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**National Low-Level Waste
Management Program
Radionuclide Report Series**

Volume 12: Cobalt-60

*National Low-Level Waste
Management Program*

June 1995

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National Low-Level Waste Management Program Radionuclide Report Series

Volume 12: Cobalt-60

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Published June 1995

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**Prepared for the
U.S. Department of Energy
Assistant Secretary for Environmental Management
Under DOE Idaho Operations Office
Contract DE-AC07-94ID13223**

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ABSTRACT

This report, Volume 12 of the National Low-Level Waste Management Program Radionuclide Report Series, discusses the radiological and chemical characteristics of cobalt-60 (^{60}Co). This report also includes discussions about waste types and forms in which ^{60}Co can be found and ^{60}Co behavior in the environment and in the human body.

FOREWORD

The purpose of the National Low-Level Waste Management Program Radionuclide Report Series is to provide information to state representatives and developers of low-level radioactive waste disposal facilities about the radiological, chemical, and physical characteristics of selected radionuclides and their behavior in the low-level radioactive waste disposal facility environment. Extensive surveys of available literature provided information used to produce this series of reports and an introductory report.

The National Low-Level Waste Management Program Radionuclide Report Series previously addressed the radionuclides technetium-99, carbon-14, iodine-129, tritium, cesium-137, strontium-90, nickel-59, plutonium-241, nickel-63, and niobium-94. These radionuclides contribute significantly to the dose estimated during a performance assessment analysis.

This report is Volume 12 of the series. It outlines the basic radiological and chemical characteristics of cobalt-60, waste types and forms that contain it, and its behavior in environmental media such as soils, plants, groundwater, air, animals, and the human body. Additional reports will be generated for other radionuclides.

CONTENTS

ABSTRACT	iii
FOREWORD	v
INTRODUCTION	12-1
RADIOLOGICAL CHARACTERISTICS	12-2
CHEMICAL AND PHYSICAL CHARACTERISTICS	12-6
COBALT-60 PRODUCTION	12-8
WASTE TYPES AND FORMS THAT CONTAIN COBALT-60	12-11
Nuclear Reactors	12-11
Medical, Academic Institutions, and Commercial Waste	12-11
BEHAVIOR OF COBALT-60 IN THE ENVIRONMENT	12-13
Cobalt in Soils	12-13
Cobalt in Groundwater	12-16
Cobalt in Plants	12-18
Cobalt in Air	12-20
BEHAVIOR OF COBALT-60 IN THE HUMAN BODY AND IN ANIMALS	12-21
Behavior of Cobalt-60 in Animals	12-21
Behavior of Cobalt-60 in Humans	12-22
CONCLUSIONS	12-26
REFERENCES	12-28
BIBLIOGRAPHY	12-33

FIGURES

1. Fission product yield curve for thermal fission of ^{235}U	12-8
2. Buildup of some important activation products in a pressurized water reactor as a function of reactor operation	12-9

TABLES

1. Comparison of the estimated maximum ranges for a 94 keV average energy beta particle emitted from ^{60}Co decay for various materials	12-3
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2.	Half-value layers for the 1,330 keV gamma-ray emitted from the decay of a ^{60}Co nucleus	12-4
3.	Comparison of the radiotoxicity of several important radionuclides	12-4
4.	Average and maximum kinetic energies of beta particles and negative (atomic) electrons released during decay of several important radionuclides	12-5
5.	Chemical and physical characteristics of cobalt	12-7
6.	Annual limits on intake and the derived air concentrations for ^{60}Co	12-25

National Low-Level Waste Management Program Radionuclide Report Series

Volume 12: Cobalt-60

INTRODUCTION

This report outlines the basic radiological and chemical characteristics of cobalt-60 (^{60}Co) and examines how these characteristics affect the behavior of ^{60}Co in various environmental media, such as soils, groundwater, plants, animals, the atmosphere, and the human body. Discussions also include methods of ^{60}Co production, waste types, and waste forms that contain ^{60}Co .

All cobalt atoms contain 27 protons ($Z = 27$) and various numbers of neutrons (typically $N = 27$ to 37 neutrons) within the atom's nucleus. There is only one stable isotope of cobalt, namely ^{59}Co . All other cobalt isotopes, including ^{60}Co , are radioactive. The radioactive isotopes of cobalt have half-lives ranging from less than a second (^{54}Co —0.19 s) to 5.2 years (^{60}Co).¹ The radioactive isotopes of cobalt are not a normal constituent of the natural environment and are generated as a result of human activities.

