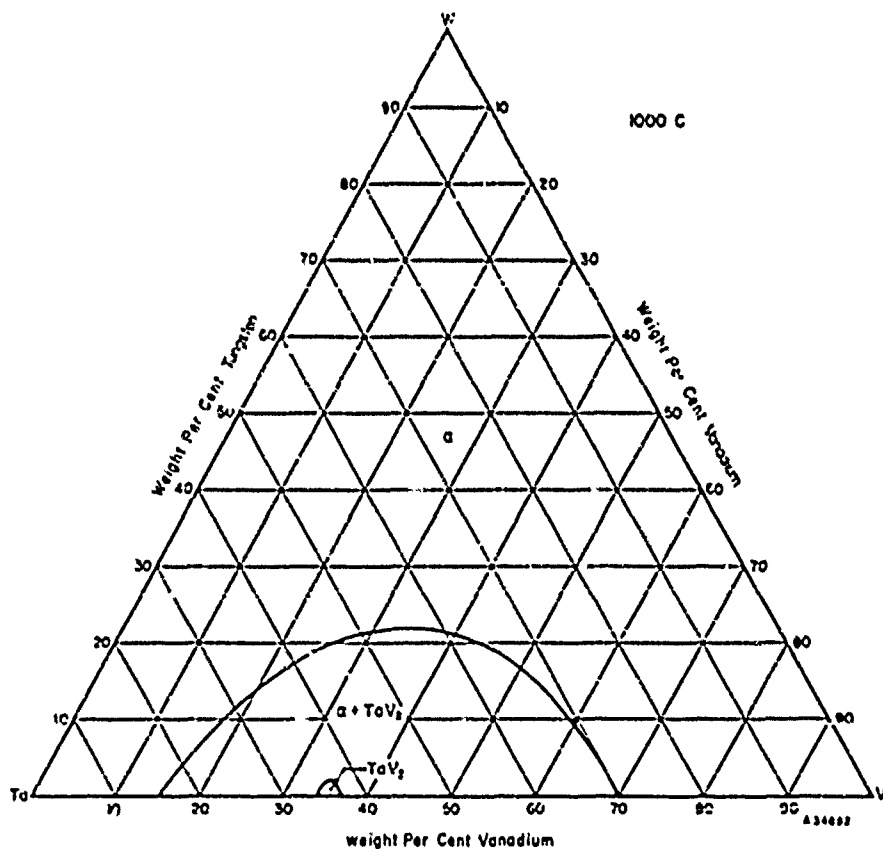
TANTALUM-TUNGSTEN-RHENIUM SYSTEM(149)



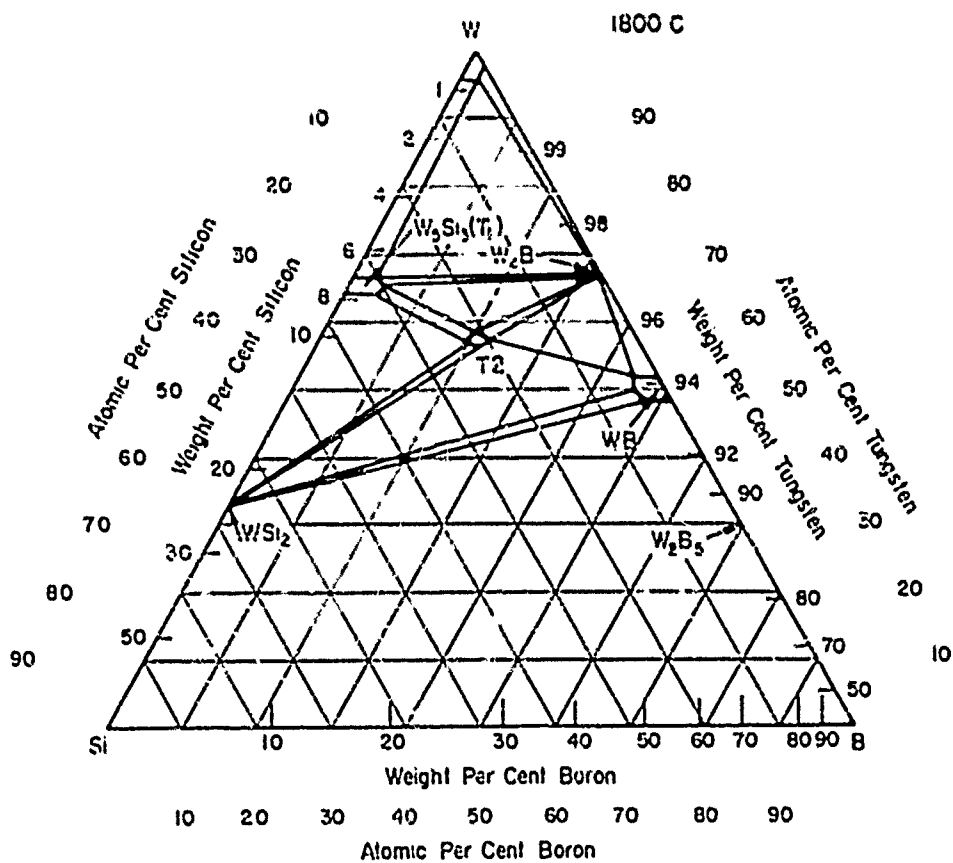
TANTALUM-TUNGSTEN-RHENIUM SYSTEM⁽¹⁴⁹⁾



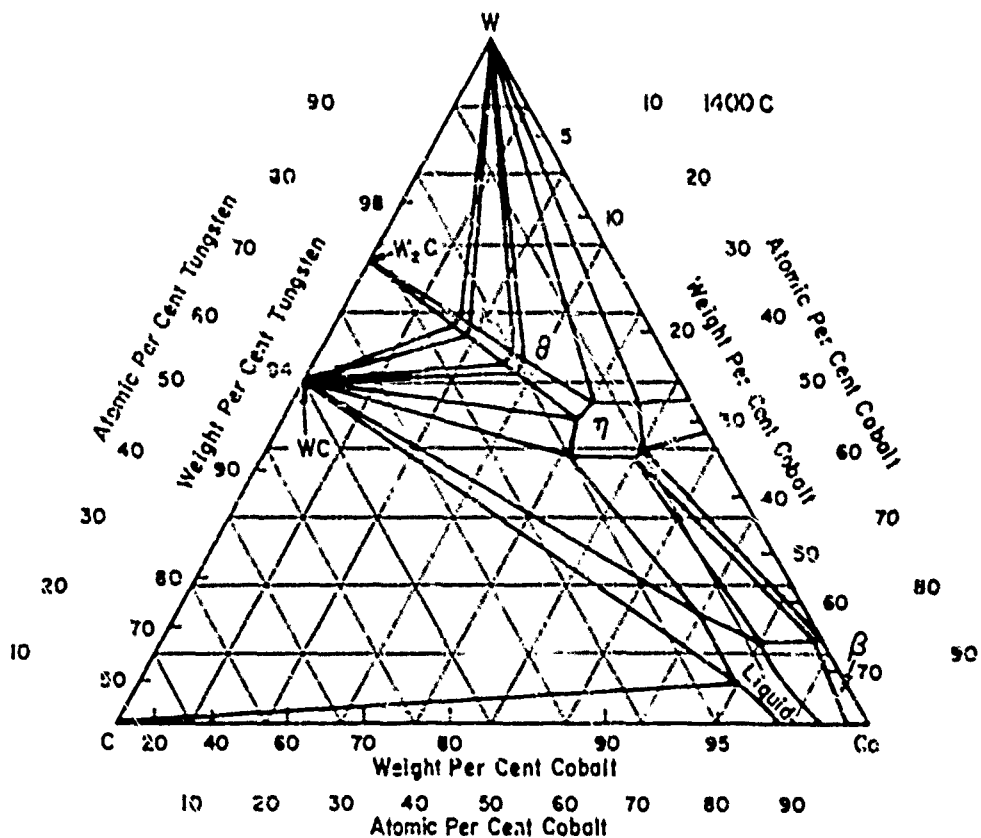
TANTALUM-TUNGSTEN-VANADIUM SYSTEM(206)



