664104

DP-1051 (Rev. 2)

AEC RESEARCH AND DEVELOPMENT REPORT

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

DU PONT
REG. U. S. PAT. OFF.

Savannah River Laboratory

Aiken, South Carolina

Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.65

664104

DP-1051 (Rev. 2)

Special Distribution*

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

Approved by

S. Mirshak, Research Manager
Reactor Engineering Division

June 1968

E. I. DU PONT DE NEMOURS & COMPANY
SAVANNAH RIVER LABORATORY
AIKEN, S. C. 29801

CONTRACT AT(07-2)-1 WITH THE
UNITED STATES ATOMIC ENERGY COMMISSION

*same as C-92a distribution, Systems for Nuclear Auxiliary Power (SNAP)-Isotopic SNAP Program.

CONTENTS

LIST OF FIGURES

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

This report is a compilation of properties of ^{60}Co and cobalt metal, and includes 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. Cobalt-rhenium alloys and solid solutions of cobalt and magnesium oxides offer the possibility of higher melting point fuel forms with reasonable power density. However, development of these forms has been deferred because of the applicability of cobalt metal for most near-term uses.

This report supersedes DP-1051 (Rev. 1) in its entirety. Future quarterly reports will report new data, and this report will be reviewed and reissued periodically.

RADIOISOTOPIC FUEL DATA

Ref.

I. ISOTOPE ^{60}Co HALF-LIFE 5.24 years 1

FUEL FORM (as produced)

A. METAL:

1. Composition

a. Recommended composition of cobalt raw material*

Element	Recommended Content
Co + Ni	99.9 wt % min
Ni	1500 ppm (wt) max
Fe	1000
Cu	100
O	100
Si	100
Th	100
U	100
Al	50
Cd	50
Mn	50
Pb	50
S	50
Cr	20
Mo	20
V	20
W	20
P	10
B	5
Gd	5
Li	5

b. Composition of radioactive cobalt 2,3

Radioactive cobalt is basically a mixture of ^{59}Co, ^{60}Co, ^{60}Ni, and ^{61}Ni. Natural cobalt is 100% ^{59}Co and is irradiated in a nuclear reactor to produce ^{60}Co, the radioactive isotope with a half-life of 5.24 years. The ^{60}Co decays by emitting beta particles and gamma rays to form ^{60}Ni. Neutron bombardment of ^{60}Ni forms ^{61}Ni in only small amounts due to the small absorption cross section of ^{60}Ni. ^{61}Ni is also

* This composition can be obtained from the following commercial producers:

Sherritt Gordon Mines Limited
Metals for Electronics (Division of Chas. Pfizer & Co.)
African Metals Corporation

formed by the neutron bombardment and subsequent beta decay of ^{60}Co. The ^{61}Co formed by neutron bombardment has a half-life of 99 minutes, and essentially all of it is converted to ^{61}Ni within a day after irradiation is completed. Since the absorption cross section for ^{60}Co is much less than that for ^{59}Co, the amount of ^{61}Co and ^{61}Ni formed during irradiation is small except for extended or high flux irradiations.

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

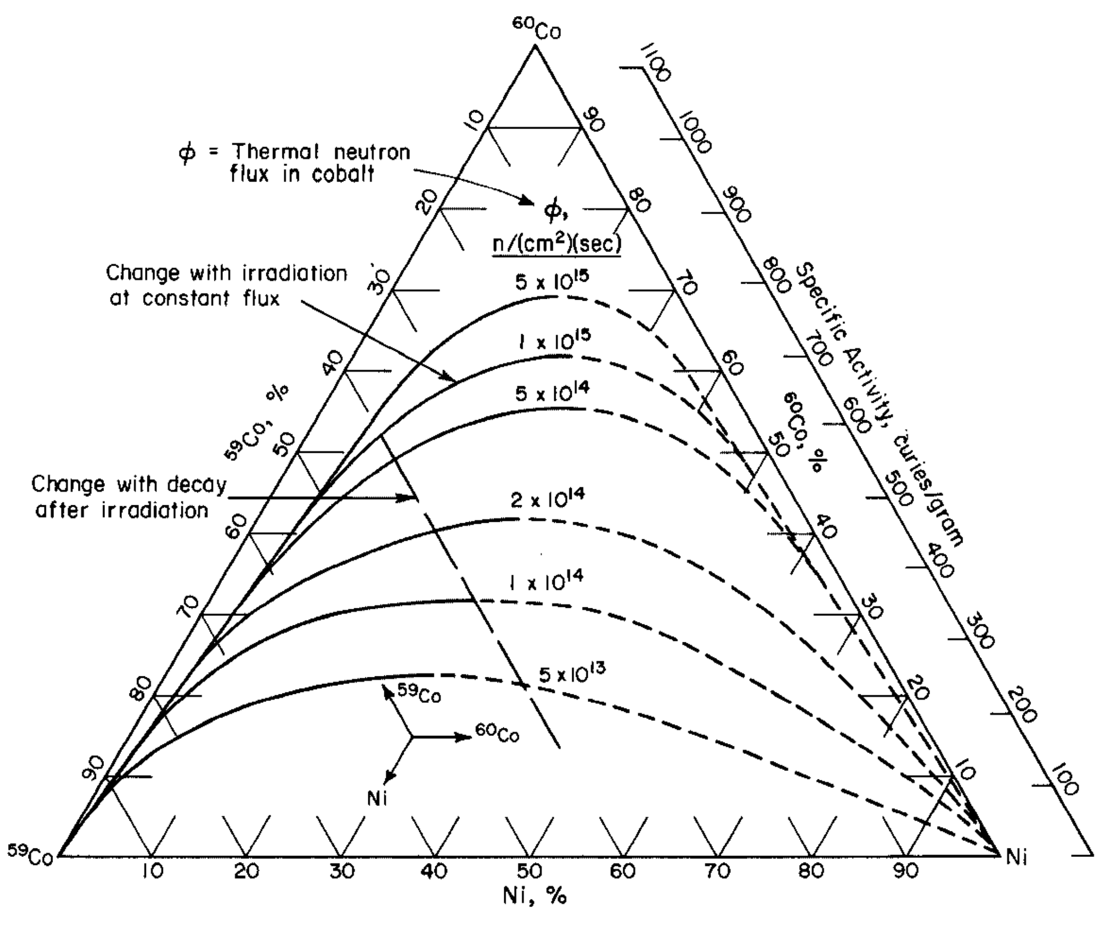

FIG. 1 COMPOSITION OF RADIOACTIVE COBALT

determining the composition of radioactive cobalt, material that had been irradiated at a flux of 10^{15} n/(cm^2)(sec) to a specific activity of 600 curies/grams would consist of 52.6% ^{60}Co, 39.4% ^{58}Co, and 8.0% Ni. After this material decays to 300 curies/gram, its composition would be 26.3% ^{60}Co, 39.4% ^{58}Co, and 34.3% Ni. Ref.

2. Specific Power 3,4

The basic activity to power conversion factor is 64.2 curies/watt. Both specific activity and specific power of radioactive cobalt are shown as a function of irradiation conditions in Figure 2. The curve of Figure 3 converts specific activity to convenient units of specific power.

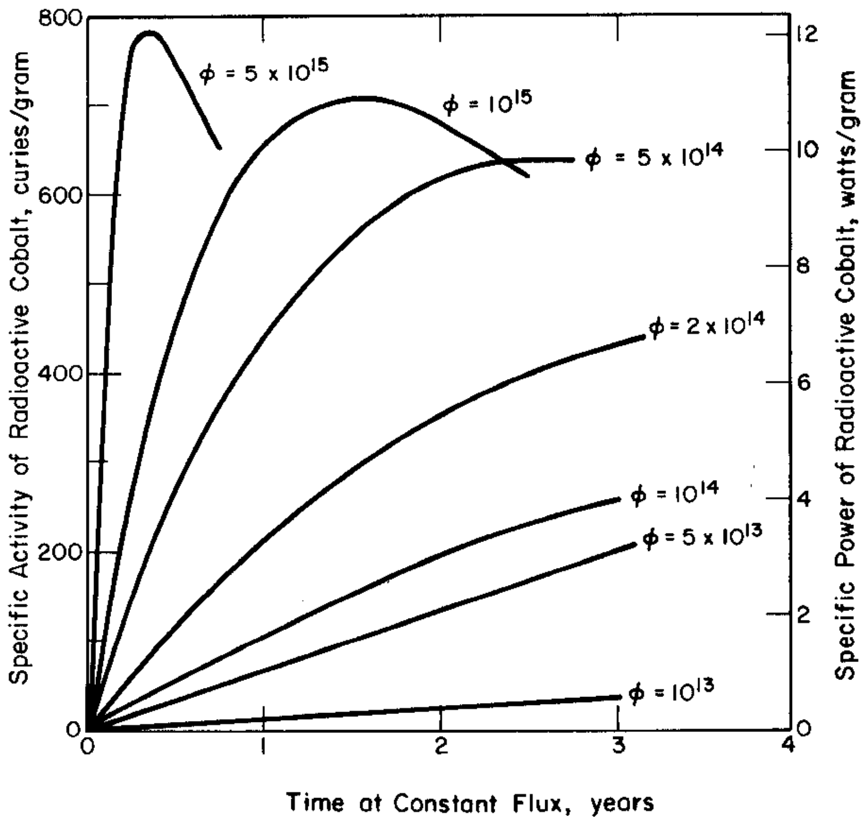

FIG. 2 SPECIFIC ACTIVITY OF RADIOACTIVE COBALT
(As a Function of Irradiation Conditions)
ϕ = thermal neutron flux in cobalt, n/(cm^2)(sec) 3,4

