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PROPERTIES OF ^{60}Co AND COBALT METAL FUEL FORMS

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PROPERTIES OF ^{60}Co AND COBALT METAL FUEL FORMS

by

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PROPERTIES OF ^{60}Co AND COBALT METAL FUEL FORMS

This report is a compilation of properties of ^{60}Co and cobalt metal, and includes preliminary information on compatibility of cobalt with possible encapsulating materials. In general, data on properties are reported for unirradiated cobalt metal, and any data specific to radioactive cobalt are so indicated.

Data for high temperature fuel forms other than metallic cobalt (melting point - 1495°C) are limited at present and are not included here. Such data are expected to be added to later compilations as the information is acquired. However, cobalt metal is believed to be a suitable form for most near-term uses.

This report is a revision of a report issued in May 1966. The format has been changed somewhat to agree with recent recommendations of the Division of Isotopes Development, and some additional data have been added. It is being published concurrently with DP-1088, Savannah River Laboratory Isotopic Power and Heat Sources - Quarterly Progress Report, July-September 1966 (Reference 21), as the supplemental cobalt data sheets to the quarterly report. Future quarterly reports will report new data for the data sheet, and this report will be reviewed and reissued periodically.

RADIOISOTOPIC FUEL DATA

REF.*

I. ISOTOPE ^{60}Co HALF-LIFE 5.26 years — 1

FUEL FORM (as produced)

A. METAL:

1. Composition

a. Recommended composition for unirradiated cobalt (^{59}Co)**

Element	Composition
Co + Ni	99.9 wt % min
Ni	1500 ppm max
Mn	50 ppm max
S	5 ppm max
C	600 ppm max
O	100 ppm max
Al	50 ppm max
Cu	50 ppm max
Si	100 ppm max
Gd	10 ppm max
Cd	100 ppm max
Pb	50 ppm max

** Preliminary information indicates that this composition is suitable to assure satisfactory performance in the reactor and in ^{60}Co heat sources operating at high temperature.

b. Composition of radioactive cobalt — 2,3

(see Figure 1)

Radioactive cobalt is basically a mixture of ^{59}Co, ^{60}Co, ^{60}Ni, and ^{61}Ni. ^{59}Co, the naturally occurring isotope, is irradiated in a nuclear reactor to produce ^{60}Co, the radioactive isotope with a half-life of 5.26 years. The ^{60}Co decays by emitting beta particles and gamma rays to form ^{60}Ni. ^{61}Ni is formed from the neutron bombardment of ^{60}Ni and ^{60}Co (with a subsequent beta decay).

* See page 22.

The alloy composition of radioactive cobalt is shown in Figure 1 as a function of irradiation flux. The solid portions of the curves give the composition for practical irradiations (irradiation times less than those required to produce the maximum ^{60}Co content possible at the irradiation flux level). The composition at any time after irradiation lies on a line of constant ^{59}Co content. As an example of determining the composition of radioactive cobalt, material that had been irradiated at a flux of 10^{15} n/(cm^2)(sec) to a specific activivity of 600 curies/gram would consist of 52.6% ^{60}Co, 39.4% ^{59}Co, and 8.0% Ni. After this material decays to 300 curies/gram, its composition would be 26.3% ^{60}Co, 39.4% ^{59}Co, and 34.3% Ni.