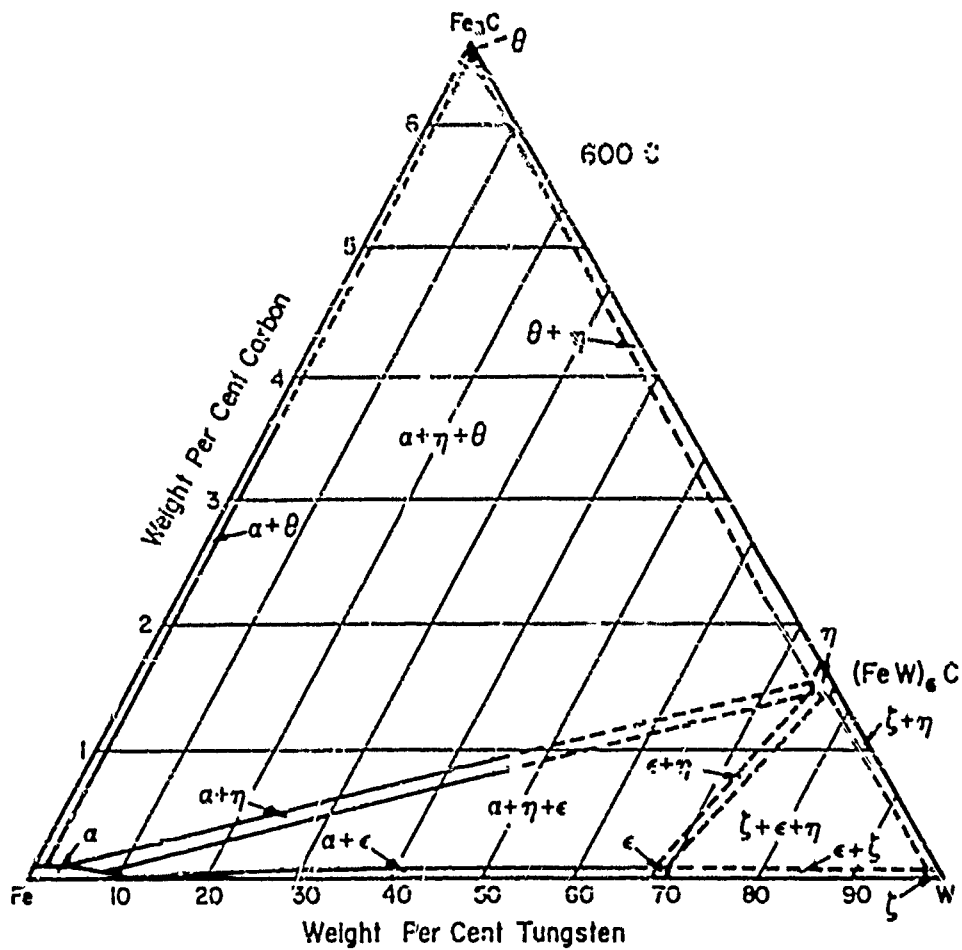
TUNGSTEN-BORON-SILICON SYSTEM(212)



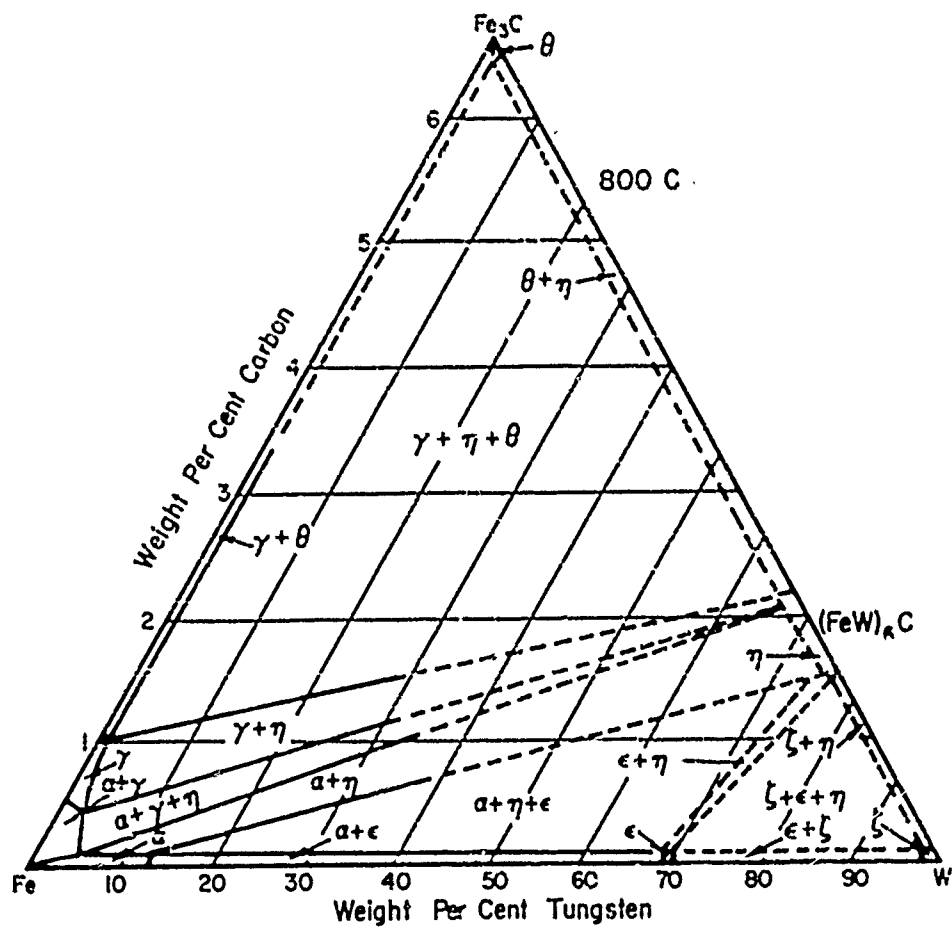
TUNGSTEN-CARBON-COBALT SYSTEM(221)