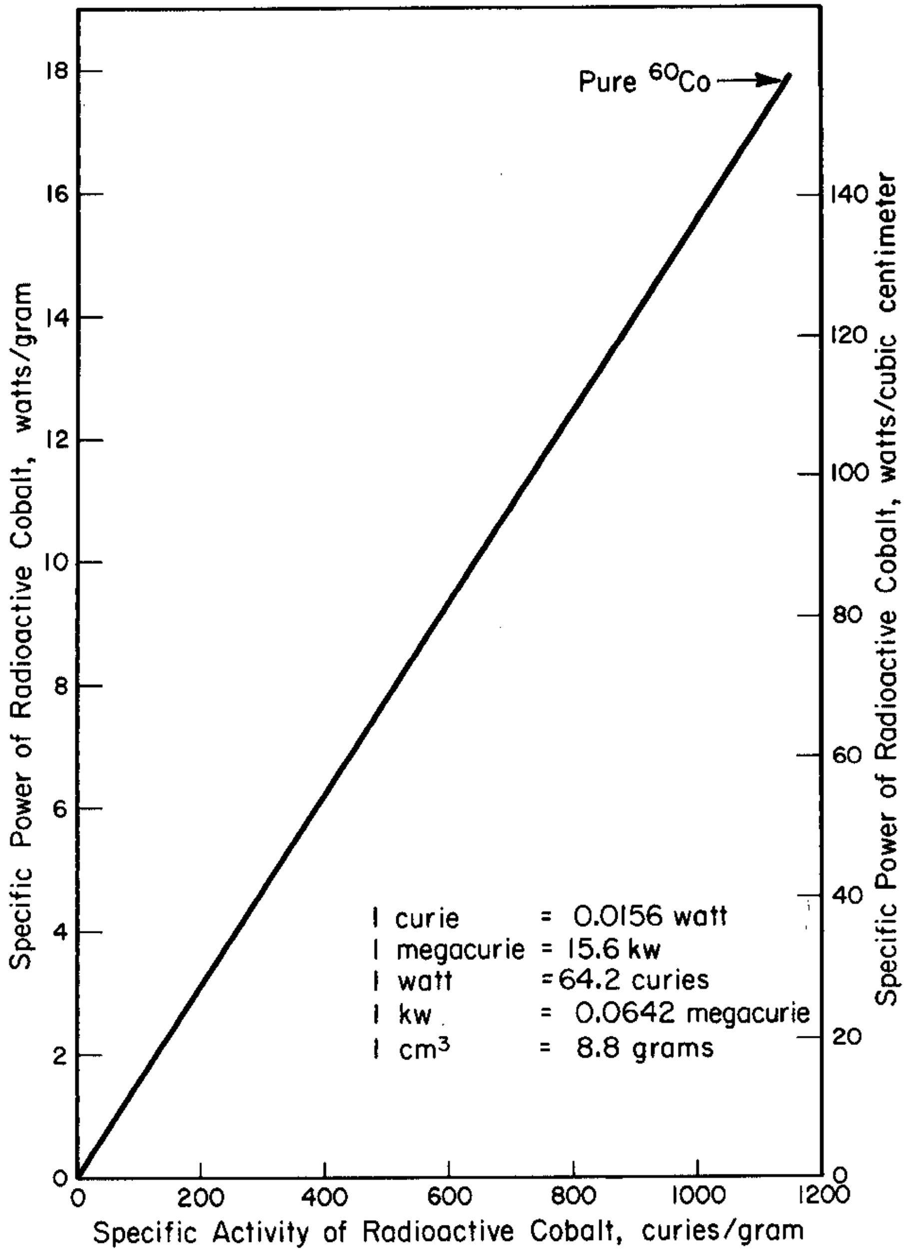

FIG. 3 CONVERSION OF ^{60}Co ACTIVITY TO POWER

3. Radiation 5

		Energy, Mev	Particles/Watt-Sec
a.	α	None	
b.	β^-	0.312 (max) 0.095 (avg)	
c.	γ	1.172 1.333	2.375×10^{12} 2.375×10^{12}
d.	Bremsstrahlung	None	
e.	Neutrons	None	

4. Critical Mass - not applicable

5. Compatibility with Materials of Encapsulation 6,19, 24,25

The principal aspect of compatibility between cobalt and cladding is interdiffusion at heat source temperatures. Of particular concern in diffusion are (1) penetration 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 diffusion of ^{60}Co into selected capsule materials has been calculated for various operating conditions, as shown in the table below. These calculations are based on radiotracer measurements of the coefficients of volume and grain boundary diffusion into the different materials during short-term tests (up to 100 hr). The analyses of the data from these tests and the extrapolations to longer times were made using the models reported by Suzuoka (Reference 25). These models include the contribution of grain boundary diffusion, which leads to deeper penetrations than when volume diffusion alone is considered. A ^{60}Co concentration of 1 ppm was selected as a reference limit since a concentration of this magnitude at the outer capsule surface could constitute a radiation hazard if the surface layers became corroded and the corrosion product were carried outside the biological shield by the heat transfer fluid.

Calculated Diffusion of ^{60}Co in Capsule Materials

Materials	Depth at Which ^{60}Co Concentration is 1 ppm, mils: Operation at 800°C, 1 yr	5 yr	Operation at 1000°C, 1 yr	5 yr
Hastelloy X	8	12	35	77
Haynes 25	12	18	37	67
Hastelloy C	12	18	45	76
Inconel 600	20	38	100	>100

Of nickel- and cobalt-based heat-resistant alloys, TD Nickel, Inconel 600, TD Nickel Chromium, Hastelloy C, and Haynes 25 have the highest degree of compatibility with cobalt (Figure 4). These results were calculated from measured widths of diffusion zones formed in multi-layered diffusion couples annealed for 168 hr at 800,

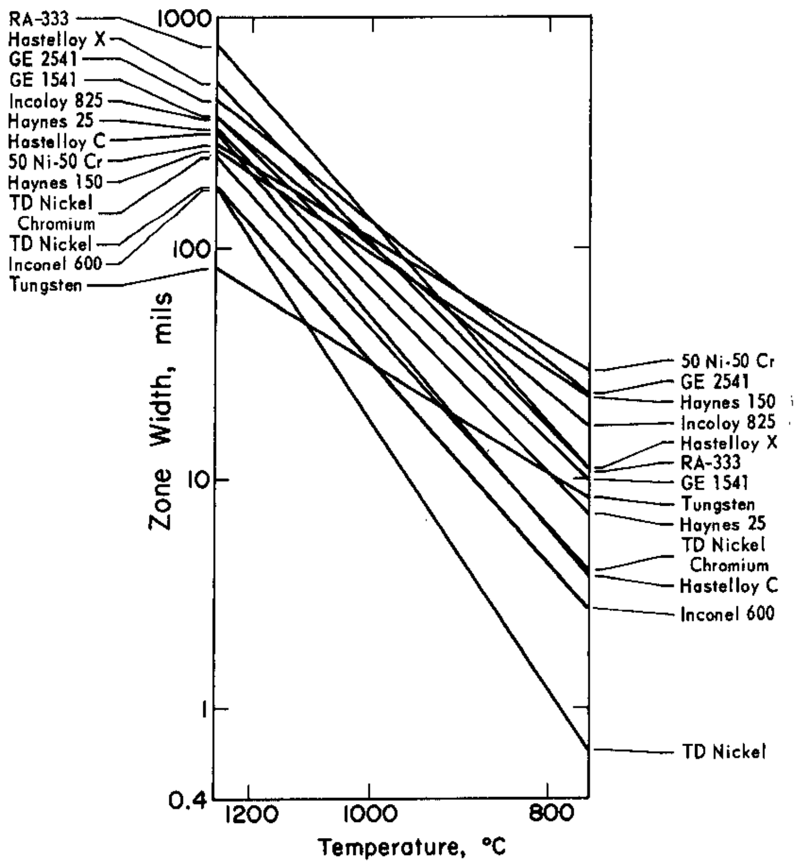

FIG. 4 CALCULATED DIFFUSION ZONE WIDTHS AFTER ONE HALF-LIFE OF ^{60}Co
(Based on 168 hr anneal)