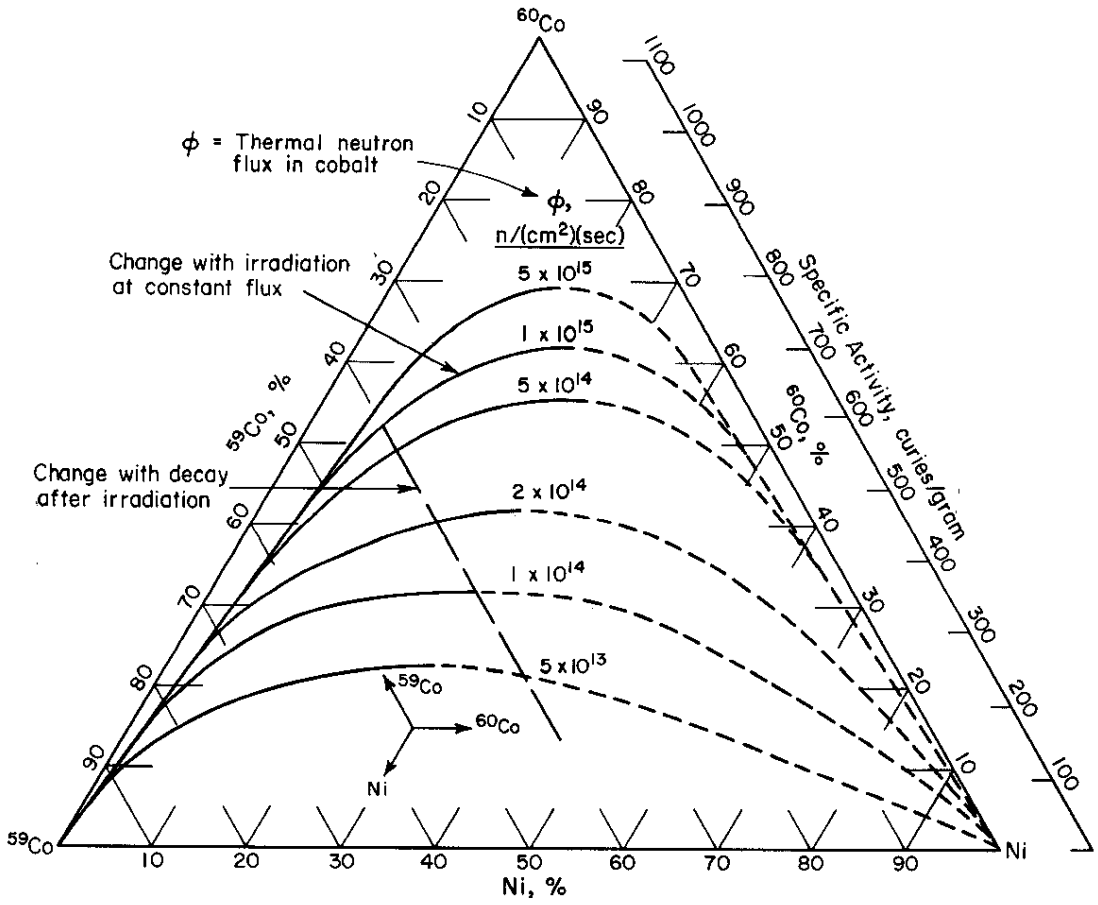


FIG. 1 COMPOSITION OF RADIOACTIVE COBALT

REF.
3,4

2. Specific Power

(see Figure 2)

curies/watt 64.2

	Typical Cases				Pure ^{60}Co
curies/g	100	200	400	700	1140
watts/g	1.6	3.1	6.2	11	17.7
watts/cm^3	14	27	55	96	156