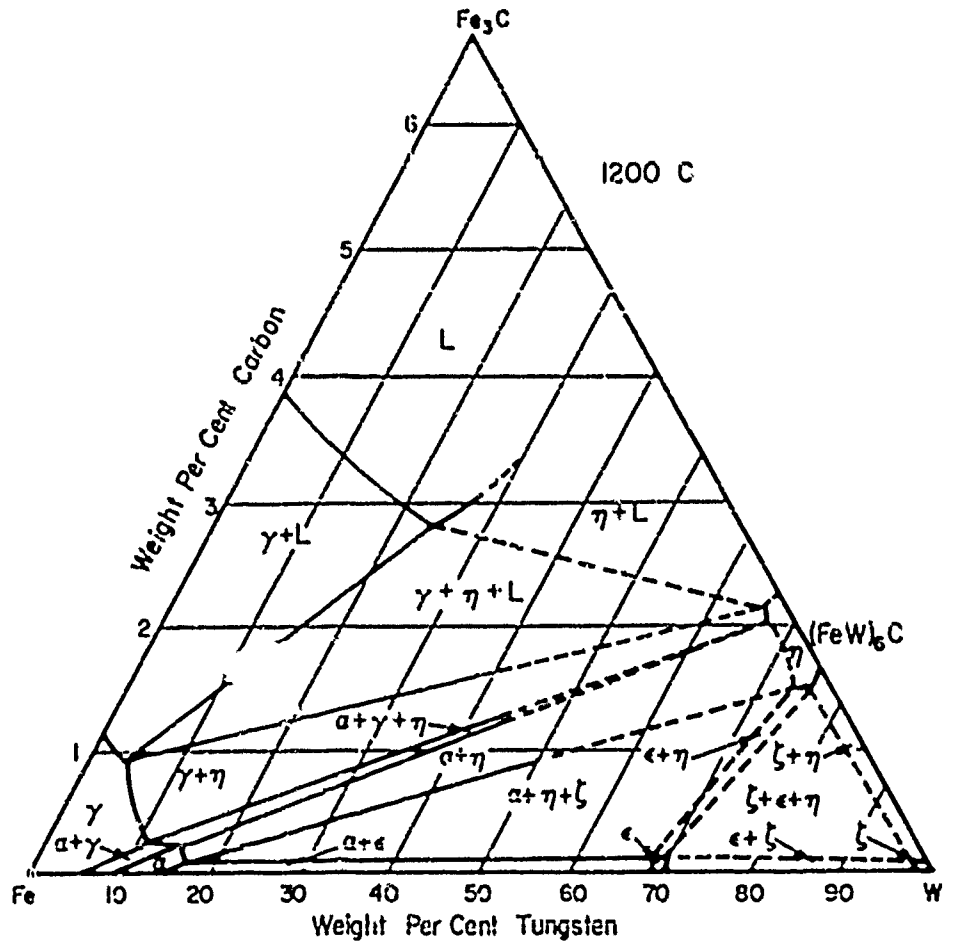
TUNGSTEN-CARBON-IRON SYSTEM⁽²²²⁾



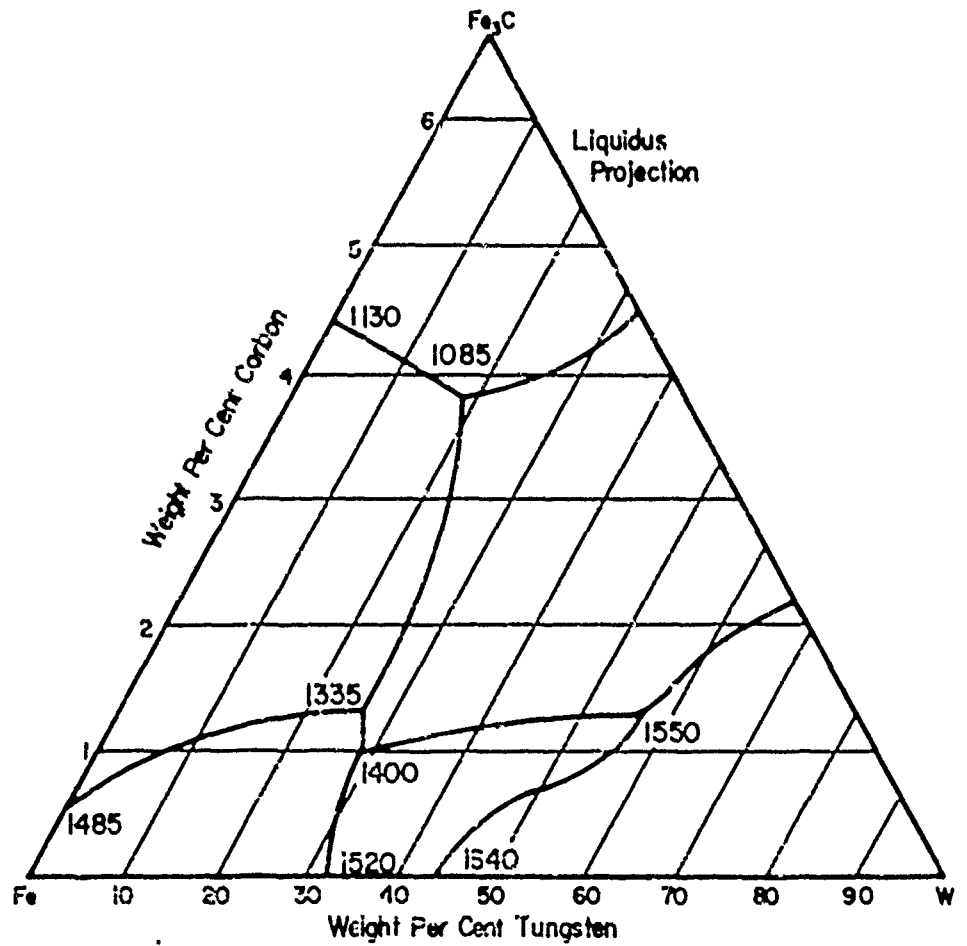
TUNGSTEN-CARBON-IRON SYSTEM⁽²²²⁾



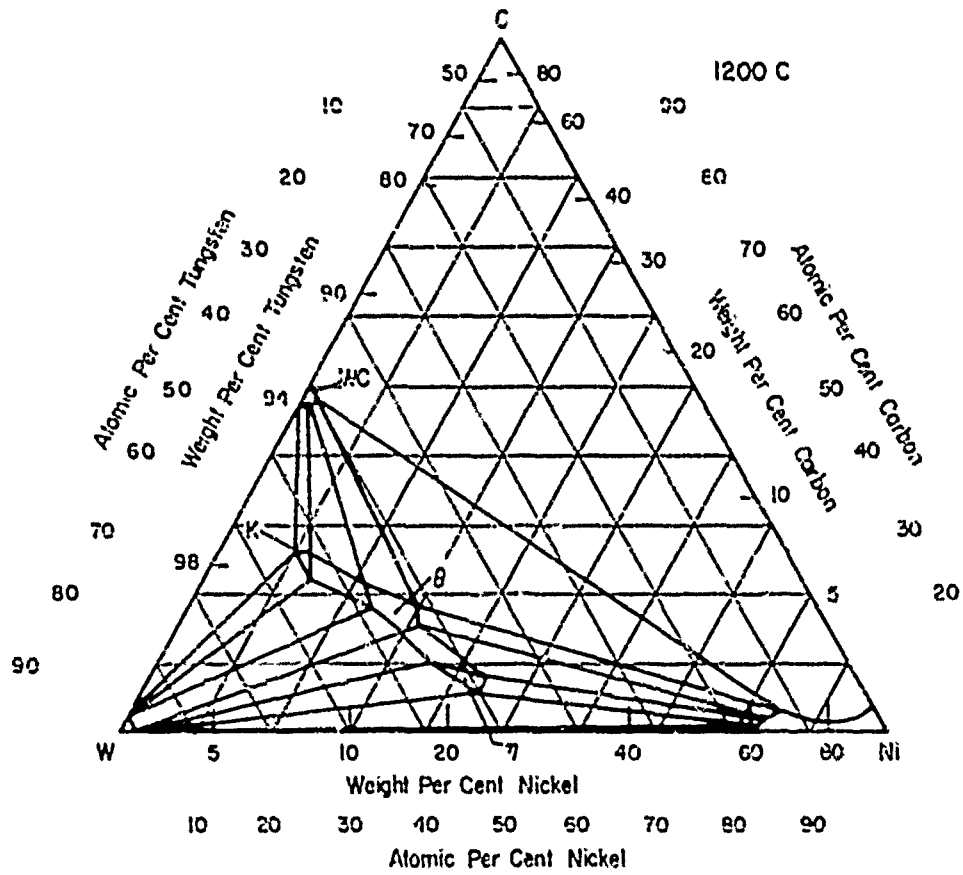
TUNGSTEN-CARBON-IRON SYSTEM(222)



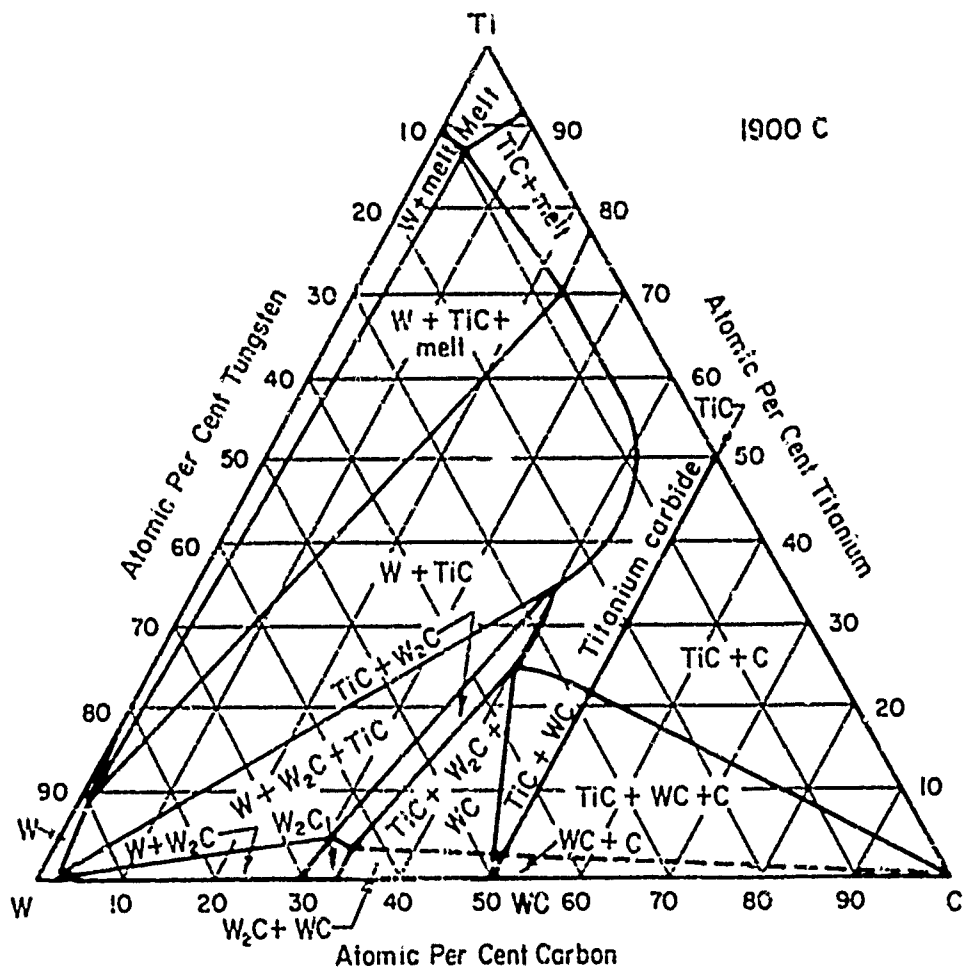
TUNGSTEN-CARBON-IRON SYSTEM(223)