1000, and 1200°C, as shown in the table below. Data from tests for up to 5000 hr at 850 and 1000°C on selected alloys are in general agreement with the short-term tests. Metallographic examinations and electron microprobe analyses show that the diffusion zone formed between each of these alloys and cobalt is a region of solid solution terminating in a band of voids. These voids are less prevalent in the cobalt-based alloys and non-existent in pure nickel. The compatibility of pure nickel depends on the rate of diffusion of ^{60}Co atoms at the expected operating temperature.

Of the refractory metals, rhenium should be the most compatible since it forms a continuous series of solid solutions with cobalt; the diffusion rate of ^{60}Co atoms is the governing factor as with pure nickel. The compatibility of tungsten has been measured as shown in Figure 4; the diffusion zone consists of two intermetallic compounds. Tantalum and molybdenum would be incompatible above 1200 and 1300°C, respectively, due to eutectic melting.

Microhardness measurements indicate that the strength of the diffusion zone in nickel- and cobalt-based alloys will be no more than 25% lower than the unreacted cladding material.

Widths of Diffusion Zones After 168 Hours, mils

Alloy	Annealing Temperature, °C 800	1000	1200
Ni-based Alloys			
TD Nickel[a]	0.06	1.1	7.0
"Inconel"[b] 600	0.6	2.5	7.3
TD Nickel Chromium[a]	0.4	3.8	10.5
"Hastelloy"[c] C	0.4	3.2	16.4
"RA-333"[d]	0.8	7.8	31.0
"Hastelloy"[c] X	0.8	5.8	22.5
"Incoloy"[b] 825	1.0	6.4	19.0
50Ni-50Cr	2.0	6.5	17.0
Co-based Alloys			
"Haynes"[c] 25	0.5	3.8	14.4
"Haynes"[c] 150	1.6	5.7	13.4
Fe-based Alloys			
GE 1541[e]	0.6	4.8	16.2
GE 2541[e]	1.7	7.7	20.5
Others			
Tungsten	-	2.0	4.2

(a) Product of Fansteel Metallurgical Corp.
(b) Trademark of International Nickel Co.
(c) Trademark of Union Carbide Corp.
(d) Trademark of Rolled Alloys, Inc.
(e) Product of General Electric Co.

6. Thermophysical Properties (^{59}Co) * Ref.

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 ±7°C

fcc = face-centered cubic structure (α phase) >417 ±7°C

The transition temperature will change with nickel content as indicated in the cobalt-nickel phase diagram of Figure 5.

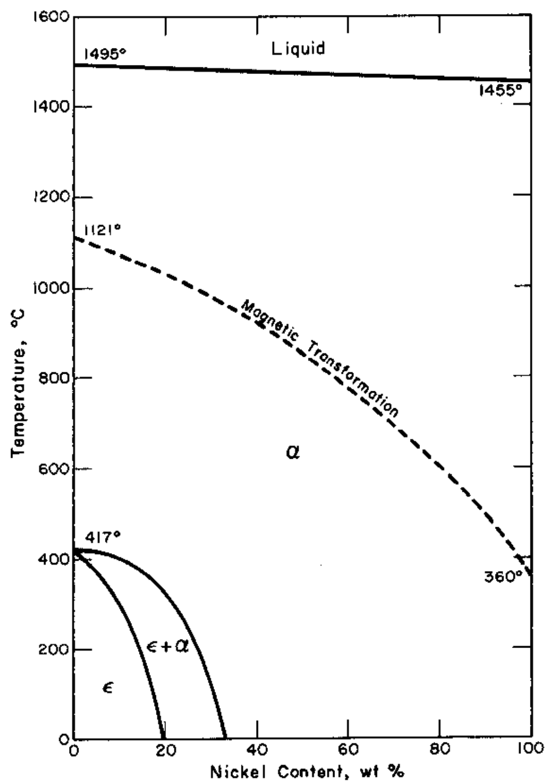

FIG. 5 COBALT-NICKEL PHASE DIAGRAM 7

*Little data are available on the properties of ^{60}Co. Properties of ^{59}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. 3

The effect of irradiation on density was negligible. Values for various samples irradiated up to 700 Ci/g ranged between 8.77 and 8.93 g/cm³. | Ref. 23

2) Liquid | 8

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

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

where T is in °K.

Temperature, °C	g/cm³
1500	7.66
1550	7.60
1600	7.54
1650	7.48
1700	7.42
1750	7.36

b. Coefficient of linear thermal expansion; volumetric changes due to transformations | 9,20

Temp, °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)	Manufacturer's Data (99.9% Co)
20-100	12.55	12.5	-	12.6
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	-	-
20-500	-	-	-	13.5
600	-	-	16.0	-
750	-	-	16.8	-
20-700	-	-	-	13.9

Temp, °C	Volume Expansion ($\Delta V/V$) 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

Ref.

c. Specific heat and enthalpy 10

Temperature, °K	Specific Heat, cal/°K g-atom	Enthalpy $H^o_T - H^o_{298}$ (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.

d. Temperatures of phase transformations (see Figure 5 for cobalt-nickel phase diagram) 11,7

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

1495°C - melting point

3100°C - boiling point

	Ref.
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 — Ref. 7

Temperature, °C	Pressure, atm
1050	7×10^{-9}
1200	3×10^{-7}
1595	1×10^{-5}
2027	1×10^{-3}
2327	1×10^{-2}
3097	1

g. Thermal conductivity — Ref. 12,20

Temperature, °C	Conductivity, cal/(sec)(cm)(°C)	
50	0.22	
70	0.23	(Manufacturer's data)
100	0.20	
150	0.19	
500	0.13	calculated using Wiedemann-Franz Law
1000	0.09	calculated using Wiedemann-Franz Law

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	0.24
100	0.21
150	0.20
500	0.12
1000	0.055

Ref.

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/cm^3	Surface Tension, dyn/cm
Kozakevitch, Urbain (1957)	1550	H_2	7.8	1886
(1961)	1550	H_2	7.6	1886
Allen (1963)	1500	Vacuum	7.67	1900
	1500	Vacuum		1855
	1500	Vacuum		1873

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) | Ref. 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

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 | 22

Soluble in acids, insoluble in cold and hot water. See section 8.b. for rates of corrosion in aqueous media.

o. Diffusion rates

The temperature dependence of the diffusion of one material into another is described by an Arrhenius-type equation, 7

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

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. 14

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

Material	Temperature, ^oC	Diffusion Constant, cm^2/sec	Activation Energy, cal/g-mole
Pure Metals			
Al (1962)	360-630	1.1×10^{-6}	19,900
^{59}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
" (1968)	800-1200	0.45	61,400
Nb (1962)	1500-2100	0.74	70,500
Co-based Alloys			
Haynes 25 (1968)	800-1200	0.035	58,700
Ni-based Alloys			
Inconel 600	800-1200	0.40	62,600
Hastelloy C	800-1200	1.4×10^{-3}	51,000

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

7. Mechanical Properties (^{59}Co)

Ref.

a. Hardness

Type	Brinell Hardness No.	Rockwell 45 T Hardness No.	Ref.
Cast	124-130	-	7,20
Annealed	48	-	
Electrolytic	270-311	-	
Strip	-	50-70	

Type	Temperature, °C	Vickers Hardness No.[(a)]	Ref.
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.