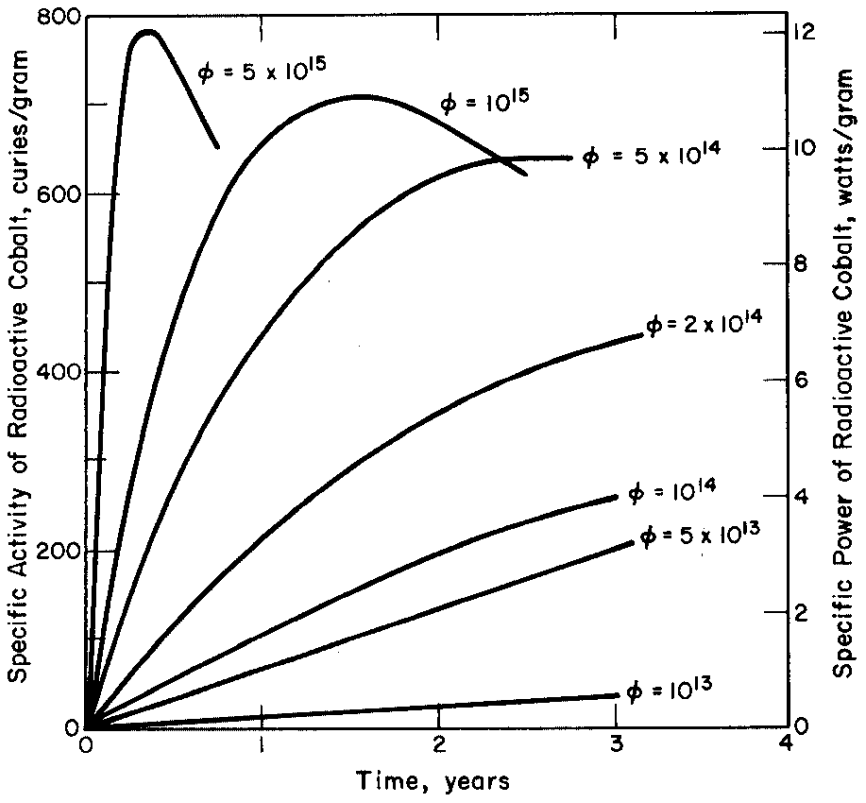


FIG. 2 SPECIFIC ACTIVITY OF RADIOACTIVE COBALT
(As a Function of Irradiation Conditions)
ϕ = thermal neutron flux in cobalt, n/(cm^2)(sec)

3,4

				REF.
3.	Radiation	Energy, Mev	Particles/Watt-Sec	5
	a. α	None		
	b. β^-	0.312 (max); 0.095 (avg)		
	c. γ	1.172	2.385×10^{12}	
		1.333	2.385×10^{12}	
	d. Bremsstrahlung	None		
	e. Neutrons	None		

