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FOREWORD

While gold was probably the first pure metallic element found and used by man, its unique combination of physical, chemical and mechanical properties has not led to any widespread usage other than for decoration or personal adornment and for monetary purposes. Since the earliest recorded history of human activities, gold has been prized as a symbol and instrument of wealth and power, but it seems remarkable today that in the long time man has valued this metal, no really significant industrial use has been developed. In fact it might appear that one of the chief attributes of gold as an international currency and monetary medium has been its relative uselessness as anything else. This has permitted an arbitrary and nominal international valuation to be maintained outside of the normal laws of supply and demand which operate in the pricing of industrial metals.

Despite the historic and traditional view of gold as money, the metallurgist can regard it more dispassionately as merely one of the large family of elements with which he is concerned. In the technology of the middle 20th century, there are other metals which cost more, are scarcer in the practical sense of availability in pure and usable form, and are possibly more familiar as scientific or engineering materials than gold. The matter of relative or absolute cost is secondary to performance in many technical devices of the atomic and space age, and the historic association of gold with costliness no longer operates against its application in the development of new and better engineering materials.

A new look at gold as a metallurgical metal appears to be warranted under present circumstances, not only because of its relative neglect in the past, but particularly because of the increasing necessity to make the best use of all available natural resources in the application of science and technology in furthering the progress of mankind.

John Convey
Director, Mines Branch

October 1961

Mines Branch Information Circular IC 129

PHYSICAL METALLURGY AND USES OF GOLD:

The Properties of Gold and Alloys Containing Gold

by

L. Badone* and N. S. Spence**

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ABSTRACT

This publication, prepared as part of a project undertaken with the aim of expanding industrial uses of gold, presents most of the relevant and currently available physical, chemical and metallurgical data on gold and its alloys. Arranged by a system of classification designed to facilitate its use, the text is divided into three parts. Part I deals with the properties of pure gold. Part II covers gold alloys, and Part III is devoted to the principal past and present industrial uses of gold and its alloys. Sources of the data presented consist of over 200 references which are tabulated at the end.

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Circulaire d'information IC 129

MÉTALLURGIE PHYSIQUE ET UTILISATIONS DE L'OR:

Propriétés de l'or et des alliages aurifères

par

L. Badone* et N.S. Spence**

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RÉSUMÉ

La présente publication, préparée dans le cadre d'un programme visant à accroître les applications industrielles de l'or, contient la majeure partie des données pertinentes recueillies jusqu'ici sur l'or et ses alliages dans les domaines physiques, chimiques et métallurgiques. La matière est disposée de façon à en faciliter l'utilisation. L'ouvrage comprend trois parties: la Partie I traite des propriétés de l'or pur, la Partie II, des alliages aurifères, et la Partie III, des principales applications industrielles passées et présentes de l'or et de ses alliages. Les données présentées proviennent de plus de 200 ouvrages de référence, énumérés à la fin de la publication.

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Note re Tables and Figures

The 26 tables and 44 figures interspersed in this report are all placed immediately following their related text and hence can be found without difficulty through the regular table of contents (pp. v-vii).

INTRODUCTION

A co-operative research program jointly sponsored by the Canadian Metal Mining Association and the Department of Mines and Technical Surveys, aimed at increasing the industrial uses of gold, was initiated in April 1959 with work on the project being carried out in the Physical Metallurgy Division.

The objective of the program has been to generate new metallurgical information which could lead to new and increased utilization of gold. The first stage of the project took the form of a literature survey of the physical metallurgy of gold and its uses. On the basis of this survey it was concluded that the field of small gold additions to base metal alloys was promising with respect to development of new and useful information, particularly since this area does not appear to have received extensive attention. Experimental work on the effect of gold additions to ferrous and non-ferrous alloys was started and some results concerning zinc galvanizing baths, aluminum and magnesium alloys have been included.

The present publication stems more from the literature survey than from the experimental program. Its aim is to collect under one cover much of the existing information on the physical metallurgy and industrial uses of gold and gold-containing alloys, thus making data more readily available for engineering design and metallurgical development.

Because of the scope of the project and the limited time available, critical evaluation of all the data has not been possible. However, it is considered that this publication and the companion bibliography, Mines Branch Information Circular IC 116 (January 1960), will render possible the easier access to information on gold, a prime requisite to achieving the objective of increased industrial uses.

This publication has been arranged in three sections, one dealing with the properties of pure gold, one with the properties of alloys containing gold, and one with the uses of gold and gold-containing alloys. In the first section, on pure gold, a letter-numeral coding has been applied to the properties dealt with and in the second section, where information on the same property was available for gold alloys, the same classification coding has been used.

The section on alloys containing gold has been based on the binary system of gold with other metals, and the data on ternary systems have been fitted into this framework on the basis of the major constituent and gold in the ternary or higher alloy.

I. PROPERTIES OF GOLD

I - A Physical Properties

(A.1) Atomic Weight

The atomic weight (on the chemical side) of naturally occurring gold, accepted by the International Union of Pure and Applied Chemistry in 1955, is: 197.0

The atomic number of gold is: 79

The atomic volume of gold is: 10.2 cm^3/g atom

(A.2) Isotopes

Gold occurs naturally as a single stable isotope of atomic mass number 197, (Au^{197}). The artificially produced isotopes of gold and their half-lives are listed in Table 1.(1)

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(1) References are listed at the end of the report in the order in which they are numbered in the text. However, in the case of certain phase diagrams the references found thereon relate to the original source.

TABLE 1

Mass Number	Half-Life	
183 to 187	4.3	minutes
187	about 15	minutes
188	about 10	minutes
189	42	minutes
191	3	hours
192	4.8	days
193	4.	seconds
193	17	hours
194	39	hours
195	30	seconds
195	180	days
196	14	hours
196	5.6	days
197	7.4	seconds
198	2.70	days
199	3.15	days
200	48	minutes
201	26	minutes
202	about 25	seconds
203	55	seconds

(A.3) Nuclear Properties

The thermal neutron capture cross section of gold is:-

98 barns (10^{-24} cm^2)(1)

(A.4) Crystal Structure and Lattice Constants

The crystallographic data for gold are listed in Table 2.

TABLE 2(2)

Allotropic Forms	None
Structure	Face-centred cubic (type A.1)
Lattice Parameter	a = 4.0783 Å
Closest Approach of Atoms	2.884 Å
Goldschmidt's Atomic Radius (12-fold co-ordination)	1.44 Å

(A.5) Melting Point

The melting point of pure gold(3) is one of the fixed points of the International Temperature Scale and is defined as:-

1063°C.

Determination of the freezing point of gold,(4) using a constant volume nitrogen gas thermometer, gave a value of 1336.84° ± 0.05°K (1063.69° ± 0.05°C) on the thermodynamic scale.

Molten gold can exhibit super-cooling to a very marked degree, and under favourable conditions this can amount to about 200°C.(5)

(A.6) Boiling Point

The boiling point of gold is listed(6) as:-

2950°C

(A.7) Vapour Pressure

Vapour pressure at 927°C:(7) 2.1×10^{-9} atm

Vapour pressure at 527° - 727°C (800° - 1000°K):(8)

$$\text{Log } P = -18{,}016/T + 8.683$$

(P in mm and T in °K.)

(A.8) Latent Heats

Latent heat of fusion:(9) 3.05 ± 0.1 kg cal/mole

Latent heat of vapourisation (at boiling point):(6) 81.8 kg cal/mole

Heat of vapourisation at 0°K:(7) 84.6 ± 0.8 kg cal/mole

Heat of vapourisation at 0°K:(8) 86.8 ± kg cal/mole

(A.9) Specific Heat

The molal heat capacity and specific heat of pure gold from 15° to 300°K (-258.16° to 26.84°C)(10) and from 100° to 900°C (373.16° to 1173.16°K)(6) are given in Table 3.

TABLE 3

Temperature (°K)	Temperature (°C)	C_p, cal/°K/g atom	Specific Heat, cal/°K/g
15	-258.16	0.354	0.0018
50	-223.16	3.409	0.017
100	-173.16	5.116	0.026
150	-123.16	5.615	0.029
200	- 73.16	5.840	0.030
250	- 23.16	5.957	0.030
298.16	25	6.066	0.031
300	26.84	6.070	0.031
373.16	100	6.1	0.031
773.16	500	6.7	0.034
1173.16	900	7.1	0.036

(A.10) Entropy, Enthalpy and Free Energy

Values of the entropy (S), enthalpy change per °K ($\frac{H^\circ - H_o^\circ}{T}$) and free energy change per °K ($\frac{F^\circ - H_o^\circ}{T}$) are given in Table 4.(10)

TABLE 4

Thermodynamic Properties of Gold, cal/°K/g atom

T (°K)	S	$\frac{H^\circ - H_o^\circ}{T}$	$\frac{F^\circ - H_o^\circ}{T}$
15	0.120	0.091	0.029
50	2.084	1.392	0.692
100	5.109	2.925	2.184
150	7.295	3.751	3.544
200	8.941	4.247	4.694
250	10.257	4.579	5.678
298.16	11.318	4.810	6.508
300	11.355	4.818	6.537

H° = heat content at temperature T; H_o° = heat content at O°K;
F° = free energy at temperature T.

(A.11) Density

The density of gold at 20 °C is generally given as:(11)

$$19.3 \text{ g/cm}^3$$

Depending on the condition of the gold other values are possible, and the figure of 19.3 g/cm^3 should be regarded as an average value. The density and specific volume of fine gold (melting point, 1063 °C) at various temperatures(12) is listed in Table 5.

TABLE 5

Condition	Density, g/cm^3	Specific Volume, cm^3/g
Solid at 20 °C	19.423	0.0515
Solid at 1063 °C	18.474	0.0541
Molten at 1063 °C	17.361	0.0576
Molten at 1300 °C	16.950	0.0590

The shrinkage on solidification is 6%, and on cooling from 1063 °C to 20 °C it is 4.9%.

The changes in volume of high-purity gold as a function of pressures up to 30,000 kg/cm^2 (326,690 psi) at 23° to 26 °C have been measured(13) and are listed in Table 6. Hysteresis was encountered, the curves for increasing and decreasing pressure forming a smooth loop.

TABLE 6

Pressure, kg/cm^2	$\frac{\Delta V}{V_o}$
5,000	0.00281
10,000	0.00558
15,000	0.00831
20,000	0.01101
25,000	0.01367
30,000	0.01626

V_o = original volume; ΔV = change in volume.

Values for the density of gold under high pressures have been obtained, with a density of 32.7 g/cm^3 at a pressure of 6 million atmospheres being recorded.(14)

(A.12) Thermal Expansion

Values of the coefficient of thermal expansion of gold for temperatures up to 900°C are given(6) in Table 7.

TABLE 7

Temperature, t°C	Coefficient of Expansion, 20 - t°C
100	14.2×10^{-6}
500	15.2×10^{-6}
900	16.7×10^{-6}

(A.13) Electrical Properties

Electrical Resistivity

The specific electrical resistivity of gold at 20 °C is listed (6) as:

2.3 microhm/cm

and the temperature coefficient of resistivity between 0 and 100 °C is:

39.0×10^{-4}

A more recent determination on highly refined gold(15) gave specific resistivities:

2.191 microhm/cm at 25 °C
2.857 " 100 °C

and the temperature coefficient of resistivity as:

45.00×10^{-4}.

The increase in the resistivity of gold which has been cold worked at liquid-air temperature is attributed to the formation of vacant lattice sites during working.(16) The extra resistivity anneals out in two stages. At -50 °C some is lost by the conglomeration of two or more vacant lattice sites. At 35 °C the remaining vacancies are annealed out and the original resistivity is regained.

A similar increase in electrical resistivity occurs when gold wires are quenched to liquid nitrogen temperature from 690° - 920°C.(17) The extra resistivity, in this case, is attributed to vacancies locked in by quenching and can be removed by low-temperature annealing. The energy to move a vacancy is about 0.4 ± 0.14 eV.

Effect of Pressure and Temperature

The effect of pressure between 1 and 1800 atm and 1 and 2600 atm on 99.95 + % gold at 25°C and 50°C has been determined.(18) The available temperature coefficients and pressure coefficients are given in Table 8.

TABLE 8

T in °C	R_t/R_o	$\frac{1}{R_o} \cdot \frac{\Delta R}{\Delta t} \cdot 10^{-3}$	$\frac{1}{R_t} \cdot \left(\frac{\Delta R_t}{\Delta P}\right) \cdot 10^{-6}$	
			1-1800 atm	1-2600 atm
49.98	1.185222		-2.906	-2.893
50-25		3.718		
24.90	1.092261		-2.860	-2.852
25-0		3.694		

The effect of temperatures, down to liquid hydrogen temperatures, on the ratio R_t/R_o (R_o = resistance at 0°C; R_t = resistance at t°C) is given in Table 9.

TABLE 9

Temperature, °C	$\frac{R_t}{R_o}$
0.00	1.0000
- 78.29	0.7079
-183.03	0.3244
-195.89	0.2749
-252.81	0.0774
-256.15	0.0732
-258.89	0.0708

Work on the electrical resistivity of gold at temperatures down to 0.006°K shows that gold is not one of the elements exhibiting superconductivity near absolute zero.(19)

The ratio of electrical resistivity of Royal Canadian Mint gold at 300°K (27°C) to that at 4°K is given as 3.73 in a zero field.(20)

Conductivity of Thin Films

The conductivity of thin gold films is sensitive to the nature of the substrate on which the films were deposited. Deposits onto glass have a very low electrical conductivity compared with that of bulk gold. If, however, bismuth oxide is deposited on the glass before the gold, thin gold deposits of high electrical conductivity and optical transmission can be obtained, especially if a second bismuth oxide layer is deposited on top of the gold.(21)(22) The conductivity of such gold deposits is about 25% of that of massive gold and this can be increased to about 75% by heat treatment. If the thickness of the gold deposit is suitably chosen, optical transmissions up to 82% can be achieved.

Selenium substrates which have been exposed to the air before deposition of gold are also reported to give gold films of higher conductivity than those deposited directly on glass.(23) Substrates of cadmium, lead and zinc oxides also result in high conductivity films.(24)

Hall Coefficient

For Royal Canadian Mint gold, the Hall coefficient at 22°C in fields up to 25 k gauss has been determined(20) as:

$$(6.97 \pm 0.03) \times 10^{-13} \Omega \text{ cm/gauss}$$

Free-Electron Value

The free-electron value of Royal Canadian Mint gold, 1/Nec, is given(20) as being 10.60, assuming one free electron per atom. (N = number of conduction electrons per cc; e = the electronic charge; c = the velocity of light.)

(A.14) Thermal Conductivity

The thermal conductivity of gold between 0° and 100°C is given as:(6)

$$R = 0.70 \text{ cal/cm}^2\text{/cm/sec/°C}$$

(A.15) Thermoelectric Properties

Thermal Electromotive Force

The thermal emf of gold relative to platinum, with the cold junction at 0°C and the hot junction at the temperatures listed, is given as:(6)

-200°C	-100°C	+100°C	+200°C
-0.21 mv	-0.39 mv	+0.74 mv	+1.77 mv

The absolute thermal emf of gold is reported(15) to be given by the function:-

$$E = 1.72 + 0.004\,t - 0.000,002,25\ t^2 \text{ (microvolt/°C)}$$

Values determined for the absolute thermal emf are given in Table 10.

TABLE 10

t (°C)	T (°K)	E (μv/°C)
0	273.1	1.72
100	373.1	2.16
200	473.1	2.55
300	573.1	2.90
400	673.1	3.20
500	773.1	3.46
600	873.1	3.67
700	973.1	3.84
800	1073.1	3.96
900	1173.1	4.04
1000	1273.1	4.07

Thomson emf

The Thomson emf of gold is reported(15) to be given by the function:-

$$\sigma = 1.26 + 0.0037t - 0.000,004,5\,t^2 \text{ microvolt/°C}$$

Values determined for the Thomson emf are given in Table 11.

TABLE 11

t (°C)	T (°K)	σ (μv/°C)
0	273.1	1.25
100	373.1	1.55
200	473.1	1.75
300	573.1	1.85
400	673.1	1.88
500	773.1	1.82
600	873.1	1.66
700	973.1	1.41
800	1073.1	1.07
900	1173.1	1.65
1000	1273.1	1.13

Thermoelectric Potential

Values reported for the thermoelectric potential (π) of gold are given in Table 12.(15)

TABLE 12

t (°C)	T (°K)	π (mv)
0	273.1	0.47
100	373.1	0.81
200	673.1	1.21
300	573.1	1.66
400	673.1	2.15
500	773.1	2.67
600	873.1	3.20
700	973.1	3.74
800	1073.1	4.25
900	1173.1	4.74
1000	1273.1	5.18

(A.16) Magnetic Susceptibility

Gold is diamagnetic. The mass susceptibility of gold(6) is:

$$\chi = -0.15 \times 10^{-6} \text{ cgs units}$$

(A.17) Emissivity

Spectral Emissivity

The spectral emissivity $\mathcal{E}_\lambda$ (ratio, energy radiated/unit area of surface at wavelength λ to energy radiated/unit area of a full radiator at the same temperature) of gold at room temperature is given in Table 13(6) for various wavelengths.

TABLE 13

Wavelength, μ	Spectral Emissivity
9.0	0.02
5.0	0.02
3.0	0.03
1.0	0.62

The spectral emissivity at temperatures close to the melting point are given in Table 14.(1)

TABLE 14

Wavelength, μ	Temperature, °C	Spectral Emissivity	
		Solid	Liquid
0.66	m.p. (1063) 1000	0.145 0.140	0.22 -
0.55	1000	0.45	-
0.49	m.p. (1063)	0.53	0.47
0.46	1000	0.63	-

Total Emissivity

The total emissivity E_t of gold (ratio, total energy radiated/unit area of surface to total energy radiated by a full radiator at the same temperature) is listed(6) as:

at 100 °C, $E_t = 0.02$

at 500 °C, $E_t = 0.03$

(A.18) Work Function

On the basis of the work function of silver the work function of an oxygen-free gold surface has been determined(25) as being:

4.74 V

(A.19) Surface Tension

Molten Gold

The surface tension of liquid gold at the melting point is:(26)

$$11.35 \text{ erg/cm}^2$$

Solid Gold

The surface tension of solid gold in the form of thin gold wires has been estimated(27) as being 1200 to 1700 dyne/cm in the temperature range 920° to 1020°C, ie, at temperatures near the melting point. In the temperature range 1007° to 1042°C, in purified helium, the solid surface tension of 99.98% gold has been determined as being:(28)

$$1400 \pm 65 \text{ dyne/cm}$$

Grain Boundary Energy

The average grain-boundary energy of gold has been determined(29) as being:

$$365 \pm 50 \text{ erg/cm}^2 \text{ at } 1027°\text{C}$$

A ratio of grain-boundary to surface energy of 0.25 at 850°C has been obtained,(30) and from this the grain-boundary energy calculated as being:

$$370\ \mathrm{erg/cm^2}\ \text{at}\ 850\,^\circ\mathrm{C}$$

(A.20) Diffusion

The rates of self-diffusion D can be expressed as the exponential function:

$$D = D_o e^{-Q/RT}$$

where D_o is the frequency factor (a constant, usually in $\mathrm{cm^2/sec}$), Q is the activation energy (a second constant, usually in cal/g atom), R is the gas constant, and T is the absolute temperature. A number of determinations of D_o and Q have been made and are summarized in Table 15.

TABLE 15

Temperature Range (°C)	Temperature Range (°K)	D_o ($\mathrm{cm^2/sec}$)	Q (cal/g atm)	Ref
-		-	53,000	(31)
-		-	51,000	(32)
800 - 1000	1073 - 1273	-	~45,000	(33)
679 - 1060	952 - 1333	0.265	45,300	(34)
600 - 954	873 - 1227	0.031	39,360	(35)
704 - 1048	977 - 1321	0.091	41,700	(36)
717 - 992	990 - 1265	0.14	42,900	(37)

It can be seen from the values in Table 15 that the determined values of D_o and Q do not exhibit good agreement. Work on the electrical resistivities of quenched gold wires has not been able to clarify the situation.

Wires were quenched from 690° - 900°C(38), 650° - 950°C(39), and 560° - 960°C(40). By means of electrical resistivity measurements the energy E_F to produce a lattice vacancy, and the activation energy E_M for vacancy motion, were calculated. If self-diffusion in gold takes place by means of vacancies, then the sum of E_F and E_M should equal Q the activation energy for self-diffusion. The values of E_F, E_M and $E_F + E_M$ obtained are given in Table 16.

TABLE 16

Quench Temp., °C	E_F, eV/atom	E_M, eV/atom	$E_F + E_M$, eV/atom	Ref.
690-900	1.28	0.68	1.96	(38)
650-950	1.02	0.66	1.68	(39)
560-960	0.95	0.68	1.63	(40)

The value of 1.96 eV for $E_F + E_M$ agrees with the value of 1.965 eV obtained by (34) for the activation energy Q. On the other hand, the values of 1.68 eV(39) and 1.63 eV(40) for $E_F + E_M$ show agreement with the value of Q, 170 eV, obtained by (35).

It was calculated(40) that the average life of a vacancy is $10^8 - 10^9$ jumps and the concentration of vacancies at the melting point of gold is 6×10^{-4}.

(A.21) Optical Properties

Colour

The colour of gold is due to strong absorption in the blue and ultra violet. Experimental work tends to confirm that the absorption is due to an internal photoelectric effect caused by the transition of an electron from the 3d shell to the conduction band. The hole created is screened by a 4s electron bound to it and absorption begins for the frequency corresponding to this excited state.(41)

Gold Blacks

Gold blacks are low-density gold deposits obtained by evaporating gold at a low pressure in an inert atmosphere such as nitrogen. The absorption and reflection properties in the infra-red region of the spectrum have been investigated.(42)(44) In the infra-red at wavelengths down to 39μ, the reflectivity of gold blacks is less than 1%.

The infra-red absorption of gold blacks is almost constand at wavelengths between 2 and 15μ and is a function of the weight of the coating. A 91.3 g/cm^2 deposit gives about 90% absorption in the 2 - 15μ region.

Above 100 °C the deposits sinter rapidly(43) and pronounced changes in optical properties take place. The gold smokes can be stabilized by heat treatment at 70 °C. After such stabilisation, sintering at above 100 °C takes place at a slower rate. The deposits will also collapse if treated with liquids which wet gold. The collapsed deposits have properties closer to those of massive gold.

(A.22) Viscosity

The viscosity of molten gold at 1200 °C is: (45)

4.63 centipoises

The viscosity decreases exponentially with increasing temperature.

I - B Mechanical Properties

(B.1) Elastic Properties

Modulus of Elasticity

The modulus of elasticity of pure gold at room temperature is listed(6) as:

$$E = 11.4 \times 10^6 \text{ psi}$$

The variation of the modulus of elasticity with temperature(46) is given in Table 17.

TABLE 17

Temperature, °C	E, 10^6 psi
-100	14.5
0	11.3
100	11.0
200	10.9
300	10.5
400	10.0
500	9.5
600	8.9
700	8.3
800	7.7
900	6.9

Modulus of Torsion

The modulus of torsion for pure gold at room temperature is listed(6) as:

$$4.0 \times 10^6 \text{ psi}$$

Poisson's Ratio

Poisson's ratio for pure gold at room temperature is given(6) as:

$$0.42$$

(B.2) Hardness

The hardness of gold is given(47) (48) as:

Annealed	20 VHN
Severely cold worked	70-75 VHN
Cold worked, 60% reduction	58 BHN

Values of the exponent "n" in Meyer's law,

$$P = ad^n,$$

were measured(49) for ball indentations in gold cold-worked in tension by various amounts. (Meyer's law deals with the load-diameter relationships of impressions in the Brinell hardness test.

P is load; a is the Meyer constant, which is the hardness of the sample unaltered by penetration hardening; d is diameter of ball indentation; and n is an exponent which provides a measure of the material's rate of work hardening.) For fully annealed gold a value of 2.65 was obtained.

(B.3) Tensile Properties

The tensile properties of gold are listed in Table 18.

TABLE 18

	Ultimate Tensile Strength, kpsi	Yield Strength, 0.2% offset, kpsi	Elong., % in 2 in.	Reference
Wrought and annealed	15.6	--	70	(47)
Wrought and annealed	19.1	3.3	-	(50)
Cold worked (60% reduction)	32.0	30.0	4	(48)

Effect of Electrochemical Polarization

Tests have been carried out (51) on the effect of cathodic or anodic polarization of gold wires on the tensile characteristics. The wires were strained in either potassium chloride or potassium nitrate as electrolytes. It was found that the velocity of plastic flow could be increased by a factor of up to ten times and the yield stress was decreased.

Effect of Adsorbed Gas

Work carried out on 0.1-mm-diameter gold wires has indicated that the UTS (ultimate tensile strength) of fine wires at room temperature is influenced by the atmosphere in which the tensile test is carried out.(52) The UTS was found to be a function of the liquefaction temperature of the gas in which the wire was tested, gases with the highest liquefaction temperature giving the greatest decrease in strength. Testing was in vacuum, hydrogen, air, argon, carbon dioxide, and ethyl chloride. The latter, with a liquefaction temperature of 280°K, gave about a 4% loss of strength compared with the strength in vacuum. The loss of strength in air only amounted to about 1%.

Effect of Temperatures

The tensile strength of gold is reported(53) to increase markedly at low temperatures. The ultimate tensile strength at -268.8°C is approximately twice the value at 20°C.

(B.4) Fatigue Properties

The fatigue strength of annealed wrought pure gold at 10^7 cycles is stated to be:(48)

4.6 kpsi

(Test method not stated).

The fatigue characteristics of annealed high-purity gold in axial compression-tension under a fixed alternating stress, and the effect of temperature on these characteristics, have been investigated.(53) The temperatures were in the range 4.2°K (-268.8°C) to 293°K (20°C). The fatigue characteristics and the UTS were found to improve with decreasing temperature. The ratio of the UTS to 10^5 cycle life remained more or less constant at about 1.5 over the temperature range. The 10^5 cycle life of about 1.24×10^9 dyne/cm^2 (18.0 kpsi) at 293°K (20°C), increased to about 2.44×10^9 dyne/cm^2 (35.0 kpsi) at 4.2°K (-268.8°C). The UTS at 293°K (20°C) was about 1.8×10^9 dyne/cm^2 (26 kpsi) and increased to about 3.7×10^9 dyne/cm^2 (54 kpsi) at 4.2°K (-268.8°C).

Although the gold used was stated to be annealed, the 20°C UTS is somewhat higher than normally accepted and may be due to the small specimens used (about 0.5 mm dia).

(B.5) Creep Properties

The room-temperature creep properties of fine gold annealed 10 minutes at 450°C and air-cooled, are given in Table 19. The ultimate tensile strength of the gold used(50) was 19.06 kpsi and the 0.2% yield strength 3.34 kpsi.

TABLE 19

Stress to give 0.2% elongation in 45 hr	-	3.27 kpsi
Stress to give 0.2% elongation in 1000 hr	-	2.99 "
Stress to give 0.2% elongation in 10,000 hr (by extrapolation)	-	2.84 "
Ratio: yield strength/ultimate tensile strength	-	17.6 %
Ratio: stress for 0.2% elongation in 10,000 hr/ yield strength	-	85 %

Data on the initial creep rate of pure gold have been correlated with stress and temperature by means of the function:(27) (54) (55)

$$\mathcal{Z} = \overset{\circ}{E}_s \, e^{\frac{\Delta H}{RT}}$$

in which

$\overset{\circ}{E}_s$ = initial creep ratio,

ΔH = activation energy for creep,

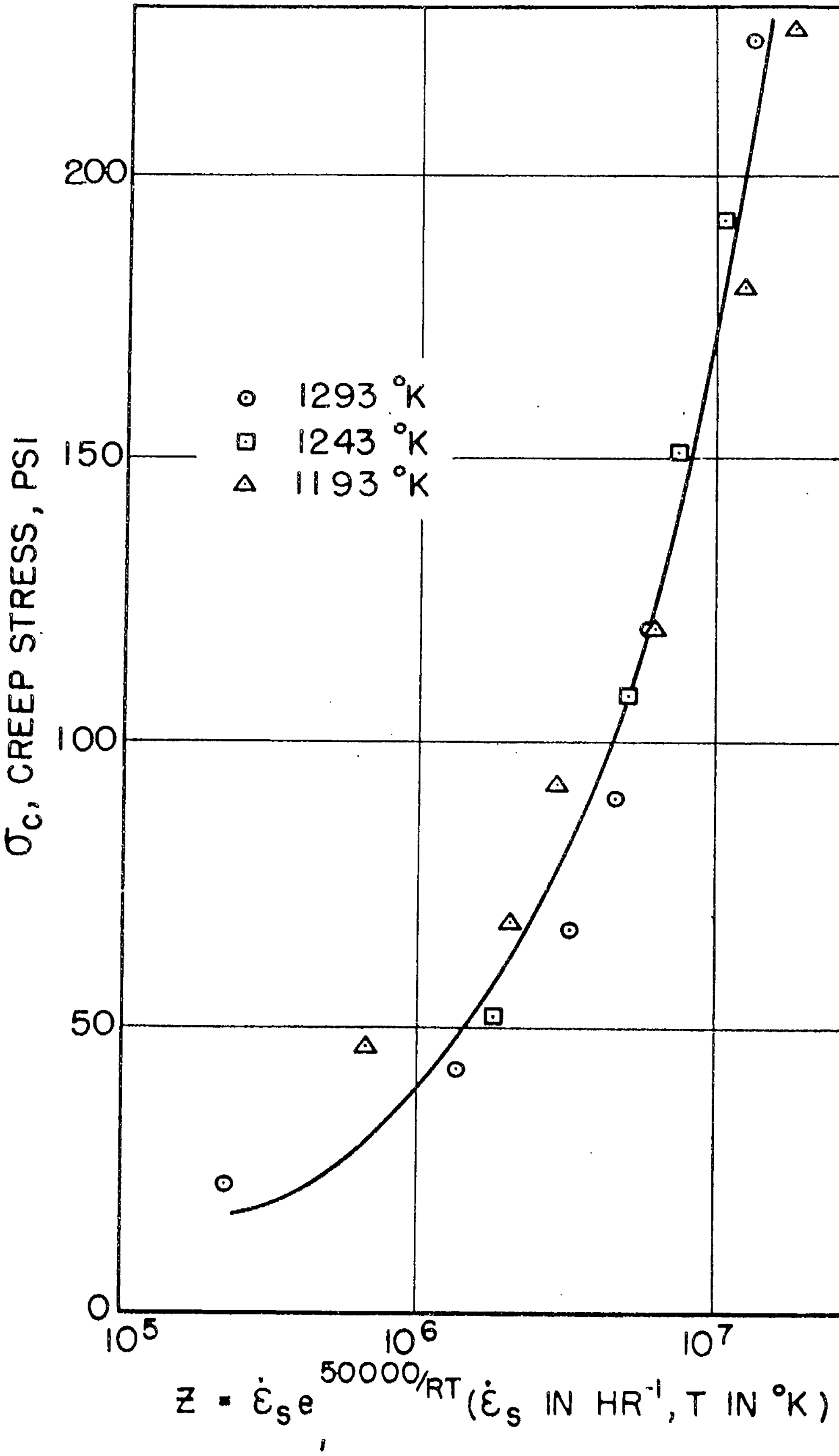
R = gas constant, and

T = absolute temperature in °K.

Figure 1 shows this correlation where creep stress has been plotted against the function. The function is generally applicable at temperatures in excess of 0.45 times the absolute melting temperature (T_m), and for gold this temperature is 328°C.

The activation energy for creep was found to be 50,000 cal/g atom for gold, and it was shown that the activation energies for creep and self-diffusion were almost identical for a number of metals (see Figure 2).

It was also shown that the activation energy for creep might be a periodic function of atomic number, and Figures 3 and 4 show plots of creep activation energies against two other properties which exhibit periodic variations, namely latent heat of sublimation and absolute melting temperature. Correlation with the latent heat of sublimation is only fair, but that with melting temperature is quite good.