The primary source of ^{60}Co in the environment has been low-level radioactive waste material generated as a result of neutron activation of stable ^{59}Co that is present in the structural components of nuclear reactor vessels. This isotope is also intentionally produced, usually in reactors but also to some degree in accelerators for industrial and medical uses, such as for radiation sources for cancer treatment and nondestructive testing of metals and welds. ^{60}Co may enter the environment as a result of the activities associated with nuclear reactor operations and decommissioning and when industrial and medical sources are being used, manufactured, or disposed.

RADIOLOGICAL CHARACTERISTICS

The most recent and best available information concerning ^{60}Co reports a half-life of 5.2 years.^{1,2} There is, however, an isomeric excited state of ^{60}Co with a measurable half-life of 10.5 minutes. This isomeric state has a long enough half-life that a small fraction ($< 1\%$) of the time it can decay directly to nickel-60 (^{60}Ni) with the emission of a negative beta particle (β^-). Otherwise, this isomeric state decays to the ground state of ^{60}Co with the emission of a gamma-ray. The principal means of ^{60}Co production is by neutron capture (n, γ) of ^{59}Co , namely

^{60}Co undergoes radioactive decay via β^- emission (i.e., 100% of all decays, both of the ground state and isomeric state, results in an electron being emitted from the nucleus) leading to the creation of a stable ^{60}Ni nucleus.

The maximum beta particle energy due to decay of the ground state of ^{60}Co is 1,480 keV (thousand-electron volts). Even though the maximum beta particle energy is 1,480 keV, more than 95% of the decay results in beta particle energies less than or equal to 314 keV. The decay of the excited isomeric state can result in a maximum beta particle energy of 1,550 keV, but this only happens for a small fraction of the decays. However, the average beta particle energy is only 94 keV per ^{60}Co disintegration (94 keV for the isomeric state).³ Since the released beta particle is usually emitted with an energy less than its theoretical maximum (e.g., 1,480 keV for ^{60}Co decay), an antineutrino particle is simultaneously emitted and this particle carries off the energy difference between the released beta particle and total energy given off by the decay process. Consequently, beta particles are emitted with a continuous energy spectrum ranging from 0 to 1,480 keV. Since neutrinos (or antineutrinos) rarely interact with matter, they are not considered radiologically important. Therefore, the antineutrino particle is usually not shown in the overall decay equation.

The probability that a neutron passing through cobalt will be absorbed by a ^{59}Co nucleus is moderate [about the same as in the production of ^{63}Ni and 20 times greater than in the production of niobium-94 (^{94}Nb)]. However, there is a relatively large mass of cobalt in a reactor system, and ^{59}Co is the only stable isotope of this element. Therefore, all of the cobalt that is in the reactor system is capable of being transmuted into ^{60}Co by the absorption of a neutron. The half-life of ^{60}Co is long enough that the equilibrium activity of this radionuclide can be large. This, coupled with the high energy gamma-rays that are emitted during ^{60}Co decay (1,170 and 1,330 keV), means that the radiation from this radionuclide is often the limiting radiation for personnel exposure during reactor maintenance activities. However, it is feasible (due to the 5.2 year half-life) to wait long enough after final shutdown of a reactor plant for this nuclide to significantly decay, reducing the personnel exposure during plant decommissioning activities. In other words, ^{60}Co normally represents a major concern in shielding during reactor plant operations, but its contribution to the overall radioactivity during decommissioning and waste storage activities can be reduced by simply waiting until it decays.

The 1,480 keV maximum energy beta particle emitted by the ^{60}Co nucleus is high, although the average beta particle energy, 94 keV, is only moderately high. Table 1 lists the estimated maximum ranges for a 94 keV (average energy) beta particle emitted from ^{60}Co decay. The ranges for the maximum energy beta particles are large. Since it requires only 70 keV for an electron to

Table 1. Comparison of the estimated maximum ranges for a 94 keV average energy beta particle emitted from ^{60}Co decay for various materials.

Material (description)	Estimated maximum range for a 94 keV β^- (mm) ^a
Air (1 atmosphere pressure)	150
Water	0.18
Plastic (Lucite)	0.14
Concrete	0.09
Glass	0.08
Aluminum	0.06
Iron	< 0.03
Copper	< 0.03
Lead	< 0.03

a. Estimates are based on the maximum beta particle range data shown in Reference 3 as a function of energy and materials.

penetrate the protective layer of human skin, the 1,480 keV beta particles have sufficient energy to penetrate the 0.07 mm (dead layer) of human skin. Therefore, exposure to the 1,480 keV maximum energy beta particles from the decay of ^{60}Co can result in a beta dose to some internal organs.