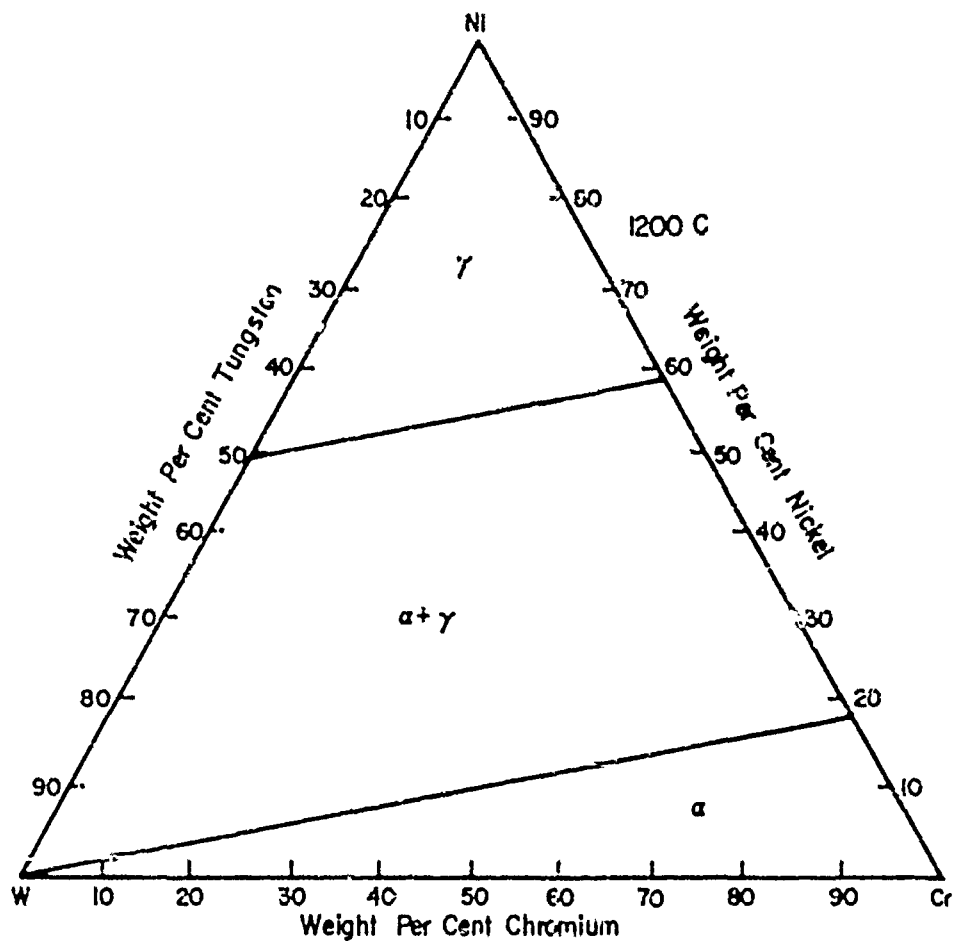
TUNGSTEN-CARBON-NICKEL SYSTEM(223)



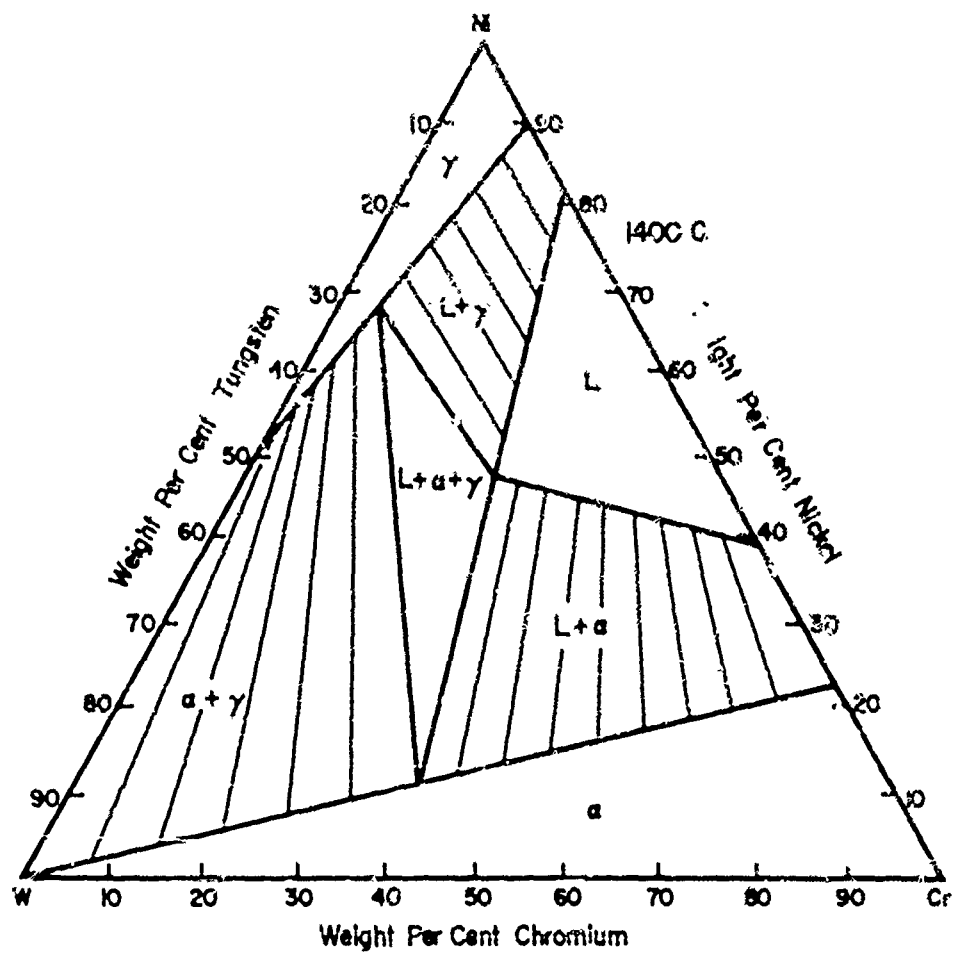
TUNGSTEN-CARBON-TITANIUM SYSTEM(217)



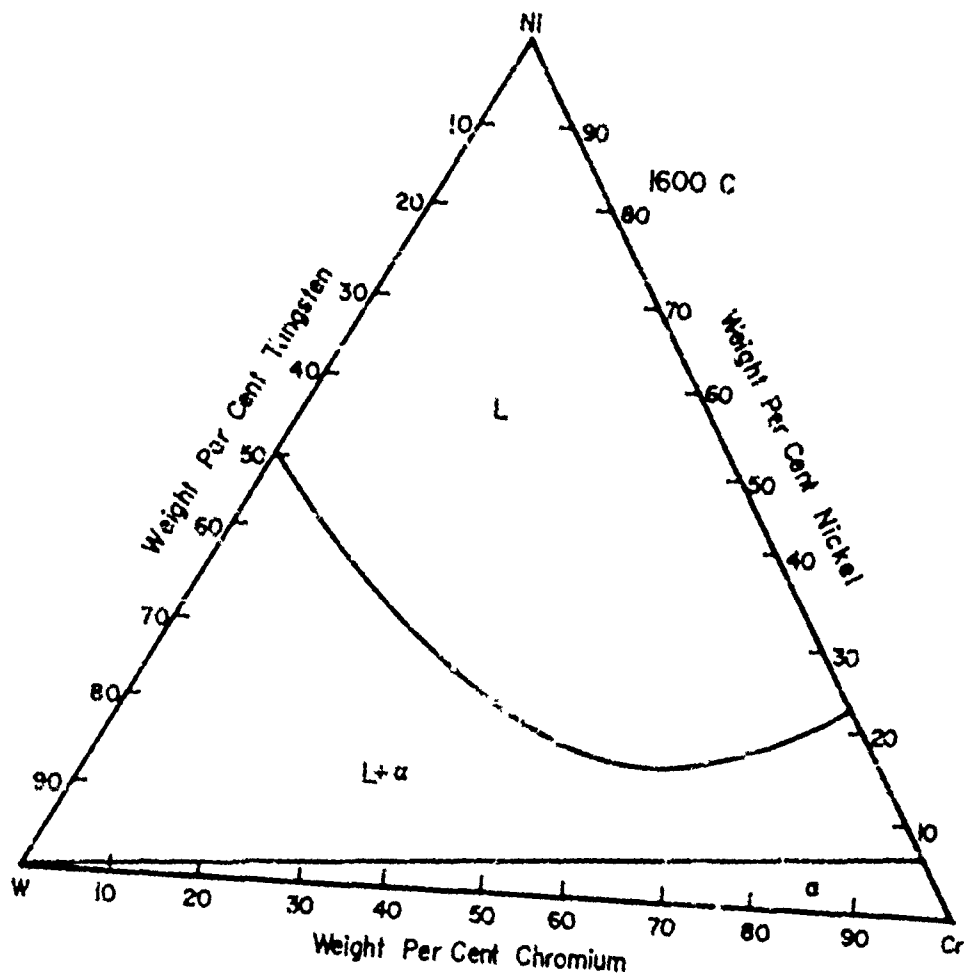
TUNGSTEN-CHROMIUM-NICKEL SYSTEM(216)