Hardness increases sharply with small amount of irradiation; small additional increases are related to increase in Ni content from radioactive decay (see Figure 6). 23

b. Compressive Strength, Room Temperature 7

Form	Compressive Strength, psi	Compressive Yield Strength, psi
Cast, unannealed	122,000	43,000
Annealed	117,200	56,100

c. Tensile Strength 20

1. Room Temperature

Form	Tensile Strength, psi	Tensile Yield Strength, psi
Strip, unannealed	110,000-125,000	45,000-50,000

2. Elevated Temperature Effects

(See Figure 7)

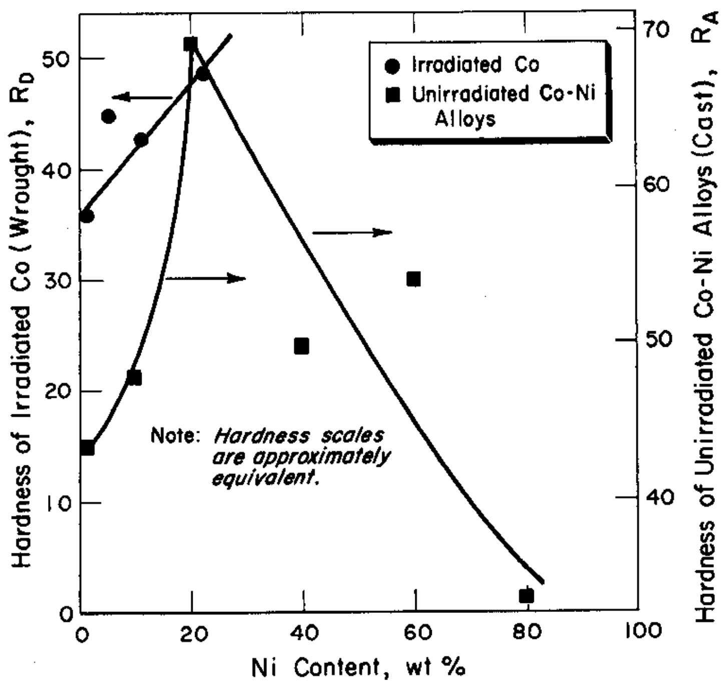

FIG. 6 HARDNESS OF Co-Ni ALLOYS

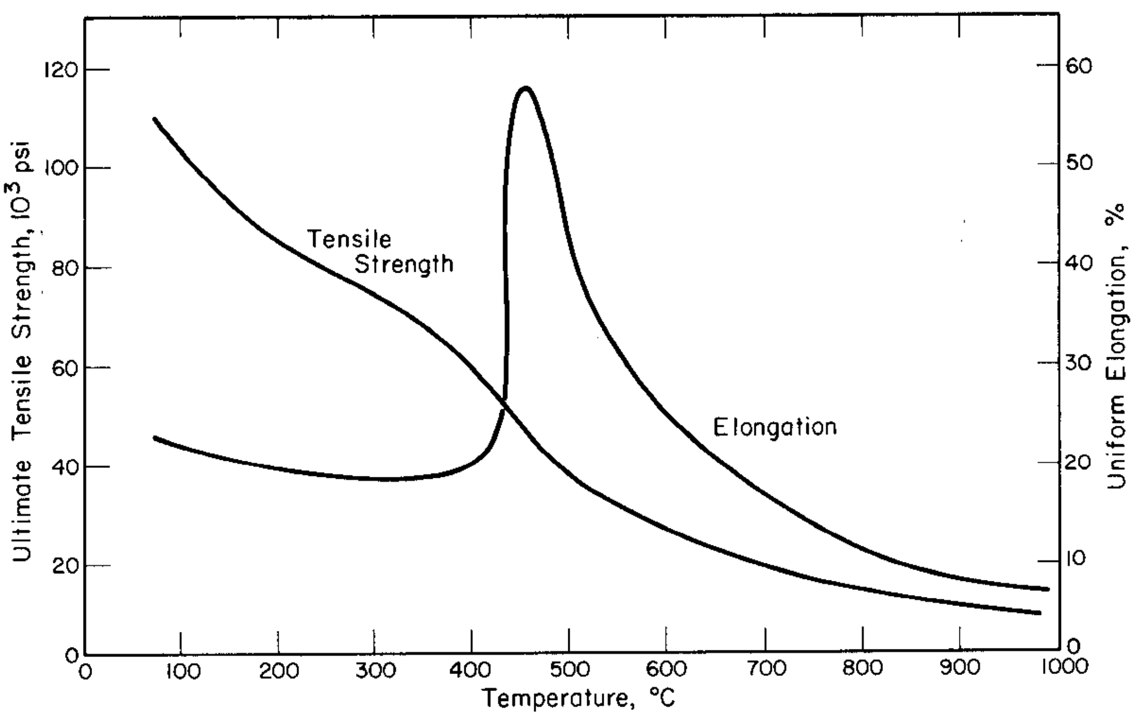

FIG. 7 ELEVATED TEMPERATURE PROPERTIES OF ANNEALED COBALT STRIP

8. Chemical Properties (^{59}Co)

Ref.

a. Heat and free energy of formation, entropy 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

The oxidation rate in air, shown in Figure 8, is defined by the equation: 7

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

where W is the grams of oxygen, A is the area, K_p 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.

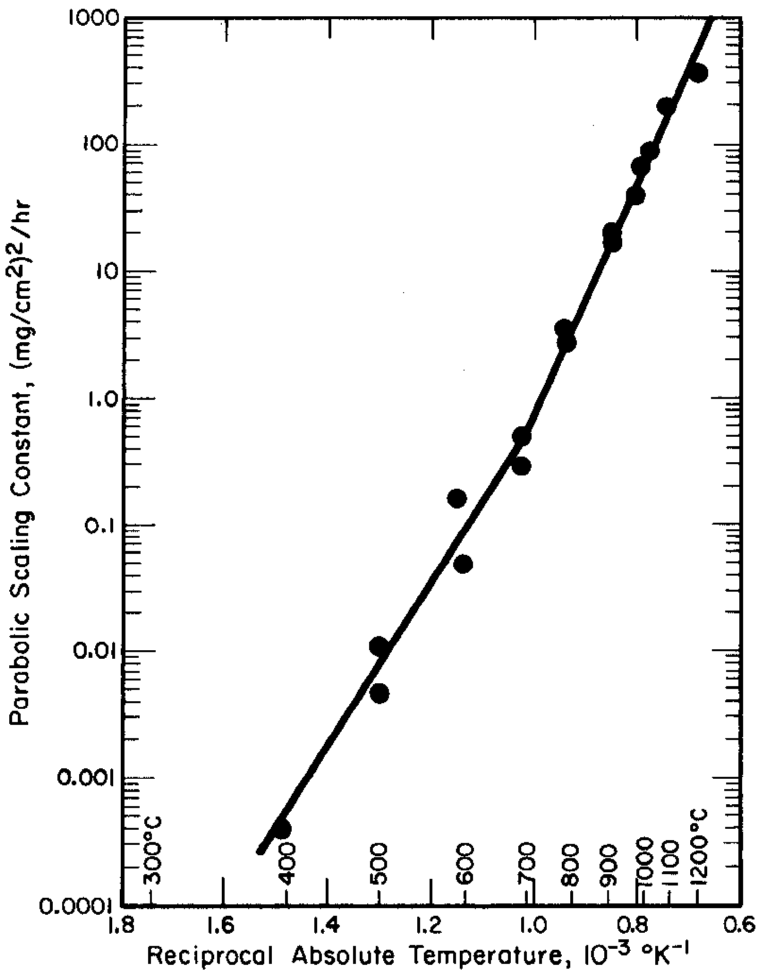

FIG. 8 ARRHENIUS PLOT OF REACTION RATE FOR COBALT HEATED IN AIR FOR 1 TO 2 HOURS

Corrosion of cobalt in aqueous media at 25°C | Ref. 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 18

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

Cobalt Form	Organ of Reference	Max Permissible Body Burden (Total Body), microcuries	Max Permissible Concentration, microcuries/cm^3 For 40-hr Week Water	Air	For 168-hr Week Water	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^{-9}
	Gastrointestinal		10^{-3}	2×10^{-7}	3×10^{-4}	6×10^{-8}

21

Cobalt Form	Critical Organ	Max Permissible Intake in 8 hr, μc for dose of: .3 Rem in 1 week
Soluble	Liver	3.7×10^2
Insoluble	Lungs	4.7

10. Shielding Data 5

Figure 9 shows gamma dose rates from unshielded 200 Ci/g ^{60}Co source. Figures 10 through 15 show dose rates from 75 and 200 Ci/g ^{60}Co shielded by iron, lead, or uranium.