200
150
100
50
0
10^5
10^6
10^7
σ_c, CREEP STRESS, PSI
$Z = \dot{\varepsilon}_s e^{50000/RT}$ ($\dot{\varepsilon}_s$ IN HR^{-1}, T IN °K)
⊙ 1293 °K
⊡ 1243 °K
△ 1193 °K

Figure 1

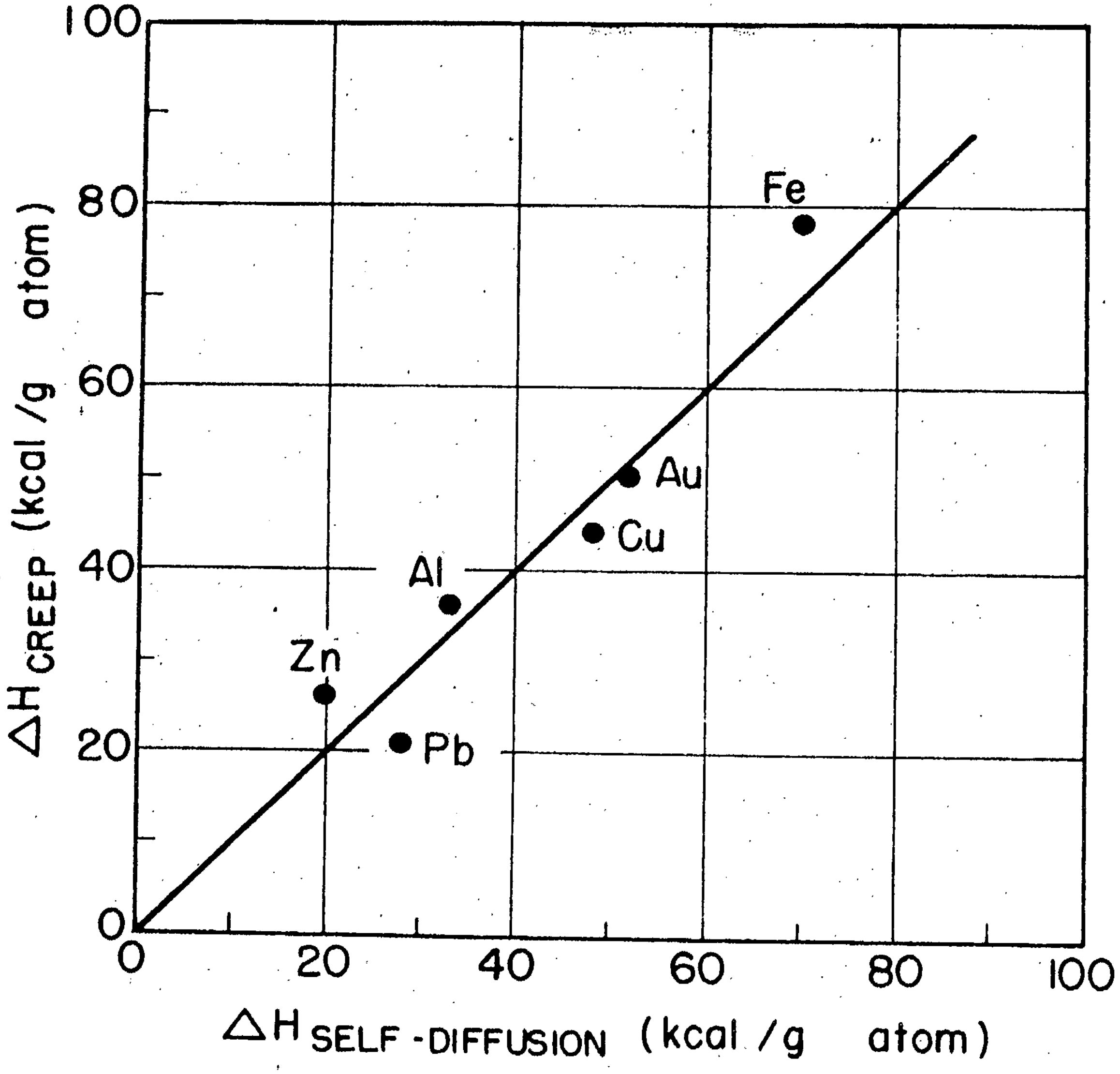

100
80
60
40
20
0
0
20
40
60
80
100
Fe
Au
Cu
Al
Zn
Pb
ΔH_{CREEP} (kcal /g atom)
$\Delta H_{\text{SELF-DIFFUSION}}$ (kcal /g atom)

Figure 2

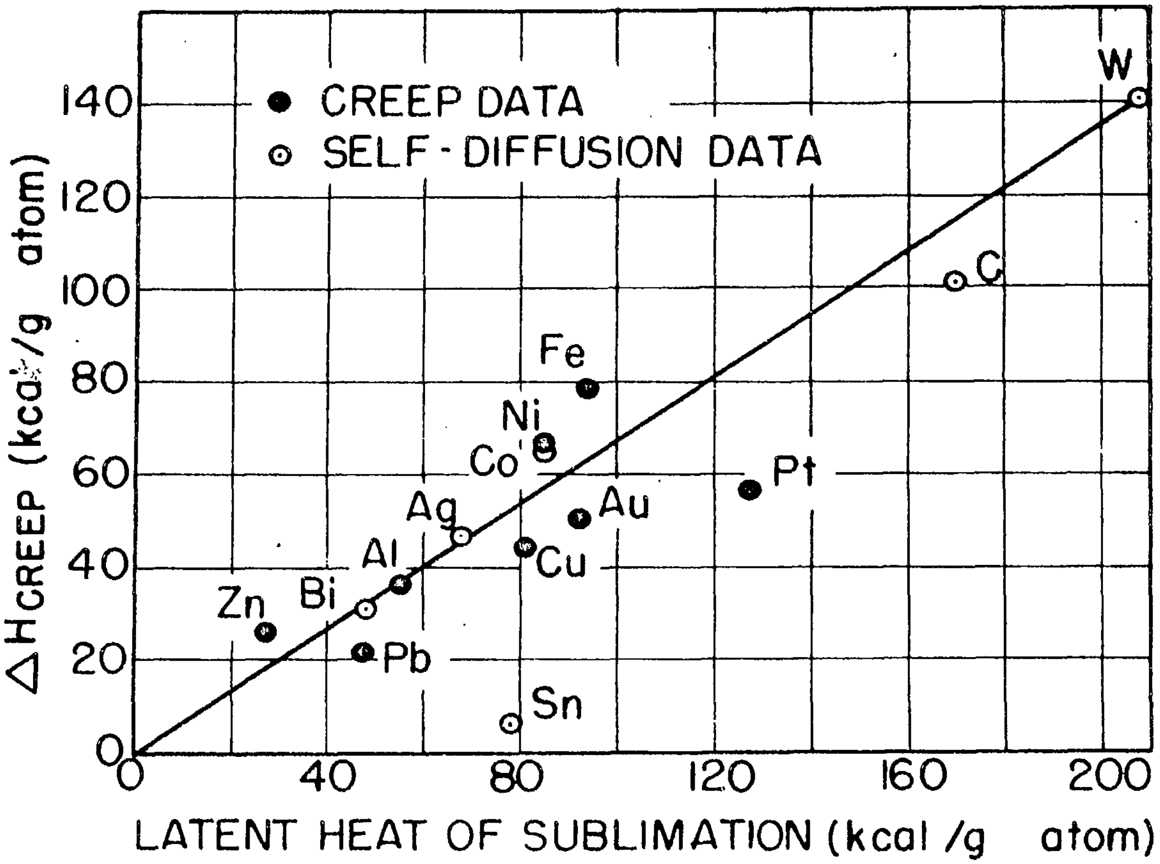

● CREEP DATA
⊙ SELF-DIFFUSION DATA
W
C
Fe
Ni
Co
Pt
Au
Ag
Al
Cu
Zn
Bi
Pb
Sn
0
20
40
60
80
100
120
140
0
40
80
120
160
200
ΔH_{CREEP} (kcal/g atom)
LATENT HEAT OF SUBLIMATION (kcal /g atom)

Figure 3

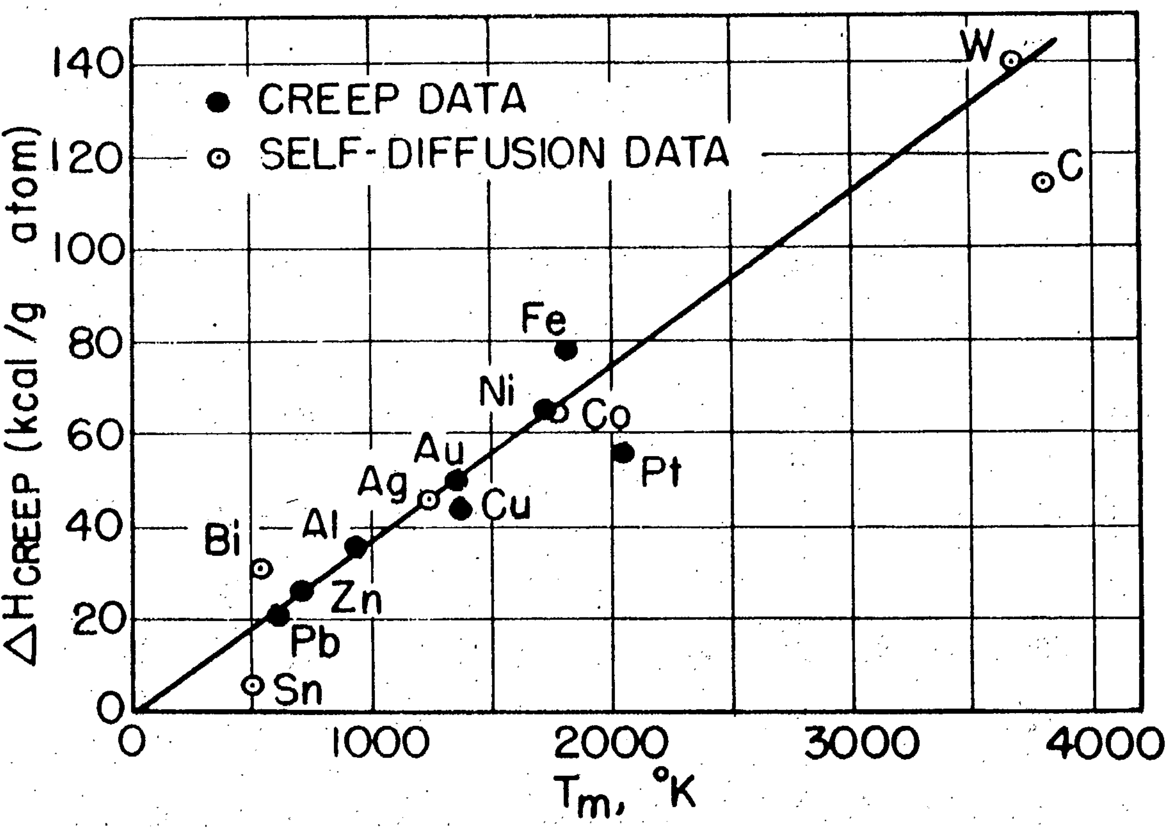

● CREEP DATA
⊙ SELF-DIFFUSION DATA
W
C
Fe
Ni
Co
Pt
Au
Ag
Cu
Al
Bi
Zn
Pb
Sn
140
120
100
80
60
40
20
0
0
1000
2000
3000
4000
ΔH_{CREEP} (kcal /g atom)
T_m, °K

Figure 4

I - C Chemical Properties

(C.1) Formation of Oxides

Gold forms the following oxides and hydroxides:(56)

Aurous oxide	-	Au_2O
Aurous hydroxide	-	$AuOH$
Auric oxide	-	Au_2O_3
Auric hydroxide	-	$Au(OH)_3$

All are unstable and decompose to give metallic gold at temperatures from 150° to 250°C. The oxides and hydroxides can be formed by anodic oxidation at low current densities.(57)(58)(59)(60)

Direct oxidation of gold in oxygen, air or oxygen containing nitrogen,at 900°C and atmospheric pressure,does not appear to take place.(61) At low pressures, however, oxygen is reported to react with a filament of gold heated to 900°C.(62) A volatile oxide was observed which decomposed to gold and oxygen atoms on condensing on the cooler parts of the apparatus.

Lubrication by Fatty Acids

Effective lubrication of metals by fatty acid solutions depends on the formation of soaps having higher melting point than the parent acid. The soaps are formed by the reaction of the fatty acid with oxide or hydroxide films on the surface of the metal.

No effective lubrication of gold surfaces by fatty acids is possible, since no oxide film (or at best only a thin film) is formed and hence no soaps are formed.(63) The lubrication by long-chain fatty acid on gold surfaces is due only to the physical adsorption of the acid, since lubrication breaks down at the melting point of the adsorbed acid.(64)

(C.2) Reaction with Gases

No strong reactions take place between metallic gold and the commoner gases (oxygen, nitrogen, hydrogen, carbon dioxide, air, argon, and water vapour), and no nitride, hydride or carbide of gold is known.

Adsorption effects and possibly some absorption effects take place between gold and gases, notably with oxygen. The variation of contact potential between freshly condensed gold films and platinum has been used to follow the adsorption onto gold surfaces at low pressures.(65) Some evidence was obtained that oxide formation and absorption were also taking place. No appreciable effect occurred when nitrogen was used in place of oxygen.

The contact angle between gold and water has been studied as a function of atmosphere and time.(66) The atmospheres used were oxygen, nitrogen, and carbon dioxide. Of these, only oxygen had any effect on the contact angle, a change from 61° to 78° in 30 minutes being observed.

Where the ratio of surface area to volume of the gold samples is high, gases are found to affect properties such as the ultimate tensile strength and electrical resistivity. Most of the observed changes are probably surface energy changes due to adsorbed layers of the gas. The change in UTS of thin wires has already been mentioned (see B.5, Tensile Properties) and here the decrease in strength is a function of the temperature at which the gases become liquid.(52)

The adsorption of water vapour on gold is reported to be chemical as well as physical.(67) The electrical resistivity of freshly formed gold films increases on exposure to water vapour and these increases have been ascribed to the adsorption of water on the surface and the subsequent absorption of oxygen and hydrogen into the film.(68) The thickness of adsorbed water and some organic vapour layers on gold foil has been found to be about two molecules thick.(69) The electrical conductivity of gold powders in a hydrogen atmosphere however, was found to be independent of hydrogen pressure.(70)

(C.3) Corrosion

Pure gold is characterized by a good resistance to corrosion. This, in the main, is due to the stability of gold in comparison with its compounds and to the nobility (high solution potential) of the metal.

The solution potential of gold in a dilute chloride solution on the N/10 calomel scale is :(6)

less than - 0.08 volt

The normal electrode potential of gold is:(6)

+ 1.68 volts at 25°C for monovalent gold

+ 1.4 " " " " trivalent "

The corresponding potential of the hydrogen electrode is taken as zero and the normal electrode potential values are for bare metal with respect to a solution containing normal activity of gold ions in the respective states of oxidation.

Effect of Elastic Strain

An effect in the electrode potential of gold of elastic strain has been reported.(71) Tension is found to shift the potential in the more noble (cathodic) direction, while compression shifts the potential in the less noble (anodic) direction. The magnitude is small and is between 0.01 and 0.1 mv/1000 psi applied load, and therefore has little influence in the macro-corrosion processes in the metal.

Attack by Specific Agents

Pure gold is unattacked by most chemicals. Free halogens such as chlorine and bromine (aqua regia attacks because of the free chlorine), and chemicals forming complex gold-containing ions such as potassium cyanide, will attack gold. Where complex ions are not formed and attack takes place, the gold is present in the reaction product as either a monovalent or a trivalent ion.

A summary of the resistance of gold to attack under some conditions is given in Table 20.(6)

TABLE 20

Resistance of Gold to Chemical Attack

Agent	Temp °C	Other Conditions	Resistance
Iodine	20	Dry solid	E
Ozone	20	Dry	E
Phosphorus	-	-	E
Selenium	-	-	S
Sulphur	-	-	E
Alum	20	10% solution	E
Alum	20	Saturated solution	E
Aluminum Chloride	20	Solution	E
Ammonia	-	Solution	E
Ammonium Sulphide	20-100	Solution	R
Arsenic Acid	-	Solution	S
Chromic Acid	20	Solution	E
Nitric Acid	-	Solution under 80%	E
Nitric Acid	-	Fuming	S
Phosphoric Acid (Ortho)	20	Solution	E
Phosphoric Acid (Ortho)	b.p.	Solution	E
Potassium Carbonate	-	Molten	S
Potassium Hydroxide	20	Solution	E
Potassium Hydroxide	-	Molten	R
Potassium Persulphate	20	Solution	S
Sulphur Dioxide	-	Moist gas	R
Acetic Acid	0-118	0-100% solution	E
Oxalic Acid	20	Solution	E
Phenol	20-100	Solution	E

E - Excellent. No appreciable attack under given conditions.

S - Satisfactory. Some attack takes place but gold may still be suitable in this environment.

R - Restricted application. Gold is attacked and is not suitable for all applications with the corrodent listed, but in some circumstances it may be satisfactory.

The corrosion of gold has been the subject of much investigation in connection with nuclear reactors and reactor fuel.(72)(73)(74)(75) Molten lithium, sodium and potassium carbonates at temperatures up to 1000°C are reported to give only slight attack of gold.(72) The action of 5% bismuth trichloride in a ternary eutectic of sodium chloride-potassium chloride magnesium chloride at 425°C has been studied.(75) With fluorine at temperatures above 100°C, the attack is too severe for the use of gold to be practical.(74) The corrosion of gold by nitric acid-uranyl nitrate systems in the processing of homogeneous reactor fuels has been investigated.(73)

Traces of metallic ions in the corroding solution have a great influence on corrosion processes. The activation and inhibition of corrosion by such ions in boiling hydrochloric acid have been studied.(76)

Selenic acid (H_2SeO_4) will attack gold by the formation of a complex ion. On thin gold wire the 67% acid gives no attack at temperatures up to 154°C and times up to 26 days.(77) The 87% selenic acid solution shows some action after 8 hr at 130°C and will completely dissolve the sample in 25 days. The action of the 98% is rapid. Complete solution takes place in 3 days at 130°C and 13 hr at 154°C.

The solution of gold in cyanide solutions is of great importance in the extraction of gold from ores, and has been studied in detail for this reason.(78)

(C.4) Catalysis

The activation energy for the parahydrogen conversion on gold is reported (79) as being 8.5 kg cal/mole.

I - D Fabrication

(D.1) Melting

Pure gold may be melted in gas, oil, coke, electric resistance or high frequency furnaces. It does not react with any of the common refractories under oxidizing conditions, and does not dissolve hydrogen, oxygen or furnace gases when molten.(80) Clay-graphite crucibles are found to be quite suitable for pure gold (and most gold alloys).

(D.2) Mechanical Working

Pure gold presents no metallurgical difficulties in mechanical working or forming. It can be worked at any temperature below the melting point. Although gold work hardens, no annealing appears to be required to permit completion of the desired working.(48) This presumably can be ascribed to the outstanding malleability which is a characteristic of the metal.

Production of Gold Leaf

Gold has been hand-beaten into leaf for decorative application for literally thousands of years. The practice is said to be over 5,000 years old and samples of leaf, ready for application, were found in the Tutankhamen tomb in Egypt.

The leaf is produced by beating between "skins" made from the intestines of oxen, and the preparation of these skins may take as long as the time spent beating.(81) The gold is beaten to a thickness of about 4 x 10^{-6} inches. In order to obtain this thinness, 970 fine gold has to be used, the alloying elements being silver or copper. Pure gold, it is claimed, cannot be hand beaten to the same thinness.

Special handling tools are required, since the leaf adheres to steel. Boxwood pincers, rattan cane cutters, and Arctic hare's foot brushes for skins are typical.

Gold leaf was formerly produced entirely by hand beating, but this is being supplemented by machine beating. A gold film for decorative purposes is also produced by vacuum deposition of gold onto a suitable backing. This method of production permits continuous rolls of film to be produced.

(D.3) Joining

Pure gold can be oxy-acetylene welded without difficulty, using pure gold as a filler rod. No flux is required and the flame can be oxidizing, neutral or reducing without any effect on the weld.(48)

Electric resistance welding can be accomplished satisfactorily by any method.

(D.4) Plating

Coatings of pure gold can be plated onto base metals from gold-containing solutions by either electrolytic (electro-plating) or chemical (electroless-plating) methods. The electroplating methods usually employ gold-containing cyanide solutions and are capable of giving coatings ranging in thickness from about 5×10^{-7} inches to several thousandths of an inch. The very thin coatings are intended only to give a coloured finish, but the thicker deposits are intended to impart the physical properties of bulk gold to the plated article and even to improve on these properties. For economic and technical reasons the electroplating process must be under close control. On the economic side it is necessary that only the thickness specified be plated, since overplating to exceed minimum specified thicknesses as is practiced in base metal plating, could be very costly.(82) On the technical aspects, close control of the process is necessary in order to obtain the desired hardness, smoothness and wear-resistance.(83) Hardness of pure-gold electroplated deposits is a function of grain size, finer grain giving harder deposits.

The periodic reversal of current during the electroplating of gold is claimed(83) to give smoother, harder and denser deposits of gold than the normal direct-current plating.

The addition of metals such as nickel will also give harder deposits and here some co-deposition of gold and nickel takes place. Some additions apparently modify grain size without lowering the purity of the gold being deposited, and cobalt salt additions are claimed to do this.(84) The addition of cobalt to gold plating baths is reported to give gold deposits of BHN 190 hardness (an 80% increase over deposits from baths not containing cobalt). The cobalt is not deposited, but gives a fine grained deposit with a wear resistance that is three times that of deposits from the non-cobalt-containing bath.

The chemical plating methods depend on the displacement of gold from a gold-containing solution by the base metal. Theoretically, any metal less noble than gold should be replaceable by a gold deposit,(85) and the process works well on copper and copper base alloys, nickel, and iron. A limiting thickness applies to the process since thickness build-up virtually stops when all the base metal surface has been replaced by gold deposit. In some cases, such as plating on zinc, the dissolved zinc can be re-deposited as a zinc-gold alloy.

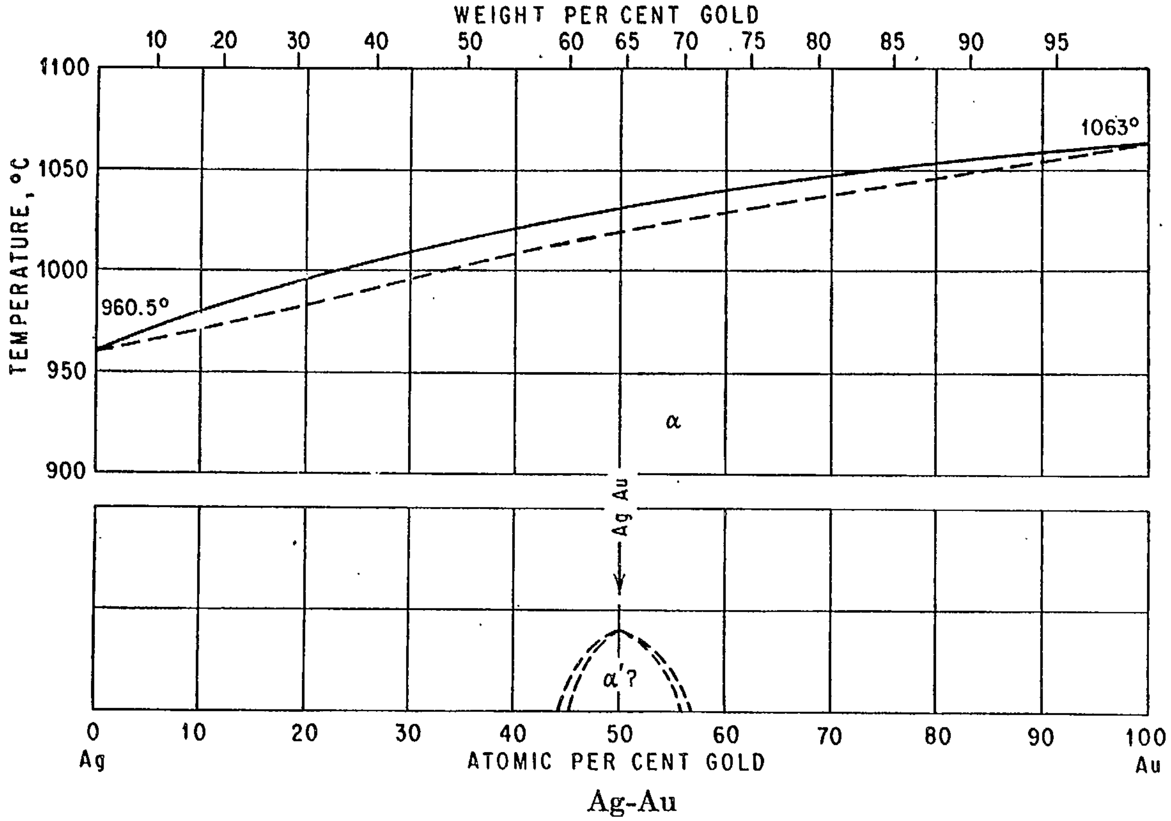
Gold deposits up to about 1 x 10^{-5} inches can be obtained and are claimed to be dense and continuous.

II. PROPERTIES OF ALLOYS CONTAINING GOLD

Au-Ag, Gold-Silver

Gold and silver form a continuous series of solid solutions. The normally accepted phase diagram(2) for the system is shown in Figure 5. A more recent determination of the solidus-liquidus boundaries (86) is given in Figure 6. This diagram was based on thermal analysis and thermodynamic calculations and shows a much smaller solidus-liquidus gap, the maximum gap being reported as 2.4°K at 23 at % gold. It is concluded(86) that the misfit energy of the similar-sized gold and silver atoms in the solid alloys is near zero and that there is a close similarity between the thermodynamic properties of the solid and liquid alloys.

There is a possibility of ordering of the atoms in the 50 at % gold alloy, (2) and Figure 5 indicates this. The value of the critical ordering temperature for the composition AuAg has been estimated(87) as 160°K (-113°C), which makes the establishment of long range order almost impossible.



Ag-Au

Figure 5

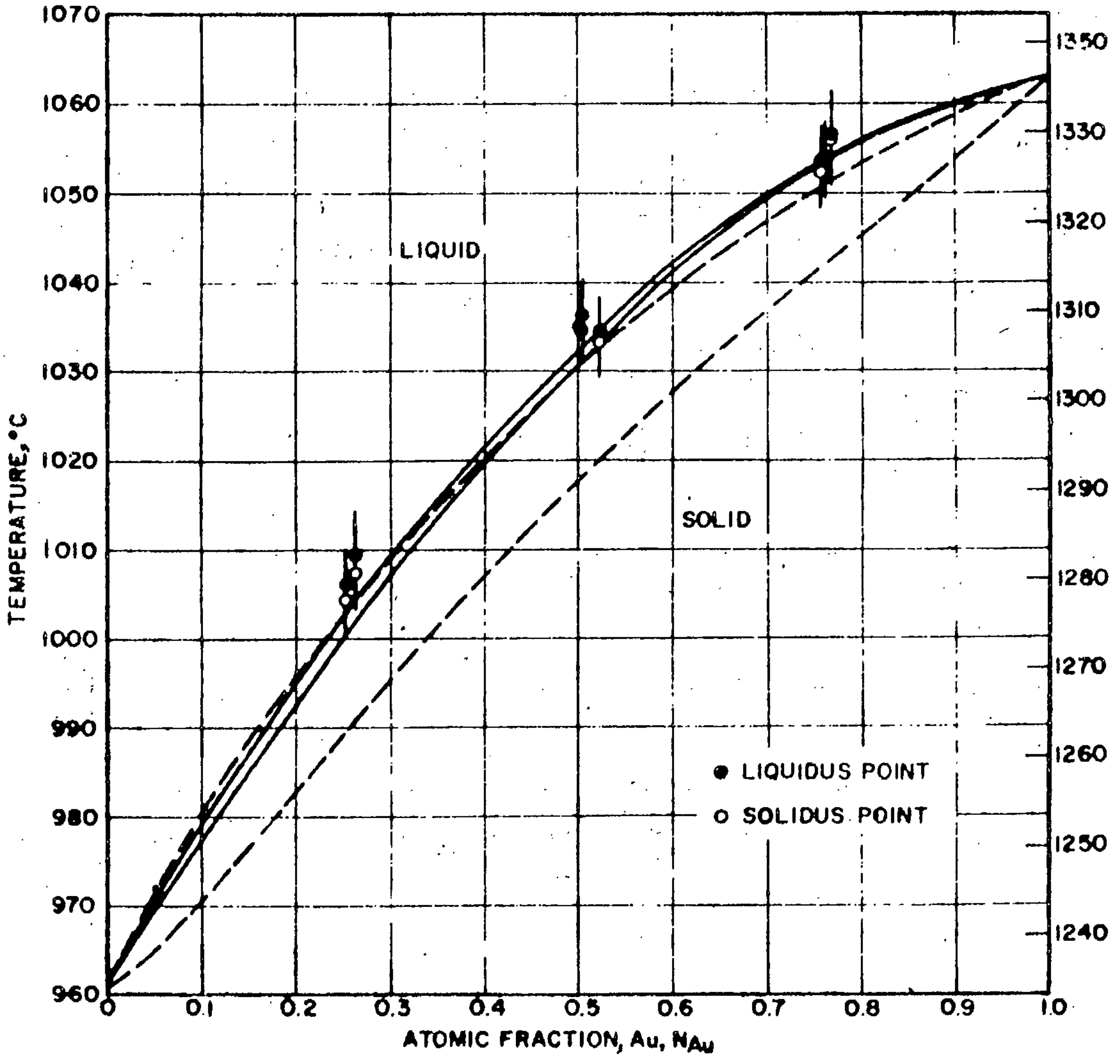


Figure 6. Ag-Au diagram. Solid lines refer to the solidus and liquidus calculated from the thermodynamic properties; dashed lines refer to the previously accepted phase diagram.

Ternary Systems

Au-Ag-Co	Gold-silver-cobalt. Data on this system are contained in reference (88).
Au-Ag-Cu	Gold-silver-copper. This system has been investigated in references (88) (89) (90) and (92).
Au-Ag-Fe	Gold-silver-iron. Data on this system are contained in reference (88).
Au-Ag-Mn	Gold-silver-manganese. Data on this system are contained in reference (88).
Au-Ag-Ni	Gold-silver-nickel. Data on this system are contained in reference (88).
Au-Ag-Pd	Gold-silver-palladium. The phase diagram has been investigated in references (91) and (93). The effect of cobalt on the mechanical properties of alloys containing palladium 40-70%, gold 10-20%, cobalt 2-6%, balance, silver, was investigated in (94). No improvement occurred and this was attributed to the cobalt being held in solid solution in the palladium-rich alloys. Data on the system are also contained in reference (88).
Au-Ag-Pt	Gold-silver-platinum. Data on this system are contained in reference (88).
Au-Ag-Zn	Gold-silver-zinc. See Au-Zn, gold-zinc.

(A.20) Diffusion

Au-Ag

The diffusion rates of silver and gold in gold-silver alloys follow the exponential function:

$$D = D_o e^{-\frac{Q}{RT}} \quad cm^2/sec$$

Determinations for D_o and Q are given in Table 21.

TABLE 21

Alloy		Diffusion of	Temp °C	D_o cm^2/sec	Q K cal/mole	Reference
Au at%	Ag at %					
49.2	50.8	Ag	-	0.39	44.7	(95)
49.2	50.8	Au	-	0.12	44.1	(95)
97.0	3.0	Ag	-	0.047	38.5	(96)
-	100	Au	650-950	0.026	45.5	(97)
75	25	Au	-	0.041	40.7	(37)
25	75	Au	-	0.064	42,8	(37)
	100	Au	-	0.041	46.4	(37)

Porosity has been found to develop(98) during the interdiffusion of gold and silver in gold-silver diffusion couples. The porosity is due to the more rapid diffusion of silver and is probably caused by precipitation from a supersaturated solution of vacancies. The vacancies are produced by the diffusion loss (99) and may also produce voids by condensation onto Ag_2O previously precipitated.(100)

Dimensional changes also occur during the interdiffusion of gold and silver. It has been found that these are greatest in the direction of diffusion.(98) The dimensional changes, normal to the diffusion direction, are about 10% of the changes in the diffusion direction.

(C.3) Corrosion

Au-Ag

The type and mechanism of stress corrosion cracking of gold-silver and gold-copper alloys in weak and strong oxidizing solutions has been surveyed.(101) The type of cracking is primarily dependent on whether or not the corrodent will attack the more noble component of the solid solution. Weakly oxidizing solutions were ferric chloride, cuprous chloride, ferric sulphate, and sodium sulphide. Strong oxidizing agents were nitric acid, potassium permanganate, chromic acid, and hydrochloric plus nitric acids.

If the noble component of the solid solution is attacked, i.e. the solid solution dissolves, transcrystalline as well as intercrystalline cracks develop, but if it is not attacked, only intercrystalline cracks develop.

The weakly oxidizing solutions only cause intercrystalline cracks if the gold content of the alloy is less than 25 at %. Strongly oxidizing solutions will cause transcrystalline cracks if the gold content is less than 50 at %.

The susceptibility of the alloy to cracking can be reduced and finally eliminated by increasing amounts of mechanical deformation.