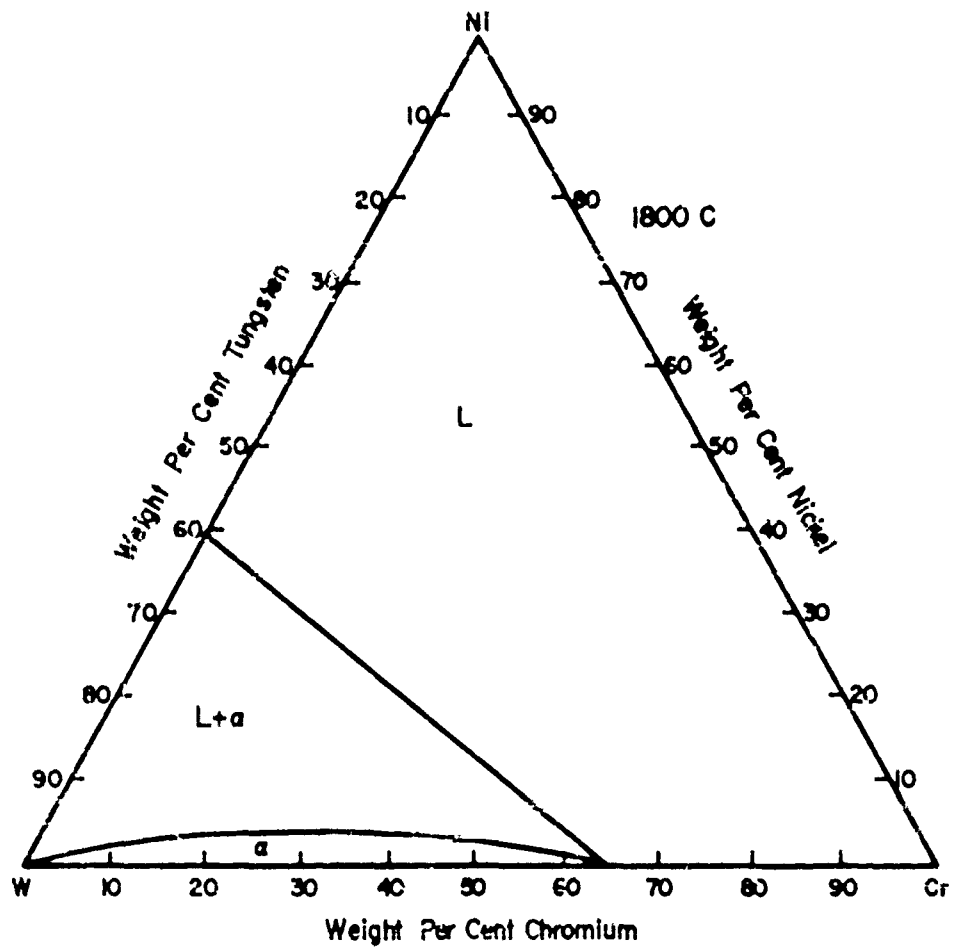
TUNGSTEN-CHROMIUM-NICKEL SYSTEM (216)



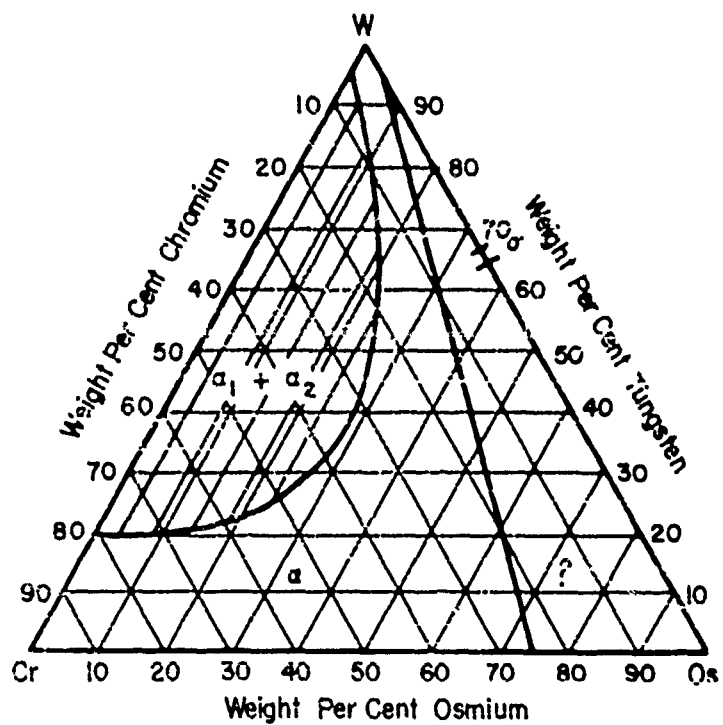
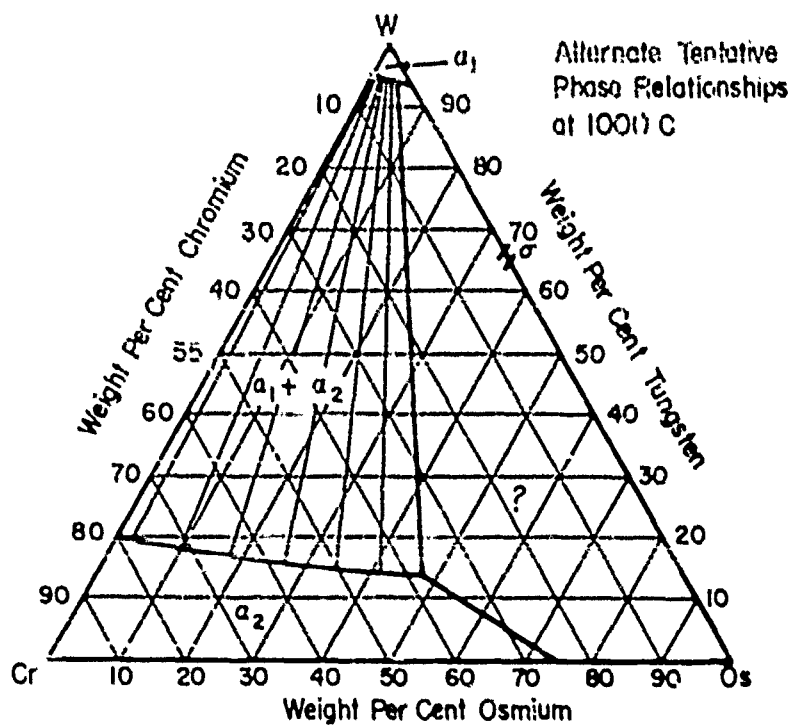
TUNGSTEN-CHROMIUM-NICKEL SYSTEM(216)