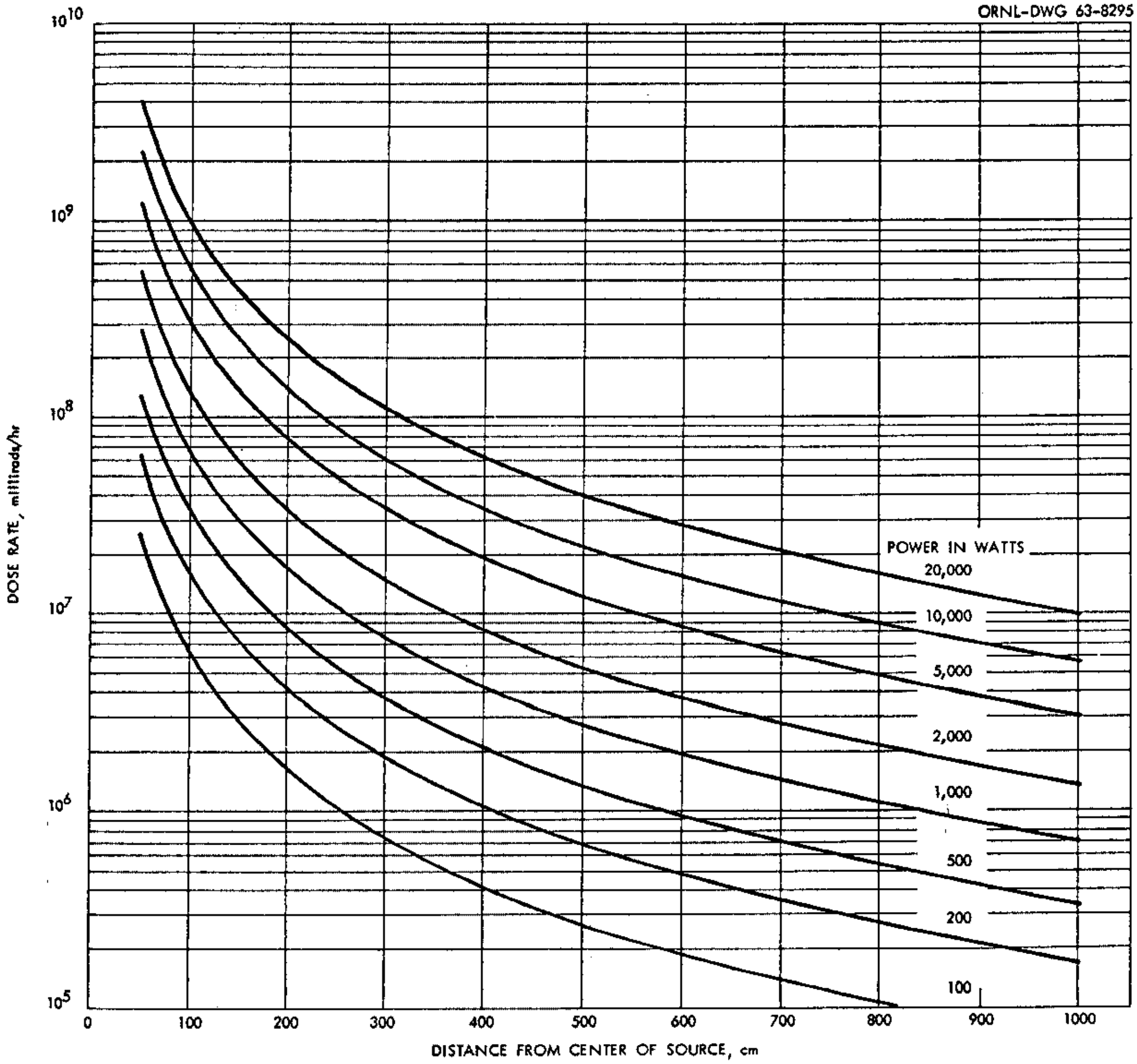

FIG. 9 GAMMA DOSE RATES FROM UNSHIELDED ISOTOPIC POWER SOURCES OF ^{60}Co
Specific activity of source = 200 curies per gram of cobalt

UNCLASSIFIED
ORNL-DWG 63-8453

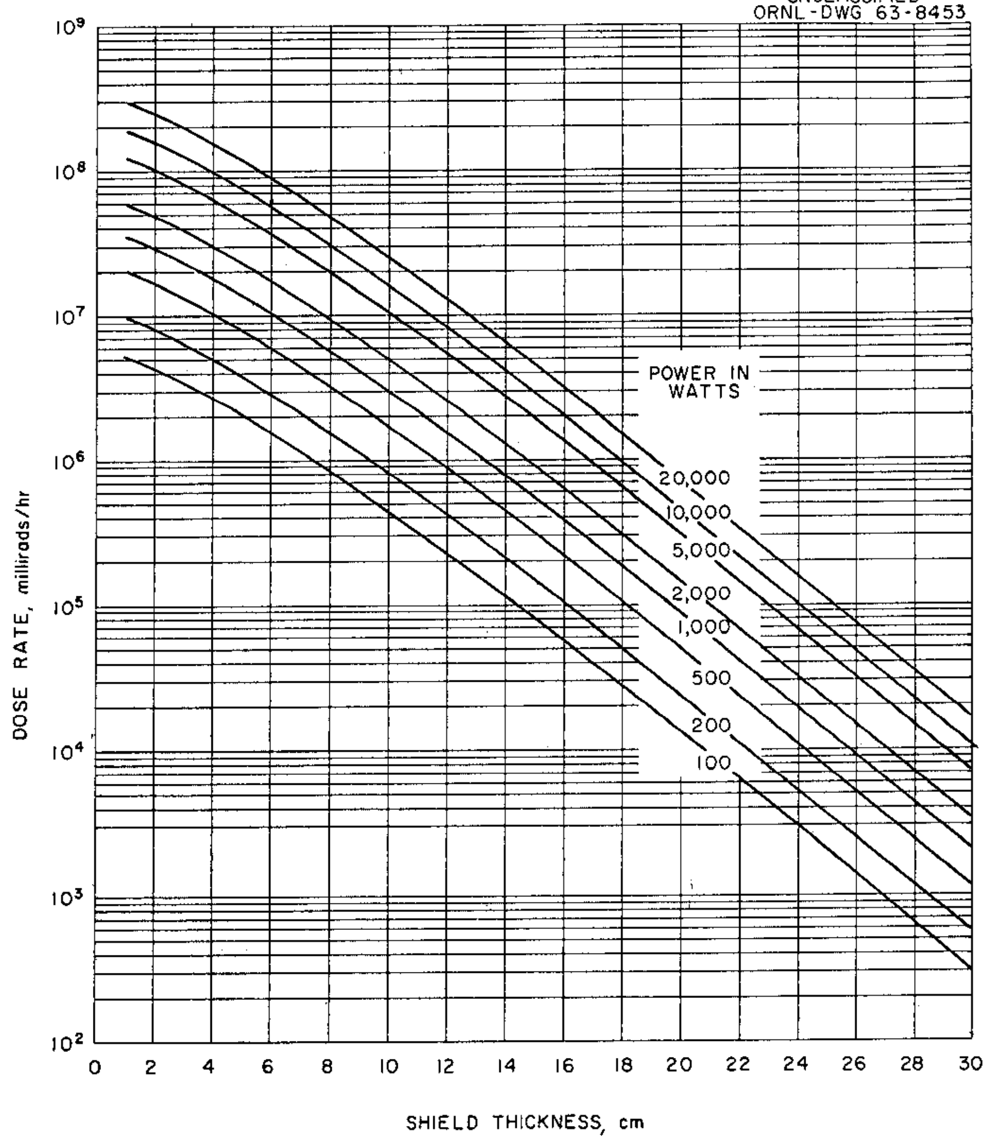

FIG. 10 GAMMA DOSE RATES FROM IRON-SHIELDED ISOTOPIC POWER SOURCES OF ^{60}Co
Center of source to dose point separation distance = 100 cm
Specific activity of source = 75 curies per gram of cobalt