(D.1) Melting

Au-Ag

Oxygen is soluble in silver and, because of this, deoxidation or the exclusion of oxygen during melting and casting is necessary if blister-free annealed worked products are required. Zinc and phosphorus are effective deoxidizing additions.(102) Blistering is less prevalent on the 75 at % gold alloys than on the 50 at % gold alloy.

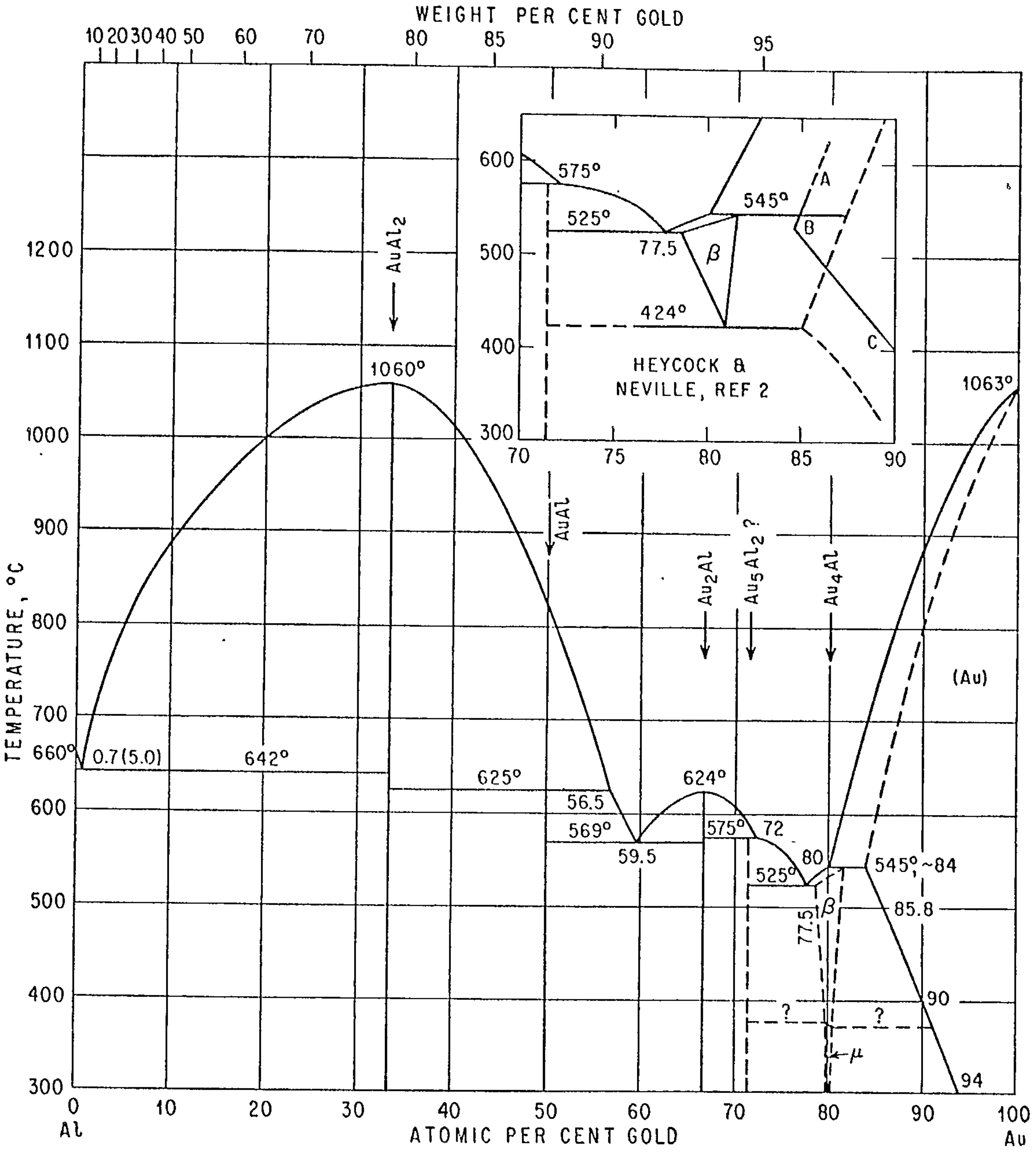
The shrinkage on solidification and on cooling to room temperature of gold-silver alloys is almost unaffected by composition(12) and is listed in Table 22.

TABLE 22

Gold Content, Wt %	Shrinkage	
	On Solidification	On Cooling, Solidus to R.T.
100	6.0	4.9
80	6.9	5.0
10	7.5	5.8
0	6.5	6.0

Au-Al, Gold-Aluminum

The constitution diagram in Figure 7(2) reflects the doubt that still exists as to the precise phase relationships and compositions between 70 and 90 at % gold. The inset in Figure 7 shows a suggested alternative diagram for this composition range. The solid solubility of gold in aluminum is not known. The maximum solid solubility of aluminum in gold (at 530° - 545°C) is given as 15.5 at% (2.45 wt %) aluminum.



Al-Au

Figure 7

Ternary Systems

Au-Al-Cu	Gold-aluminum-copper. See Au-Cu, gold-copper.

(C.2) Reaction with Gases

Au-Al

Aluminum-3.5% lithium alloys when cast into sand moulds react with the water vapour present to form macroporosity. The effect of 0.01 and 0.1 at % Au on this reaction was investigated.(103) It was concluded that gold was not surface active in aluminum and was not useful as a mould reaction suppressant in sand-cast aluminum-lithium alloys.

(D.2) Mechanical Working

Au-Al

The addition of 3% aluminum to gold results in a practically useless alloy. The alloy of gold with 1% aluminum has fairly good working properties, and the alloy with 0.1% aluminum works readily.(102)

Au-As, Gold-Arsenic

Phase Diagram

The phase diagram in Figure 8(2) represents all that is known about the gold-arsenic system. The solid solubility of arsenic in gold appears to be about 0.2 at % (0.08 wt %) at 611°C and nil at 400°C.

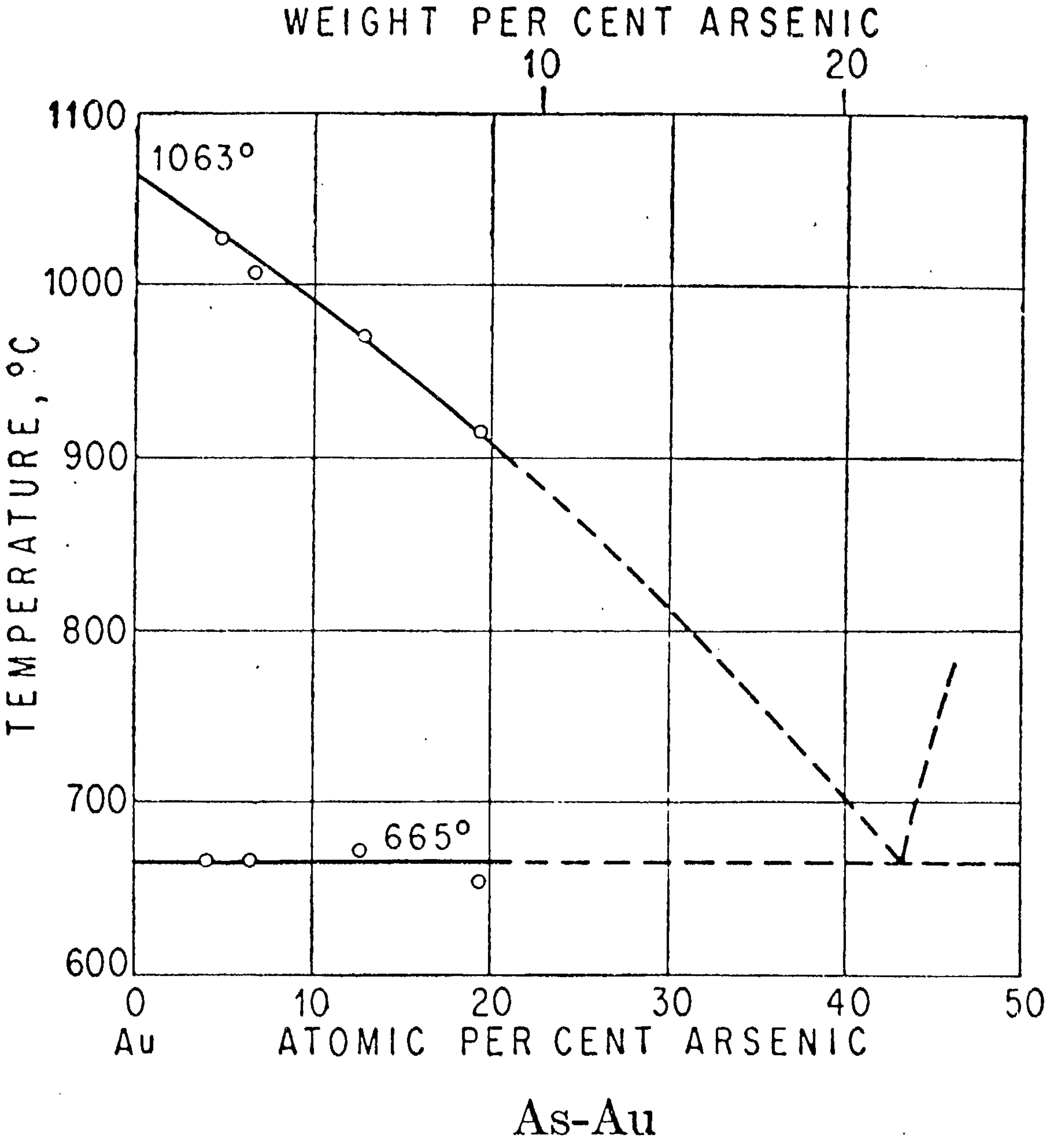

WEIGHT PER CENT ARSENIC
10
20
1100
1000
900
800
700
600
TEMPERATURE, °C
1063°
665°
0
Au
10
20
30
40
50
ATOMIC PER CENT ARSENIC
As-Au

Figure 8

Au-B, Gold-Boron

Phase Diagram

It has not been possible to determine any phase relationships for this system.(2)

Au-Ba, Gold-Barium

Phase Diagram

No phase diagram has been constructed, although gold and barium are known to form intermetallic compounds.(2) The existence of a phase Au_5Ba has been established, and the compounds Au_2Ba and Au_3Ba_2 are reported.

(A.4) Crystal Structure and Lattice Constants

Au-Ba

Au_5Ba is reported to crystallize in the Cu_5Ca type of lattice.(104) Lattice constants for Au_5Ba are given as a = 5.66 A, c = 4.57 A.

Au-Be, Gold-Beryllium

Phase Diagram

The phase relationships for gold-beryllium alloys containing up to 50 at % beryllium are given in Figure 9.(2)

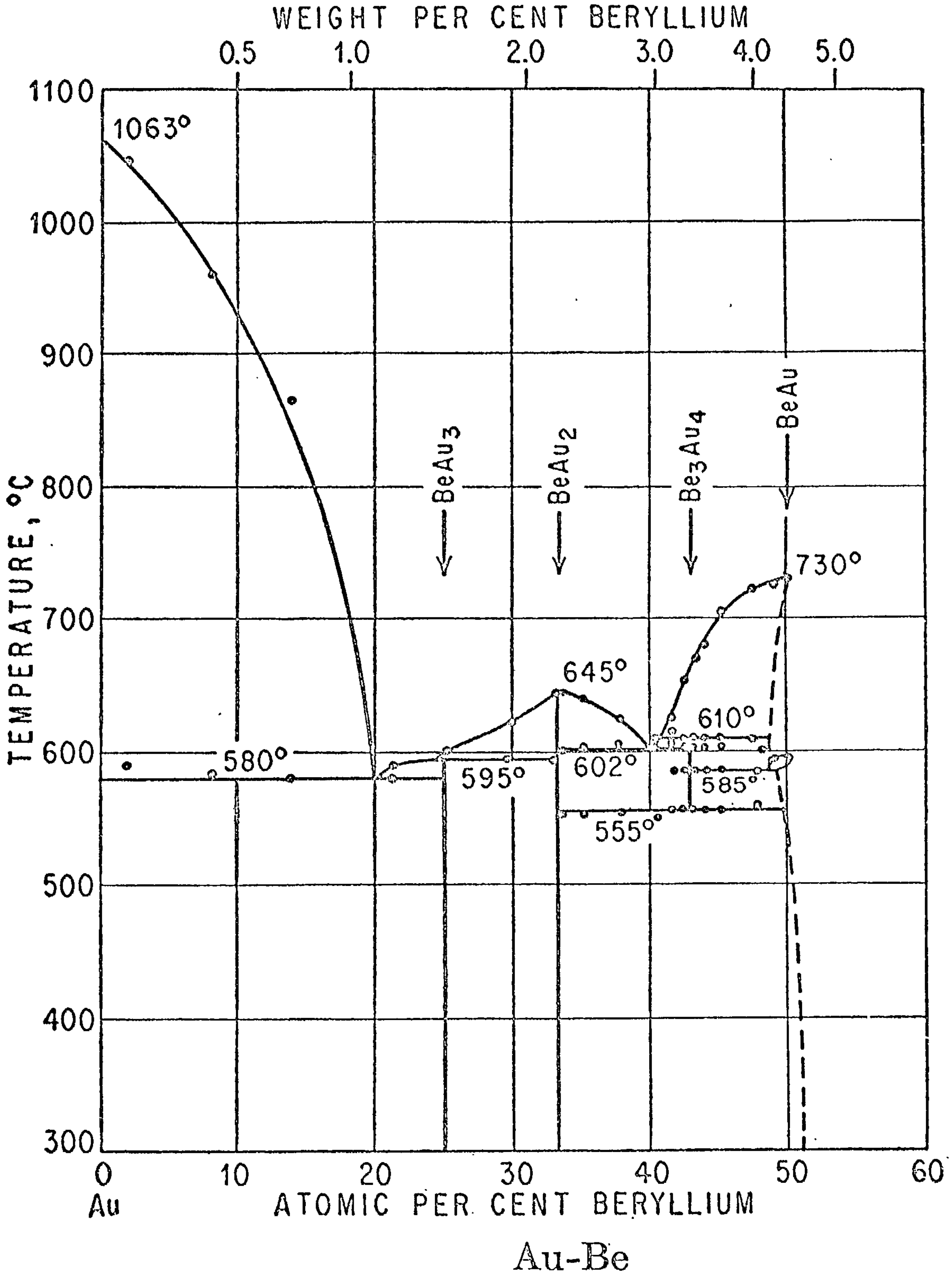

WEIGHT PER CENT BERYLLIUM
0.5
1.0
2.0
3.0
4.0
5.0
TEMPERATURE, °C
1100
1000
900
800
700
600
500
400
300
1063°
BeAu$_3$
BeAu$_2$
Be$_3$Au$_4$
BeAu
730°
645°
610°
580°
595°
602°
585°
555°
0
10
20
30
40
50
60
Au
ATOMIC PER CENT BERYLLIUM
Au-Be

Figure 9

The solid solubility of beryllium in gold appears to be restricted and not more than a few tenths of 1 at % beryllium. The solid solubility of gold in beryllium has been predicted on theoretical grounds as being up to about 3 at % gold.

(D.1) Melting
Au-Be

The cast form of a gold - 66.7 at % beryllium alloy was too hard and brittle to be machined.(105) When made by powder metallurgical means, compacts with 98% theoretical density and a Rockwell B scale hardness of 88 to 92, were obtained.

(A.12) Thermal Expansion
Au-Be

The linear coefficient of expansion for a gold - 66.7 at % beryllium alloy produced by powder metallurgical means(105) is 11.7×10^{-6} in./in/°C up to 300°C. Between 300°C and 400°C a length increase of over 8% takes place.

Au-Bi, Gold-Bismuth

Phase Diagram

Figure 10(2) depicts the known relationships between gold and bismuth. The compound Au_2Bi is superconductive and is also reported to decompose at low temperatures. The maximum solid solubility of bismuth in gold is 0.07 at % at 900°C, decreasing to less than 0.03 at % at 500°C and 600°C.

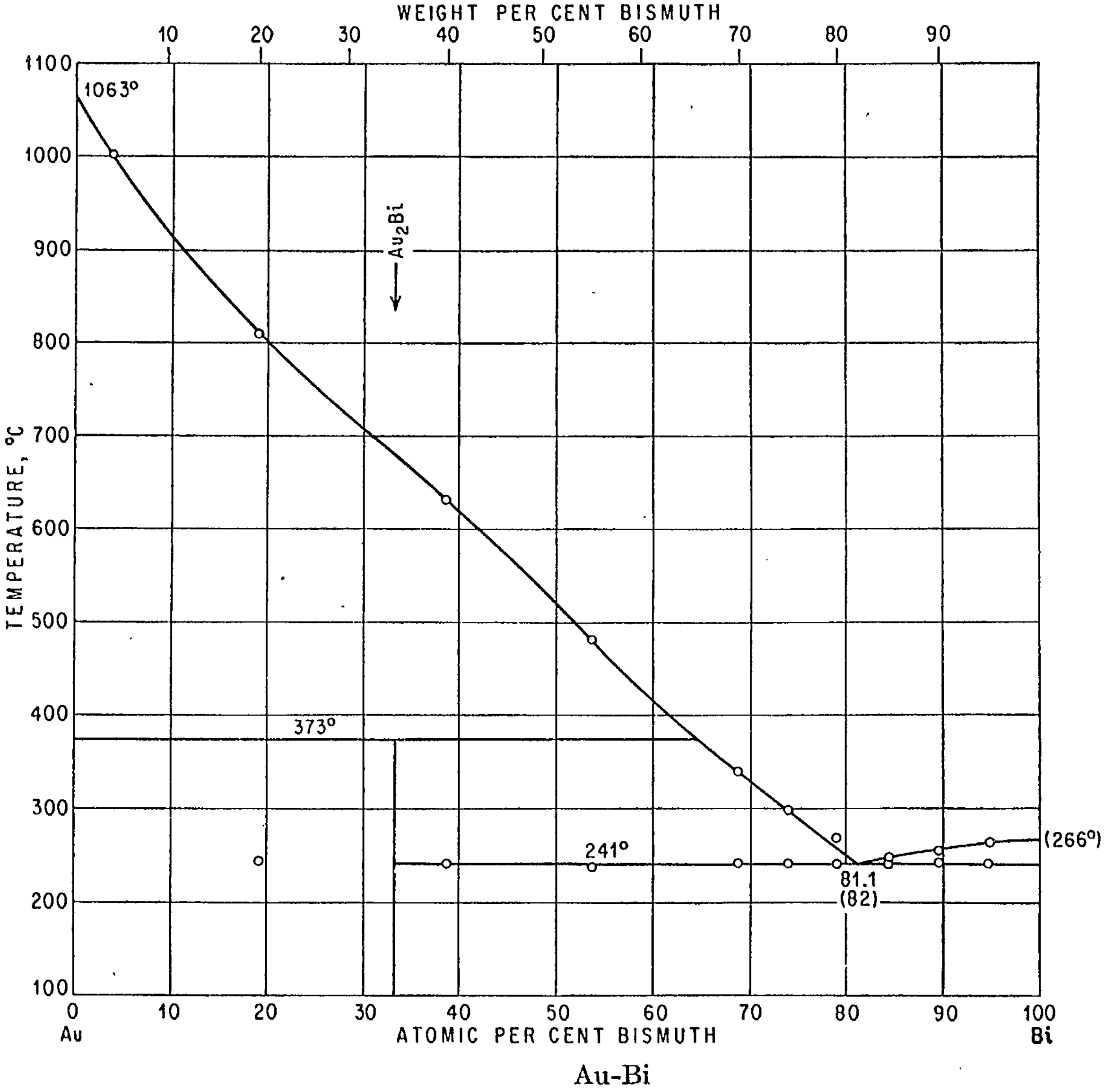

WEIGHT PER CENT BISMUTH
10
20
30
40
50
60
70
80
90
1100
1000
900
800
700
600
500
400
300
200
100
TEMPERATURE, °C
1063°
Au_2Bi
373°
241°
81.1
(82)
(266°)
0
Au
10
20
30
40
50
60
70
80
90
100
Bi
ATOMIC PER CENT BISMUTH
Au-Bi

Figure 10

(D.2) Mechanical Working

Au-Bi

A gold alloy containing 0.1% bismuth breaks easily on rolling, while an alloy with 0.01% is more rollable, but is more brittle than fine gold.(102)

Au-C, Gold-Carbon

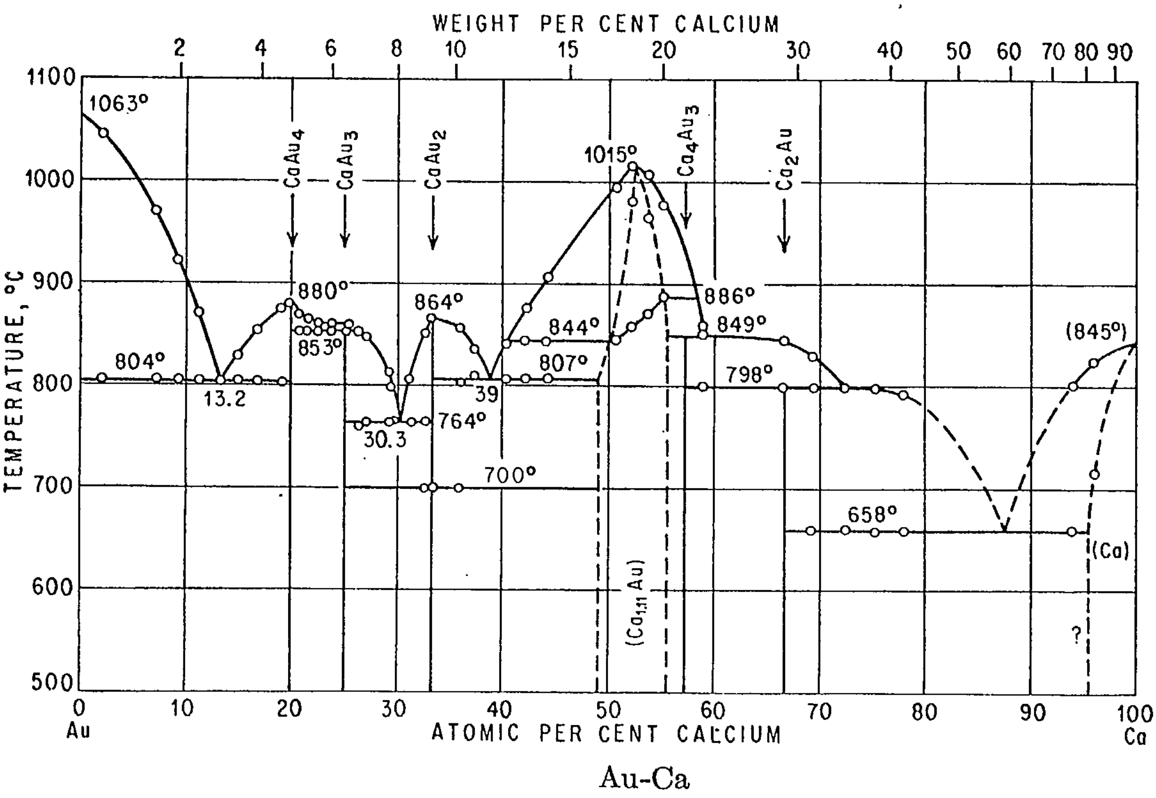
Phase Diagram

No phase diagram has been constructed,(2) but gold will dissolve small amounts of carbon at its boiling point which will crystallize out as graphite on cooling of the melt.

Au-Ca, Gold-Calcium

Phase Diagram

The diagram for the gold-calcium system is given in Figure 11.(2) The solid solubility of calcium in gold at 800°C is estimated as being less than 1.8 at % calcium, while the solid solubility of gold in calcium at 658°C is approximately 4.5 at %.



Au-Ca

Figure 11

Au-Cd, Gold-Cadmium

Phase Diagram

The diagram in Figure 12 (2) is not finally fixed. Much work continues to be done, especially on the mechanism of the diffusionless transformations of the β phases containing 47.5 at % and 50 at % cadmium.

The maximum solid solubility of cadmium in gold is about 32.5 at % at 625°C, while the maximum solid solubility of gold in cadmium is 3.5 at % at 309°C.

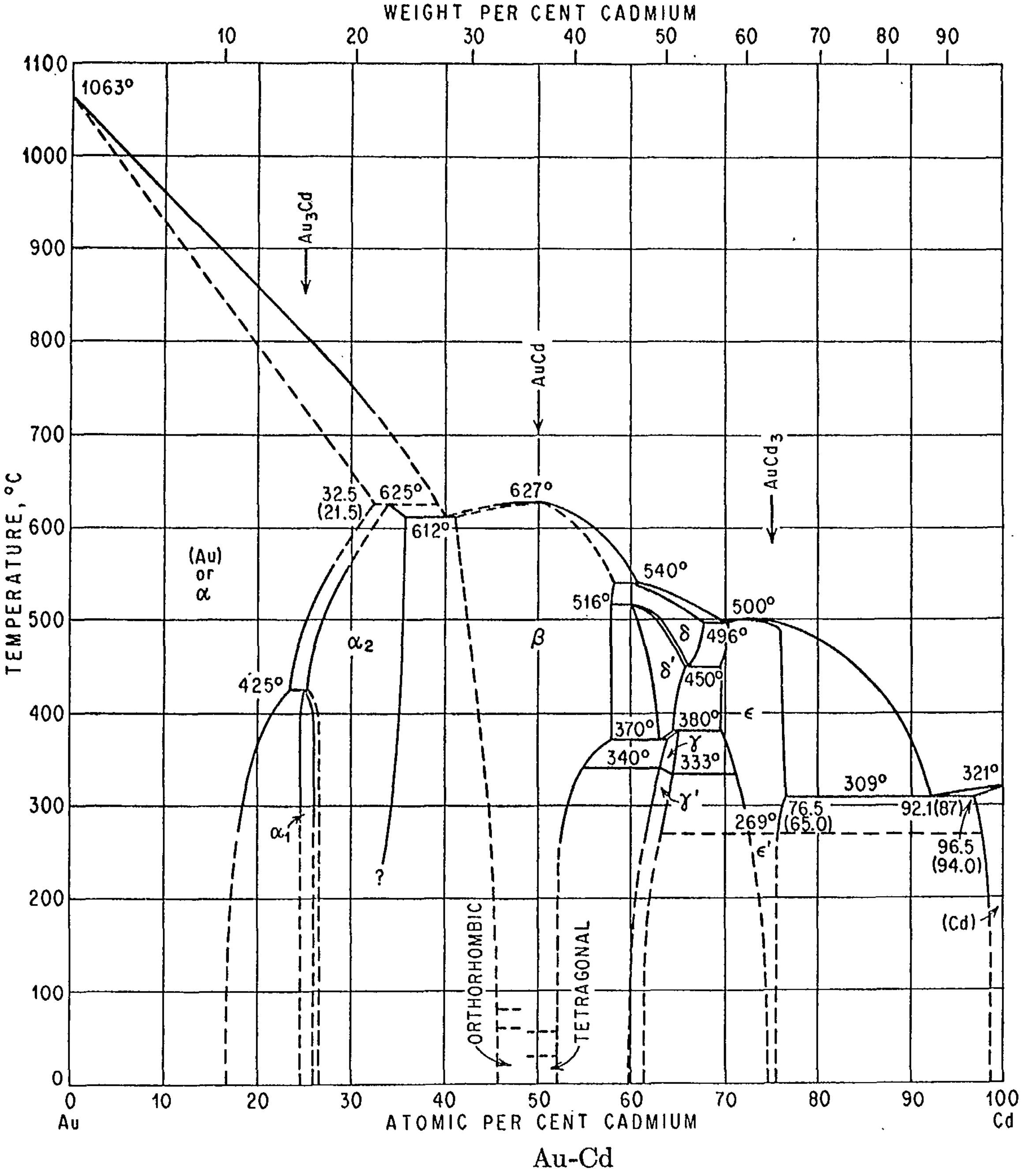

WEIGHT PER CENT CADMIUM
10
20
30
40
50
60
70
80
90
1100
1000
900
800
700
600
500
400
300
200
100
0
TEMPERATURE, °C
1063°
Au3Cd
AuCd
AuCd3
32.5
(21.5)
625°
612°
627°
540°
516°
500°
496°
450°
380°
370°
340°
333°
309°
321°
269°
425°
(Au)
or
α
α2
α1
β
δ
δ'
γ
γ'
ε
ε'
76.5
(65.0)
92.1(87)
96.5
(94.0)
(Cd)
?
ORTHORHOMBIC
TETRAGONAL
0
Au
10
20
30
40
50
60
70
80
90
100
Cd
ATOMIC PER CENT CADMIUM
Au-Cd

Figure 12

Ternary Systems

Au-Cd-Cu	Gold-cadmium-copper. See Au-Cu, gold-copper.
Au-Cd-In	Gold-cadmium-indium. See reference (106).
Au-Cd-Zn	Gold-cadmium-zinc. See Au-Zn, gold-zinc.

Au-Ce, Gold-Cerium

Phase Diagram

The phase diagram in Figure 13(2) is only a rough outline and was based on the assumption that gold forms the same compounds with cerium as with lanthanum and praseodymium.