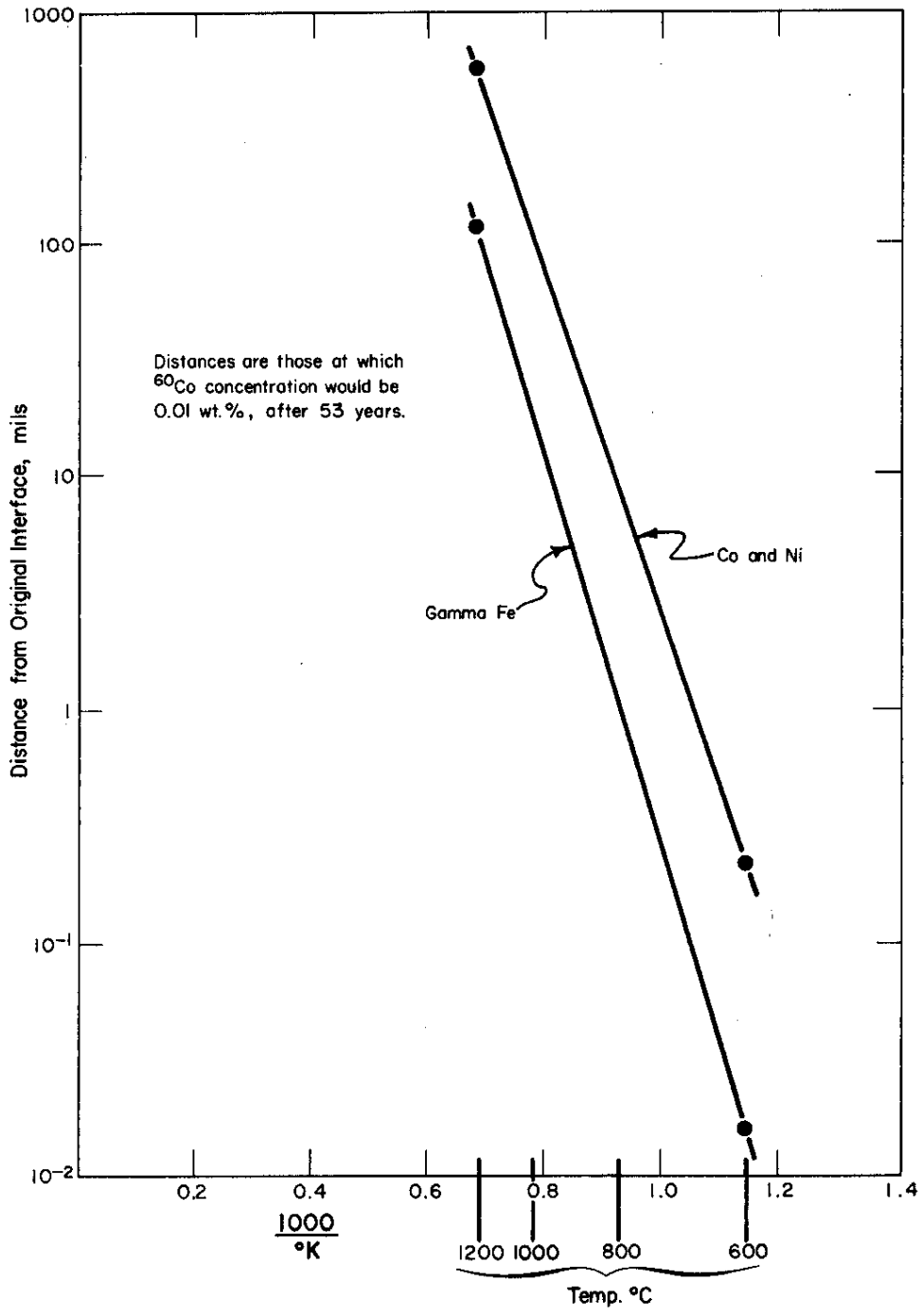
4. Critical Mass - Not applicable

5. Compatibility with Materials of Containment 6

The principal aspect of compatibility between cobalt and cladding is the interdiffusion at heat source temperatures. Of particular concern in diffusion are (1) penetration rate of ^{60}Co through the cladding, (2) formation of brittle and highly corrodable intermetallic compounds at the cobalt-cladding interface, and (3) changes in mechanical and physical properties of the cobalt or cladding.

The rate of ^{60}Co penetration has been estimated from reported ^{60}Co diffusion rates through various pure metals. Diffusion data for various temperatures were extrapolated to predict the distance from the original interface at which the ^{60}Co concentration would reach 0.01 wt % after 10 half-lives (53 years). The variation in ^{60}Co penetration with temperature is shown in Figure 3. These data indicate that stainless steels whose matrices are gamma iron, or Hastelloy* C and Inconel** 600 whose matrices are nickel, as well as cobalt itself can be used as cladding materials at temperatures in excess of 1000°C.

* Trademark of Haynes Stellite Co., Union Carbide Corporation.
** Trademark of International Nickel Company, Inc.



REF.
6

FIG. 3 PENETRATION OF ^{60}Co

REF.
6

To study formation of intermetallic compounds and the effects of cladding diffusion into cobalt, couples between ^{59}Co and 347 stainless steel, Hastelloy C, Inconel 600, tantalum, and tungsten were fabricated and annealed at 600, 1000, and 1200°C for up to 14 days. Metallographic examinations after the diffusion anneals at 600°C showed no intermetallic compounds at the interfaces. The hardnesses of both cobalt and cladding material immediately adjacent to the interface were not significantly changed. Intermetallic layers formed at the interfaces between cobalt and each of the materials (except tantalum) during anneals at 1000 and 1200°C for 7 days. Of these materials, Inconel 600 would be the best cladding material below 1200°C, because the rate of growth of its layer was slowest. Voids were also formed at the cobalt - 347 stainless steel, cobalt - Inconel 600, and the cobalt - Hastelloy C interfaces because diffusion into the cobalt was more rapid than diffusion from the cobalt. Although for long operating times there may be some reduction in heat transfer and in mechanical properties because of these voids, the reductions are not expected to be prohibitive.

No intermetallic layers were formed at the cobalt-tantalum interface during the anneal at 1000°C, but melting occurred at the interface during the anneal at 1200°C. This melting resulted from the formation of the eutectic mixture, which occurs at 30 wt % tantalum.

These results are for ground surfaces initially in intimate contact. The Savannah River Laboratory program also includes diffusion tests of actual capsule configurations with some nominal clearance between cobalt and cladding. Results of these tests will be included in future topical reports.

REF.