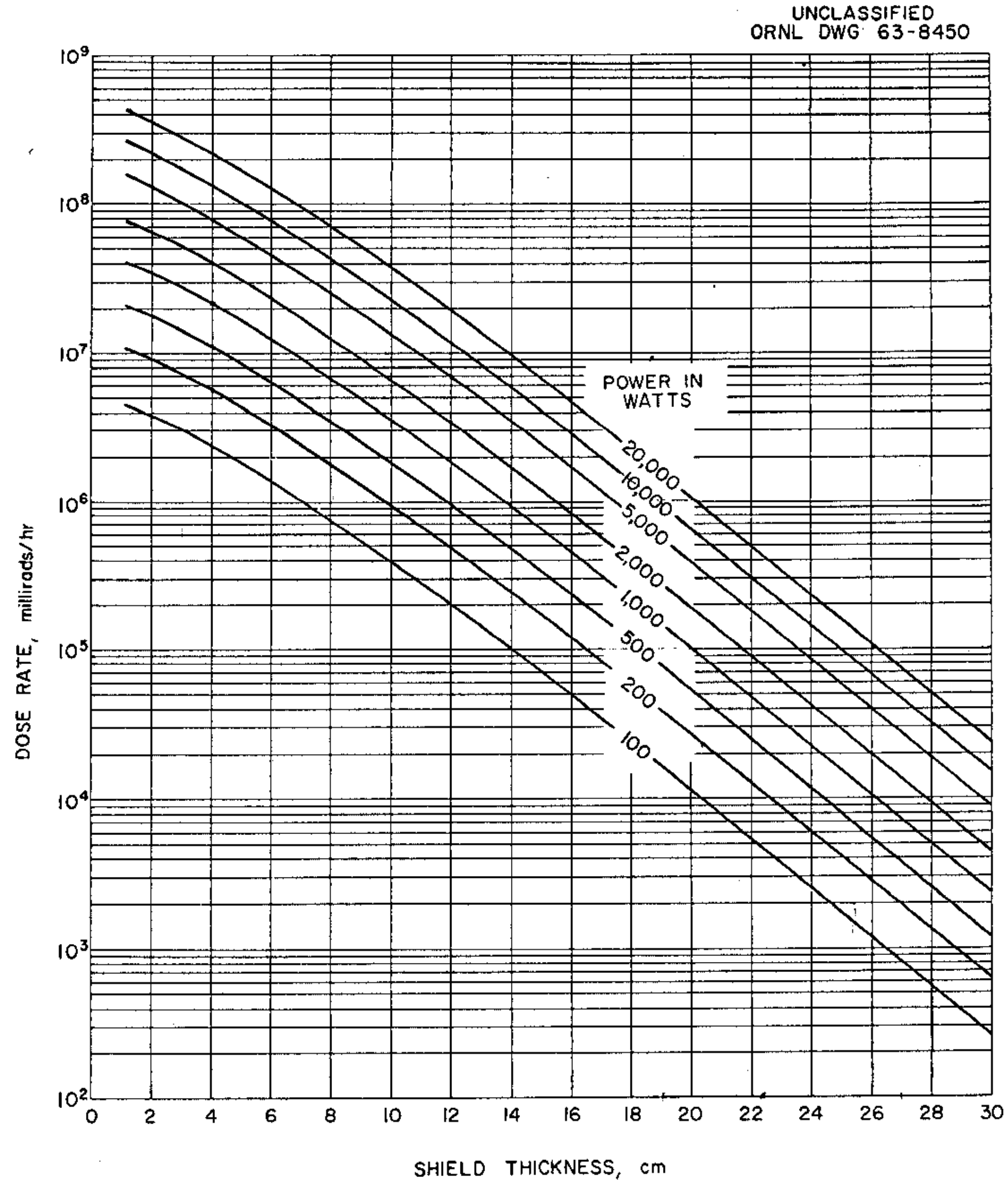

FIG. 11 GAMMA DOSE RATES FROM IRON-SHIELDED ISOTOPIC POWER SOURCES OF ^{60}Co
Center of source to dose point separation distance = 100 cm
Specific activity of source = 200 curies per gram of cobalt

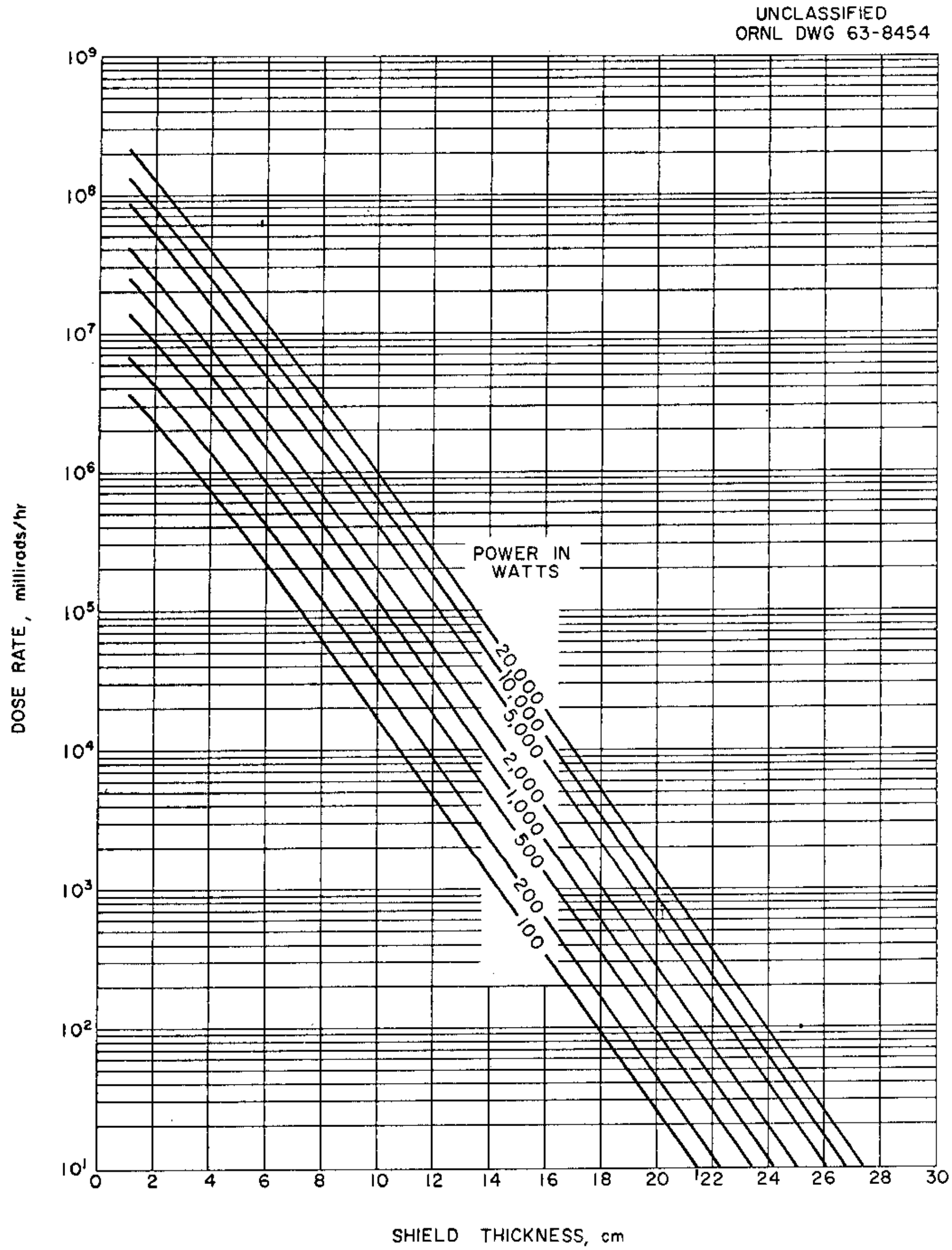

FIG. 12 GAMMA DOSE RATES FROM LEAD-SHIELDED ISOTOPIC POWER SOURCES OF ^{60}Co
Center of source to dose point separation distance = 100 cm
Specific activity of source = 75 curies per gram of cobalt