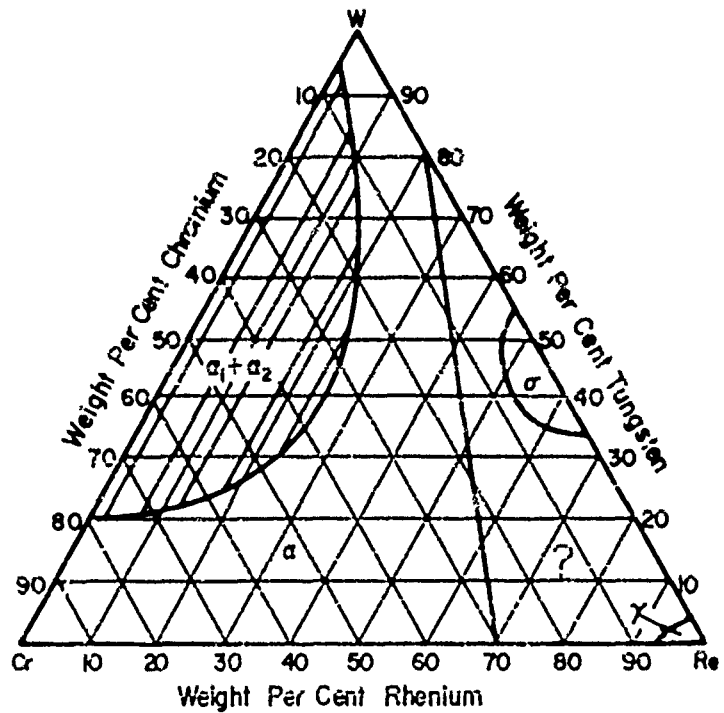
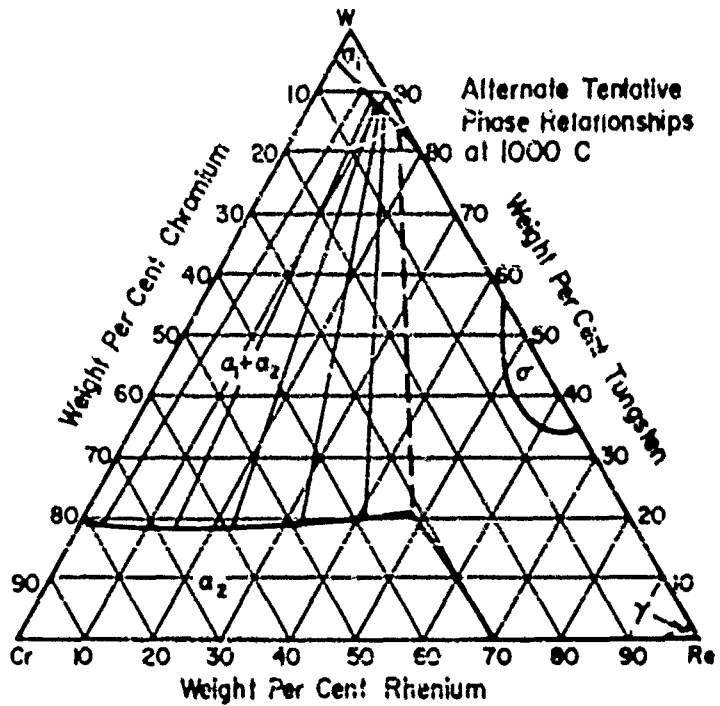
TUNGSTEN-CHROMIUM-NICKEL SYSTEM⁽²¹⁶⁾



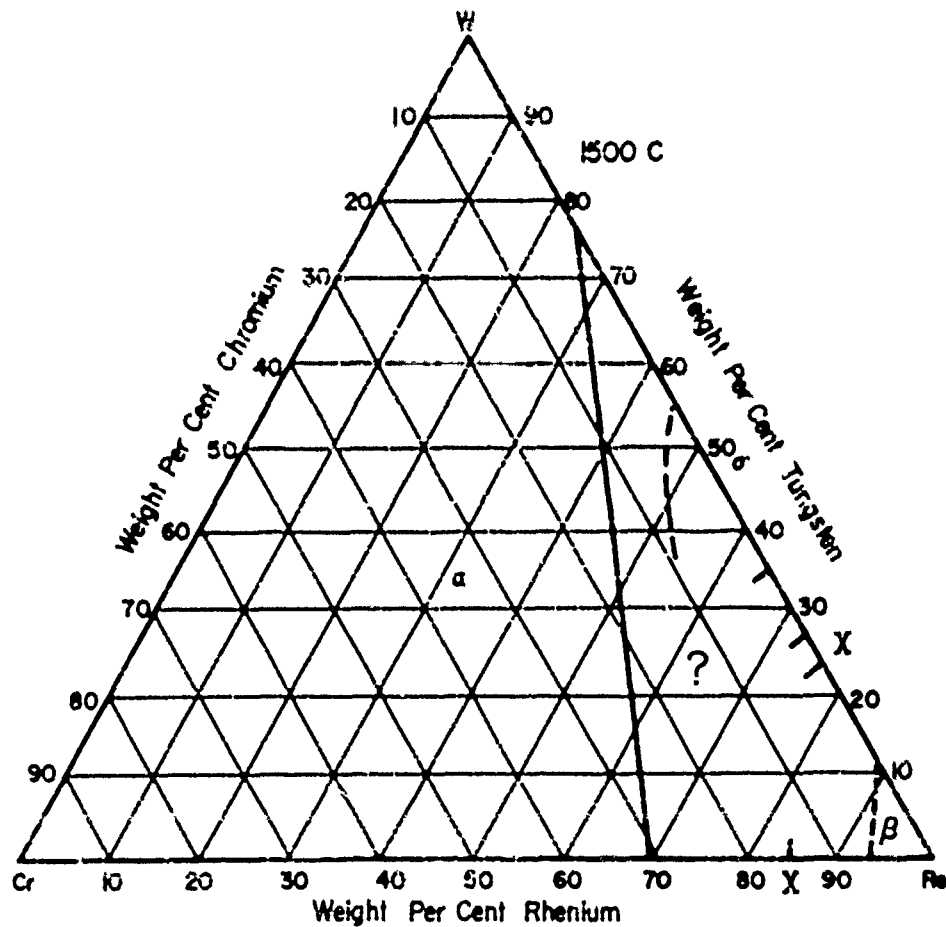
TUNGSTEN-CHROMIUM-OSMIUM SYSTEM (206)



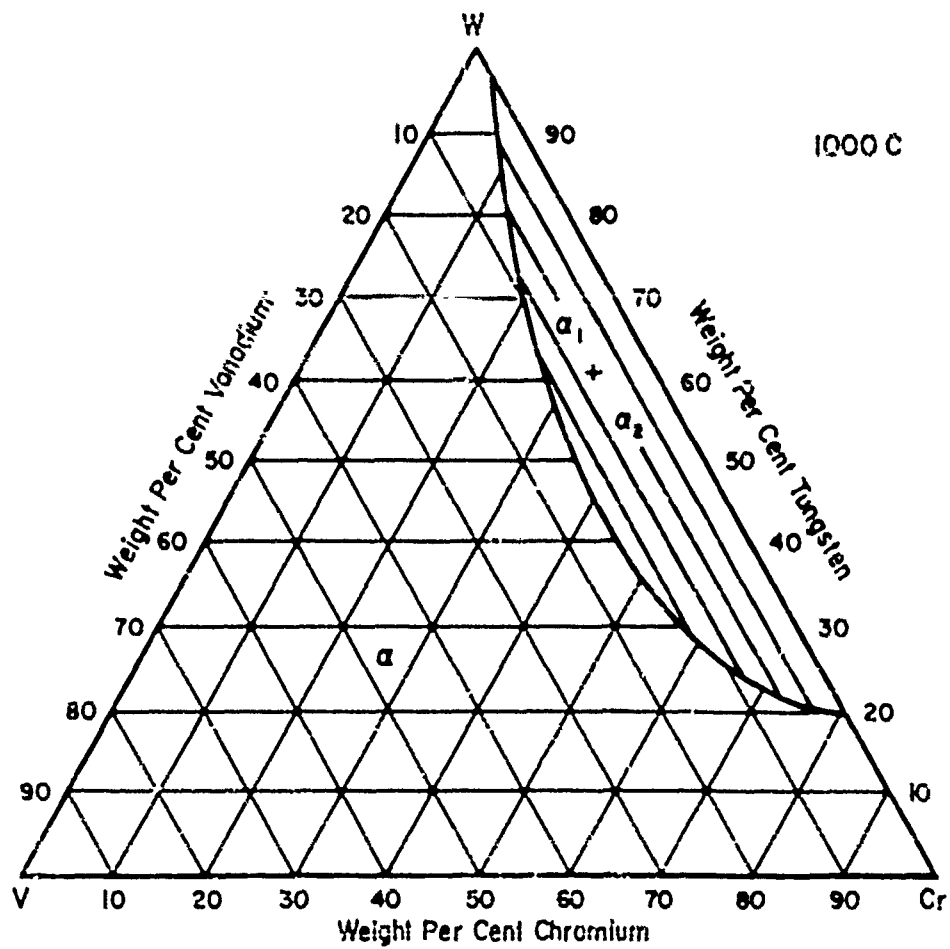
TUNGSTEN-CHROMIUM-RHENIUM SYSTEM(206)