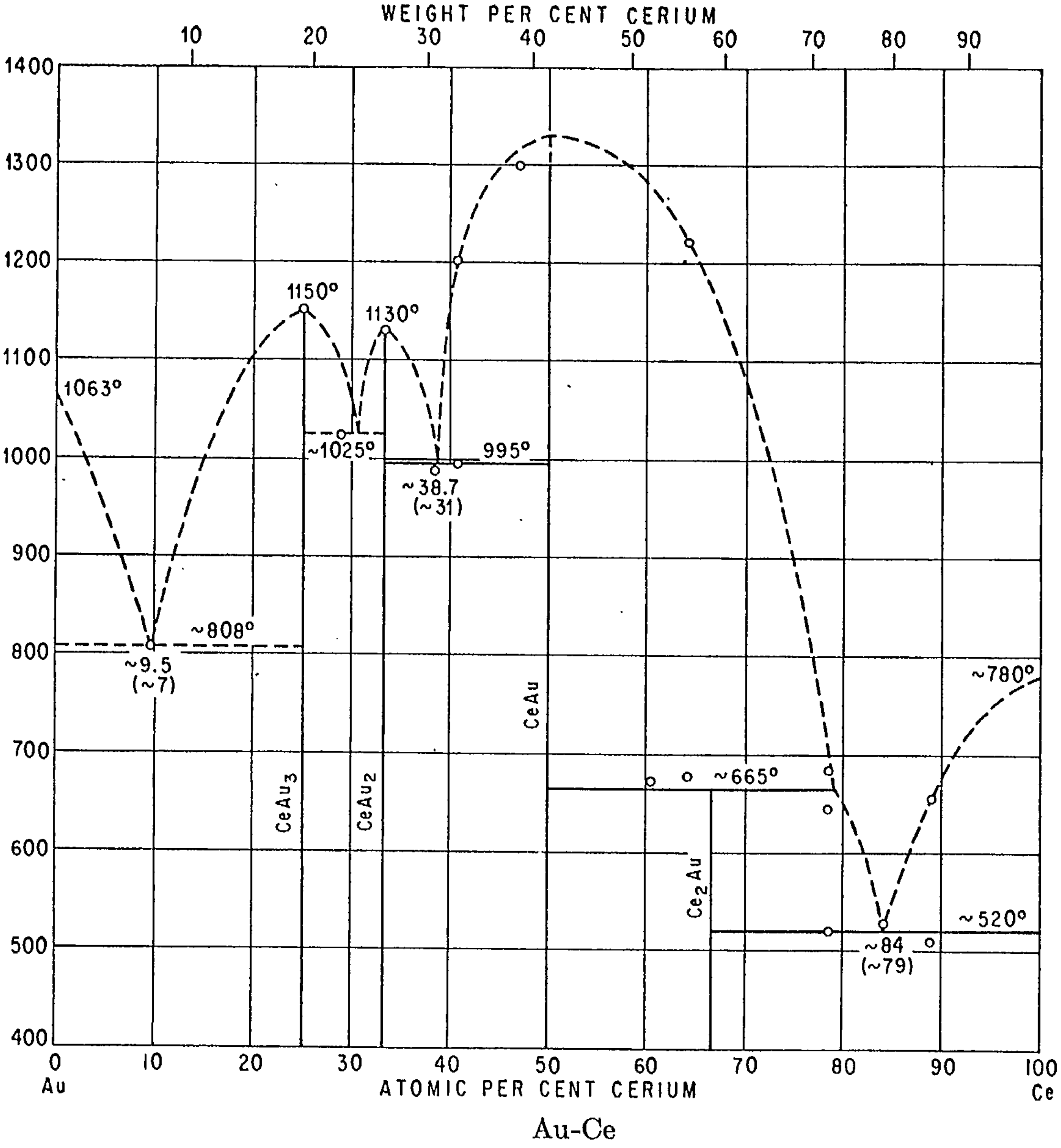
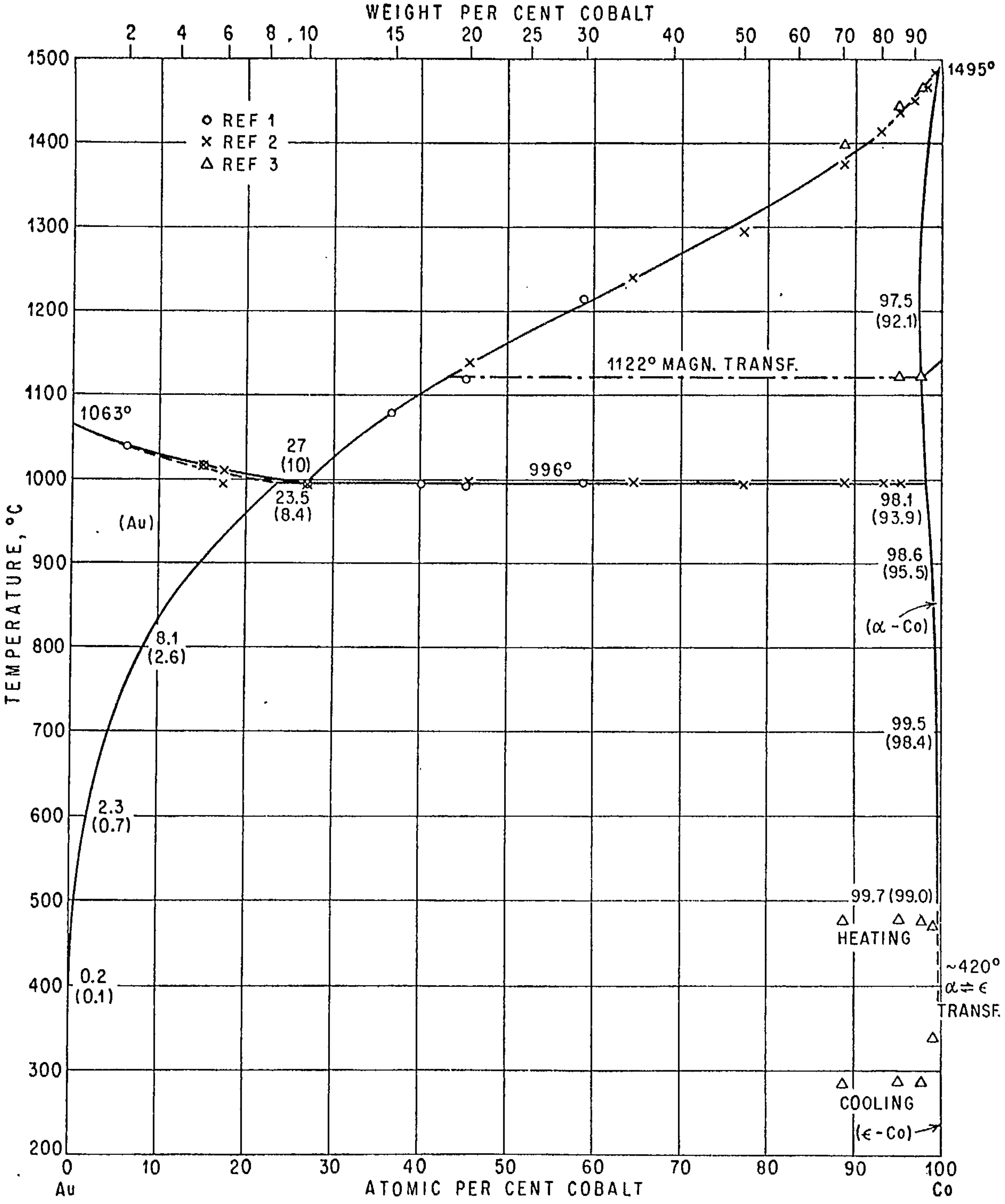

WEIGHT PER CENT CERIUM
10
20
30
40
50
60
70
80
90
1400
1300
1200
1100
1000
900
800
700
600
500
400
1063°
1150°
1130°
~1025°
995°
~38.7
(~31)
~808°
~9.5
(~7)
CeAu
CeAu3
CeAu2
Ce2Au
~665°
~780°
~520°
~84
(~79)
0
Au
10
20
30
40
50
60
70
80
90
100
Ce
ATOMIC PER CENT CERIUM
Au-Ce

Figure 13

Au-Co, Gold-Cobalt

Phase Diagram

The gold-cobalt diagram in Figure 14(2) is a simple eutectiferous one with limited mutual solid-solubilities. The maximum solid-solubility of gold in cobalt is 2.5 at % at 1200 °C, while the maximum solid-solubility of cobalt in gold is 23.5 at % at the eutectic temperature of 996 °C.



Au-Co

Figure 14

Ternary Systems

Au-Co-Ag	Gold-cobalt-silver. See Au-Ag, gold-silver.
Au-Co-Cu	Gold-cobalt-copper. Data on this system are contained in reference (88).
Au-Co-Fe	Gold-cobalt-iron. See reference (88).
Au-Co-Mn	Gold-cobalt-manganese. See reference (88).
Au-Co-Ni	Gold-cobalt-nickel. See reference (88).
Au-Co-Pd	Gold-cobalt-palladium. This system has been investigated in references (107) and (88).
Au-Co-Pt	Gold-cobalt-platinum. See reference (88).

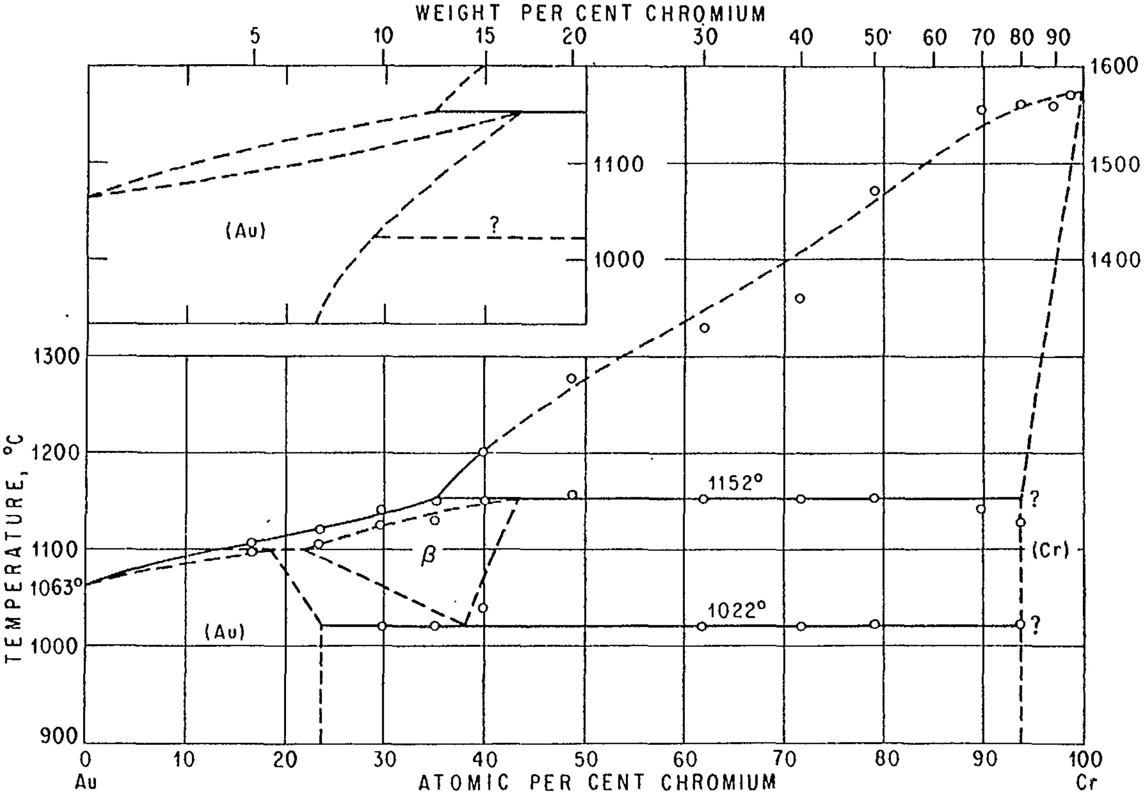
Au-Cr, Gold-Chromium

Phase Diagram

Very little information exists on the gold-chromium system, and the diagrams in Figure 15(2) are based on work carried out with carbon- and nitrogen-contaminated melts and are thus not true binary diagrams. The inset provides an alternative to the main diagram for the 0-50 at % chromium range, but does not explain the transformation at 1022°C.

The limits of solid solubility are not definite. Maximum solid solubility of chromium in gold may either be about 43 at %

at 1152°C, or about 24 at % at 1022°C. Maximum solid solubility of gold in chromium may be about 6 at % at 1152°C.



Au-Cr

Figure 15

Au-Cs, Gold-Cesium

Phase Diagram

No detailed phase relationships are known for this system, but intermetallic gold-cesium compounds have been reported.(2)

Au-Cu, Gold-Copper

Phase Diagram

Because of its practical significance as the most commonly used gold alloy system for jewelry and other uses, and also because of the low temperature superlattice formation in what is otherwise a continuous system of solid solutions, the gold-copper phase diagram has been exhaustively investigated. It has been a favourite for theoretical as well as experimental studies in ordering. During the last ten years, emphasis has been placed on the kinetics of the ordering transformations and the diffusion mechanisms involved. The diagram in Figure 16(2) is probably the most generally accepted, with three superlattice compositions, Au_3Cu, AuCu and $AuCu_3$, being recognized.

The effect of a third element on the ordering of gold-copper alloys has also received attention. Additions of silver, cadmium and manganese will lower the critical ordering

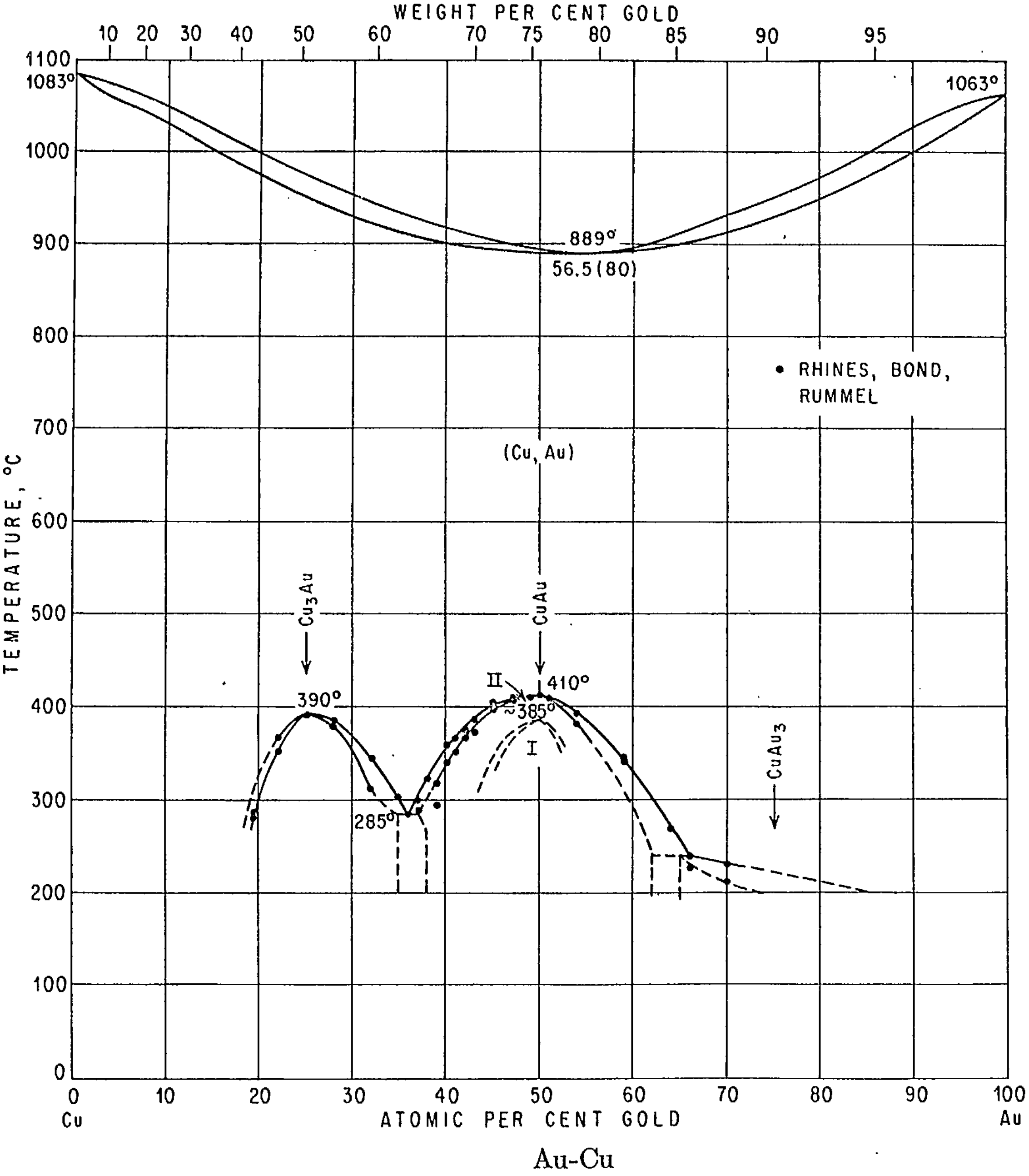

WEIGHT PER CENT GOLD
10 20 30 40 50 60 70 75 80 85 90 95
1100
1083°
1063°
1000
900
889°
56.5(80)
800
700
600
500
400
300
200
100
0
• RHINES, BOND, RUMMEL
(Cu, Au)
Cu3Au
CuAu
CuAu3
II
410°
390°
385°
I
285°
TEMPERATURE, °C
0 Cu
10 20 30 40 50 60 70 80 90
100 Au
ATOMIC PER CENT GOLD
Au-Cu

Figure 16

temperatures of AuCu, but aluminum, manganese and titanium leave the critical temperature unaltered.(92) (108) The former elements are appreciably soluble in the binary AuCu at the critical temperature, while the latter elements are not.

Some lowering of the critical ordering temperature of $AuCu_3$ (92) takes place when silver is added to the alloy.

Ternary Systems

Au-Cu-Ag	Gold-copper-silver. See Au-Ag, gold-silver. Silver additions have been found (92) to lower the critical ordering temperature of AuCu and, to a lesser extent, that of $AuCu_3$.
Au-Cu-Al	Gold-copper-aluminum. 8.15 at % aluminum has no effect on the critical ordering temperature of AuCu.(108) Aluminum is only slightly soluble in the binary at the critical temperature.
Au-Cu-Cd	Gold-copper-cadmium. 5 to 11 at % cadmium lowers the critical ordering temperature of AuCu.(108) Cadmium is appreciably soluble at the critical temperature.
Au-Cu-Co	Gold-copper-cobalt. See Au-Co, gold-copper.
Au-Cu-Fe	Gold-copper-iron. Data on this system are contained in reference (88).
Au-Cu-Mg	Gold-copper-magnesium. 6.6 at % magnesium is only slightly soluble in the AuCu binary at the critical ordering temperature, and has no effect on this temperature.(108)
Au-Cu-Mn	Gold-copper-manganese. 12.9 at % manganese is appreciably soluble in the AuCu binary at the critical ordering temperature and lowers this temperature.(108) Other data are contained in reference (88).
Au-Cu-Ni	Gold-copper-nickel. This system has been investigated in references (109) and (88).

Au-Cu-Pd	Gold-copper-palladium. This system has been investigated in references (110) and (111).
Au-Cu-Pt	Gold-copper-platinum. Data on this system are contained in reference (88).
Au-Cu-Ti	Gold-copper-titanium. 7.2 at % titanium has no effect on the critical temperature of ordering of AuCu and is only slightly soluble in the binary alloy at this temperature.(108)
Au-Cu-Zn	Gold-copper-zinc. See Au-Zn, gold-zinc. The effect of zinc on the orderings of AuCu and $AuCu_3$ is covered in reference (112).

(A.20) Diffusion

Au-Cu

The diffusion of gold into polycrystalline copper has been studied.(113) Values of Q, the activation energy, and D_o, the diffusion-frequency factor, in the diffusion relationship $D = D_o e^{-\frac{Q}{RT}}$ were determined. Between 750° and 1000°C, values of $Q = 44,900 \pm 1300$ cal/mole and $D_o = 0.10 \pm 0.06$ cm^2/sec were obtained.

(C.3) Corrosion

Au-Cu

The resistance of gold-copper solid solutions to various corrodents follows the "Tamman $\frac{n}{8}$ Rule".(114) At a composition represented by $\frac{n}{8}$ mole gold, the copper-gold alloys become stable, and the corrosion rate drops to that of pure gold. The limits of stability for certain corrodents is given in Table 23.

TABLE 23

Corrodent	Limits of Stability	
	at % Au	n /8 mole Au
Nitric Acid sp gr 1.3	49-50	4/8
Palladium Chloride	24.5-25.5	2/8
Ammonium Sulphide	24.5-25.5	2/8
Picric Acid	22	2/8
Mercuric Chloride	24	2/8
Silver Salts	8-15	1/8
Mercurous Chloride	None	
Mercurous Nitrate	None	
Mercuric Nitrate	None	

The resistance to stress corrosion cracking of gold-silver and gold-copper alloys has been investigated.(101) Tamman's rule appears to apply to the stress corrosion of these alloys. In weakly oxidizing solutions such as ferric chloride, cuprous chloride, ferric sulphate and sodium sulphide, intercrystalline cracks will only occur if the gold content is less than 25 at %, i.e. 2/8 mole Au. In strongly oxidizing agents such as nitric acid, potassium permanganate, chromic acid and hydrochloric plus nitric acids, transcrystalline cracking takes place at gold contents of less than 50%, i.e. 4/8 mole Au.

Unstressed wires will not corrode in a normal solution of sodium sulphate containing copper sulphate and sulphuric acid, if the gold exceeds 10 at %, due to almost immediate anodic polarization.(115) Mechanical stresses produce depolarization, and corrosion will proceed. Anodic currents will inhibit stress corrosion in gold-copper alloys.

In the stress corrosion of gold-copper alloys, a "Solid Solution Effect" has been observed in the attack by mercury, ammonia or aqueous 2% ferric chloride.(116)(117) The effect is due to an increasing reactivity of the grain boundaries of the homogeneous solid solution as the solute element concentration increases. The high reactivity of the boundaries is enhanced by notch effects due to plastic deformation and intercrystalline failures due to stress-corrosion result.

<u>Corrosion in Ammonia and Ammonium Salts</u>. The corrosion of gold-copper alloys containing up to 15 at % gold in aqueous ammonia and ammonium salts under oxygen partial pressures of up to 6.8 atmospheres has been studied. Only the copper dissolves, and the rate of corrosion decreases as the metal surface becomes enriched in gold.(118)

Corrosion in Ferric Chloride. The effect of ordering on the corrosion rate of Cu_3Au in aqueous ferric chloride solutions has been investigated.(119) It was found that the disordered structure corrodes about 1.4 times as fast as the ordered structure, but in both cases the attack was confined to the copper in the alloy.

(D.2) Mechanical Working

Au-Cu

Surface Roughness due to Forming. Gold alloys of the gold-silver-copper series used in jewelry manufacture are prone to develop surface roughness during forming operations. This roughness is due to coarse crystal formation and is often referred to as "orange peel". The 10 - 18 carat alloys containing 1 - 55% copper, 1 - 15% silver, 1 - 15% zinc and 0 - 4% nickel are particularly prone to roughening, and it is reported that the incorporation of about 1% iron and 0.3% silicon will inhibit coarse crystal formation.(120) These additions have little effect on mechanical properties and hardness, but, if allowed to become excessive, can give hard brittle constituents which spoil the appearance of polished surfaces.

Au-Fe, Gold-Iron

Phase Diagram

Figure 17 (2) gives main features of the phase relationships of gold and iron. An eutectoid transformation from the gamma (γ) iron solid solution to alpha (α) iron solid solution takes place at 855° to 903°C (903°C shown) and a gold content of 2.2 to 2.3 at % (2.3 at % shown). The maximum solid solubilities are:

Gold in gamma iron, 8 at % at 1168°C

Iron in gold, 75 at % at 1168°C

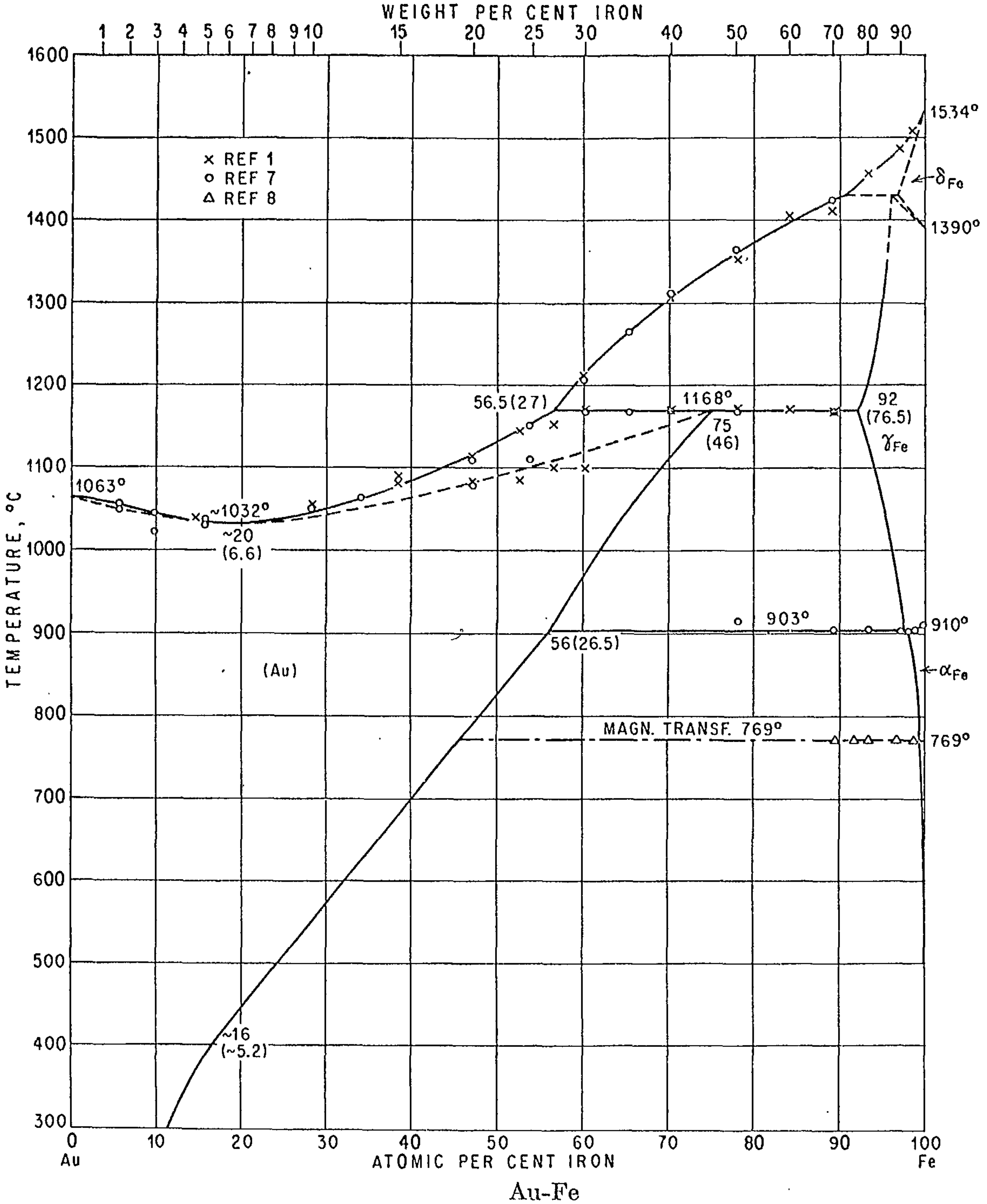

WEIGHT PER CENT IRON
1 2 3 4 5 6 7 8 9 10 15 20 25 30 40 50 60 70 80 90
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
TEMPERATURE, °C
× REF 1
o REF 7
Δ REF 8
1534°
δFe
1390°
56.5(27)
1168°
75
(46)
92
(76.5)
γFe
1063°
~1032°
~20
(6.6)
903°
910°
56(26.5)
(Au)
αFe
MAGN. TRANSF. 769°
769°
~16
(~5.2)
0 10 20 30 40 50 60 70 80 90 100
Au
Fe
ATOMIC PER CENT IRON
Au-Fe

Figure 17

Ternary Systems

Au-Fe-Ag	Gold-iron-silver. See Au-Ag, gold-silver.
Au-Fe-Co	Gold-iron-cobalt. See Au-Co, gold-cobalt.
Au-Fe-Cu	Gold-iron-copper. See Au-Cu, gold-copper.
Au-Fe-Mn	Gold-iron-manganese. See reference (88).
Au-Fe-Ni	Gold-iron-nickel. See reference (88).
Au-Fe-Pd	Gold-iron-palladium. See reference (88).
Au-Fe-Pt	Gold-iron-platinum. See reference (88).

(D. 2) Mechanical Working

Au-Fe

Gold alloys with 10% iron can be worked without fracturing, while an alloy with 1% iron is as workable as pure gold.(102)

(B. 2) Hardness

Au-Fe

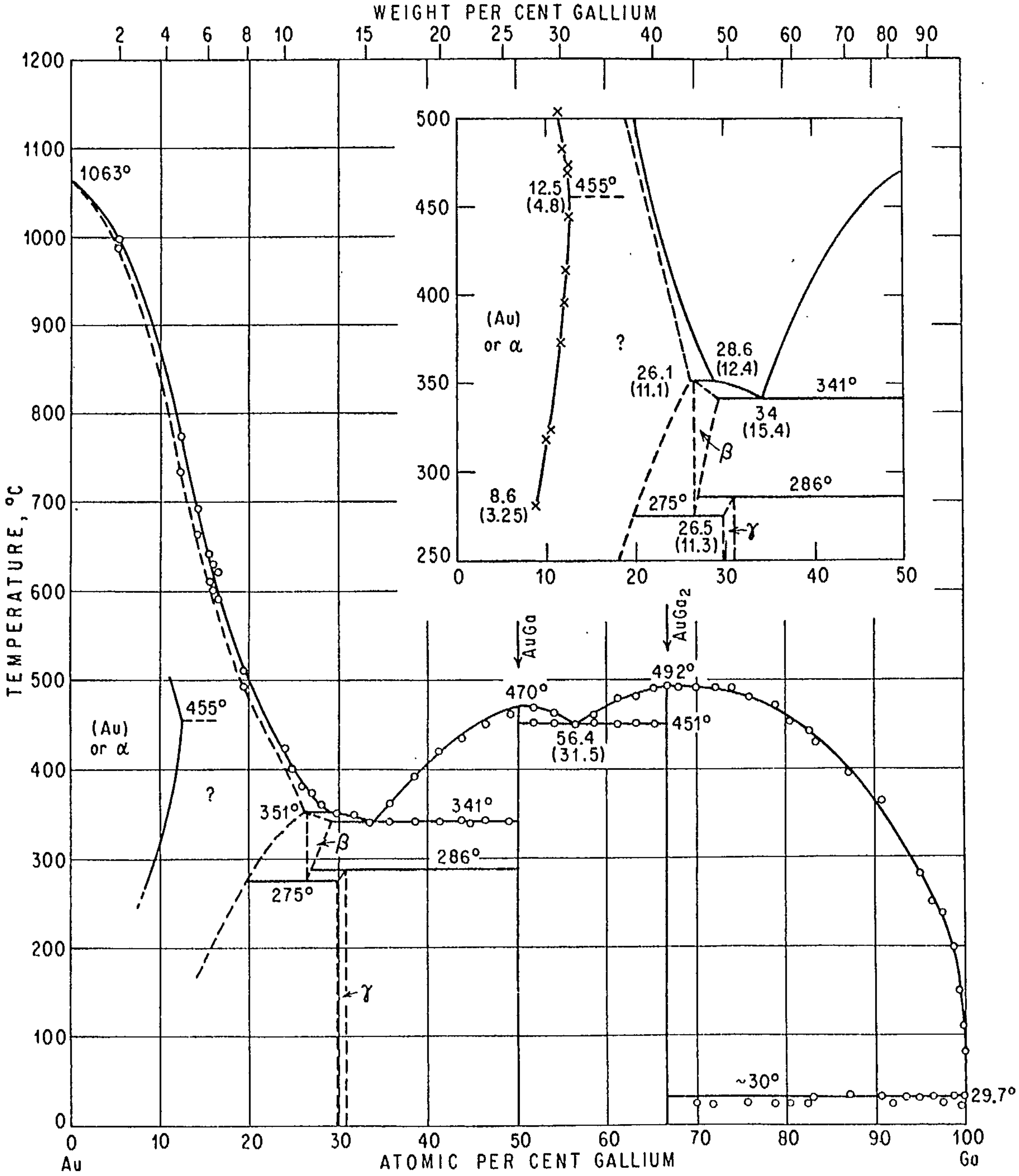
Iron - 10% Gold. The effect of solution treatment and artificial ageing on an iron - 10% gold alloy has been investigated.(121) Solution treatment was at 1200°C followed by water quenching.

Ageing was at temperatures between 400° and 700°C for times up to 30 hours. Maximum hardness was developed by 30 hours at 400°C and resulted in VPN 410. Changes in coercive force on ageing showed a maximum at 550°C. The ageing process is characterised by an activation energy of about 72,000 cal/mole.

Au-Ga, Gold-Gallium

Phase Diagram

The region between 13 and 25 at % gallium in Figure 18(2) is open to question. The maximum solid solubility of gallium in gold appears to be 12.5 at % at 455°C.



Au-Ga

Figure 18

Au-Ge, Gold-Germanium

Phase Diagram

A more probable value for the eutectic temperature in Figure 19 is 363°C, rather than the 356°C shown.(2) Solid solubility of germanium in gold at this temperature is reported to be 3.12 at %. The solid solubility of gold in germanium has been given as being 10^{15} atoms/cc.(122)

(A.13) Electrical Properties
Au-Ge

Gold when added to germanium has been shown to be an acceptor capable of taking up electrons at two distinct energy levels,(122) (123) one 0.15 eV above the valence band and the other 0.2 eV below the conduction band. Gold-doped germanium is an infra-red photo-conductor with response up to wavelengths of about 8 μ.