UNCLASSIFIED
ORNL DWG 63-8451

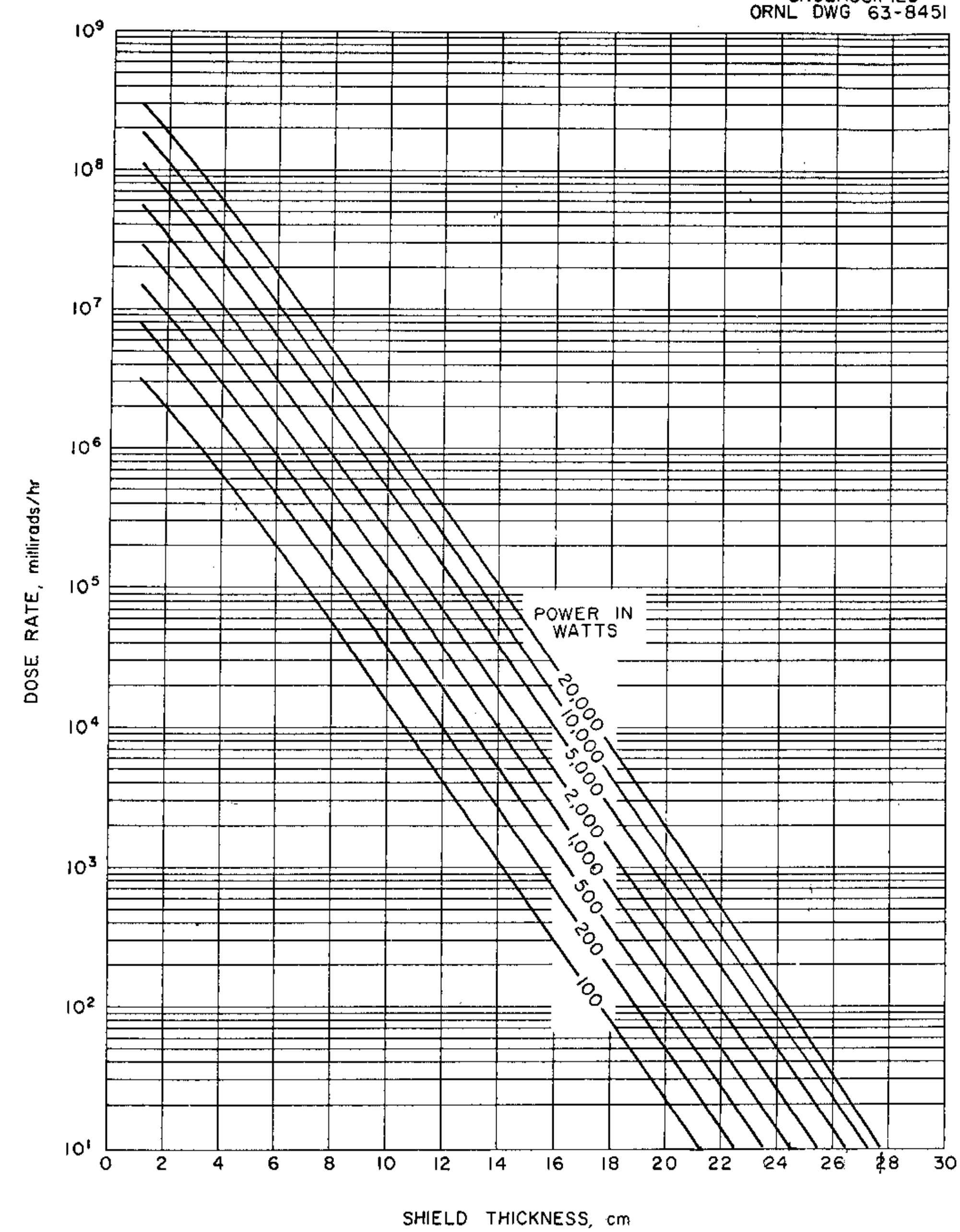

FIG. 13 GAMMA DOSE RATES FROM LEAD-SHIELDED ISOTOPIC POWER SOURCES OF ^{60}Co
Center of source to dose point separation distance = 100 cm
Specific activity of source = 200 curies per gram of cobalt

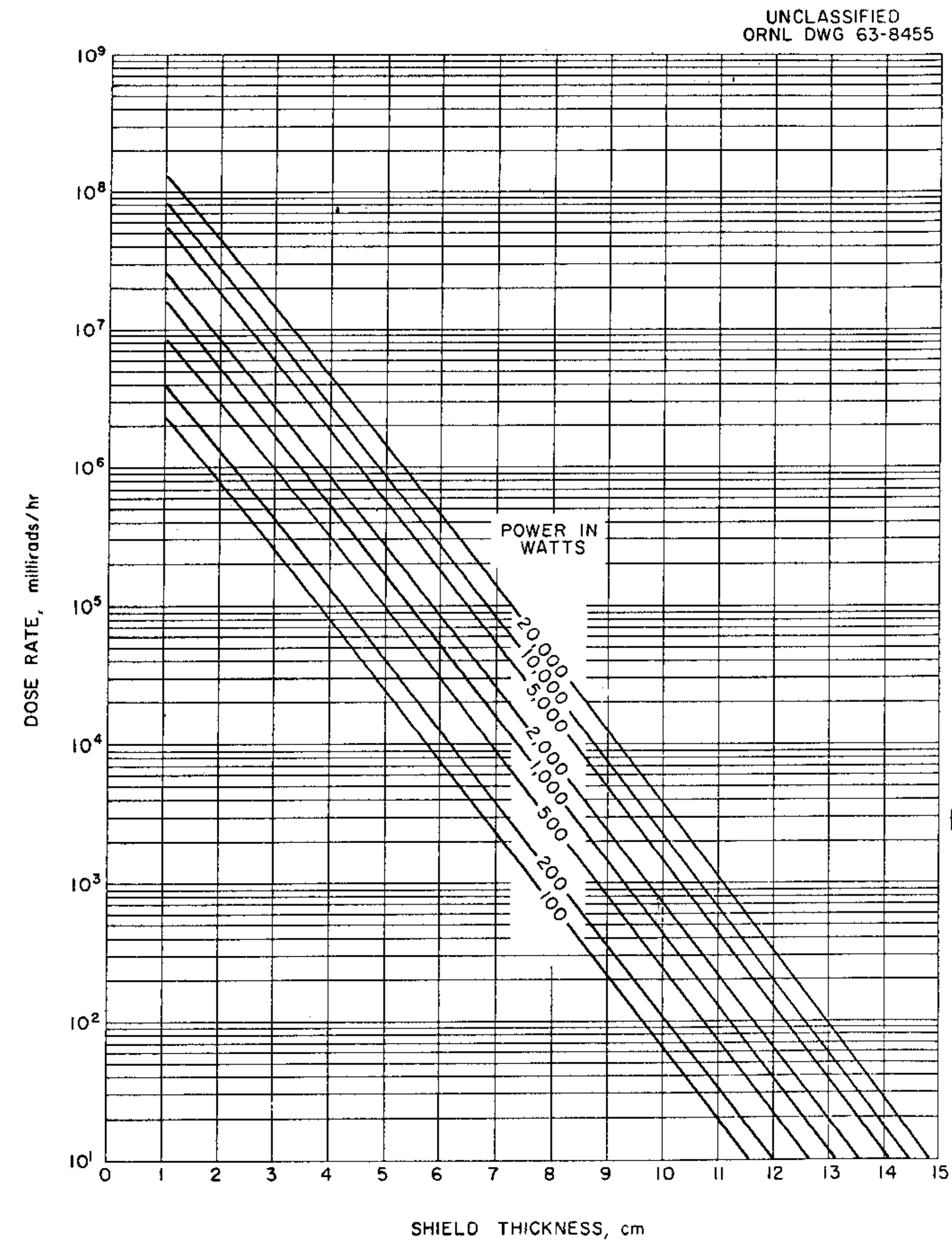

FIG. 14 GAMMA DOSE RATES FROM URANIUM-SHIELDED ISOTOPIC POWER SOURCES OF ^{60}Co
Center of source to dose point separation distance = 100 cm
Specific activity of source = 75 curies per gram of cobalt