Note:

Little data are available on the properties of ^{60}Co. Properties of ^{58}Co are listed for sections I.A.6 through I.A.8 (except as noted), since its properties will be very similar to those of radioactive cobalt, as discussed in the reference. Density, hardness, and microstructure of cobalt that had decayed from 300 to 150 Ci/g were not significantly different from unirradiated cobalt. 3

6. Thermophysical Properties (^{58}Co)

a. Density

1. Solid 7

$8.85\ g/cm^3$ (hcp) at room temperature

$8.80\ g/cm^3$ (fcc) at room temperature

hcp = close-packed hexagonal structure (ϵ phase) $<417 \pm 7^{\circ}C$

fcc = face-centered cubic structure (α phase) $>417 \pm 7^{\circ}C$

The transition temperature will change with nickel content as indicated in the cobalt-nickel phase diagram of Figure 4.

2. Liquid 8

Density is the inverse of the specific volume v expressed by the following equation proposed by L. D. Lucas (1964):

$$v = 0.1304 + 20.9 \times 10^{-6}(T - 1766),$$

where T is in $^{\circ}K$.

Temperature, $^{\circ}C$	g/cm^3
1500	7.66
1550	7.60
1600	7.54
1650	7.48
1700	7.42
1750	7.36

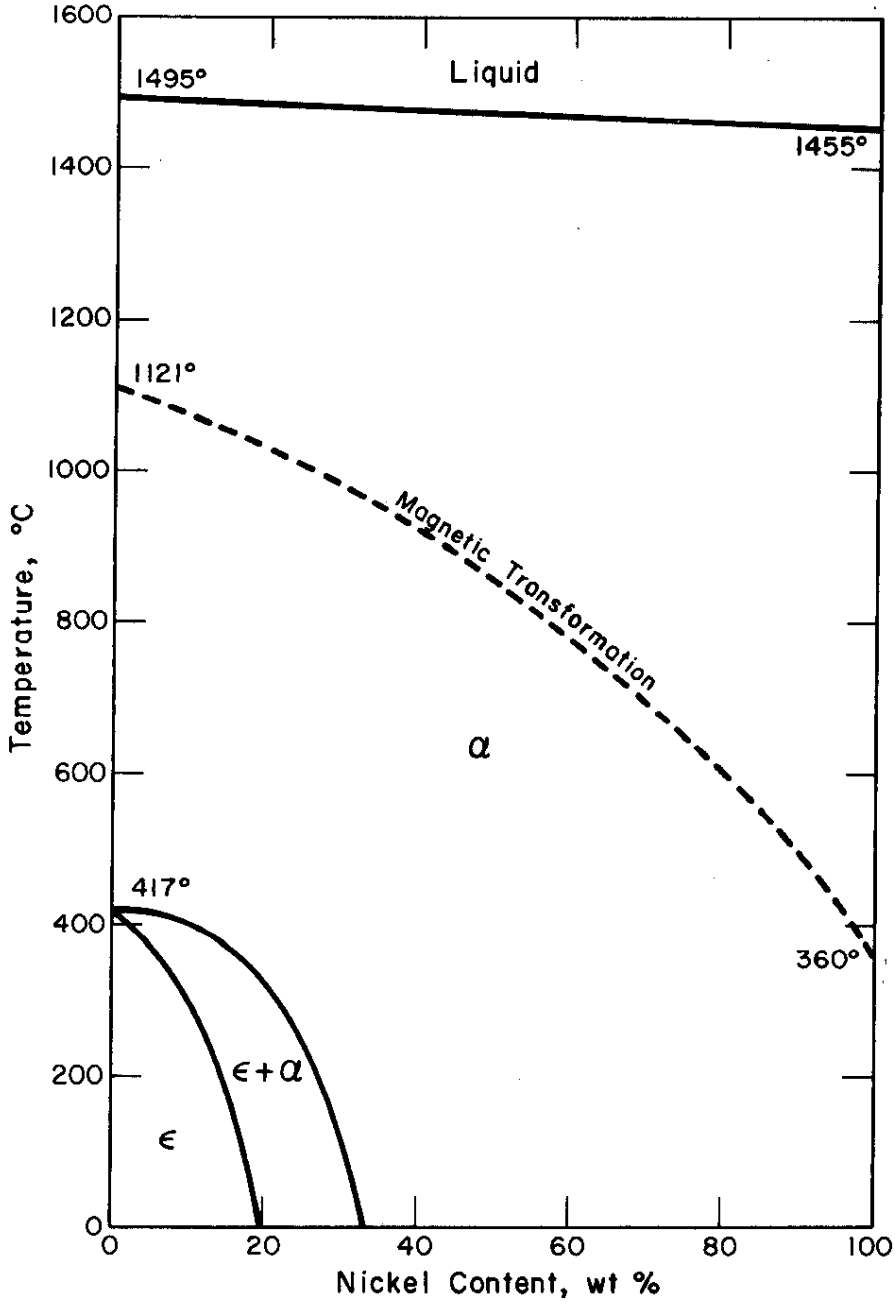


FIG. 4 COBALT-NICKEL PHASE DIAGRAM

REF. 7

REF.

b. Coefficient of linear thermal expansion; volumetric changes due to transformations

9

Temperature, °C	Coefficient of Linear Thermal Expansion, 10^{-6}/°C: Masumoto and Nara (1926)	Schulze (1927) (99.2% Co)	Fine and Ellis (1948) (99.9% Co)
20-100	12.55	12.5	-
100-200	13.57	13.6	14.2
200	-	-	14.2
200-300	14.37	14.4	14.2
300-400	15.4	15.1	14.8
400	-	-	15.7
450-500	-	14.0	-
600	-	-	16.0
750	-	-	16.8

	Volume Expansion (ΔV/V) on Transforming from ε(hcp) to α(fcc) Cobalt, %: Masumoto and Nara (1926)	Schulze (1927) (99.2% Co)	Fine and Ellis (1948) (99.9% Co)
~417	0.30	0.24	0.27-0.36

c. Specific heat and enthalpy

10

Temperature, °K	Specific Heat, cal/°K g-atom	Enthalpy $H_T^o - H_{298}^o$ (a), cal/g-atom