In addition to beta particle radiation, each ^{60}Co decay results in two high-energy gamma-rays, 1,170 and 1,330 keV. Both of these are more energetic than the 660 keV gamma-ray associated with the decay of cesium-137 (^{137}Cs). Table 2 illustrates this by listing the half-value layers, or the thicknesses of various materials required to reduce a beam of 1,330 keV gamma-rays to one-half of its original intensity. As shown, shielding the environment from ^{60}Co requires a substantial thickness, as opposed to some of the nuclides in this series, such as ^{63}Ni , which is only a beta emitter.⁴

The decay sequence for ^{60}Co showing the emission of a negative beta particle (e.g., an electron) and the two gamma-rays is illustrated in the following nuclear transformation:

(1,170 and 1,330 keV)

Table 3 lists the radiotoxicity of several important radionuclides, and Table 4 compares the average and maximum electron energies associated with ^{60}Co decay with other well-known electron (beta particle) emitters. Notice that ^{60}Co is shown in the same radiological group as ^{94}Nb and

Table 2. Half-value layers for the 1,330 keV gamma-ray emitted from the decay of a ^{60}Co nucleus.^a

Material	Half-value layer thickness (cm) ^b
Lead	1.03
Iron	1.7
Aluminum	4.7
Stone concrete	5.3
Water	11.2
Air	9.6×10^3

a. The half-value layer for a given material is the thickness of that material that will attenuate a beam of gamma-rays (of a specific energy) to one-half of its intensity.

b. These values were taken from Table 6.2 of Reference 3.

Table 3. Comparison of the radiotoxicity of several important radionuclides (from Appendix 2 of Reference 5).

Radiotoxicity		Species
Very high	Group 1	^{241}Pu , ^{242}Cm , ^{241}Am , ^{237}Np
High	Group 2	^{60}Co , ^{90}Sr , ^{94}Nb
Moderate	Group 3	^{14}C , ^{63}Ni , ^{137}Cs
Low	Group 4	^3H , ^{59}Ni , $^{99\text{m}}\text{Tc}$, ^{99}Tc , ^{129}I

Table 4. Average and maximum kinetic energies of beta particles and negative (atomic) electrons released during decay of several important radionuclides. (Information compiled from data presented in References 1, 2, 3, 6, and 7.)

Radionuclide	Released electron energy	
	Average energy (keV) ^a	Maximum energy (keV)
Nickel-59 (⁵⁹ Ni)	4.1 ^b	~7.7 ^b
Tritium-3 (³ H)	5.7	19.0
Nickel-63 (⁶³ Ni)	17.1	67.0
Iodine-129 (¹²⁹ I)	40.0	150.0
Carbon-14 (¹⁴ C)	49.0	156.0
Technetium-99 (⁹⁹ Tc)	85.0	293.0
Niobium-94 (⁹⁴ Nb)	156.0	500.0
Iodine-131 (¹³¹ I)	180.0	806.0 ^c
Cesium-137 (¹³⁷ Cs)	195.0	1176.0
Potassium-40 (⁴⁰ K)	541.0	1330.0
Cobalt-60 (⁶⁰Co)	94.0	1480^d
Phosphorous-32 (³² P)	694.0	1710.0

a. 1,000 keV = 1 MeV (million-electron volt). Beta particle energy unless otherwise noted.

b. The data for ⁵⁹Ni represent Auger electrons and not electrons emitted from the nucleus (i.e., beta particles). The maximum electron energy was estimated based on the assumption that an electron from the ⁵⁹Co atom (e.g., the daughter product from ⁵⁹Ni decay) absorbs a maximum energy x-ray.

c. 90.4% of the beta particle intensity for ¹³¹I occurs at 606 keV and only 0.6% occurs at 806 keV.

d. 99% of the beta particle intensity of ⁶⁰Co occurs at 314 keV.

strontium-90 (⁹⁰Sr). ⁶⁰Co decay results in a lower average (but higher maximum) beta energy emission and higher gamma energy emission than ⁹⁴Nb. ⁶⁰Co decay also results in lower average and higher maximum beta energy but lower gamma energy emissions than ⁹⁰Sr. [The high-energy (1,750 keV) gamma radiation due to ⁹⁰Sr decay is actually from the decay of its relatively short-lived (T_{1/2} = 64 h) daughter, yttrium-90 (⁹⁰Y).]^{2,3}

CHEMICAL AND PHYSICAL CHARACTERISTICS

Cobalt is a member of the eighth group, or the First Transition Series of the periodic table, which includes iron, nickel, scandium, titanium, vanadium, chromium, manganese, copper, and zinc.⁸ Of these, cobalt is chemically most like iron and nickel. In nature, cobalt always occurs in association with nickel and usually arsenic.