(A.20) Diffusion
Au-Ge

The diffusion coefficient of gold in germanium at 900°C has been given as about 4×10^{-9} cm^2/sec, and the activation energy for diffusion as about 2.5 eV.(122)

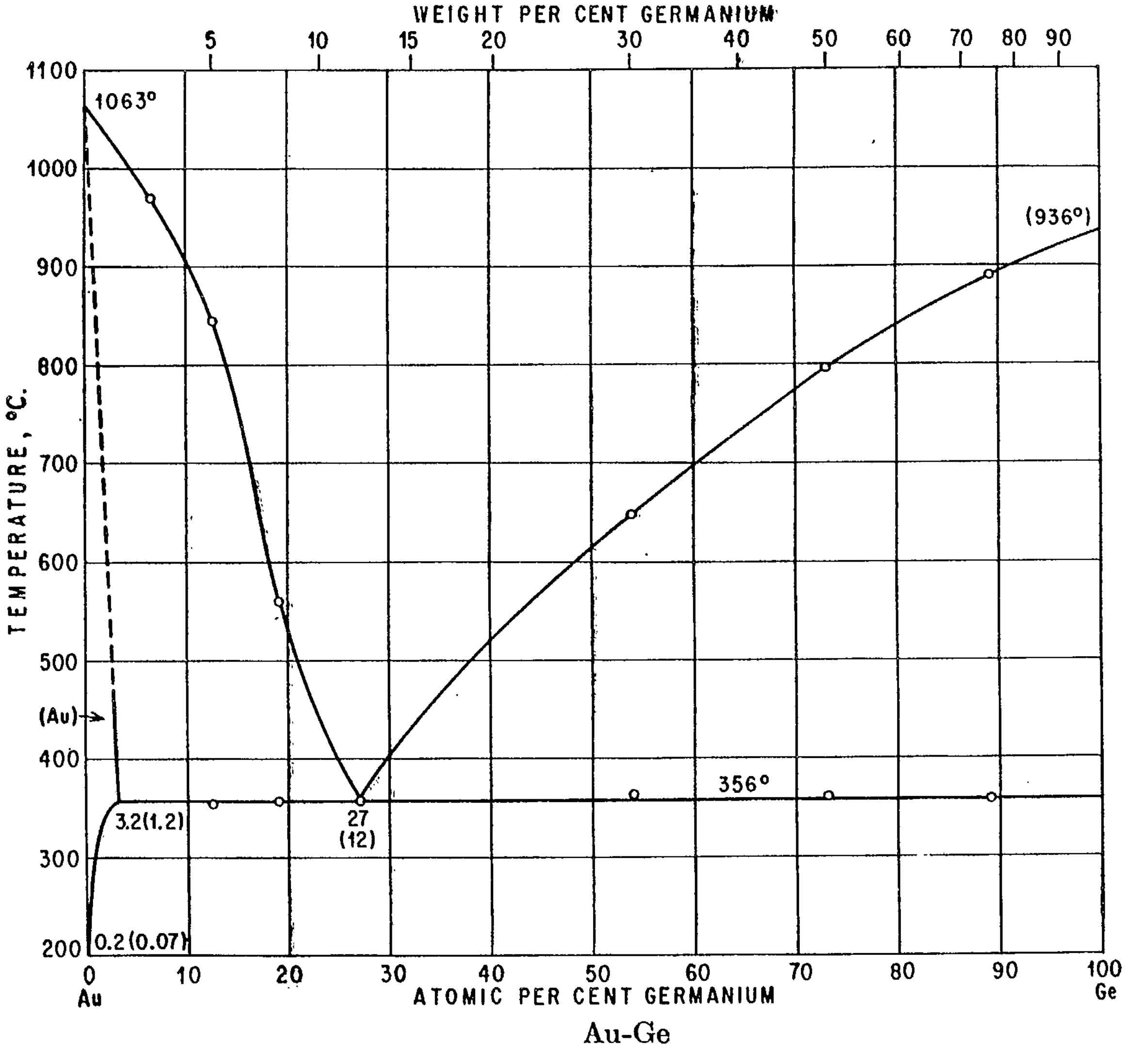

WEIGHT PER CENT GERMANIUM
5
10
15
20
30
40
50
60
70
80
90
1100
1000
900
800
700
600
500
400
300
200
TEMPERATURE, °C.
1063°
(936°)
(Au)→
356°
3.2(1.2)
27
(12)
0.2(0.07)
0
Au
10
20
30
40
50
60
70
80
90
100
Ge
ATOMIC PER CENT GERMANIUM
Au-Ge

Figure 19

Au-H, Gold-Hydrogen

Phase Diagram

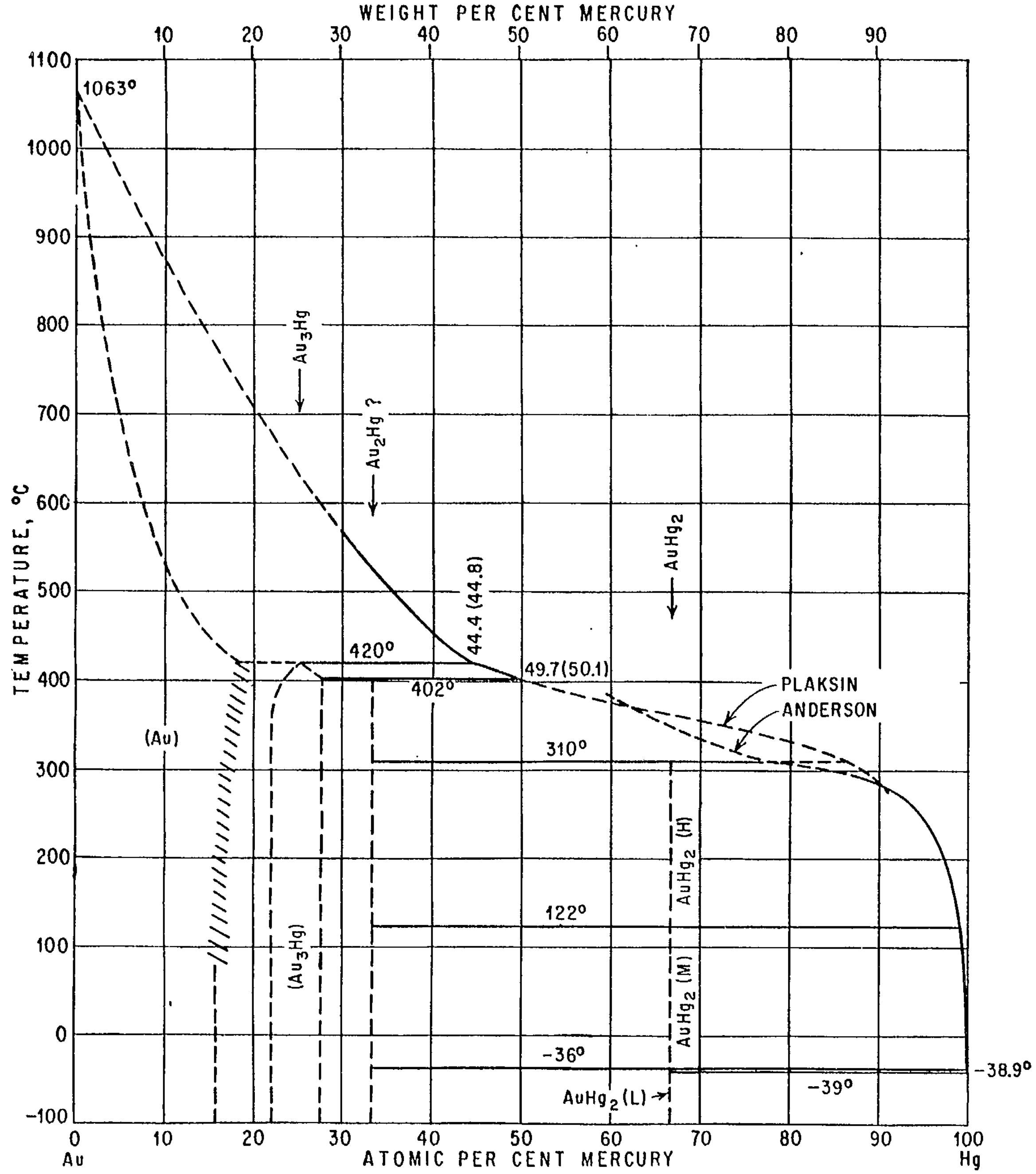
Hydrogen does not appear to be soluble in liquid or solid gold(2) and thus no phase relationships are possible.

Gold has been shown to possess no occlusive capacity for hydrogen sufficient to be detected, and is classed with tungsten by Smith(207) as a non-occluder. Reported finding of hydrogen absorption by gold in earlier work is considered very doubtful in the light of later knowledge. Any solubility of hydrogen in gold can reasonably be expected to be less than that in silver (0.006 volumes at 400°C and 800 mm),(208) and is therefore essentially negligible.

Au-Hg, Gold-Mercury

Phase Diagram

The diagram in Figure 20(2) is probably the most satisfactory one at the present time. Recent work(124) has given the solid-solubility limits of mercury in gold as 19.1, 16.1 and 17.8 at % at 416°, 225° and 100°C, respectively.



Au-Hg

Figure 20

Au-In, Gold-Indium

Phase Diagram

The phase relationships shown in Figure 21(2) have not yet been fully defined. The maximum solid solubility of indium in gold occurs at about 682°C and is about 12.6 at %. Recent work(125) has described a compound, Au_3In_2, which is not shown in Figure 21. This compound is stated to have a Ni_2Al_3-type structure.

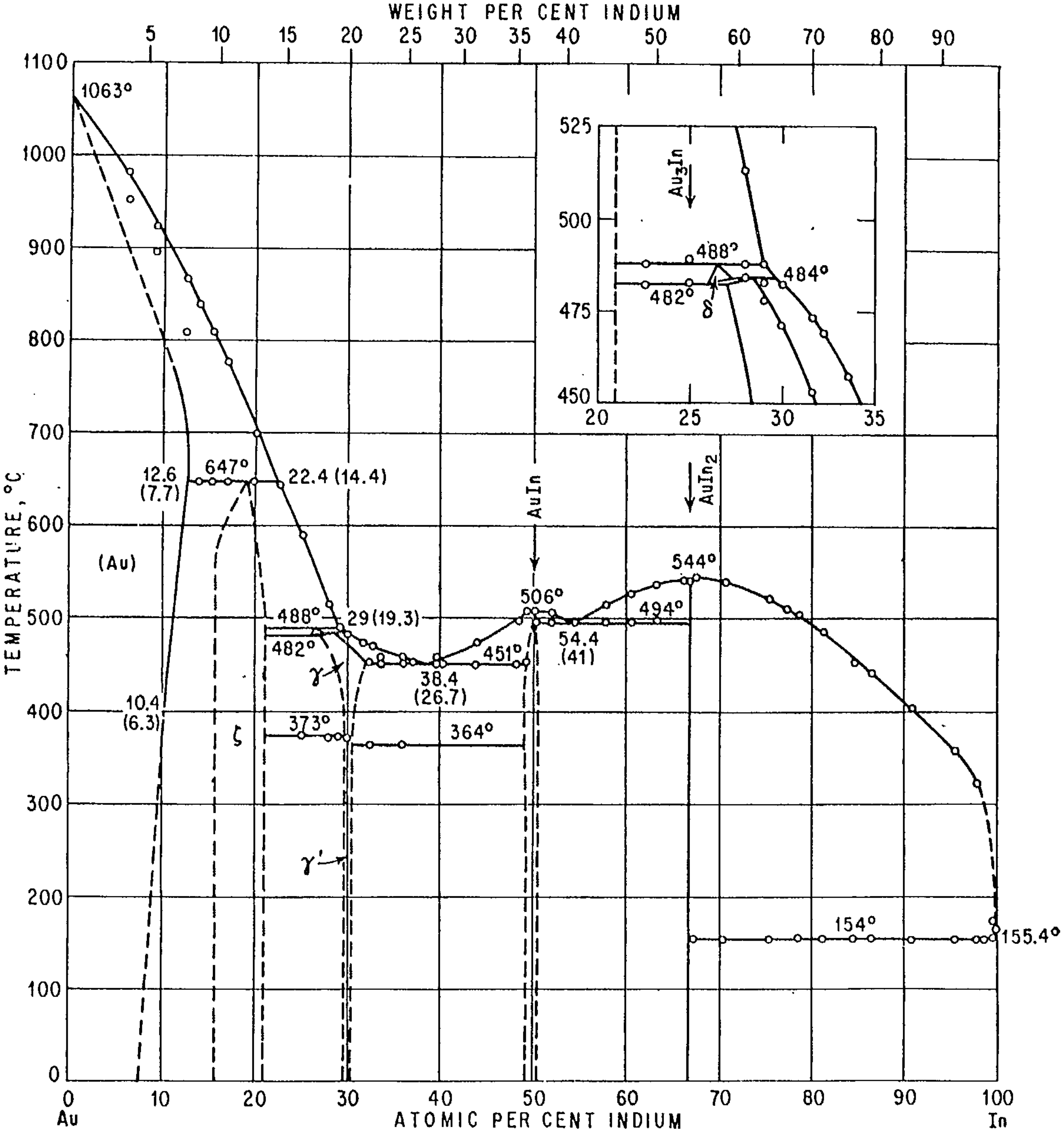
Ternary Systems

Au-In-Cd	Gold-indium-cadium. See Au-Cd, gold-cadmium.
Au-In-Sn	Gold-indium-tin. See reference (125).

(B.2) Hardness

Au-In

The 92% gold - 8% indium alloy is precipitation hardenable, a hardness increase from 58 to 69 VHN after two hours ageing at 299°C (570°F) being reported.(126) Still higher increases are possible after cold work.



Au-In

Figure 21

Au-Ir, Gold-Iridium

Phase Diagram

The solid solubility of iridium in gold is probably very small, and no phase relationships have been determined for this system.(2)

Au-K, Gold-Potassium

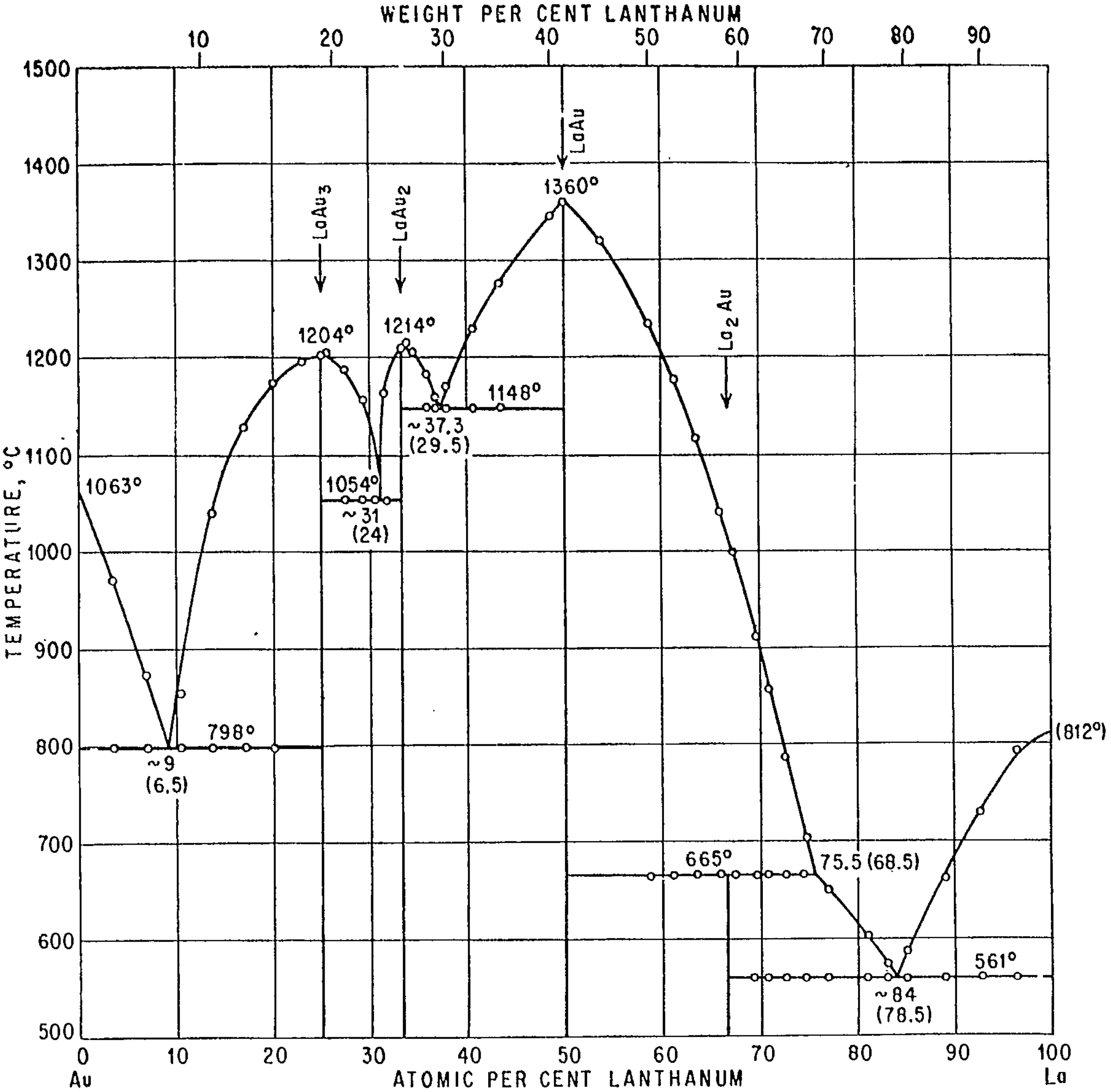
Phase Diagram

No phase diagram has been prepared for this system, but two compounds (KAu_4 and KAu_2) have been identified and a eutectic possibly exists at about 3 at % gold and 58° - 59°C.(2)

Au-La, Gold-Lanthanum

Phase Diagram

A phase diagram has been prepared for the gold-lanthanum system and is given in Figure 22, but no data are available on the solid solubilities.(2)



Au-La

Figure 22

Au-Li, Gold-Lithium

Phase Diagram

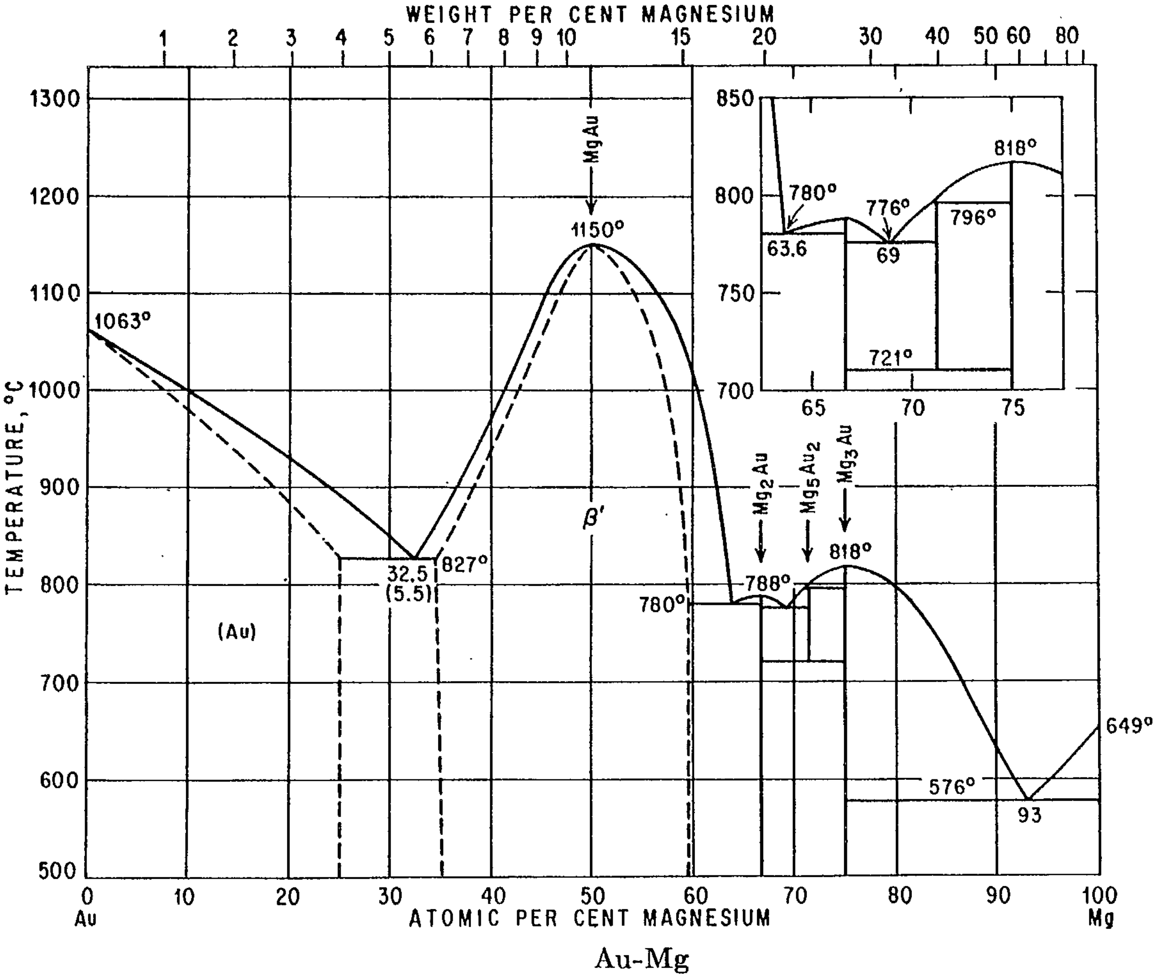
Insufficient data exist for a diagram to be constructed for the gold-lithium system.(2)

Au-Mg, Gold-Magnesium

Phase Diagram

The phase relationships for the gold-magnesium system have not been fully defined.(2) The solid solubility of magnesium in gold is about 25 at % at 827°C. The solid solubility of gold in magnesium was estimated as being about 0.1 at (0.8 wt) % at the eutectic temperature of 561°C. Work at the Physical Metallurgy Division done in connection with the Gold Research Project indicated the solid solubility to be 0.55 wt % at the eutectic temperature.(127)

Figure 23 represents the present known data for the system.



Au-Mg

Figure 23

Ternary Systems

Au-Mg-Cu	Gold-magnesium-copper. See Au-Cu, gold-copper.

(B.5) Creep

Au-Mg-Li

The effect of gold on the over-ageing and creep of cast magnesium-lithium alloys (beta and alpha-beta) has been briefly evaluated. 0.5% gold had a slight beneficial effect on the creep resistance of the alloys, but the resulting creep rates were still unsatisfactory.

(C.3) Corrosion

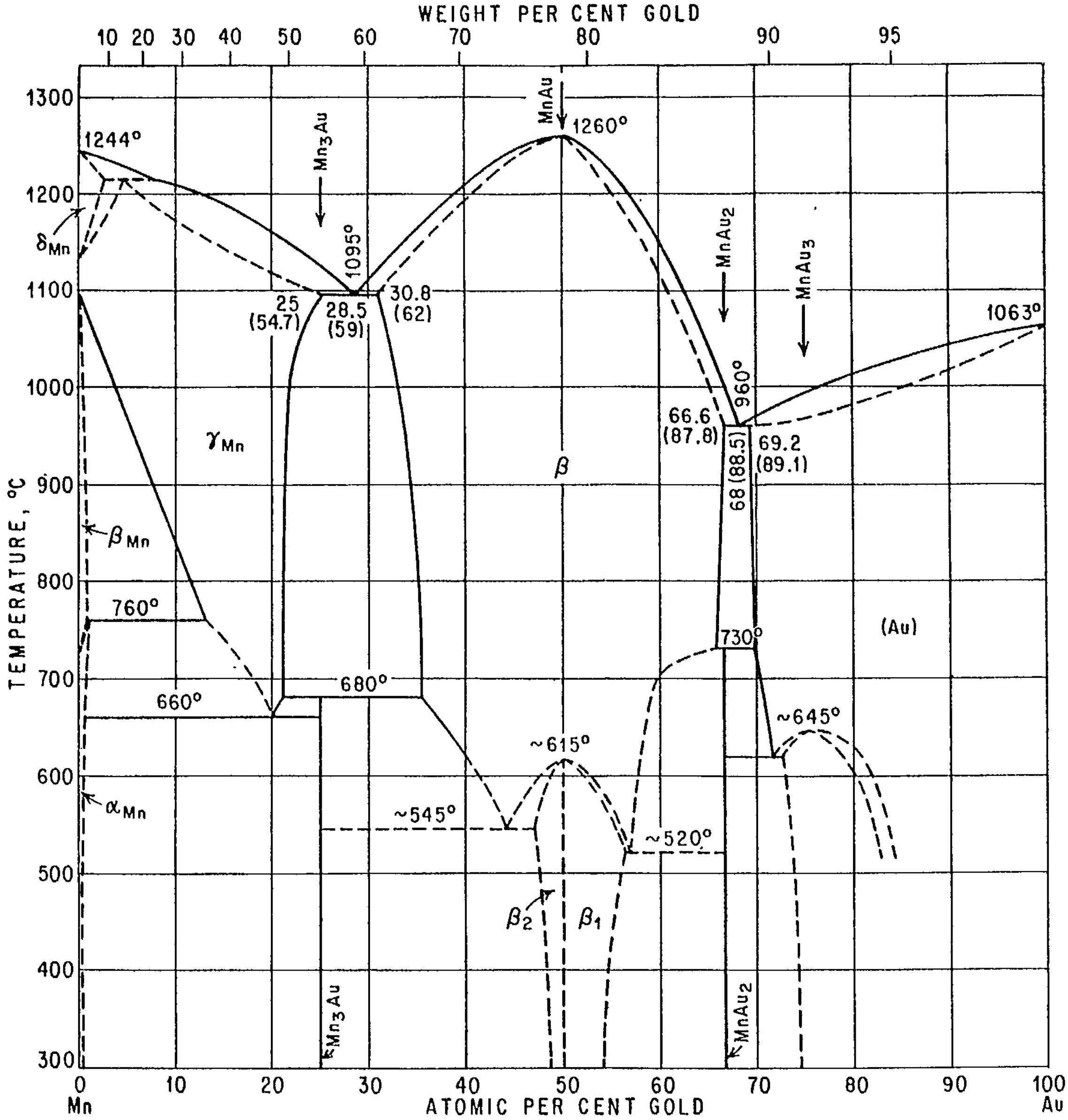
Au-Mg

The effect of gold additions up to 1.47% on the corrosion resistance of hot-rolled magnesium has been studied.(128) The corrosion rate in aqueous 2% sodium chloride at 74°F (23°C) is increased by gold, and the increase is approximately proportional to the gold content.

Au-Mn, Gold-Manganese

Phase Diagram

The phase relationships in the gold-manganese system are complex and Figure 24 is probably the best representation to



Au-Mn.

Figure 24

date.(2) The maximum solid solubility of manganese in gold is 30.8 at % at 960°C according to this, while the solid solubility of gold in manganese (α and β) is probably below 1 at %.

Ternary Systems

Au-Mn-Ag	Gold-manganese-silver. See Au-Ag, gold-silver.
Au-Mn-Co	Gold-manganese-silver. See Au-Co, gold-cobalt.
Au-Mn-Cu	Gold-manganese-copper. See Au-Cu, gold-copper.
Au-Mn-Fe	Gold-manganese-iron. See Au-Fe, gold-iron.
Au-Mn-Ni	Gold-manganese-nickel. See reference (88).

Au-Mo, Gold-Molybdenum

Phase Diagram

Gold and molybdenum do not form any compounds and the system contains a eutectic at 1054 °C.(2) The solid solubility of molybdenum in gold at this temperature is estimated as being 1.25 at % (0.61 wt %). The solubility of gold in solid molybdenum appears to be very small.

Au-N, Gold-Nitrogen

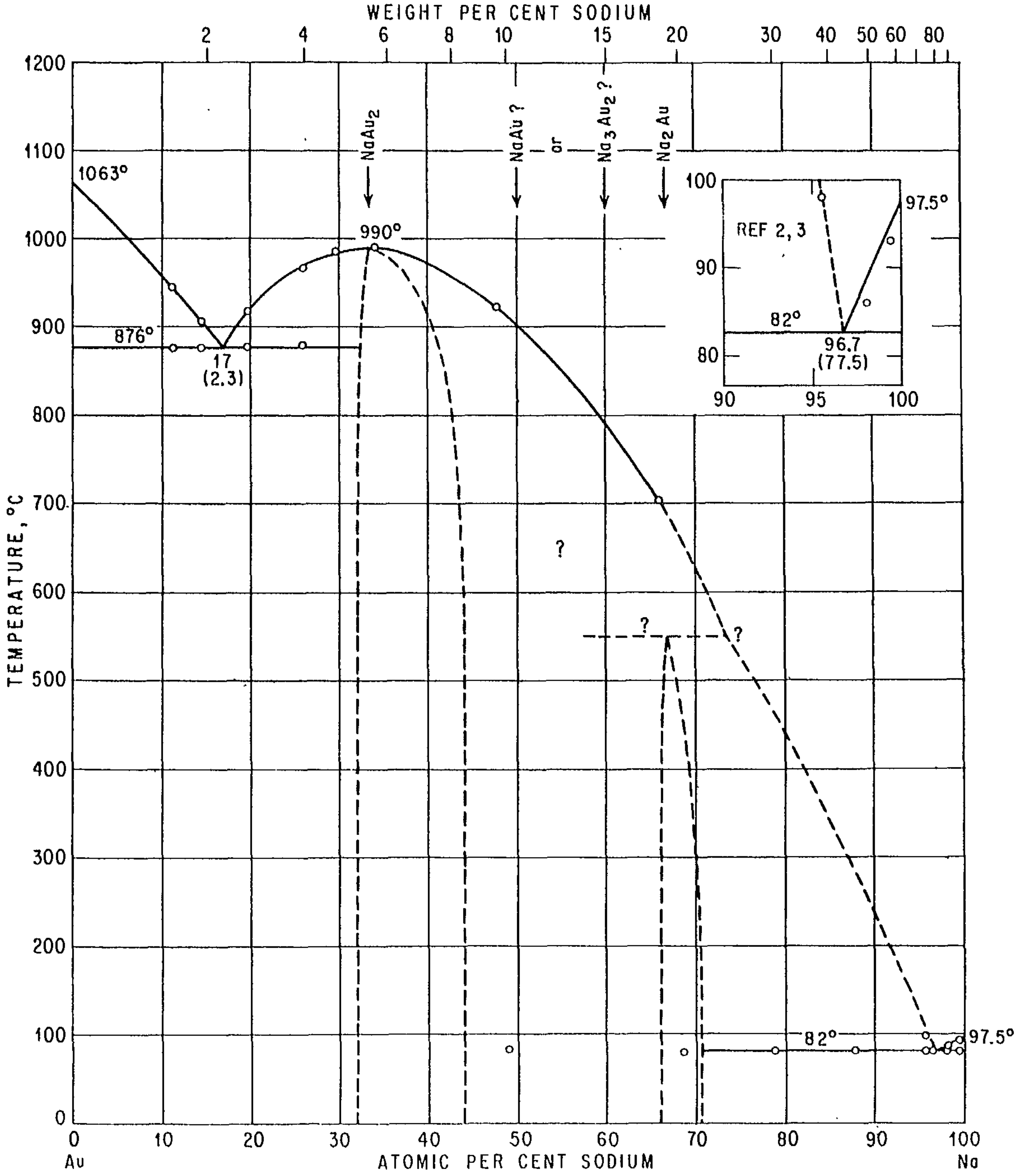
Phase Diagram

Nitrogen does not dissolve in solid or liquid gold.(2)

Au-Na, Gold-Sodium

Phase Diagram

The partial phase diagram for the gold-sodium system is given in Figure 25.(2) The solid solubility of sodium in gold is considered to be extremely small.



Au-Na

Figure 25

Au-Nb, Gold-Niobium (Columbium)

Phase Diagram

No phase diagram has been constructed for this system, but the existence of a phase Nb_3Au is reported.(129) This phase is stated to have the cubic structure of β tungsten and have a lattice constant $\alpha = 5.21 \pm 0.01$ A.