298	5.89	0
300	5.90	10
400	6.35	623
500	6.80	1280
600	7.17	1980
700	7.35	2710
800	7.65	3510
900	8.20	4305
1000	8.90	5160
1100	9.64	6090
1200	10.50	7090
1300	11.50	8190
1400	9.60	9520
1500	9.60	10,480
1600	9.60	11,440
1700	9.60	12,400
1800	8.30	16,950
1900	8.30	17,780
2000	8.30	18,610
2100	8.30	19,440
2200	8.30	20,270
2300	8.30	21,100
2400	8.30	21,930
2500	8.30	22,760
2600	8.30	23,590
2700	8.30	24,420
2800	8.30	25,250
2900	8.30	26,080
3000	8.30	26,910

(a) Reference enthalpy taken at 298°K.

REF.

d. Temperatures of phase transformations (see Figure 4 for cobalt-nickel phase diagram) — 11,7

417 ±7°C - The transformation from α to ε phase or ε to α phase is sluggish and typically occurs at 390°C on cooling or 430°C on heating.

1495°C - melting point

3100°C - boiling point

e. Latent heats of phase transformations — 9

1 cal/g ε-α phases

62 cal/g heat of fusion

1500 cal/g heat of vaporization

f. Vapor pressure — 7

Temperature, °C	Pressure, atm
1050	7×10^{-8}
1200	3×10^{-7}
1595	1×10^{-5}
2027	1×10^{-3}
2327	1×10^{-2}
3097	1

g. Thermal conductivity — 12

Temperature, °C	Conductivity, cal/(sec)(cm)(°C)	
50	0.22	
100	0.20	
150	0.19	
500	0.13	{calculated using
1000	0.09	Wiedemann-Franz Law}

REF.

h. Thermal diffusivity (α) - Calculated from previous data

$$\alpha = \frac{k}{\rho c}$$

where α = thermal diffusivity

k = thermal conductivity

ρ = density

c = specific heat

Temperature, °C	α, cm²/sec
50	0.242
100	0.213
150	0.197
500	0.117
1000	0.055

i. Viscosity 8

Temperature, °C	Viscosity, centipoises	
	Cavalier (1963)	Frohberg, Weber (1964)
1450 (supercooled)	4.46	
1495	4.18	
1500	4.14	5.21
1550	3.85	4.75
1600	3.61	4.36
1700	3.20	
1750	3.03	

j. Surface tension 8

Investigators	Temp., °C	Atmos.	Density, g/cm³	Surface Tension, dyn/cm
Kozakevitch, (1957)	1550	H_2	7.8	1886
Urbain (1961)	1550	H_2	7.6	1886
Allen (1963)	1500	Vacuum	7.67	1900
	1500	Vacuum		1855
	1500	Vacuum		1873