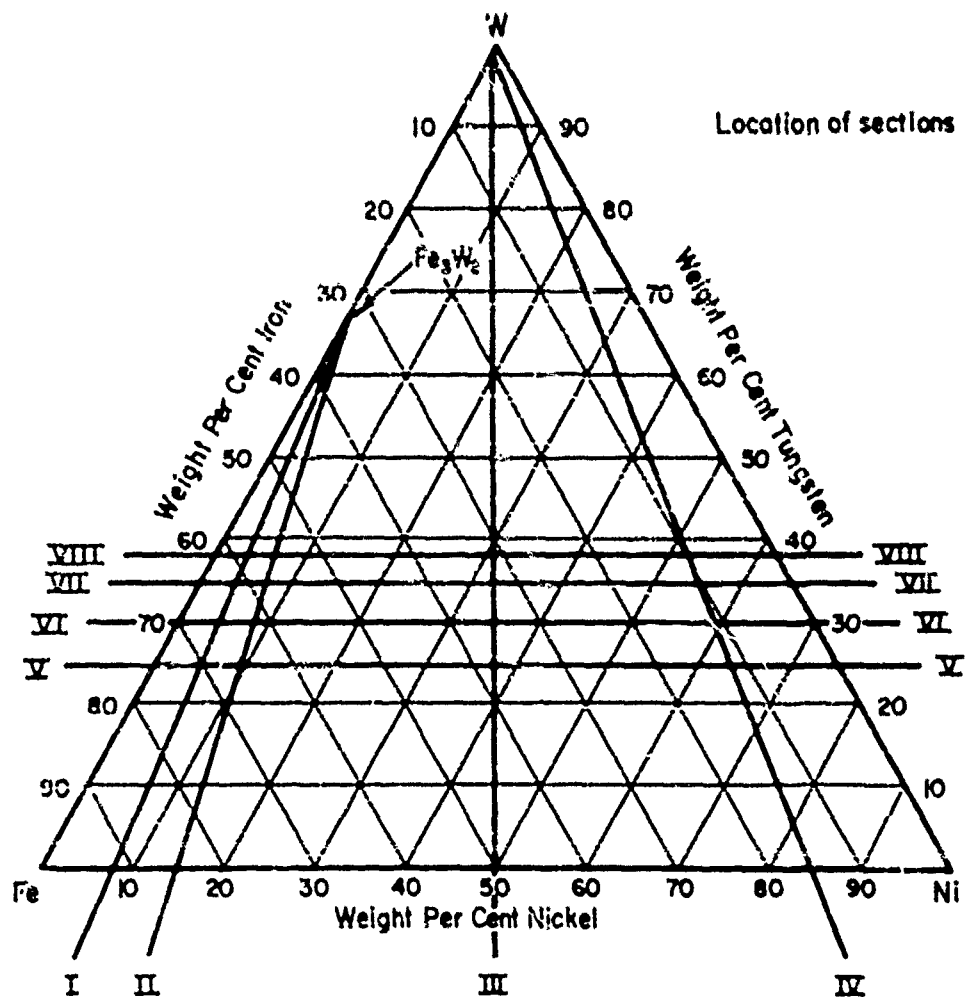
TUNGSTEN-CHROMIUM-RHENIUM SYSTEM(206)



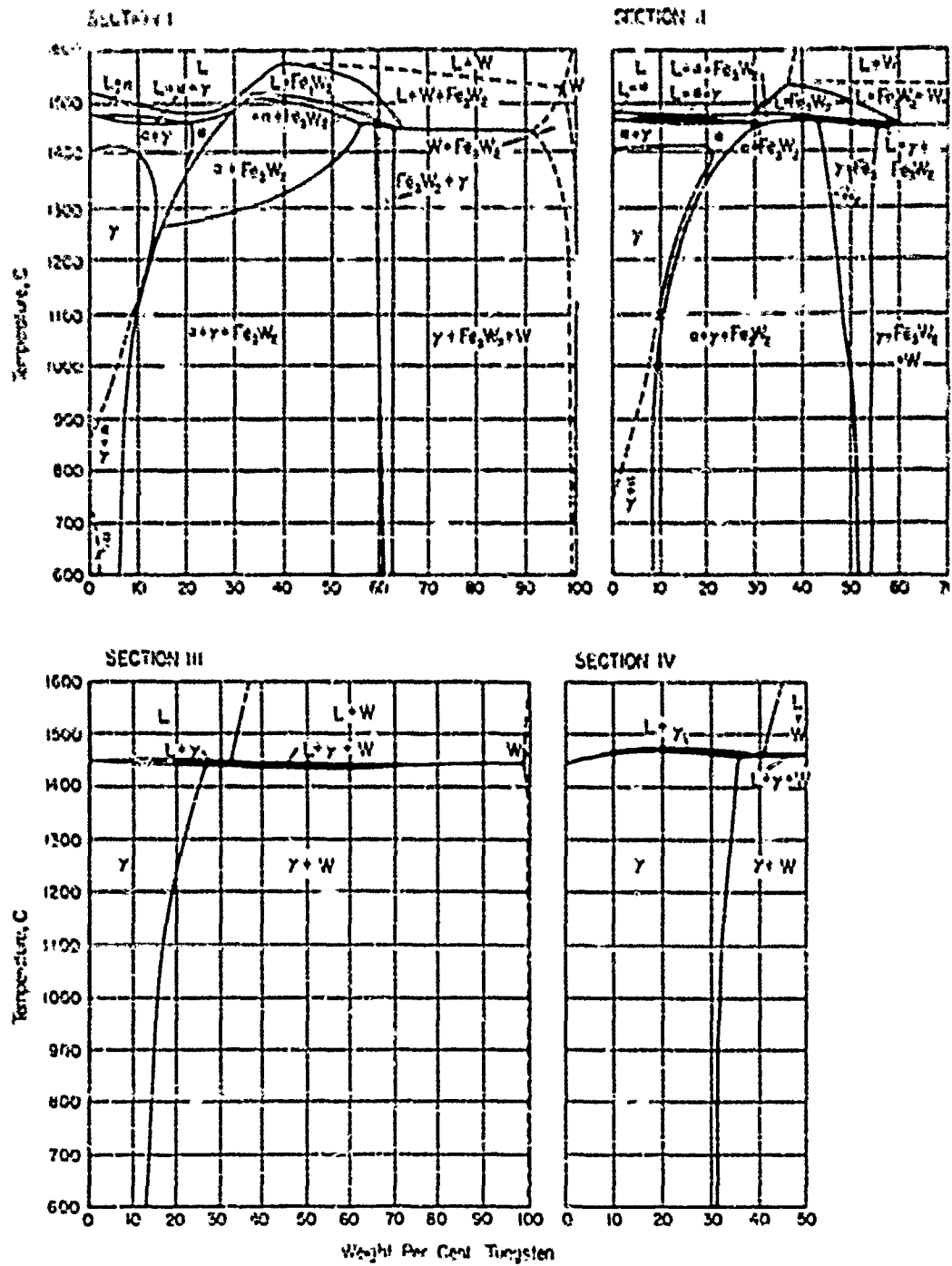
TUNGSTEN-CHROMIUM-VANADIUM SYSTEM (206)