(A.13) Electrical
Au-Nb

Compound Nb_3Au becomes super-conducting at 11.5°K.(129)

Au-Ni, Gold-Nickel

Phase Diagram

The gold-nickel system consists of a continuous range of solid solutions at high temperatures and a miscibility gap at lower temperatures. The phase diagram is given in Figure 26.(2)

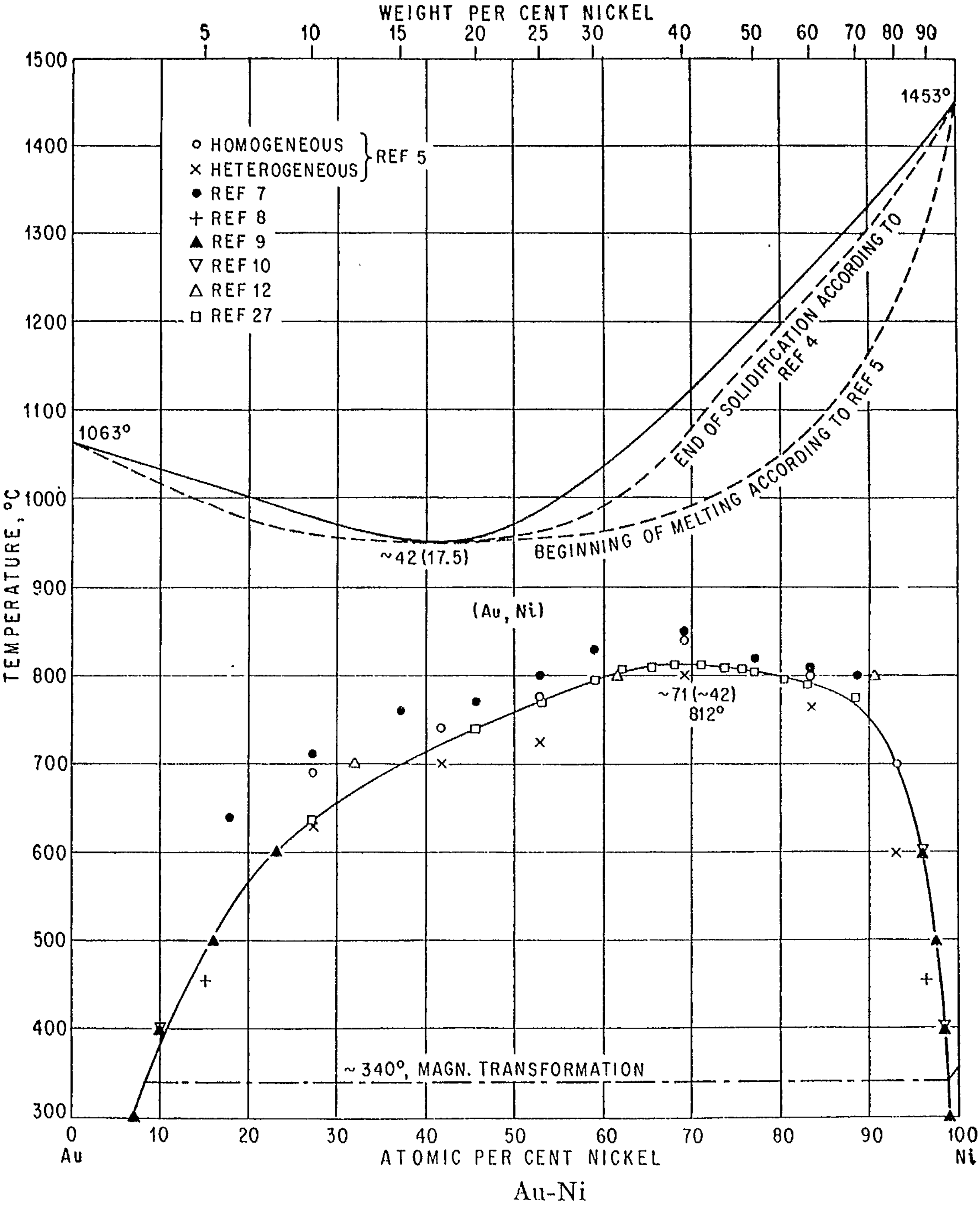

WEIGHT PER CENT NICKEL
5
10
15
20
25
30
40
50
60
70
80
90
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
TEMPERATURE, °C
1453°
1063°
○ HOMOGENEOUS
× HETEROGENEOUS
REF 5
● REF 7
+ REF 8
▲ REF 9
▽ REF 10
△ REF 12
□ REF 27
END OF SOLIDIFICATION ACCORDING TO REF 4
BEGINNING OF MELTING ACCORDING TO REF 5
~42 (17.5)
(Au, Ni)
~71 (~42)
812°
~340°, MAGN. TRANSFORMATION
0
Au
10
20
30
40
50
60
70
80
90
100
Ni
ATOMIC PER CENT NICKEL
Au-Ni

Figure 26

Ternary Systems

Au-Ni-Ag	Gold-nickel-silver. See Au-Ag, gold-silver.
Au-Ni-Co	Gold-nickel-cobalt. See Au-Co, gold-cobalt.
Au-Ni-Cu	Gold-nickel-copper. See Au-Cu, gold-copper.
Au-Ni-Fe	Gold-nickel-iron. See Au-Fe, gold-iron.
Au-Ni-Mn	Gold-nickel-manganese. See Au-Mn, gold-manganese.
Au-Ni-Pd	Gold-nickel-palladium. See reference (88).
Au-Ni-Pt	Gold-nickel-platinum. See reference (88).

(C.1) Formation of Oxides

Au-Ni

The effect of small (up to 1 at %) additions of gold on the oxidation resistance of pure nickel at temperatures up to 900°C has been investigated.(130) It was found that, in common with other elements tested, a lowering of oxidation resistance took place.

Au-O, Gold-Oxygen

Phase Diagram

The relationships between gold and oxygen are not certain.

Au-Os, Gold-Osmium

Phase Diagram

The solid solubility of osmium in gold is negligibly small.(2)

Au-P, Gold-Phosphorus

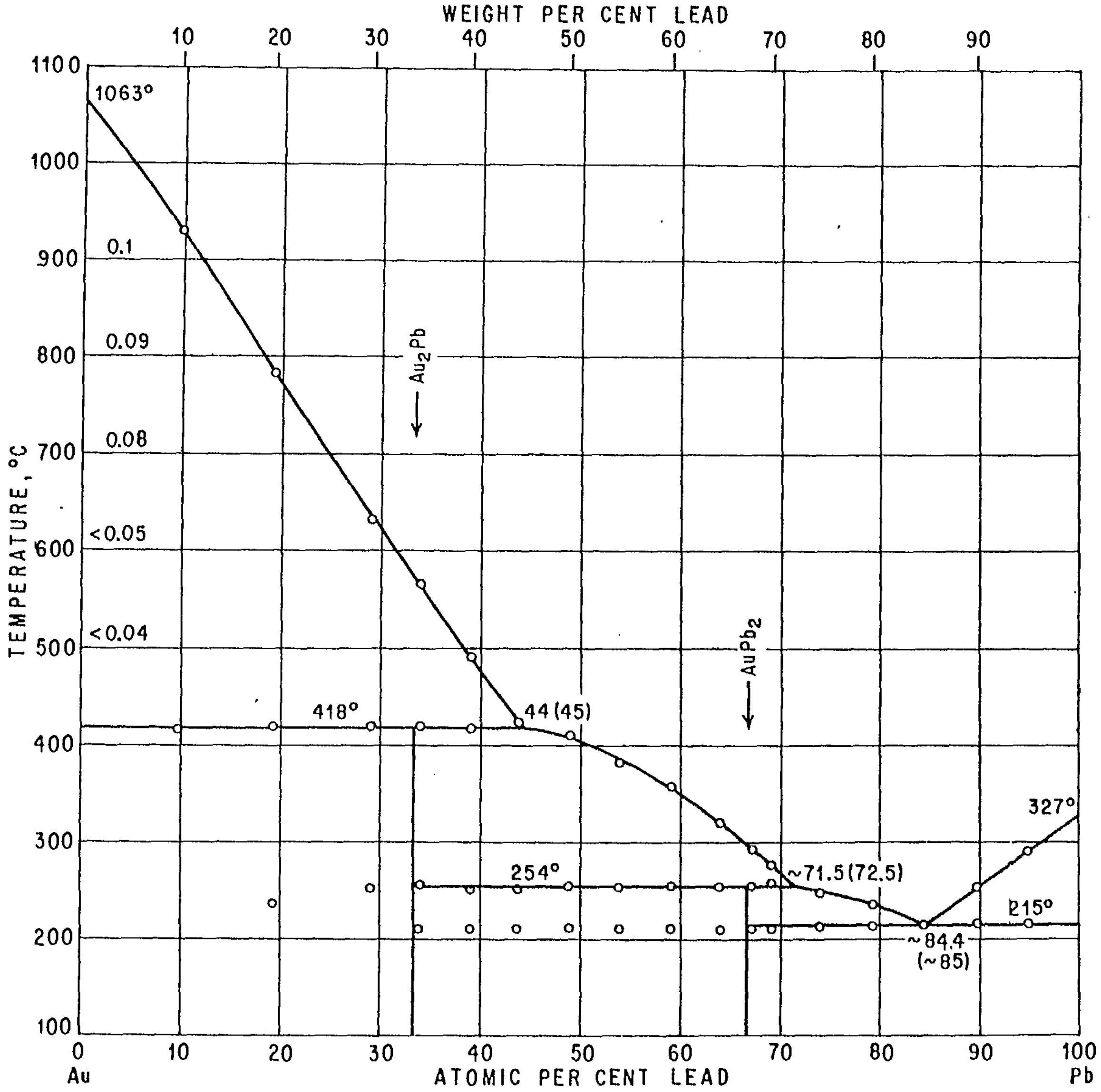
Phase Diagram

Phosphorus is soluble in molten gold, but is ejected on solidification. The solubility in liquid gold at 935°C has been reported as 2.4% phosphorus. No solubility could be detected in solid gold.(131) A compound Au_2P_3 is capable of being formed.(2)

Au-Pb, Gold-Lead

Phase Diagram

The constitution diagram for the gold-lead system is given in Figure 27.(2) The solid solubility of lead in gold is a maximum at 900°C when 0.1 wt % goes into solution. Maximum solid solubility of gold in lead is 0.08 at % at 200°C.



Au-Pb

Figure 27

(A.20) Diffusion
Au-Pb

The activation energy for the diffusion of gold in lead between 190° and 300°C has been determined as being 8.91 ± 0.18 K cal/mole(132) by radioactive tracer methods.

(D.2) Mechanical Working
Au-Pb

As little as 0.06% lead renders pure gold unworkable. Gold with 0.005% lead can be rolled like fine gold.(102)

Au-Pd, Gold-Palladium

Phase Diagram

Gold and palladium form a continuous series of solid solutions and no transformations in the solid state appear to take place. The diagram for the system is given in Figure 28.(2)

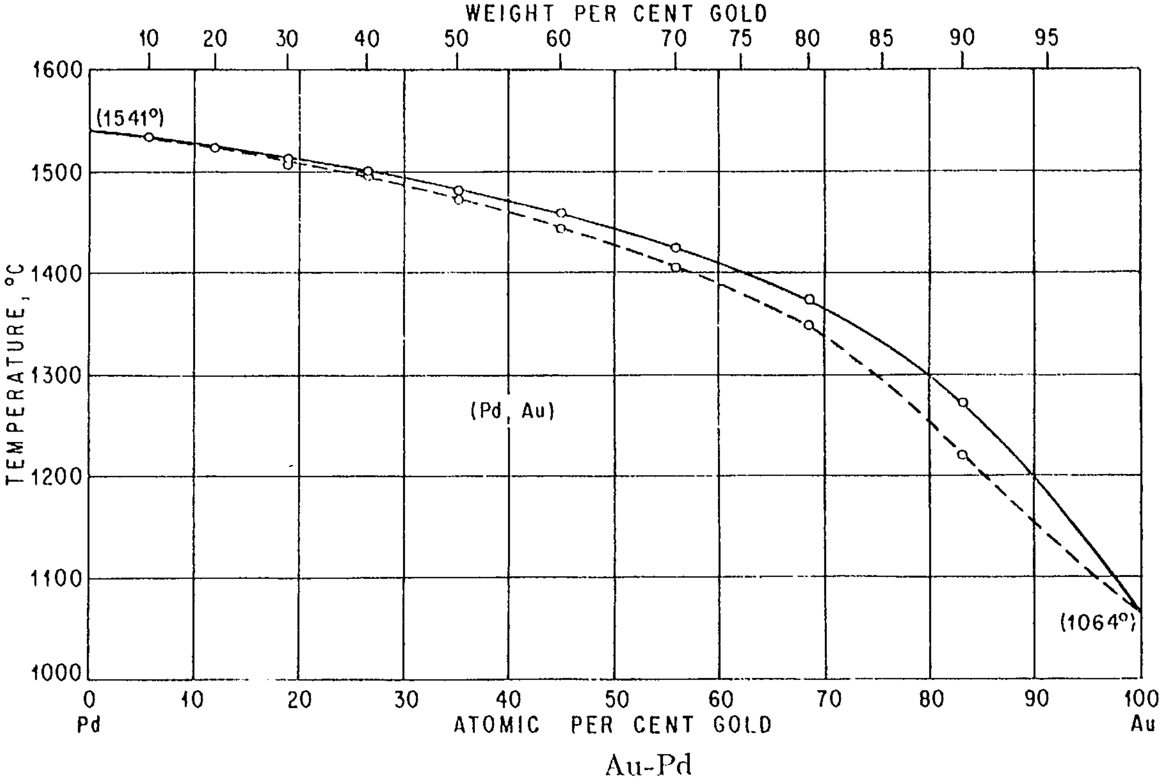

WEIGHT PER CENT GOLD
10
20
30
40
50
60
70
75
80
85
90
95
1600
1500
1400
1300
1200
1100
1000
TEMPERATURE, °C
(1541°)
(Pd, Au)
(1064°)
0
Pd
10
20
30
40
50
60
70
80
90
100
Au
ATOMIC PER CENT GOLD
Au-Pd

Figure 28

Ternary Systems

Au-Pd-Ag	Gold-palladium-silver. See Au-Ag, gold-silver.
Au-Pd-Co	Gold-palladium-cobalt. See Au-Co, gold-cobalt.
Au-Pd-Cu	Gold-palladium-copper. See Au-Co, gold-copper.
Au-Pd-Fe	Gold-palladium-iron. See Au-Fe, gold-iron.
Au-Pd-Ni	Gold-palladium-nickel. See Au-Ni, gold-nickel.
Au-Pd-Pt	Gold-palladium-platinum. This system has been investigated in references (133), (134) and (88).

(C.3) Corrosion

Au-Pd

The corrosion of gold alloys in HF-H_2O atmospheres at 566°C (1050°F) has been investigated.(135) "Palau", an alloy containing 80% gold and 20% palladium, showed good corrosion resistance in this environment.

(C.4) Catalysis

Au-Pd

The catalytic activity of gold-palladium alloys has been investigated.(79)(136)(137) It has been found that the catalytic activity hardly changes between 100 at % palladium and 40 at % palladium for the parahydrogen conversion on gold-palladium alloys, but at 40 at % palladium the activity falls off sharply. The activation energy is 3.5 kg cal/mole for alloys containing 40 - 100 at % palladium. For alloys with more than 70 at % gold, the activation energy is the 8.5 kg cal/mole of gold. In the catalytic decomposition of formic acid, the sharp rise in activation energy takes place at 60 at % palladium.

Au-Pr, Gold-Praseodymium

Phase Diagram

The phase relationships for the gold-praseodymium system are given in Figure 29.(2) The solid solubility of praseodymium in gold is estimated to be about 0.55 at %.

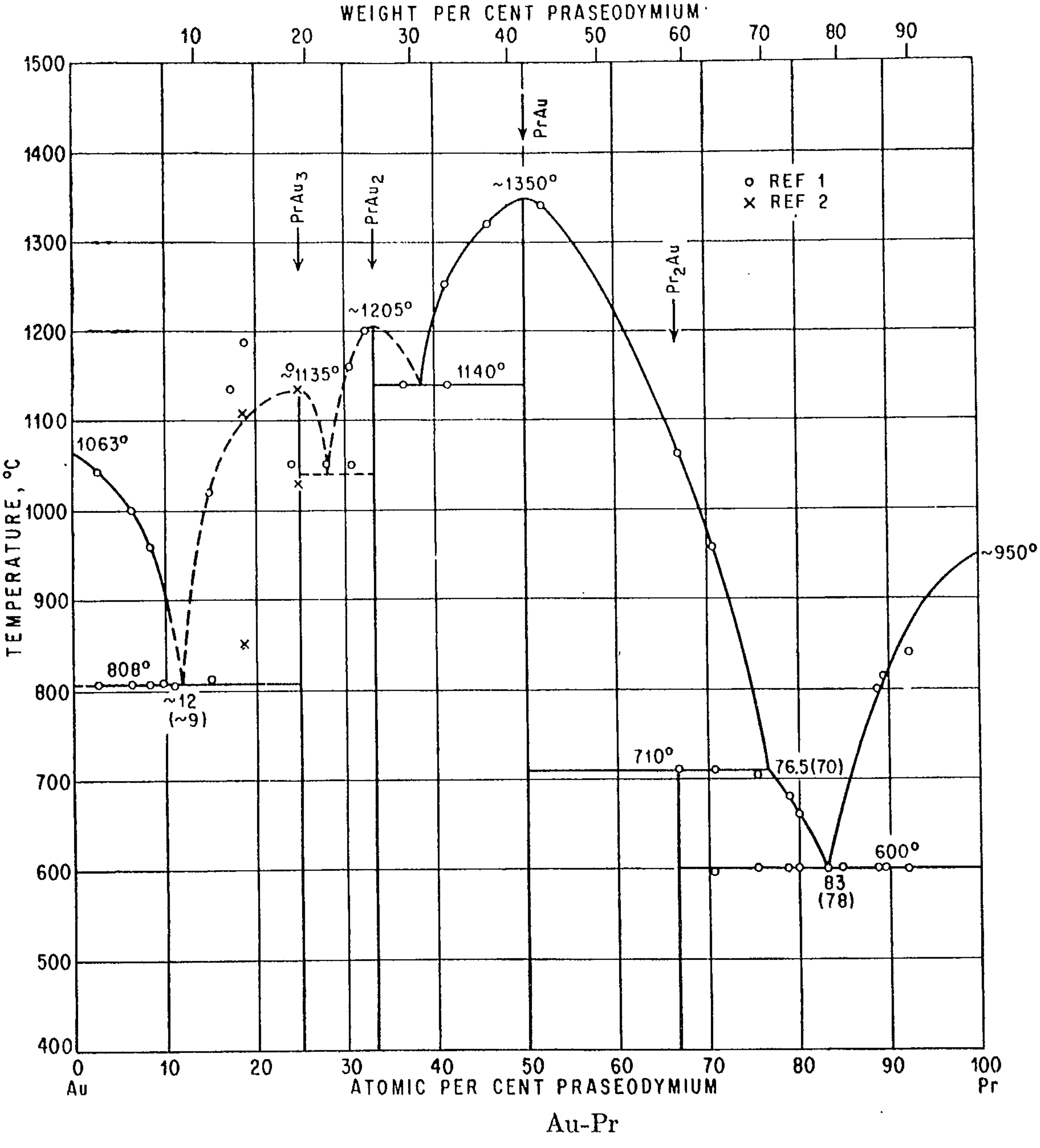
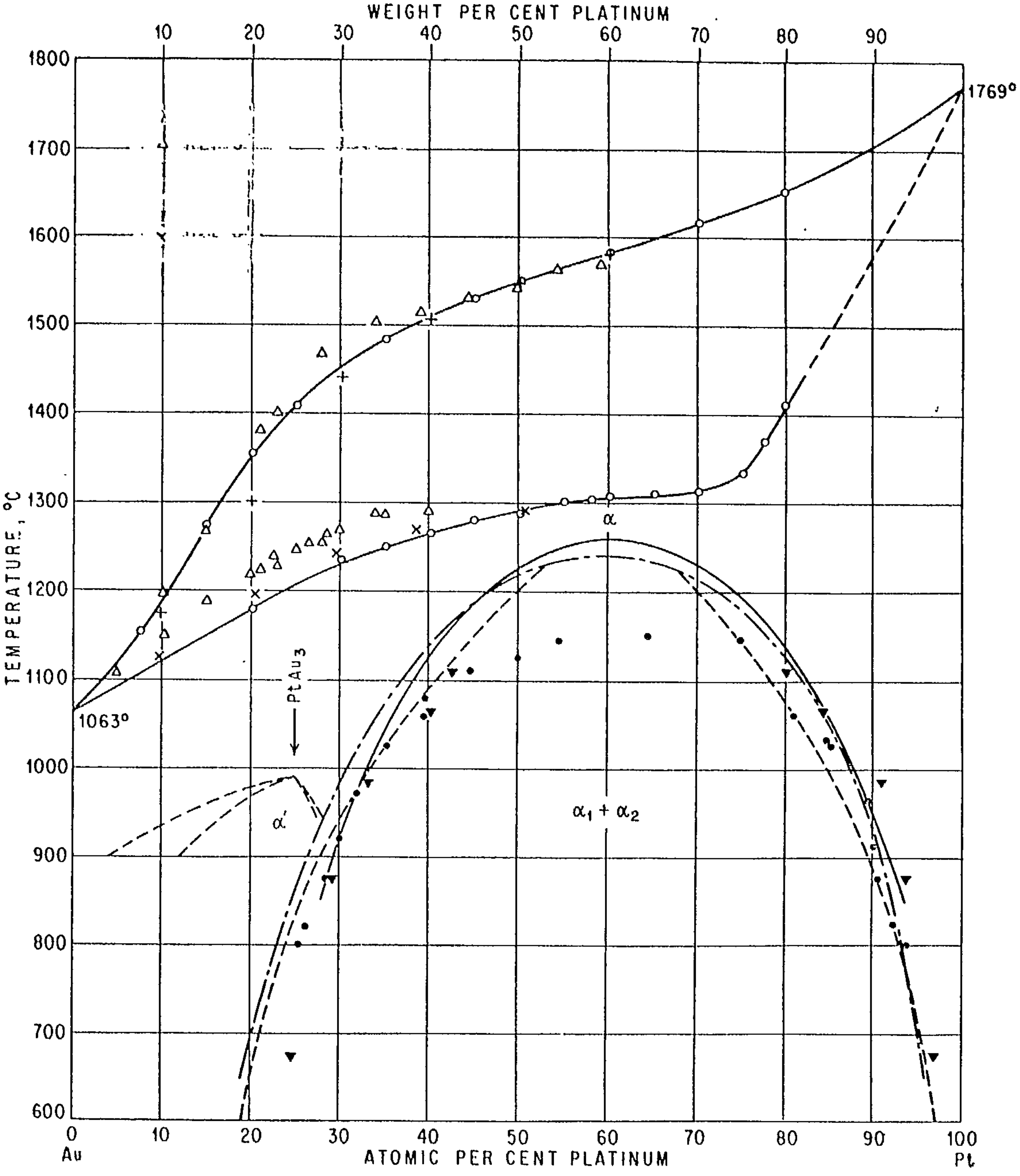

WEIGHT PER CENT PRASEODYMIUM
10
20
30
40
50
60
70
80
90
TEMPERATURE, °C
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
PrAu
PrAu$_3$
PrAu$_2$
Pr$_2$Au
~1350°
○ REF 1
× REF 2
~1205°
~1135°
1140°
1063°
808°
~12
(~9)
710°
76.5(70)
~950°
600°
83
(78)
0
Au
10
20
30
40
50
60
70
80
90
100
Pr
ATOMIC PER CENT PRASEODYMIUM
Au-Pr

Figure 29

Au-Pt, Gold-Platinum

Phase Diagram

The gold-platinum system Figure 30$^{(2)}$ consists of a continuous series of solid solutions at high temperatures. At lower temperatures an apparently ordered phase $PtAu_3$ (α') and a two phase region ($\alpha_1 + \alpha_2$) exist.



Au-Pt

Figure 30

Ternary Systems

Au-Pt-Ag	Gold-platinum-silver. See Au-Ag, gold-silver.
At-Pt-Co	Gold-platinum-cobalt. See Au-Co, gold-cobalt.
Au-Pt-Cu	Gold-platinum-copper. See Au-Cu, gold-copper.
Au-Pt-Fe	Gold-platinum-iron. See Au-Fe, gold-iron.
Au-Pt-Ni	Gold-platinum-nickel. See Au-Ni, gold-nickel.
Au-Pt-Pd	Gold-platinum-palladium. See Au-Pd, gold-palladium.

(A.11) Density

Au-Pt

Changes in dimensions of up to 10% on annealing 70% gold 30% platinum are reported,(138) and attributed to the equalization of concentration differences caused by heavy segregation during solidification of the alloy.

Au-Rb, Gold-Rubidium

Phase Diagram

No detailed phase relationships have been established. A compound $RbAu_2$ has been determined and the formation of a compound RbAu reported.(2)

Au-Rh, Gold-Rhodium

Phase Diagram

The gold-rhodium system consists of terminal solid solutions of the elements with no intermediate phases.(2) The solid solubility of rhodium in gold is about 0.56 at % at 900°C; that of gold in rhodium is between 1.1 and 2.4 at %.

Au-Ru, Gold-Ruthenium

Phase Diagram

Data are practically non-existent for this system. The phase diagram and physical properties of gold-ruthenium alloys containing 0.5, 1.2 and 3% ruthenium have been recently investigated.(139) Alloys with 1% ruthenium are reported to recrystallize with a peritectic reaction.

(E) Uses

Au-Ru

Minor additions of ruthenium (about 0.1%) are used to refine the grain size and improve the mechanical properties of gold-base casting alloys, particularly those alloys used in dentistry.(140)

Au-S, Gold-Sulphur

Phase Diagram

Attempts to prepare gold-sulphur melts were unsuccessful.(2)

Au-Sb, Gold-Antimony

Phase Diagram

The phase diagram for the gold-antimony system is given in Figure 31.(2) The maximum solid solubility of antimony in gold occurs at about 600°C and is 1.1 at %. The solid solubility of gold in antimony is negligible at 300°C.

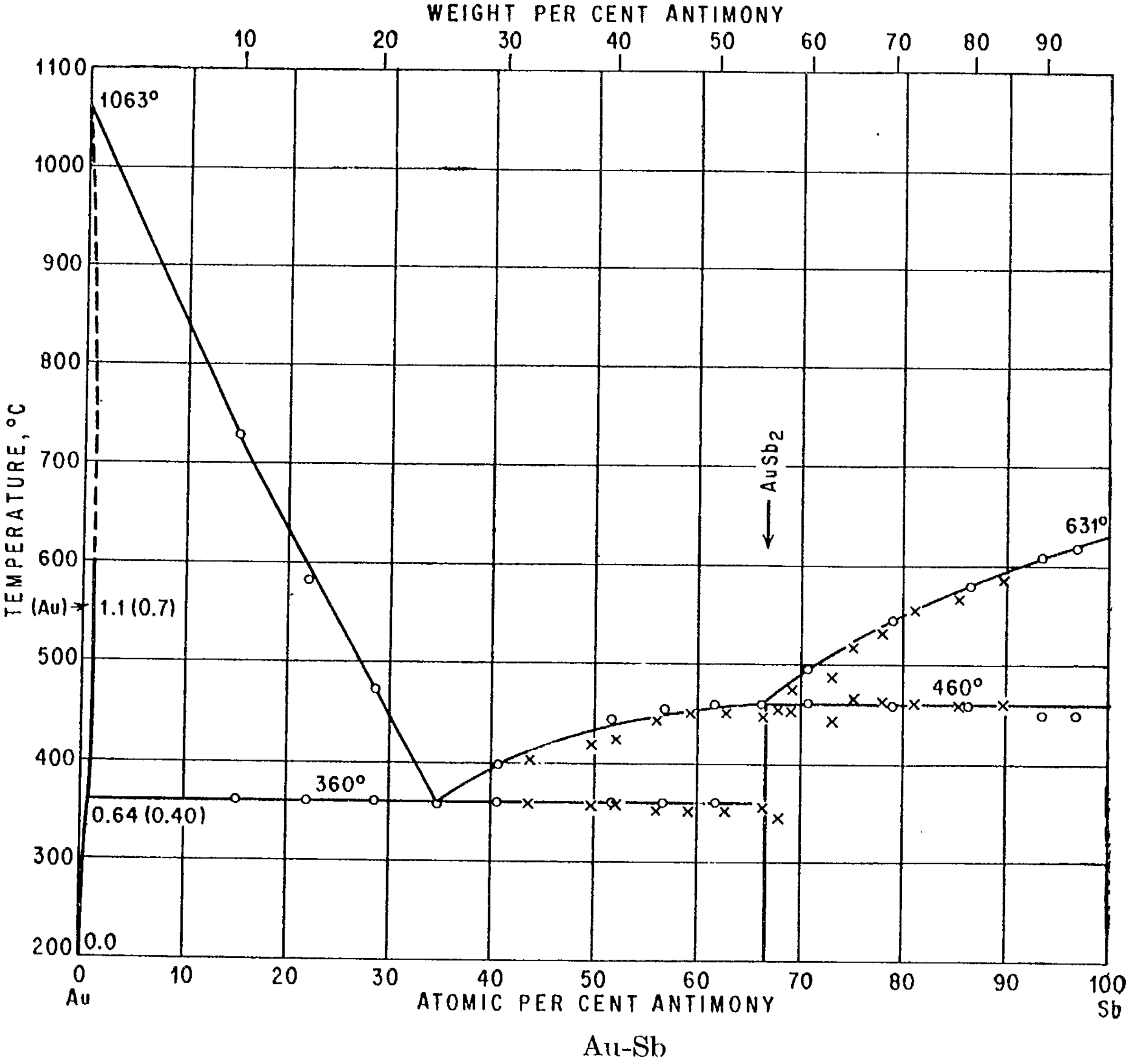

WEIGHT PER CENT ANTIMONY
10
20
30
40
50
60
70
80
90
1100
1000
900
800
700
600
500
400
300
200
TEMPERATURE, °C
1063°
(Au)→ 1.1 (0.7)
360°
0.64 (0.40)
0.0
AuSb₂
631°
460°
0
Au
10
20
30
40
50
60
70
80
90
100
Sb
ATOMIC PER CENT ANTIMONY
Au-Sb

Figure 31

Ternary System

Au-Sb-Sn	Gold-antimony-tin. See reference (125).

(D.2) Mechanical Working

Au-Sb

A gold alloy with 1.0% antimony is unworkable, but the alloy with 0.1% antimony rolls fairly well.(102)

Au-Se, Gold-Selenium

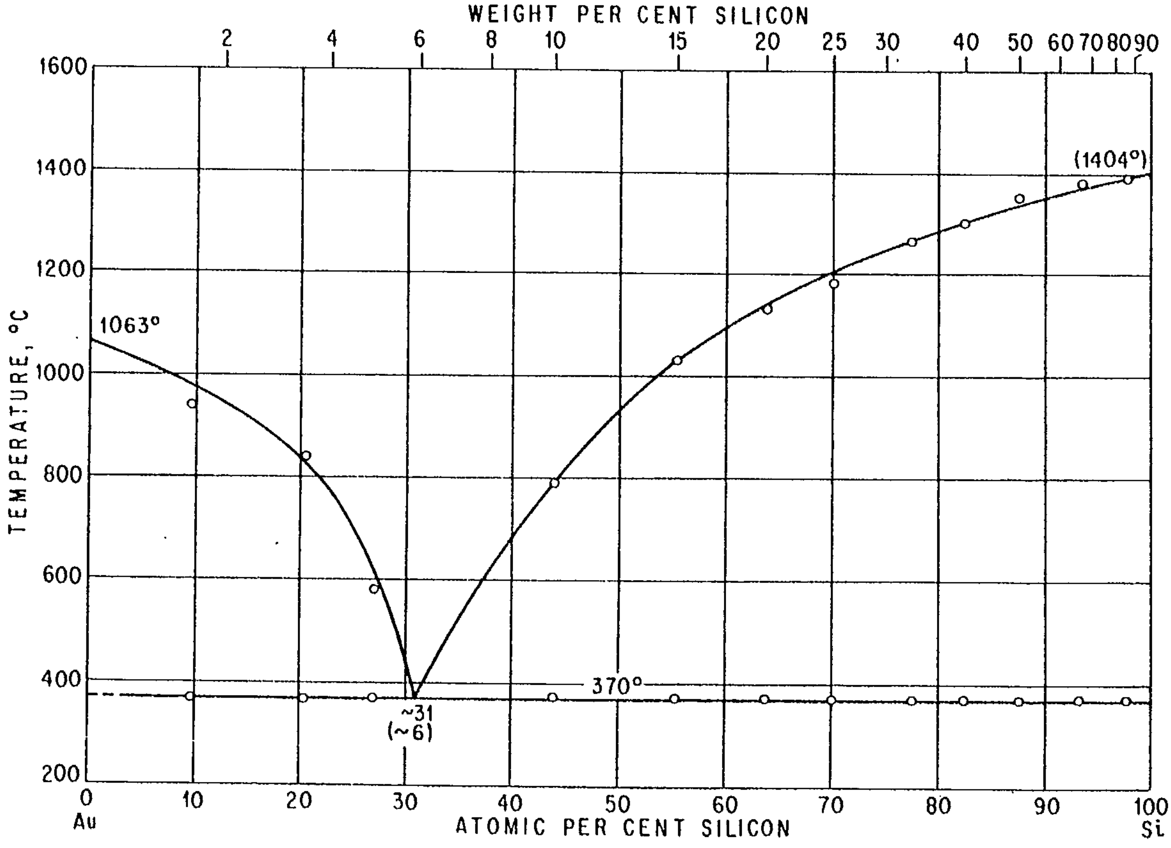
Phase Diagram

It has not been found possible to prepare gold-selenium melts.(2)

Au-Si, Gold-Silicon

Phase Diagram

The diagram in Figure 32(2) is uncertain. Some limited solid solubility of silicon in gold takes place.