REF.

k. Total normal emissivity (ϵ_n) — 13

Temperature, °C	ϵ_n (surface unoxidized)
Room temp	0.03
500	0.13
1000	0.23

Total hemispherical emissivity ≈ 1.2 ϵ_n for most metals

l. Spectral emissivity (ϵ_λ, T) — 13,7

Wavelength, μ	Temperature, °C	ϵ_λ, T
0.65	Room temp	0.75(a)
0.65	1280	0.36(b)
0.65	1500	0.37(b) (liquid)
1.0	Room temp	0.32
2.0	"	0.28
3.0	"	0.23
4.0	"	0.19
5.0	"	0.15
7.0	"	0.07
9.0	"	0.04
10.0	"	0.03
12.0	"	0.03
14.0	"	0.03

(a) Value for cobalt oxide formed on smooth metal.
(b) Surface unoxidized

REF.

m. Crystallography 7

Variations in Lattice Parameters for 99.9% Cobalt

Temperature, °C	Cobalt (hcp) a, Å	Cobalt (hcp) c/a	Cobalt (fcc) a, Å
Room temp	2.507	1.623	3.544
295	2.532	1.630	3.581
420	2.541	1.631	3.587
625			3.597
843			3.610
1099			3.625
1121			3.637
1148			3.652
1187			3.655

hcp = close-packed hexagonal structure (ϵ phase)

fcc = face-centered cubic structure (α phase)

n. Solubility - Data to be added later

o. Diffusion rates 7

The temperature dependence of the diffusion of one material into another is described by an Arrhenius-type equation,

$$D = A\, e^{-Q/RT}$$

where D = diffusion coefficient, cm^2/sec

T = temperature, ^oK

A = diffusion constant, cm^2/sec

Q = activation energy, cal/g-mole

R = 1.987 cal/(g-mole)(^oK)

Values of these constants for the diffusion of cobalt in various metals are summarized below.

REF.

Diffusion of ^{60}Co in Various Materials[a]

14

Material	Temperature, °C	Diffusion Constant, cm^2/sec	Activation Energy, cal/g-mole
Al (1962)	360-630	1.1×10^{-6}	19,900
^{58}Co (1951)	1050-1250	0.367	67,000
" (1951)	1000-1250	0.032	61,900
" (1952)	1000-1300	0.2	62,000
" (1955)	1100-1405	0.83	67,700
" (1962)	772-1048	0.5	65,400
" (1962)	1192-1297	0.17	62,200
Cu (1958)	700-950	5.7	52,200
" (1958)	701-1077	1.93	54,100
Fe_α (1954)	700-790	0.2	54,000
" (1954)	700-850	0.4	54,000
" (1961)	800-905	64.4	64,600
" (1963)	690-905	118	68,300
Fe_γ (1954)	1050-1250	1.2×10^5	104,000
" (1955)	1100-1200	300	87,000
" (1961)	1138-1340	1.25	72,900
Fe_δ (1963)	1396-1502	5.5	61,200
Ni (1951)	900-1250	1.46	68,300
" (1962)	748-1192	0.75	64,700
Nb (1962)	1500-2100	0.74	70,500

(a) "No distinction has been made between the data as far as reliability is concerned ..." (Reference 14).

REF.