Cobalt is a hard, bluish white metal. It is ferromagnetic with a Curie temperature of about 1,150°C. The metal is relatively unreactive and does not combine directly with either hydrogen or nitrogen. However, it will combine with carbon, phosphorus, and sulfur at high temperatures. It is also attacked by atmospheric oxygen and water vapor at elevated temperatures.

Cobalt is widely distributed in nature, making up about 0.001% of the igneous rocks in the Earth's crust, compared with 0.02% for nickel.⁹ The most important cobalt ore deposits are located in Canada, Zaire, Morocco, and the Soviet Union. About 80% of cobalt is used in the metallic state. Reactors use the alloy, stellite, which contains cobalt and is hard and used for valve surfaces. The most important commercial applications are in making alloys for use at high temperatures, magnetic alloys, and alloys for use in machine tools.

The radionuclide, ⁶⁰Co, is widely used in industry, research, and medicine. This nuclide is widely used as a gamma radiation source to examine internal structures, such as welds, for defects or foreign objects. It is also employed in cancer therapy and as a radioactive tracer in biology and industry. ⁶⁰Co is also used in medical supplies and food irradiators.

Cobalt oxidizes primarily to two oxidation states, II and III. The most common state is II. Its most common oxide, CoO, is olive-green, has the rock salt structure, and is antiferromagnetic. Cobalt, in the II oxidation state, forms an extensive group of simple and hydrated salts, including hydroxide, sulfides, and various halides. The only apparently simple III salts are CoF₃ and hydrated forms of CoF₃ and Co₂(SO₄)₃.

Cobalt(II) forms numerous complexes with implications for waste storage, which will be discussed later. The complexes include ammonia and chelate amines such as ethylenediamine-tetraacetic acid (EDTA). Cobalt(III) also forms a number of complexes, especially those containing ammonia, amines, and halide ions. Cobalt(I) can also form complexes, although it is more difficult to obtain this oxidation state.

The mechanical properties of cobalt are dependent on the purity of the metal. Certain minor and trace elements fulfill necessary functions in cobalt alloys. For example, rupture strength and ductility benefit from adding boron, zirconium, titanium, and aluminum. Manganese and silicon additions aid castability and minimize grain boundary reactions. Conversely, the presence of parts per million amounts of elements such as lead, tellurium, bismuth, and selenium can be detrimental to creep and fatigue properties. Cobalt-based alloys have been extensively used in medicine and dentistry for surgical instruments and implants.¹⁰

The most common cobalt ore is cobaltite, a combination of CoAsS and FeS. The most common oxide, CoO, can show significant deviation from this stoichiometry without exhibiting heterogeneity.

The majority of soluble Co(II) salts are pink. However, the halides range from pale blue (CoCl₂) to green (CoBr₂).¹¹

Table 5 summarizes some of the chemical and physical characteristics of the element.

Table 5. Chemical and physical characteristics of cobalt (from References 12, 13, and 14).

Physical property (units)	Cobalt data
Melting point (K) ^a	1,753
Boiling point (K) ^a	3,173
Solid density (g/cm ³)	8.9
Ionization potential (V)	7.81
Oxidation potential (V)	0.28
Crystal form	Face-centered cubic

a. Zero Kelvin equals -273.15°C, -459.67°F.

COBALT-60 PRODUCTION

The structural materials inside the reactor vessel of a nuclear power plant are exposed to neutron radiation. This radiation can cause many components of these materials to become radioactive with time via neutron activation. Those elements most susceptible to neutron activation are iron, nickel, and cobalt, which are found primarily in stainless steel and other important alloys (e.g., Inconel). Depending on the amount of time these materials are irradiated and the neutron fluence (i.e., integrated neutron flux), any of these nuclides may become the critical activation product affecting the dismantling activities of the reactor.