Au-Si

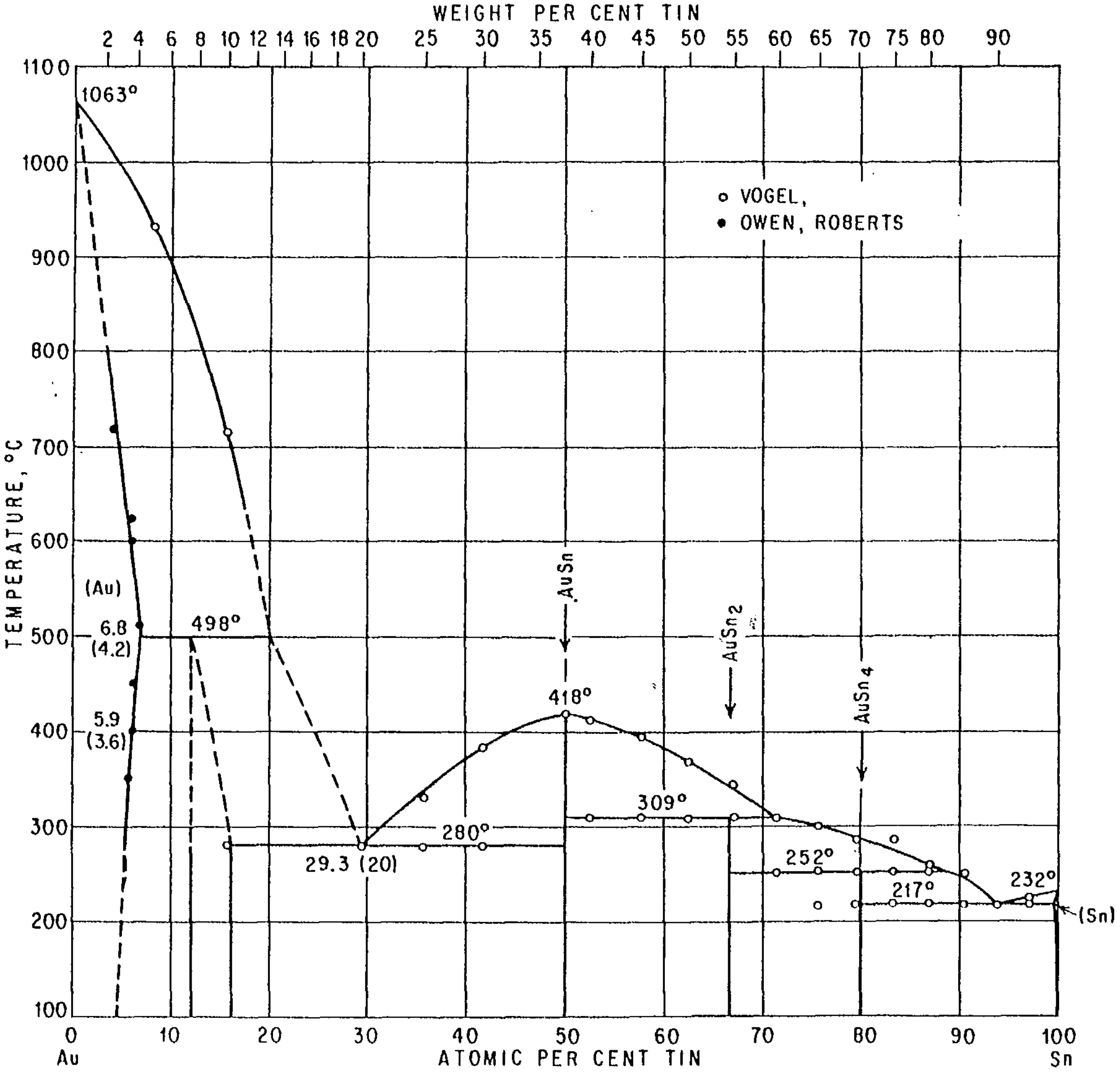
Figure 32

Au-Sn, Gold-Tin

Phase Diagram

The constitution diagram for this system is given in Figure 33.(2) The maximum solid solubility of tin in gold is 6.8 at % at 498°C. About 0.2 at % gold can go into solid solution in tin at 200°C.

The structure of $AuSn_2$ is reported to be orthorhombic and a stacking variant of the FeS_2 (C_2) type of structure.(125)



Au-Sn

Figure 33

Ternary Systems

Au-Sn-In	Gold-tin-indium. See reference (125).
Au-Sn-Sb	Gold-tin-antimony. See reference (125).

(A.19) Surface Tension
Au-Sn

The interfacial tensions between molten gold-tin alloys and the molten potassium chloride-lithium chloride eutectic at 450°C have been measured.(141) A maximum interfacial tension is reported to occur at about 10 at % gold.

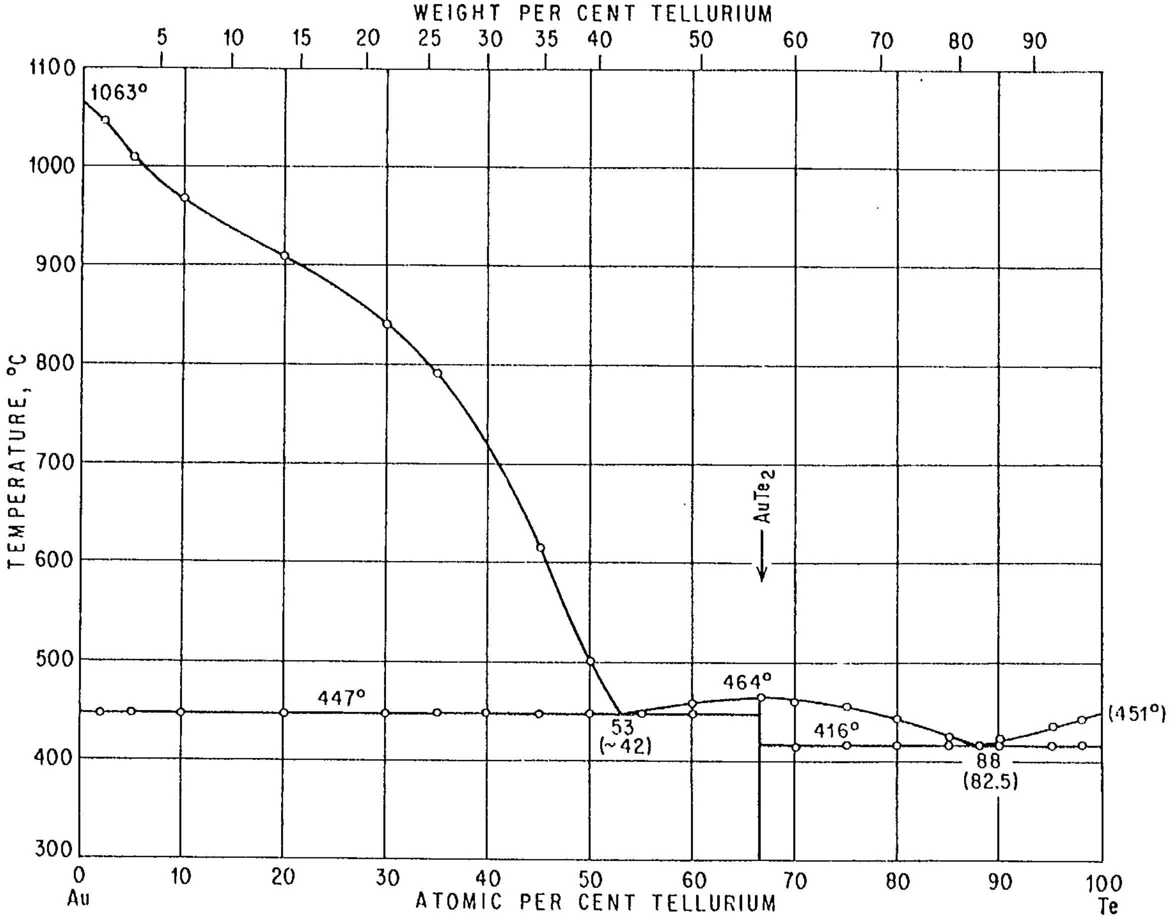
(D.2) Mechanical Working
Au-Sn

Gold alloys with 0.1% tin roll as easily as fine gold. The working properties of an alloy with 1% tin are fair, while 10% tin gives an alloy which is very brittle.(102)

Au-Te, Gold-Tellurium

Phase Diagram

The phase diagram for gold and tellurium is given in Figure 34.(2) The solid solubility of tellurium in gold is very small.



Au-Te

Figure 34

(D.2) Mechanical Working Au-Te

A gold alloy containing 0.01% tellurium can be rolled, but an alloy with 0.1% tellurium is unworkable.(102)

Au-Th, Gold-Thorium

Phase Diagram

Only part of the gold-thorium diagram has been determined and is given in Figure 35.(2) Thorium is practically insoluble in solid gold.

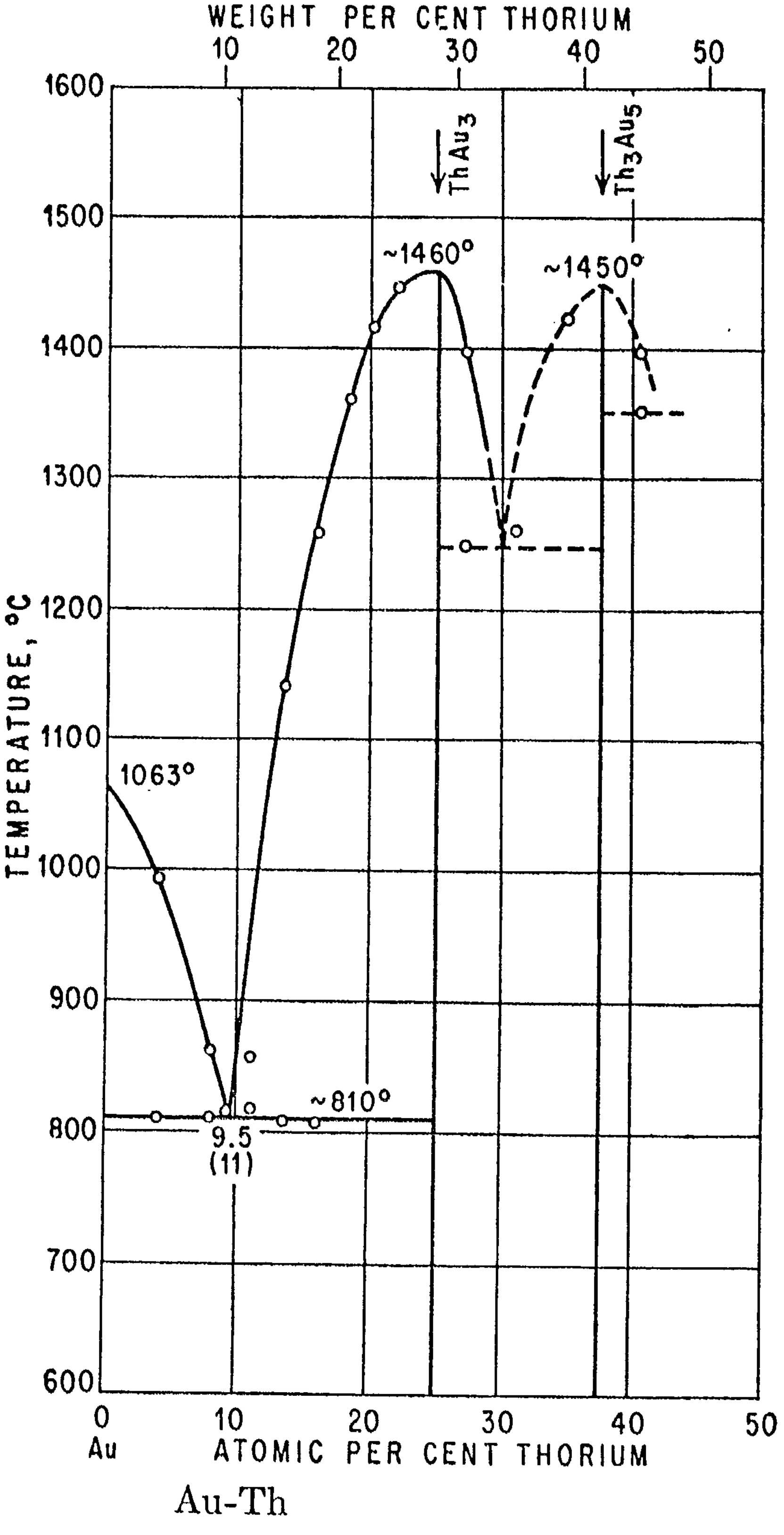

WEIGHT PER CENT THORIUM
10
20
30
40
50
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
TEMPERATURE, °C
ThAu3
Th3Au5
~1460°
~1450°
1063°
~810°
9.5
(11)
0
Au
10
20
30
40
50
ATOMIC PER CENT THORIUM
Au-Th

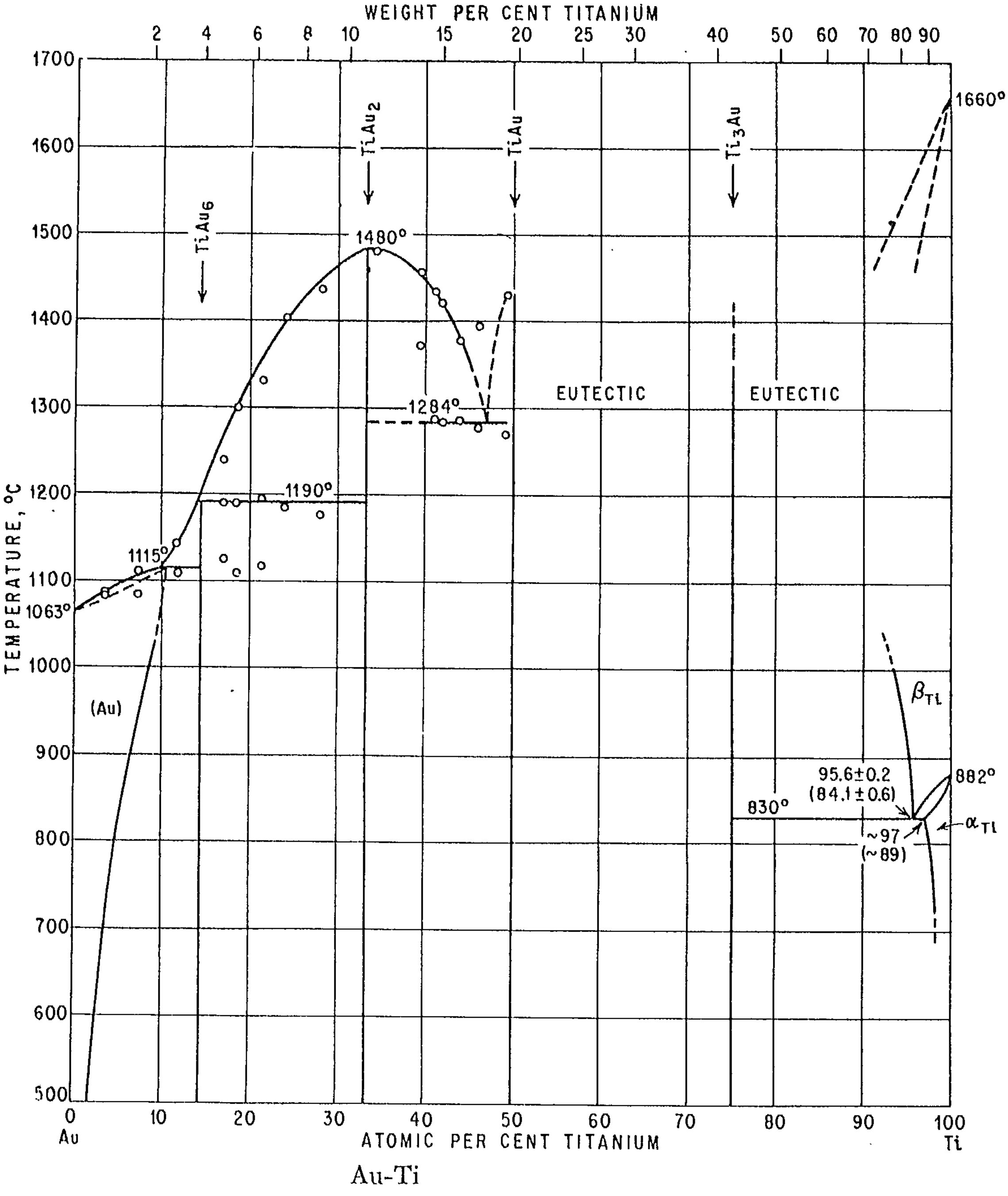
Figure 35

Au-Ti, Gold-Titanium

Phase Diagram

The following data are additional to those contained in the gold-titanium phase diagram in Figure 36:

Maximum melting temperatures: $TiAu_2$, 1455 °C; TiAu, 1490 °C; Ti_3Au, 1395 °C. Eutectic $TiAu_2$ - (TiAu), at about 40 at % titanium and 1385 °C. Eutectic (TiAu) - Ti_3Au, at about 67 at % titanium and 1310 °C. Eutectic Ti_3Au-β (with about 85 at % titanium), at about 79 at % titanium and 1367 °C. Eutectoid decomposition of β titanium solid solution to Ti_3Au and α titanium solid solution, at 95.6 at % titanium and 833 °C. Maximum solid solubility of gold in β titanium, about 15 at % at 1367 °C. Maximum solid solubility of titanium in gold, about 10 at % at 1115 °C.(2)



Au-Ti

Figure 36

Ternary Systems

Au-Ti-Cu	Gold-titanium-copper. See Au-Cu, gold-copper.

(C.3) Corrosion

Au-Ti

Additions of noble metals to titanium alloys have been shown to markedly improve the corrosion resistance of the alloys in reducing acids without any impairment of the resistance to oxidizing media.(142) Gold is beneficial in this respect, but only in higher concentrations than platinum, palladium and rhodium.

Au-Tl, Gold-Thallium

Phase Diagram

The phase diagram for this system is given in Figure 37.(2) The maximum solid solubility of thallium in gold takes place at about 800°C and is 0.9 at %.

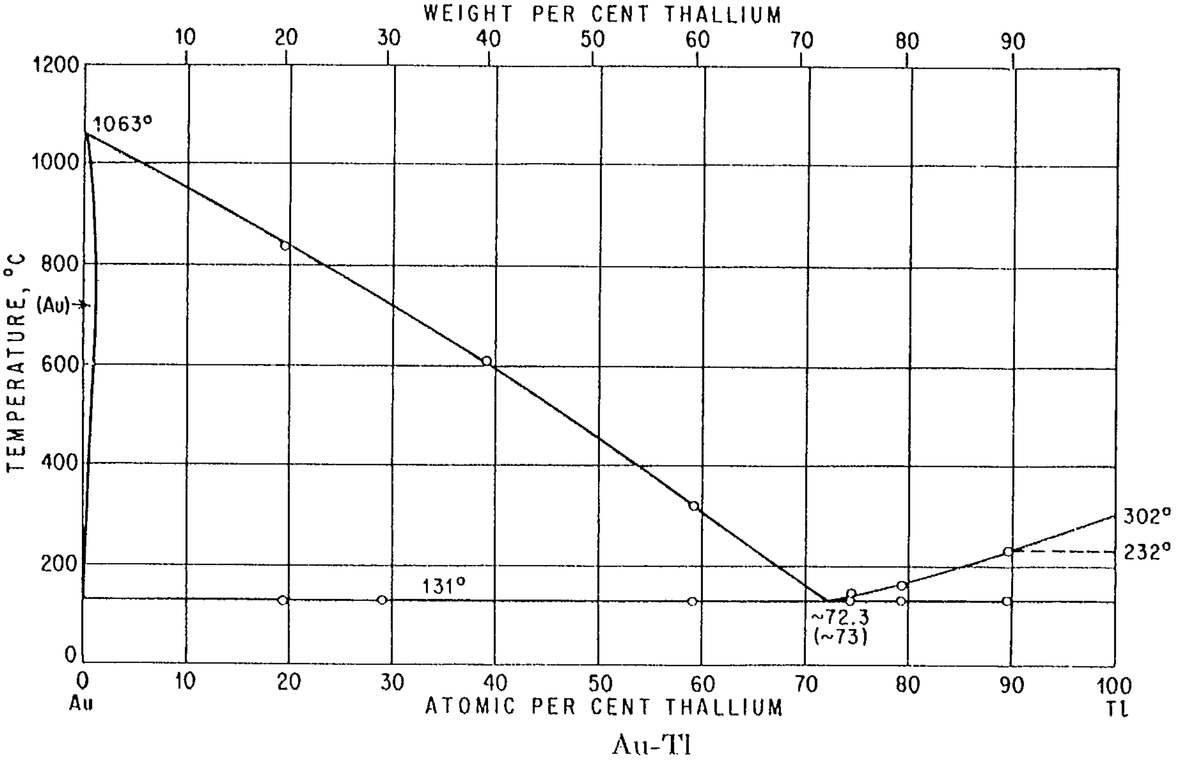

WEIGHT PER CENT THALLIUM
10
20
30
40
50
60
70
80
90
1200
1000
800
600
400
200
0
TEMPERATURE, °C
1063°
(Au)
131°
~72.3
(~73)
302°
232°
0
Au
10
20
30
40
50
60
70
80
90
100
Tl
ATOMIC PER CENT THALLIUM
Au-Tl

Figure 37

Au-U, Gold-Uranium

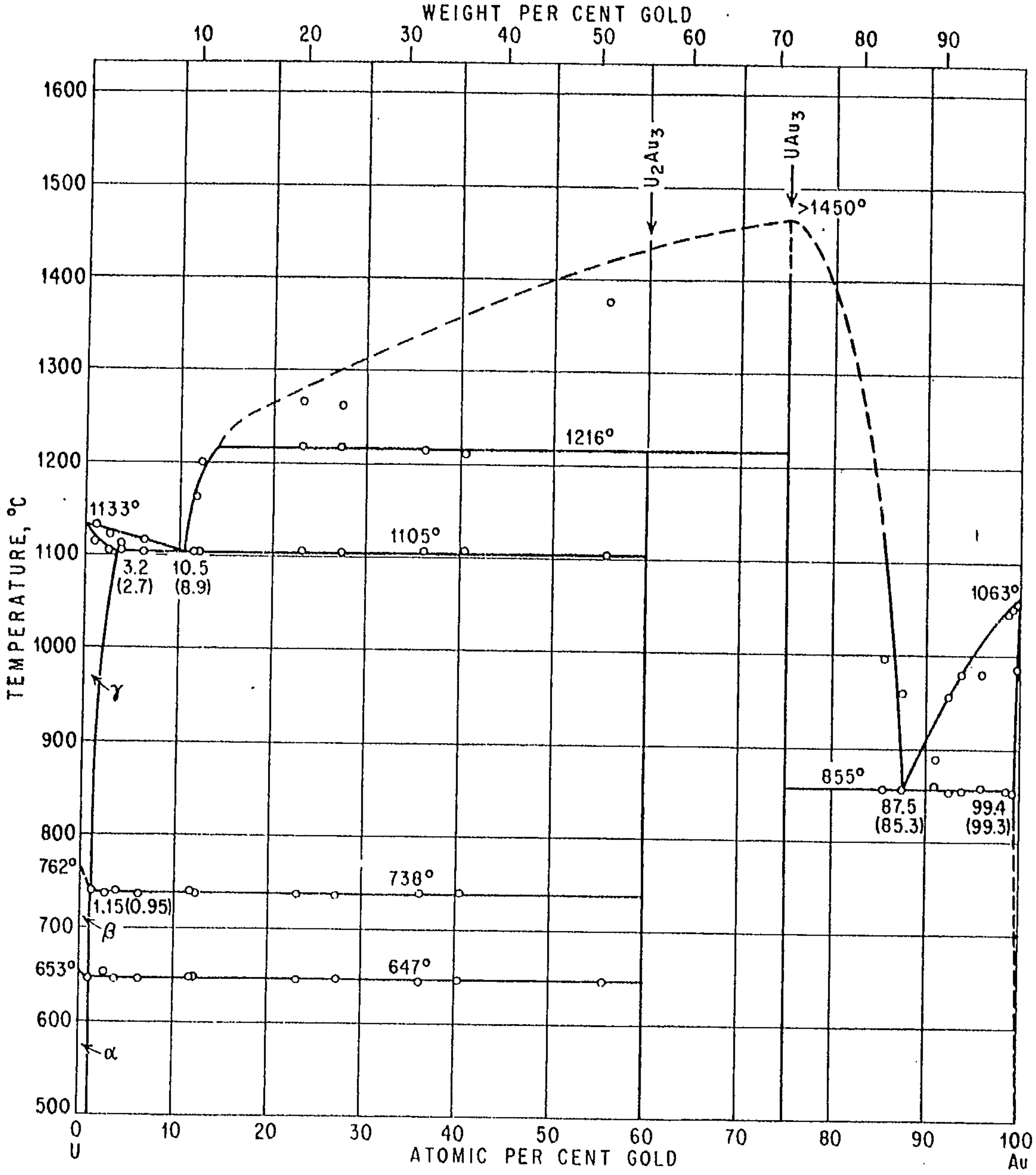
Phase Diagram

The phase relationships for gold-uranium are shown in Figure 38.(2) The maximum solid solubility of uranium in gold is 0.6 at % at 855°C; that of gold in gamma-uranium is 3.2 at % at 1105°C.

(A.20) Diffusion
Au-U

A determination has been made of the diffusion coefficient of gold in polycrystalline alpha-uranium at 640°C, which yielded:(206)

$$D \cong 2 \times 10^{-14} \quad m^2/sec$$



Au-U

Figure 38

(B.3) Tensile Properties

Au-U

Uranium alloys containing 0.1 to 5% by weight of gold (or rhodium or palladium) have been the subject of a patent(143) claiming heat-treatable alloys of improved tensile and compressive properties and good machinability.

Au-V, Gold-Vanadium

Phase Diagram

A partial diagram indicating the gold-rich solid solution limits for the gold-vanadium system is given in Figure 39.(2) The maximum solid solubility of vanadium in gold is about 17.5 at % at about 970°C. The existence of a phase V_3Au is reported.(129) It has the cubic structure of β-tungsten and is fully ordered. The lattice constant $a = 4.88 \pm 0.01$ Å.

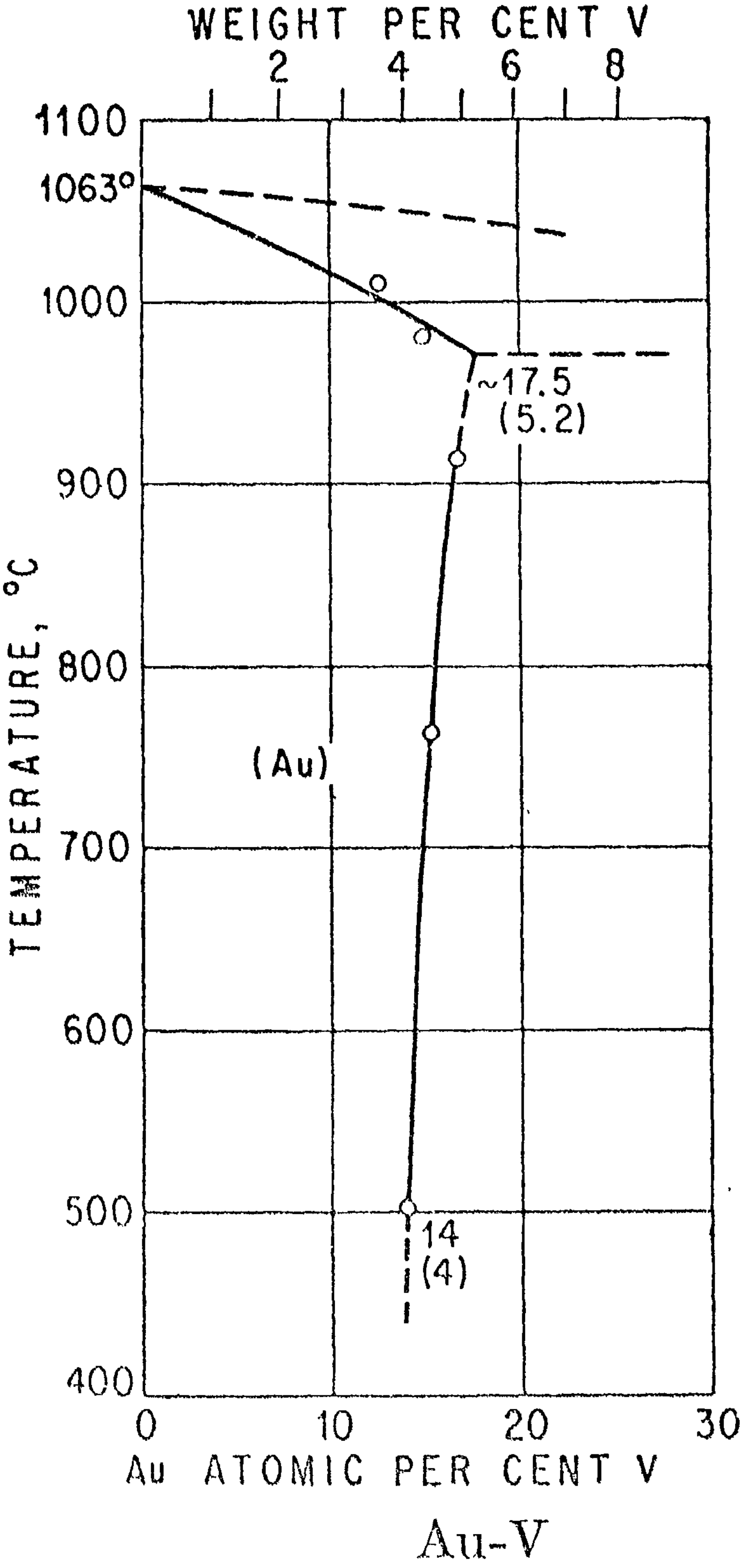
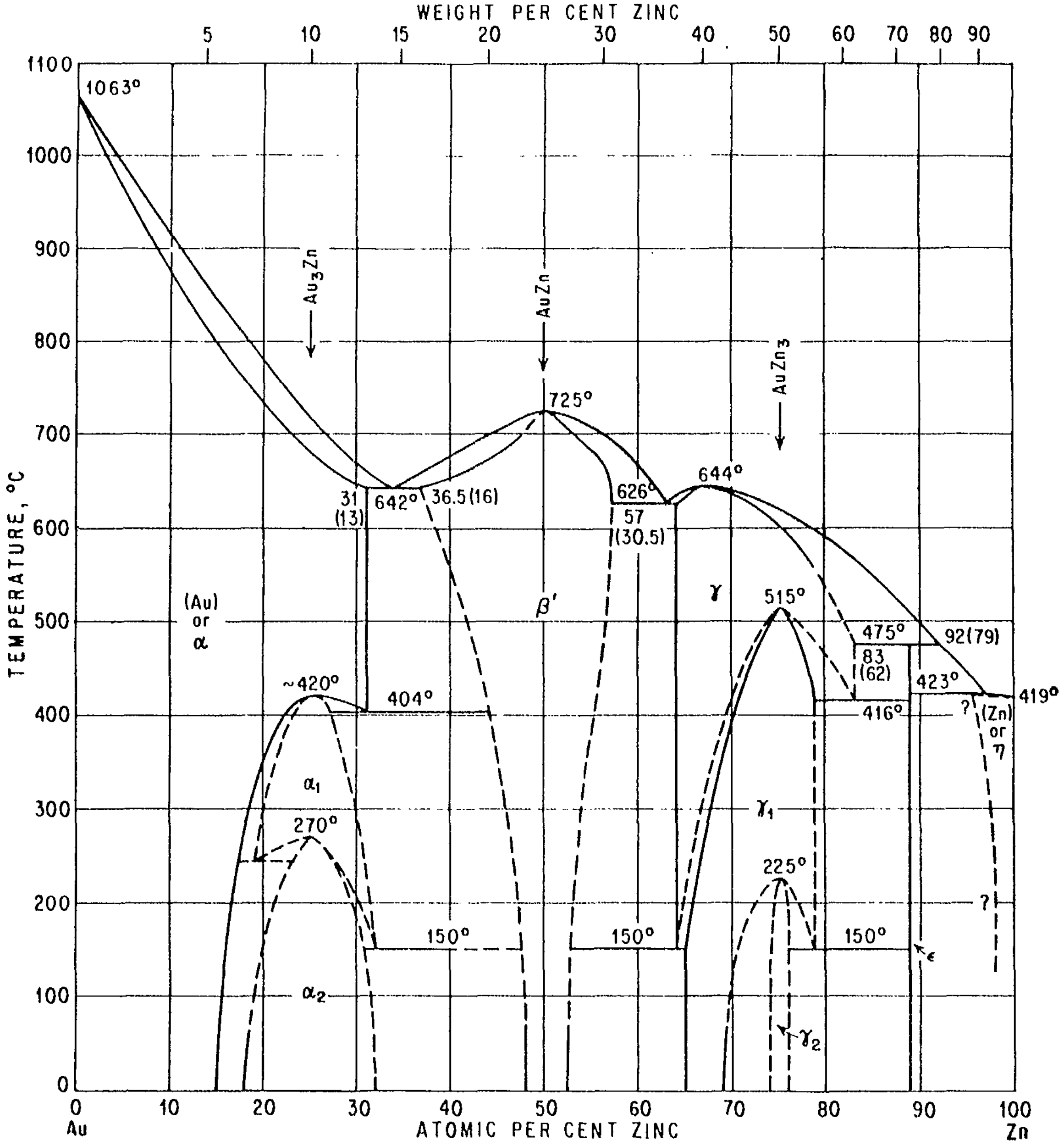

WEIGHT PER CENT V
2
4
6
8
1100
1063°
1000
900
800
700
600
500
400
TEMPERATURE, °C
~17.5
(5.2)
(Au)
14
(4)
0
10
20
30
Au ATOMIC PER CENT V
Au-V

Figure 39

Au-Zn, Gold-Zinc

Phase Diagram

The diagram for this system is given in Figure 40.(2). The maximum solid solubility of zinc in gold is 31 at % at 642°C. The solid solubility limits for gold in zinc have not yet been reliably determined, but values of 2 and 3 at % have been given for the room-temperature solubility.