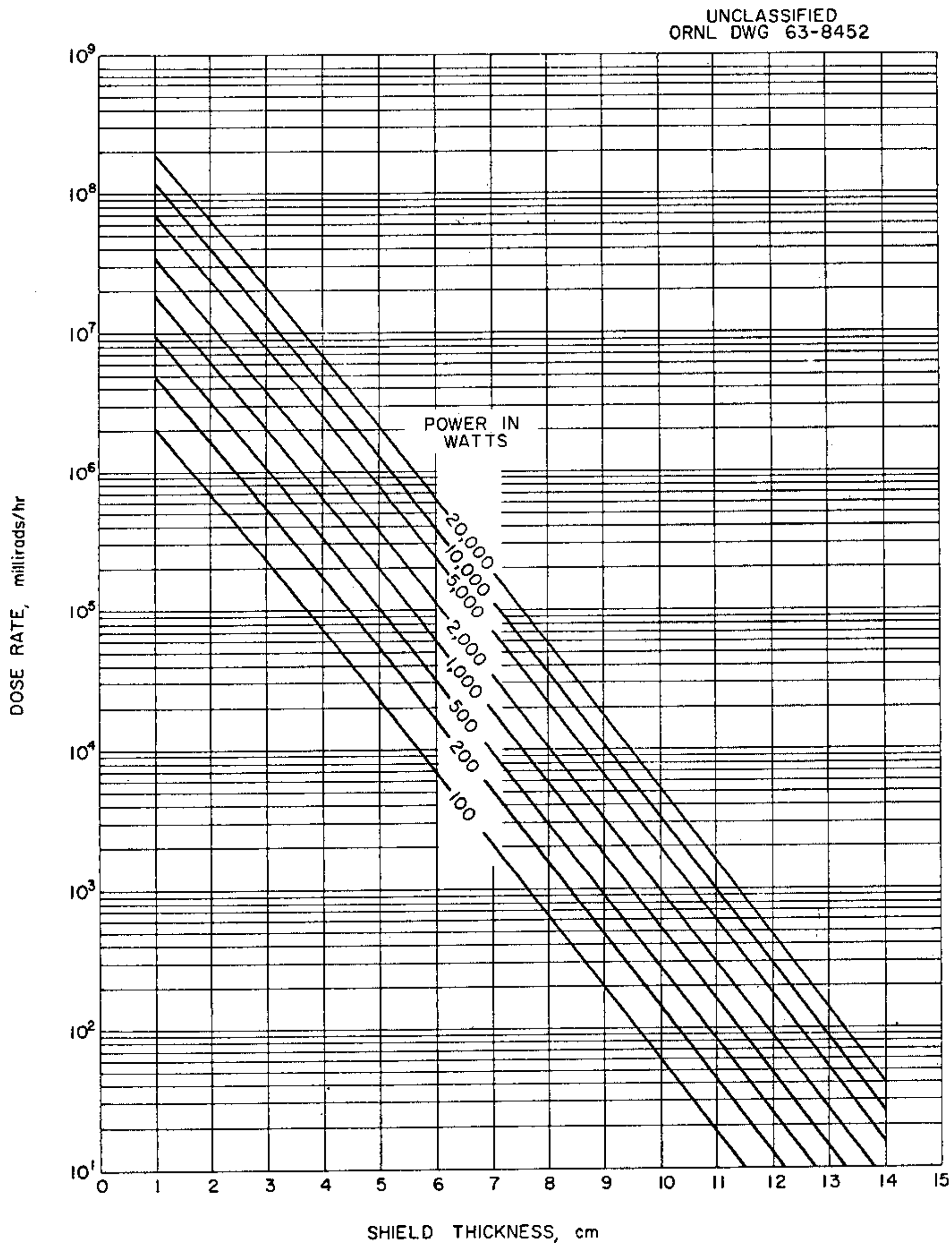

FIG. 15 GAMMA DOSE RATES FROM URANIUM-SHIELDED ISOTOPIC POWER SOURCES OF ^{60}Co
Center of source to dose point separation distance = 100 cm
Specific activity of source = 200 curies per gram of cobalt

II. REFERENCES

1. D. T. Goldman. Chart of Nuclides. Ninth Edition, Copyright 1966 by General Electric Company, Schenectady, N. Y.

2. D. Strominger, J. M. Hollander, and G. T. Seaborg. "Table of Isotopes." Rev. Modern Phys. 30, 585-904, 1958.

3. J. W. Joseph, et al. Radioactive Cobalt for Heat Sources. USAEC Report DP-1012, E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, S. C. (1965).

4. H. F. Allen. "Cobalt-60 Production at Savannah River." Nuclear News 7, No. 6, 21, 1964. Paper presented at Process Radiation Meeting sponsored by Washington Section of the American Nuclear Society, Washington, D. C. (May 13, 1964).

5. E. D. Arnold. Handbook of Shielding Requirements and Radiation Characteristics of Isotopic Power Sources for Terrestrial, Marine, and Space Applications. USAEC Report ORNL-3576, Oak Ridge National Laboratory, Tenn. (1964).

6. F. D. King and C. L. Angerman. "Large Scale Cobalt-60 Heat Sources." Large Scale Production and Applications of Radio-isotopes. (Proceedings of the American Nuclear Society, National Topical Meeting, March 21-23, 1966, Augusta, Georgia.) USAEC Report DP-1066, Vol. II, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1966).

7. Cobalt Monograph. Centre d'Information du Cobalt (prepared in collaboration with the staff of Battelle Memorial Institute) Brussels, Belgium (1960).

8. H. Winterhager and J. Krüger. "Pure Cobalt and Its Properties." Cobalt, No. 30, 27-38 (1966).

9. Rare Metals Handbook. C. A. Hampel (editor). Reinhold Publishing Corp., New York (1954).

10. D. R. Stull and G. C. Sinke. Thermodynamic Properties of the Elements. American Chemical Society, Washington, D. C. (1956).

11. J. B. Hess and C. S. Barrett. "Transformation in Cobalt-Nickel Alloys." Trans. AIME 194, 645-647 (1952).

12. R. W. Powell. "Some Preliminary Measurements of the Thermal Conductivity and Electrical Resistivity of Cobalt." Cobalt, No. 24, 145-150 (1964).

13. B. H. Billings, et al. (editors). American Institute of Physics Handbook. McGraw-Hill Book Co., Inc., New York (1963).

14. J. Askill. A Bibliography on Tracer Diffusion in Metals. USAEC Report ORNL-3795, Oak Ridge National Laboratory, Tenn. (November and May 1965) Parts I and II.

15. F. R. Morral. "High-Purity Cobalt ... Its Properties." J. of Metals 10, No. 10, 662-664 (1958).

16. R. S. Young. "Corrosion Resistance of Cobalt." Corrosion Tech. 4, 396 (1957).

17. R. S. Young. "Resistance of Cobalt to Certain Solutions." Corrosion Tech. 6, No. 3, 89 (1959).

18. "Report of ICRP Committee II on Permissible Dose for Internal Radiation (1959), with Bibliography for Biological Mathematical and Physical Data." K. Z. Morgan, W. S. Snyder, and J. A. Auxier (editors). Health Physics 3, 380 pp. (June 1960).

19. C. P. Ross, et al. Development of ^{60}Co Capsules for Heat Sources. USAEC Report DP-1096, E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, South Carolina (1967).

20. R. W. Fraser, D. J. I. Evans, and V. N. Mackiw. "The Production and Properties of Ductile Cobalt Strip." Cobalt No. 23, 72-81 (1964).

21. K. Z. Morgan, W. S. Snyder, and M. R. Ford. "Maximum Permissible Concentration of Radioisotopes in Air and Water for Short Period Exposure." Proc. U. N. Intern. Conf. Peaceful Uses Atomic Energy, 1st, Geneva, 13, 139-158 (1955).

22. Handbook of Chemistry and Physics. 47th Edition. R. C. Weast (editor-in-chief). The Chemical Rubber Co., Cleveland, Ohio (1966).

23. C. L. Angerman. "Effects of Irradiation on the Properties of Cobalt." Paper presented at 1967 Annual Meeting of the American Nuclear Society, San Diego, California, June 11-15, 1967.

24. C. L. Angerman, F. D. R. King, J. P. Faraci, and A. E. Symonds. "^{60}Co Heat-Source Encapsulation." Nuclear Applications 4, No. 2, 88 (1968).

25. T. Suzuoka. "Exact Solutions of Two Ideal Cases in Grain Boundary Diffusion Problem and the Application to Sectioning Method." J. Phys. Soc. Japan 19, 839 (1964).

Quarterly Progress Reports Issued Include:

DP-1088
DP-1094
DP-1105-I
DP-1120-I
DP-1129-I
DP-1143-I
DP-1155-I

SA McNeight

EXTERNAL RELEASE OF TECHNICAL INFORMATION

Description of Material   No. DP-1051 (Rev. 2)   Date 7/2/68

Title: Properties of ^{60}Co and Cobalt Metal Fuel Forms

Author:

Type of Material

- [ ] Classified DP Report
- [x] Unclassified DP Report
- [ ] Classified Letter
- [ ] Unclassified Letter
- [ ] Classified Paper
- [ ] Unclassified Paper
- [ ] Classified Abstract or Summary
- [ ] Unclassified Abstract or Summary

Technical Content

Approved by S. Mirshak   Date: 7/3/68

Classification

Approved by S. Mirshak   Date: 7/3/68

Approved by S. W. O'Rear   Date: 7/2/68

Authority:

Topic 3.3.1 CG-UF-2

Topic 1004 SROO Classification Guide

Category if DP Report

Approved by S. W. O'Rear   Date: 7/2/68

Final Du Pont Release

Approved by Coordinating Organization Director   Date: 7/24/68

Released by:

J. A. Koch: 7/6/68