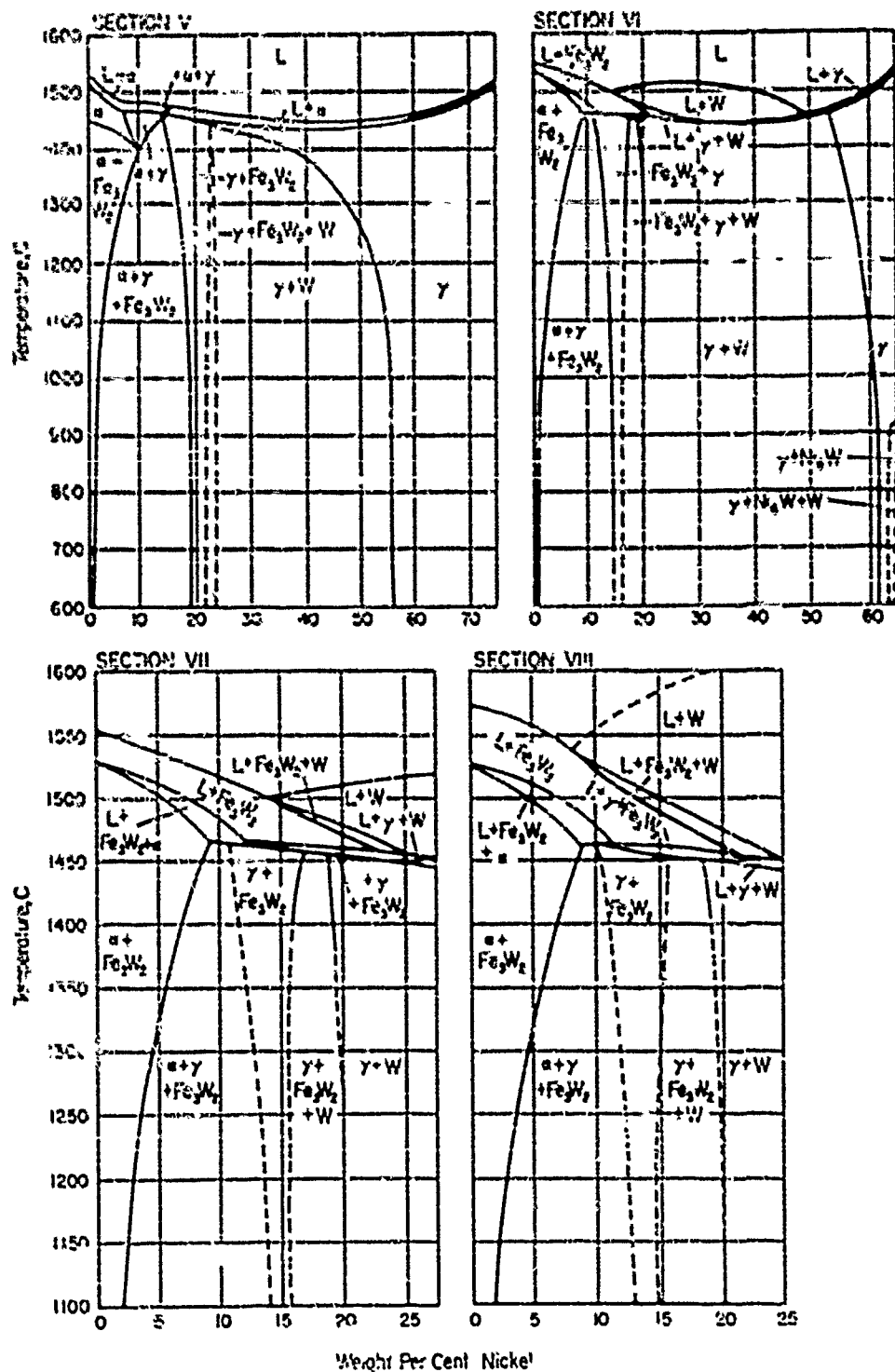
TUNGSTEN-IRON-NICKEL SYSTEM (224)



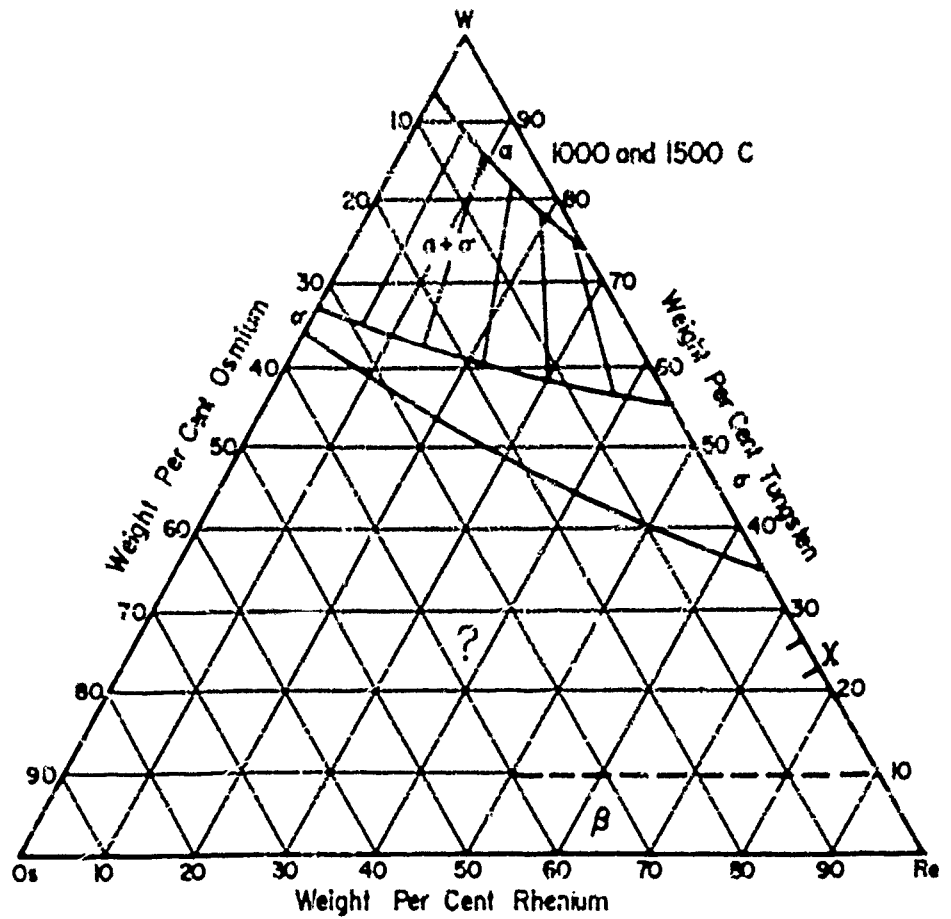
TUNGSTEN-IRON-NICKEL SYSTEM (224)



TUNGSTEN-IRON-NICKEL SYSTEM(224)



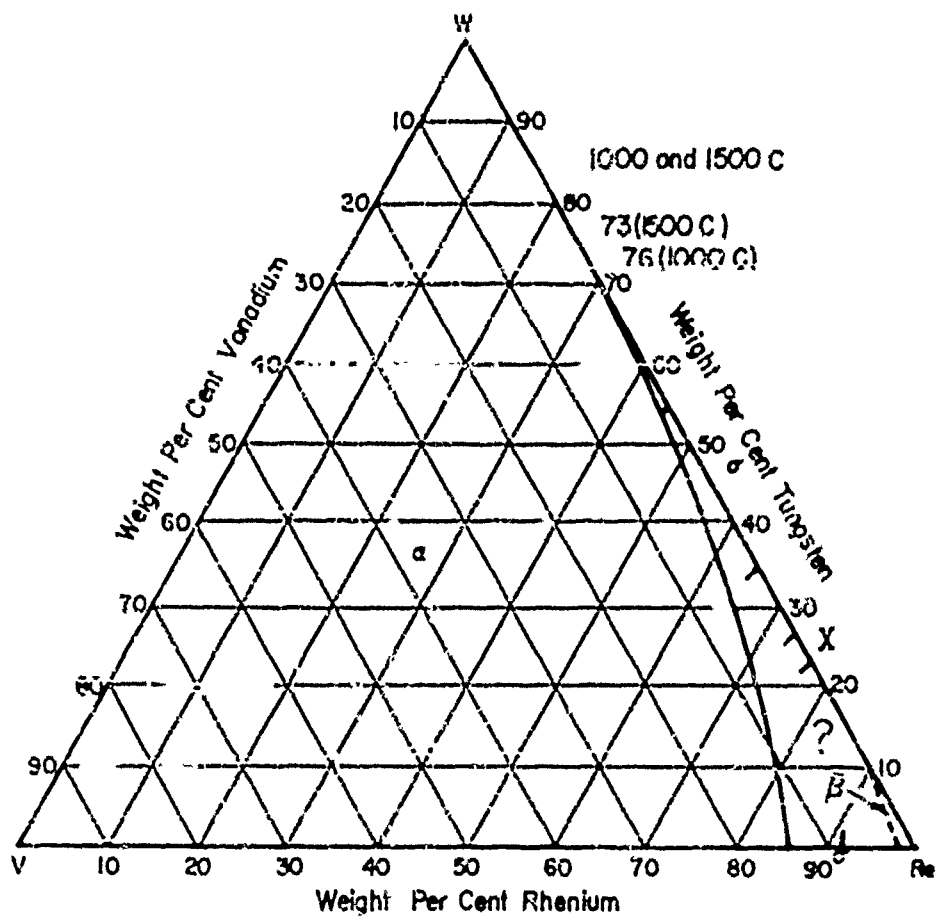
TUNGSTEN-OSMIUM-RHENIUM SYSTEM(206)



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TUNGSTEN-RHENIUM-VANADIUM SYSTEM (206)



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