Au-Zn

Figure 40

Ternary Systems

Au-Zn-Ag	Gold-zinc-silver. The effect of silver on the structure of Au_3Zn has been investigated by (144).
Au-Zn-Cd	Gold-zinc-cadmium. The effect of cadmium on the structure of Au_3Zn has been investigated by (144).
Au-Zn-Cu	Gold-zinc-copper. The effect of copper on the structure of Au_3Zn has been investigated by (144). Effect of zinc on ordering of AuCu and $AuCu_3$; see Au-Cu, gold-copper.

(C.3) Corrosion

Au-Zn

Gold in Galvanized Coatings

Work has been carried out on the influence of gold on the structure, properties and corrosion resistance of galvanized coatings.(145) This work constituted part of the Gold Research Project of the Department of Mines and Technical Surveys, and surveyed the effect of 0.01% gold additions on the galvanizing characteristics of iron-saturated zinc baths. Two types of bath were used, both iron-saturated, with one containing 0.15% aluminum and 0.50% lead.

The gold additions failed to have any influence on the surface appearance, ductility and adherence of the coatings, or on their susceptibility to "white rust" corrosion. A tendency for gold to neutralize the inhibiting effect of aluminum on the iron-zinc reaction was noted. (Aluminum is added to limit the formation of the iron-zinc compound layers and thereby produce coatings with good bending properties.)

Au-Zr, Gold-Zirconium

Phase Diagram

The partial diagram in Figure 41(2) is not fully reliable, since experimental difficulties were encountered in this system. The solid solubility of zirconium in gold at about 1065°C is probably about 7.25 at %.

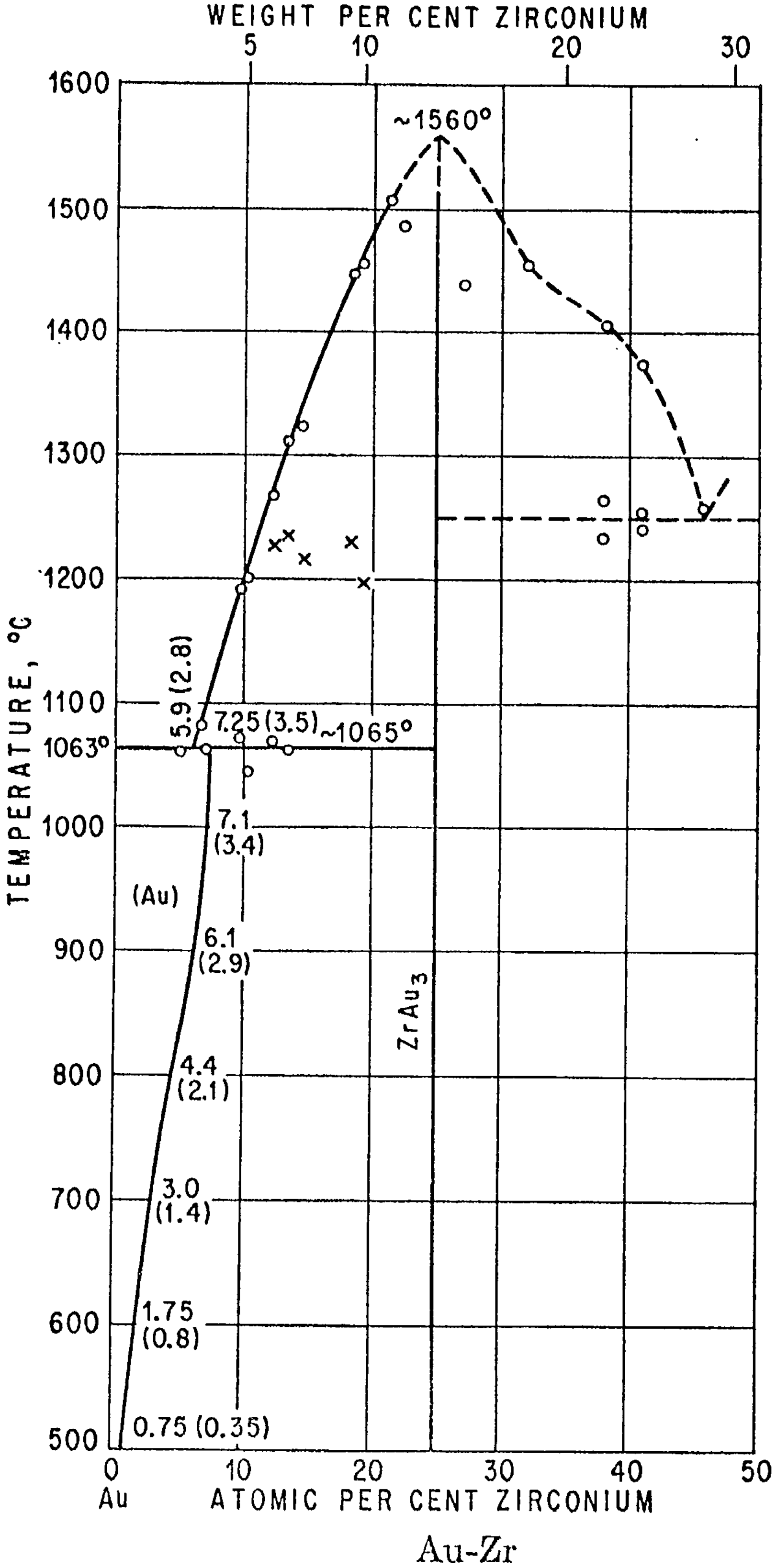

WEIGHT PER CENT ZIRCONIUM
5
10
20
30
1600
1500
1400
1300
1200
1100
1063°
1000
900
800
700
600
500
TEMPERATURE, °C
~1560°
~1065°
5.9 (2.8)
7.25 (3.5)
7.1
(3.4)
(Au)
6.1
(2.9)
4.4
(2.1)
3.0
(1.4)
1.75
(0.8)
0.75 (0.35)
ZrAu$_3$
0
Au
10
20
30
40
50
ATOMIC PER CENT ZIRCONIUM
Au-Zr

Figure 41

III. USES

(E.1) Jewelry and Decorative Uses

Undoubtedly one of the earliest uses of gold was in jewelry and decorative ware. Some of the early examples of the goldsmith's art have survived through the ages and today pose interesting problems of non-destructive metallurgical examination.(146)(147) Electrum, a naturally occurring alloy of gold, silver and copper was much used, and Egyptian articles in the Louvre have been shown to contain gold 69-75%, silver 22-28%, and copper about 3%.

A less common decorative use of gold is its use in Damascene.(148) Damascene articles consist of blued steel which has been inlaid with gold and silver, resulting in a precious metal pattern on a blue-black background.

Gold Alloys Used in Jewelry

Composition, other than the gold content, and mechanical properties of gold alloys are of relatively little interest to jewelry manufacturers. Provided the alloy has adequate strength and hardness in the annealed condition, has good formability and is solderable, the jewelry manufacturer is primarily interested in colour and gold content (the carat of the alloy where pure gold equals 24 carats).

The composition and mechanical properties of some jewelry alloys are given in Table 24.(149) Many of the gold-copper alloys are hardenable by heat treatments giving ordered phases, but this property is little used in the production of jewelry although it has been utilized in the dental field. A possible reason for this may be that the strength advantage of ordered gold-copper alloys over the disordered alloys decreases with increasing cold-working of the disordered alloy.

TABLE 24

Alloy	Au %	Ag %	Cu %	Ni %	Zn %	Other %	UTS kpsi	Elong % in 2 in.	Hardness BHN
Coloured Golds									
18-carat yellow	75.0	15.0	10.0	-	-	-	67	42	125
14-carat red	58.3	-	41.7	-	-	-	57	50	85
14-carat pink	58.3	4.9	31.6	5.2	-	-	82	42	170
14-carat yellow	58.3	20.8	20.8	-	-	-	77	34	180
14-carat yellow	58.3	10.4	29.1	-	2.1	-	-	40	-
14-carat green	58.3	30.0	6.0	1.5	4.2	0.1 Mn	80.4	32	-
10-carat yellow	38.5	15.4	41.9	1.2	3.1	-	83.3	34	-
10-carat yellow	41.2	8.8	42.1	1.6	5.8	-	-	-	110
White Golds									
18-carat	75.0	-	3.5	16.5	5.0	-	100.8	47	245
18-carat	75.0	-	-	-	-	25 Pd	44	-	76
14-carat	58.3	-	16.0	17.0	8.6	-	105	43	206

Potter's Gold

Thermally decomposing gold solutions which are applied like a lacquer and then converted to gold by heating the object coated, have been used for many years for the decoration of pottery. Today many solutions for the application of gold to porcelain, ceramics, glass, quartz, mica, etc., are available. The compositions are usually trade secrets, but all are lacquer-like liquids. They consist of a solution or colloidal suspension of an organic gold compound in a natural or synthetic resin medium and may contain a solvent or thinner. In addition, most of the solutions contain small amounts of dissolved metals or oxides which are added to control the appearance and adherence of the gold deposit.(150). This type of solution is used today, not only for decoration, but also in aircraft and rocket applications.

(E.2) Anticorrosive Uses

Gold and gold alloys naturally find many uses where corrosion resistance is of importance. They are used both in bulk and on plated or clad base metals. In the latter, it is important that no break exist in the coating, since accelerated corrosion of the base metal generally takes place if it is exposed, due to the high electrode potential of gold relative to other metals.

Gold-platinum alloys were used in Germany during World War II as substitutes for platinum in chemical laboratory ware.(151) (152) The gold-10% platinum alloy was employed for laboratory apparatus used below 1000 °C. An iridium-5% gold alloy was also used in chemical apparatus.(152)

Resistance to Hydrochloric Acid

An alloy containing 30% gold, 40% silver and 30% palladium and named "Pallacid" has been developed(153) for use in contact with aqueous 20% hydrochloric acid. A maximum loss of 0.1 $gm/m^2/day$ in the presence of air and acid vapour is encountered with this alloy. The alloy is also resistant to other concentrated mineral acids. By the addition of a small amount of chromium to the alloy, corrosion rates in 20% hydrochloric acid can be reduced to 1/4 to 1/6th of the rate for the chromium-free alloy.

Nuclear Uses

Gold has been used as the lining of two homogeneous liquid fuel reactors.(154) (155) The reactors were the first of a series (Los Alamos Power Reactor Experimentation) ultimately intended to be transportable power reactors. The gold shell is backed by steel and intended to withstand temperatures of 430 °C and 750 psi pressure.

The reactors were experimental and both used phosphoric acid solutions of uranium as the fuel. The first reactor, LAPRE - 1, failed as a result of excessive corrosion. In the second reactor being tested, LAPRE - 2, all the structural materials in contact with the fuel solution are either gold-plated or gold-clad, in an attempt to overcome the corrosion difficulties.(156)

(E.3) Joining

Brazing alloys containing gold are widely used in the manufacture of vacuum tubes for electronic applications. The alloys most commonly used(157) are listed in Table 25.

TABLE 25

Composition	Solidus		Liquidus	
	°C	°F	°C	°F
Au 75%, Ag 5%, Cu 20%	893	1640	899	1650
Au 80%, Cu 20%	882	1620	888	1630
Au 37.5%, Cu 62.5%	932	1710	963	1765
Au 82.5%, Ni 17.5%	949	1740	949	1740
Au 41.7%, Ag 2.8%, Cu 55.5%	932	1710	963	1765

The gold alloys are frequently used for the initial joints in an assembly, and subsequent joints are made with lower melting point silver alloy, thus avoiding melting of the gold joints. The brazing alloys are all characterized by low vapour pressures. In some critical assemblies, vacuum-melted brazing alloys are used to prevent any possibility of out-gassing attributable to the filler metal in the joint.

Gold-indium alloys make possible use of high gold content, low melting point alloys. A 77.5% gold 22.5% indium brazing alloy has a working temperature of 499°C (930°F) and is suitable for metal-to-glass seals.(126)

Gold-copper brazing alloys are used for the joining of radio-tube components without damage to metal-to-glass seals.(158) Brazing is carried out in an atmosphere of hydrogen using high-frequency pulse heating.

Gold brazing alloys are particularly useful where intergranular penetration of the base metal cannot be tolerated and where high strength and excellent oxidation resistance are required near 871°C (1600°F). The gold brazing alloys have lower hardness, better ductility and less tendency towards intergranular penetration than the high nickel alloys when used in Inconel and stainless steel joints.(159)

A brazing alloy consisting of 72% gold, 6% chromium and 22% nickel is used to braze 18-8 stainless steel missile parts.(160) The process is carried out at 998°C (1900°F) and is reported to be capable of joining graphite to many types of stainless steel. After 7 days soaking at 871°C (1600°F), tensile strengths of 40,000 psi at 649°C (1200°F) and 22,000 psi at 871°C (1600°F) in stainless steel joints are reported.

An 82% gold - 18% nickel alloy has been used(161) to make brazed joints in Inconel and Inor 8 (a nickel-molybdenum-chromium alloy). These joints were subsequently exposed to the action of a molten lithium fluoride-beryllium fluoride-uranium tetrafluoride nuclear fuel at 704°C (1300°F) for 1000 hours. A tendency towards the formation of diffusion voids in the fillets was noted.

In some applications, diffusion bonding with gold will give satisfactory joints in structures where distortion would occur if brazing and heat treatment had to be carried out after machining. One such application concerned the joining of a copper - 2% beryllium alloy part to a Monel backing block. It was successfully accomplished by using plated diffusion couples of gold/copper or gold/silver and heating the parts with the plated joint under pressure for 3 hours at 340°C. This temperature was selected as it allowed the joints to be made and the ageing of the copper-beryllium part to take place at the same time.(162)

(E.4) Dental Uses

Gold alloys in wrought and cast forms have many uses in orthodontic applications. Wrought gold alloys similar to the jewelry alloys are used for striking and swaging dental plates. More complex heat-treatable gold-platinum-copper-silver alloys (with or without small quantities of other elements) are used for orthodontic sheet, strip and wire. Gold alloys are preferred(163) over stainless steels for orthodontic arches and springs. The gold alloy springs can be heat treated after soldering to obtain the required properties. Stainless steel springs lose strength as a result of soldering.

Gold wire gauze has also been used to reinforce dentures made of acrylic plastic.(164) The gold reinforcement was preferred to one of stainless steel, because the latter gave the dentures an objectionable colour.

A wide range of gold alloys is used for making small castings for inlays, clasps, lingual bars, and partial and full dentures. These are cast to shape by specially developed precision casting techniques.

For dental castings four main types of alloy are recognized:(80)

Soft:	Brinell hardness,	40-75.	Minimum gold plus platinum	83%
Medium:	" "	70-100.	" " " "	78%
Hard:	" "	90-140.	" " " "	78%
Very Hard (Partial Denture):	" "	over 130, quenched; over 200, age-hardened.	" " " "	75%

The detailed requirements sought in dental casting alloys vary over a wide range and according to the purpose for which the castings are to be used. Some compositions, covering the four groups listed, are given in Table 26.

TABLE 26

	Au %	Pt %	Ag %	Cu %	Ni %	Zn %	Brinell Hardness Softened*	Brinell Hardness Hardened**
Soft	97	3	-	-	-	0.03	34	-
	91.5	-	5.7	2.8	-	-	47	-
	87.4	2.1	6.2	4.2	-	0.3	59	-
Medium	83.3	-	8.3	8.3	-	-	91	-
Hard	78.8	3.0	7.0	7.8	-	1.1	120	-
Very Hard	72.4	2.8	5.0	15.6	2.0	2.4	145	249

*Softened by quenching from 700 °C into water.

**Hardened by cooling from 450° to 250° over a period of 30 minutes.

A good correlation exists between the hardness of dental alloys and their mechanical properties.(165) The hardness can therefore be used to estimate the ultimate tensile strength and yield strength of wrought and cast alloys.

The use of gold in dental amalgams in amounts as low as 0.1% is reported (166) to strongly inhibit the solution of mercury in saliva and to decrease the volatility of the mercury in the amalgam.

(E.5) Optical Uses

Many of the applications of gold and gold alloys are directly or indirectly linked to the optical characteristics of gold. The reflectance, transmission, emissivity, and absorption of visible and infra-red radiation by gold are some of the properties used.

Because of its good infra-red reflectivity and corrosion resistance, gold has been used in many applications as a reflector material. It has been used in many industrial heating applications, such as paint-drying ovens. The melting point of gold is not necessarily a temperature limit. By appropriate design, a testing furnace operating at temperatures up to 1650 °C (3000 °F) has been constructed. (167)

The high infra-red reflectance and visible light transmission of gold films are used to produce steel mill face masks which protect against heat without affecting visibility. (168) The masks are made of gold-coated plastic and are claimed to reflect 95% of the incident infra-red rays.

Glass windows capable of reflecting infra-red radiation are made in a similar manner. Optimum performance is obtained when a vapour-deposited multilayer of bismuth oxide-gold-bismuth oxide is used, consisting of a 130 Å layer of gold and 450 Å layers of bismuth oxide.(169)

The high infra-red reflectance and low emissivity of the metal are used in many aircraft, missile and space-vehicle applications. The engine shrouds of turbojet-powered aircraft are plated with gold by means of a "potter's gold" type of gold solution.(170) The inside of the shroud is then protected by the reflection of engine heat away from the shroud, while the aircraft structure around the shroud is protected from radiated heat by the low emission from the outside of the shroud.

Gold blacks reverse the optical properties available in the bulk metal. Gold blacks are formed by the evaporation of gold in a low-pressure atmosphere of nitrogen and have low reflectivity and high absorption in the infra-red region of the spectrum. This property makes gold blacks useful as coatings where high absorption of radiant energy is required. One suitable application is as a coating on thermopile receiver elements.(42)

Although actually concerned with the wave length of light emitted by mercury rather than any optical property of gold, the use of gold in producing primary optical standards of length is interesting.

Because gold occurs in nature as a single isotope (Au^{197}), it can be converted by neutron irradiation into mono-isotopic mercury (Hg^{198}). This isotope, when used in a vapour discharge lamp, gives a single wavelength of green light. This monochromatic wavelength is then used as a primary length standard.(171)

(E.6) Electrical Uses

Electrical Contacts

Alloys which have been used for electrical contacts include gold-3% zirconium and gold-25% silver-3 to 5% nickel. A gold-10% platinum alloy is suitable for currents less than 0.1 amp, while the gold-5% nickel alloy is suitable for currents (including high-frequency) up to 1 amp.(152)(172)

Other alloys used for electrical contacts are gold-3% cobalt and gold with 1 to 16% nickel.(174)

When the currents being carried are sufficiently high, an arc will form between opening contacts. It has been shown(173) that arcs in gold and platinum contacts are preceded by the formation of a molten metal bridge. The temperature of this bridge rises rapidly to the boiling point and provides the initial metal vapours for the arc discharge. At low currents, transfer of metal still takes place by melting and boiling even though arcs are not struck. It has also been shown(175) that the metal transfer, in D.C. contacts under non-arcing conditions, can be considerably reduced if ordered gold-copper alloys are used instead of the disordered alloy. With gold-3% cobalt alloys, smaller transfer occurs if precipitation-hardened rather than solution-treated contacts are used.(174)

Platinum and palladium contacts used under non-arcing conditions are liable to fail by the catalytic polymerisation of organic vapours condensing on the contact surface. A non-conducting organic layer is built up, and rubbing the contacts only aggravates the situation by frictional activation of the polymerisation. Gold alloy contacts do not exhibit the same catalytic activity,(176) (177) and the use of a gold alloy layer on palladium contacts can reduce the effects of the polymers on contact performance.

Contacts made of copper, nickel or cobalt fail by bridging combined with oxidation.(178) The oxides formed on the molten metal bridge eventually build up a high enough resistance to stop the passage of a current. Additions of gold will reduce the metal transfer. Copper-2% gold will no longer fail by oxidation, but some oxidation still takes place in nickel-16% gold and cobalt-8% gold alloy contacts.

Resistance Alloys

A gold alloy containing 3 to 5% nickel and a total of 1.3% of iron plus manganese plus vanadium has been used for potentiometer wires, while a gold alloy containing nickel, silver, manganese and tin can be substituted for silver-palladium resistance alloys.(152)

A gold-2% chromium alloy is used for standard resistances.(179) The alloy has a lower temperature coefficient of resistance than Manganin and attains constant resistance after only a few weeks ageing compared to the one year at 140°C required for Manganin. One disadvantage of the gold-chromium alloy is changes in resistance due to humidity variations. This is overcome by sealing the standards in argon-filled enclosures. The same alloy finds use in high-pressure gauges.(180) Here the gold-2.1% chromium alloy wire is preferred to Manganin because of its lower temperature coefficient of resistance, even though the pressure sensitivity of Manganin is greater.

Heating Elements

Thin films of gold deposited on mica have been used as heating elements in such articles as domestic electric irons.(150) In these applications the gold is deposited from a lacquer-like liquid of the same type as used for the decoration of ceramics.

Similar films of gold vapour, deposited on glass with an intermediate layer of bismuth oxide, give windows of high optical transparency capable of being electrically heated.(21)(181) Such windows are a pale straw colour and absorb about 5-8% of the incident light. They are capable of carrying up to 1000 watts/ft^2. This type of heated window finds application in aircraft, locomotives, the bridge windows of arctic vessels, cameras, microscopes, and humidity chambers. Electrically heated gold film windows are free of the diffraction effects which occur when fine wire elements are used in the windows.

Condensers

Mica with gold deposited on it has been used as condenser plates.(150) The gold is applied by use of a thermally decomposing lacquer-like liquid of the type used for ceramics.

Thermal Fuses

A very simple and convenient method of protecting electric furnaces from overheating damage is by means of a metal fuse extending into the heated zone which will melt and cut off the power supply if overheating takes place. Such fuses have to have a short melting range and high resistance to oxidation and deterioration in use. Gold and gold-palladium alloys are widely used, since they admirably meet these requirements.(182) Gold will give a fuse failing at 1063 °C, while gold-palladium alloys can be selected to give protection in the range 1100° to 1500 °C. Such fuses should not be connected to nickel-chromium leads inside the heated zone, as interdiffusion between leads and fuse will lead to failure.

(E.7) Electronic Uses

Radio Tube

A minimum thickness of 1 μ of gold plated on the molybdenum and nickel-5% manganese grids of radio tubes will suppress grid emission of electrons.(183) This suppression is of use in tubes which cannot be designed to give a grid operating below 150 °C in the presence of an oxide-coated cathode.

Printed Circuits

Printed circuits are widely used in modern electronic and other industries. Gold plating of the circuit by immersion (electroless) plating will protect the circuit from corrosion and tarnishing in storage and the subsequent assembly difficulties when soldered connections are made.(184)

Gold Film Thermometers

Gold film thermometers have been used to detect the passage of shock waves in shock tubes.(185) They respond to rapid changes of several degrees Centigrade in gas temperature and have a negligible effect on the gas flow. The response time is very short, 10^{-8} sec being possible. Film thicknesses are of the order of several hundred atom layers.

X-Ray

Gold is sometimes used as the target material (186) in x-ray tubes to obtain specific radiation. Its high density makes it suitable as an x-ray source, but its relatively low melting point places limitations on the load which can be applied to tubes using gold as a target material.

Bolometers

Bolometers are heat-sensing devices of very high sensitivity, used for the measurement of temperatures at a point remote from the heat source. They are employed in astronomy and in industry -- in the latter for measuring temperatures in inaccessible locations or on moving machinery surfaces.

Vapour-deposited gold electrodes have been used to give the lowest electrical noise in iron oxide thermistor bolometer flakes.(187). Bolometers have also been constructed with the active element made of plastic-backed evaporated gold.(188)

Transparent Windows

Gold-coated glass windows have a number of possible uses in the electronic field.(181) If the gold film is grounded, a transparent window acting as a screen for radio-frequency radiation is obtained, and it is possible to observe equipment without leakage. In a similar way, if the gold film is made the external surface of the window and grounded, a leak is provided that prevents static charges from building up on the window. Other possible applications of this type of window are as transparent electrodes for electro-luminescent lighting and as transparent radio antennae.

Semi-Conductors

Some gold is used in "doping" semi-conductors for electronic purposes. The amounts of gold used are very small, but the purity requirements are very high and gold for these purposes commands a premium price. Gold-gallium alloys are used in the high purity form to make alloy junctions in silicon and germanium semi-conductor devices.

(E.8) Textile Industry

Spinnerets

The gold-10% platinum-0.5% magnesium and gold-5% nickel-2 to 3% tin alloys were both developed during World War II for the spinning nozzle tips used in synthetic fibre production.(152)

In rayon production the spinnerets have to resist the simultaneous action of caustic soda and sulphuric acid. Materials for these parts are thus limited to tantalum, zirconium and the noble metals. One of the most widely used alloys for rayon production is a gold-30% platinum alloy.(189) This alloy has good hardness, takes a fine polish and has good resistance to "ring formation" (an electro-chemical action which mars the polished surface of the spinneret).

The age hardening and grain size of gold-platinum alloys for spinnerets and the effects of rhodium additions of up to 1% have been studied.(190) The alloys contained up to 50% platinum and the rhodium, where added, replaced gold. Rhodium will give the as-cast alloys a fine-grained structure, but this can also be obtained by correct casting and cooling. In both the homogeneous and heterogeneous alloys, age hardening after solution treatment and quenching is time-dependent, and reversion takes place after a maximum hardness has been obtained. The homogeneous gold-25% platinum alloy will not age harden unless rhodium is present. The heterogeneous 30 to 50% platinum alloys exhibit a higher hardness in the aged condition when they do not contain rhodium additions.

Gold Thread

Gold thread, which consists of a textile thread around which a gold, or gold-plated, flattened wire has been wound, has long been used for ornamental purposes in clothing and uniforms. It is reported (191) that the plating of the wire can be accomplished after it has been wound around the textile thread. The plating is a continuous process in sodium or potassium auricyanide baths.

(E.9) Surface Coatings

The application of gold coatings to base metals can be accomplished by several methods, which include:

Cladding (rolled gold)
Electroplating
Chemical (electroless) plating
Thermally decomposing organic compounds
Vacuum deposition

The coatings can be applied for decorative purposes only, and here colour is of prime importance. Alternatively they can be applied for specific purposes such as corrosion resistance, electrical characteristics, wear resistance, and the like.

Cladding and electroplating permit thick coatings to be applied, but the chemical, thermally decomposed and vacuum-deposited coatings are thin coatings.

For chemical engineering applications electroplated coatings must be firmly adherent and free from porosity, and a minimum coating thickness of 40μ (about 0.0015 inch) is reported necessary to give porosity-free coatings.(192)

Chemically plated coatings are about 1 x 10^{-5} inches thick, and thermally decomposed coatings about double this thickness. Both are claimed to be continuous coatings which can give corrosion and oxidation resistance.(184) Their thinness, however, makes them very prone to mechanical damage. The two types of coating can be applied to areas where electroplating would be difficult due to electrical shielding.

Cladding and electroplating can be used to give either pure gold or gold alloy coatings. In electroplating the deposition of alloys requires close control of plating bath composition and plating conditions.

Where electroplating is used for decorative purposes (and this application is increasing), coatings are very thin. They are usually 2 x 10^{-6} inch or under, and frequently no more than 5 x 10^{-7} inch.(193) Such coatings are made for colour only. The wear resistance is provided by a clear lacquer, baked epoxy types giving very good service. Electro-deposited gold less than 2.5 x 10^{-8} inch thick is translucent and the base metal colour will show through. Undercoatings are therefore necessary to achieve acceptable colours. A flash coating of green brass will give the gold a 24-carat colour, while a flash coating of copper gives a 14-carat colour. The thin decorative electroplates are being used on appliance and automotive trim, furniture, household and office equipment and ornaments, costume jewelry, and personal accessories.

On the industrial side, gold coatings are being used for an increasing number of applications, a few of which are listed below:

Oxidation Resistance

Non-porous gold-plated coatings can be used to prevent access of oxygen to the underlying base metal, but the same result can often be obtained with harder, cheaper coatings such as nickel and chromium. One application where chromium and gold complement each other is in the protection of molybdenum.(194)(195)

Chromium alone is unsuitable as the molybdenum diffuses through the chromium, oxidizes at the surface, and the oxide volatilizes. By using a composite plated coating of chromium-gold-chromium, a gold-chromium alloy through which molybdenum cannot diffuse is formed and the loss of basis metal is stopped. This type of coating can be used at temperatures of about 982°C (1800°F).

Electrical Contacts

The electrical contact surface of beryllium-copper spring components can be produced by plating gold on top of a silver-plated layer.(196) Plating with gold increases the conductivity of the components, especially at high frequencies when a skin conduction effect operates.

Reflectance

The high reflectance of gold in the infra-red region, coupled with a low emissivity, has resulted in an increasing number of gold plating applications in aircraft, missiles and space vehicles.

The original Project Vanguard satellite consisted of a magnesium alloy sphere with a composite plated surface intended to give temperature control of the satellite's interior. Gold plating formed one of the layers. In addition, gold plating of the instrumentation was widely used.(197)

Thermally decomposing "liquid golds" (potter's gold) are being widely used in rockets. The Chance Vought "Scout" research rocket has the interior of the fourth stage, a structure 20 ft long and 5 ft in diameter, gold plated by this method.(184) The gold coating deposited is very thin (about 2×10^{-5} inch) but is very adherent and continuous. In addition to the high reflectance and low spectral emissivity, it gives the structure high temperature oxidation resistance and good corrosion resistance.

At elevated temperatures, thin gold-plated coatings will diffuse rapidly into steel, nickel and many other metal substrates. A diffusion barrier is therefore necessary; a suitable one for many missiles is the National Bureau of Standards, A-418 ceramic coating.

Ultra high strength steel parts made from the H-11 type hot work tool steel for aircraft parts are given low emissivity gold coatings to reduce service temperatures.(198) Here again, thermally decomposing gold plating solutions are used. These have the advantage that no hydrogen is picked up by the steel in this plating process.

Semi-Conductors

An electroless (chemical) plating process, carried out in the presence of light, is used to make ohmic contacts on silicon diodes and to indicate the negative side of the junction in the diode.(199) The gold plates out first onto the negative side of the junction, but will only do this consistently if light (from an infra-red lamp) is falling on the diode surface while plating is taking place.

(E. 10) Mechanical Uses

Some of the present or potential uses of gold in mechanical applications are listed below:

Gaskets

Gold has been used as a gasket material(200) for process piping. On a well-designed gasket, a moderate bolting pressure of 25 ft-lb torque on a 1-inch pipe flange produces good seals for lines carrying liquids at 90 psig or less.

The galvanic action between gold and stainless steel results in accelerated corrosion of the steel in hot oxidizing solutions such as nitric acid. Gold gaskets should not, therefore, be used in such environments.

Gaskets made of gold have also been used for sealing pressure-resistant windows.(201)

Machining of Tungsten

Gold is used in the machining of large tungsten parts. The sintered ingots of tungsten produced by powder metallurgy processes are too porous to machine. Machining is accomplished by first infiltrating the porous ingot with gold, gold-copper alloy or copper.(202) The machining can then be carried out with carbide-tipped or high-speed tools in a normal manner. After machining the gold is recovered from the chips and machined part by volatilisation.

Thickness Gauges

Radioactive materials are used, in a variety of processes, for measuring and controlling the thickness of a product such as paper, plastic film or metal sheet during passage through rolls. In one such gauge recently described,(203) the radioisotope is mixed with gold powder, compacted, and then encased in a solid gold covering. The object of the gold as a dispersion medium and covering is one of safety. The method of construction gives a radiation source impervious to most chemical reagents, and if severe overheating takes place, the radioisotope remains trapped in the gold, even if the gold should melt.

Bearings

Gold alloys have been tested for use as sleeve bearings operating in corrosive environments such as 60 to 65% nitric acid.(204) Lubrication of the bearings was by the process solution itself. The ten gold alloys tested contained copper, silver, graphite, platinum, nickel or zinc as alloying elements, and only the gold-graphite alloys (49% and 10% graphite) showed rapid corrosion rates.

Gold and gold-copper and gold-copper-silver alloys have also been evaluated as bearings against various journals in chemical pumps.(205)

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