7. Mechanical Properties (^{59}Co)

a. Hardness

Type	Brinell Hardness No.	
Cast	124-130	7
Annealed	48	
Electrolytic	270-311	

Type	Temperature, °C	Vickers Hardness No.(a)	
Zone Refined	Room temp	253	15
	300	145	
	425	109	
	450	98	
	600	43	
	750	26	
	900	17	

(a) Held one hour at 500°C after hot rolling.

b. Compressive Strength

Form	Compressive Strength, psi	Compressive Yield Strength, psi	
Cast, unannealed	122,000	42,000	7
Annealed	117,200	56,100	

8. Chemical Properties (^{59}Co)

a. Heat and free energy of formation, entropy — REF. 10

Temperature, °K	Absolute Entropy, S^o_T, cal/°K g-atom	Free Energy Function, $-(F^o - H^o_{298})/T$, cal/°K g-atom
298	7.18	7.18
300	7.21	7.18
400	8.97	7.42
500	10.44	7.88
600	11.71	8.41
700	12.84	8.97
800	13.91	9.53
900	14.84	10.06
1000	15.74	10.58
1100	16.62	11.09
1200	17.50	11.60
1300	18.38	12.08
1400	19.36	12.56
1500	20.02	13.04
1600	20.64	13.49
1700	21.22	13.93
1800	23.80	14.39
1900	24.25	14.90
2000	24.68	15.38
2100	25.08	15.83
2200	25.47	16.26
2300	25.84	16.67
2400	26.19	17.06
2500	26.53	17.43
2600	26.85	17.78
2700	27.17	18.13
2800	27.47	18.46
2900	27.76	18.77
3000	28.04	19.07

b. Chemical reactions and reaction rates

REF.

Oxidation rate in air

7

Temperature, °C	Parabolic Scaling Constant $(Kp)^2$, $(mg/sq.\ cm)^2/hr$
400	0.0004
600	0.1
800	2.1
1000	70.0
1200	400.0

The oxidation rate is defined by the equation:

$$W/A = Kp\ t^{1/2}$$

where W is the grams of oxygen, A is the area, Kp is the square root of the parabolic scaling constant, and t is the oxidation time. Oxidation follows the parabolic rate law and is more rapid for hcp than for fcc form. Some evidence indicates that irradiated cobalt oxidizes more rapidly than unirradiated cobalt at room temperature.

Corrosion of cobalt in aqueous media at 25°C

16,17

Reagent	Corrosion Rate, mg/dm^2-day
5 vol % CH_3COOH	12.5
5 vol % NH_4OH	5.3
5 vol % H_2SO_4	56.8
10 vol % NaOH	5.6
1:1 HF	178.6
Conc HF	101.5
1:1 H_3PO_4	65.1
Conc H_3PO_4	7.4
5 vol % H_2NNH_2	7.8
H_2O	1.1

REF.

9. Biological Tolerances

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Maximum Permissible Concentrations of ^{60}Co for Occupational Exposure

Cobalt Form	Organ of Reference	Max Permissible Body Burden (Total Body), microcuries	Max Permissible Concentration, microcuries/cm³ For 40-hr Week Water	For 40-hr Week Air	For 168-hr Week Water	For 168-hr Week Air
Soluble	Gastrointestinal		10^{-3}	3×10^{-7}	5×10^{-4}	10^{-7}
	Total body	10	4×10^{-3}	4×10^{-7}	10^{-3}	10^{-7}
	Pancreas	70	0.02	2×10^{-6}	7×10^{-3}	6×10^{-7}
	Liver	90	0.03	10^{-6}	9×10^{-3}	5×10^{-7}
	Spleen	200	0.05	4×10^{-6}	0.02	2×10^{-6}
	Kidney	200	0.07	6×10^{-6}	0.03	2×10^{-6}
Insoluble	Lung		-	9×10^{-9}	-	3×10^{-8}
	Gastrointestinal		10^{-3}	2×10^{-7}	3×10^{-4}	6×10^{-8}

10. Shielding Data

19,20

Material	Density g/cm³	Total Mass Absorption Coeff.(a) cm²/g	Shielding to Attenuate(b) by a factor of 100 g/cm²	cm
Iron	7.6	0.053	126.4	16.65
Lead	11.4	0.058	97.6	8.56
Uranium	18.7	0.064	85.9	4.59
Tungsten	19.3	0.055	106.	5.5

(a) For average gamma energy of 1.25 Mev.
(b) For isotropic point source, using the relation

$$I/Io = 1/100 = B_r (E, \mu r)\, e^{-\mu r}$$

where B_r = dose buildup factor
μ = absorption coefficient
r = thickness of shield

Note:

Reference 5 gives a more thorough treatment of shielding requirements for cylindrical sources.

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