Although not a principal structural material, based on total mass, cobalt does form an important constituent of some materials, especially those structures that require a high degree of hardness, such as valve bearing surfaces and core internal components. Much of this material is outside of the reactor vessel, and over time, cobalt-alloy surfaces can corrode/erode and the material can be transported to the reactor with the coolant where it is irradiated and then transported and deposited in various "hot spots" in the primary coolant system.

The principal means of producing ^{60}Co is through neutron capture of ^{59}Co , the only stable isotope of cobalt. Even though the total cobalt mass is relatively small and because ^{59}Co constitutes the only stable isotope, all of the cobalt mass is available for activation and this fact increases the total amount of ^{60}Co that can be produced.

Nuclear fission does not play a significant role in the production of ^{60}Co . This can be seen in Figure 1, which illustrates the fission yield for ^{235}U . The ^{60}Co position is shown with respect to the

Figure 1. Fission product yield curve for thermal fission of ^{235}U . Note that the total fission yield summed over all mass numbers is 200% since a single fission event results in two fission products.

fission product yield information for other mass numbers. The cumulative fission yield of ^{60}Co from the fission of ^{235}U is essentially zero. This information was obtained from the fission yield data from the ORIGEN2¹⁵ computer code cross-section data.

^{59}Co atoms have a moderately high probability to absorb thermal neutrons. However, cobalt comprises only a small fraction of the total structural mass in a nuclear reactor. Therefore, the total mass of ^{60}Co in a reactor system is never large. However, the 5.2 year half-life means that the inventory of this nuclide is close to the equilibrium mass by the end of reactor operations (based on a reactor life of 30 years). In addition, radioactive decay during normal maintenance shutdowns will not appreciably reduce the inventory between irradiations.

Therefore, the buildup of ^{60}Co in a reactor system can be approximated by assuming a continuous irradiation throughout the reactor lifetime, as shown in Figure 2. Figure 2 shows the buildup of several different activation products in a pressurized water reactor vessel, including ^{63}Ni , ^{59}Ni , ^{94}Nb , and ^{60}Co , as a function of reactor operation. The data in Figure 2 were normalized to 1 at 30 years and do not reflect absolute activities.

Figure 2. Buildup of some important activation products in a pressurized water reactor as a function of reactor operation. Note that the lowest curve from 0 to ~30 years represents ^{59}Ni , and the second lowest curve from 0 to ~30 years is ^{94}Nb (from References 16 and 17).

There are two groups in Figure 2: those that buildup relatively rapidly and reach a saturated condition, such as ^{60}Co and iron-55 (^{55}Fe); and those, typically with half-lives long compared to the relevant reactor lifetime, that never reach saturated conditions, such as ^{94}Nb and ^{63}Ni . The significance is that the nuclides in the first category also tend to decay more rapidly. Therefore, the attaining near-equilibrium inventories coupled with the high-energy gamma-rays associated with the decay of ^{60}Co , results in this nuclide being one of the dominant sources of personnel exposure during the first few years following reactor shutdown, especially for those areas removed from the core with its high inventory of fission products. Due to the 5.2 year half-life, it is feasible to delay decommissioning and decontamination activities after final shutdown to significantly reduce the ^{60}Co activity.

WASTE TYPES AND FORMS THAT CONTAIN COBALT-60

Nuclear Reactors

Cobalt is used in many reactor materials. It is a trace element in zircaloy-2 and -4 and is a major constituent of several types of Inconel and stainless steel.¹⁸ The only stable isotope of cobalt is ⁵⁹Co, which can become radioactive by capturing a neutron and being transmuted into ⁶⁰Co. As previously mentioned, ⁶⁰Co emits highly energetic beta and gamma-rays during the decay process and is a major source of gamma radiation from activated metal components. For a typical light water reactor, the activity of ⁶⁰Co ranges from 640,000 Ci (2.47×10^{16} Bq) at reactor shutdown down to 170,000 Ci (6.3×10^{15} Bq) after 10 years of decay. The maximum concentration of this nuclide that would qualify for waste disposal as Class A is 700 Ci/m³ (2.6×10^{13} Bq/m³) of waste.¹⁹ Therefore, after 10 years of decay, the 170,000 Ci (6.3×10^{15} Bq) would have to be distributed throughout 243 m³ of reactor structural materials to qualify for this waste disposal classification. The limits for Class B or Class C waste depend on additional considerations such as the effects of external radiation and internal-heat generation on the transportation, handling, and disposal.

Since this nuclide is produced exclusively by activation of stable cobalt in the reactor structural materials, the reactor fuel will only contain it in the cladding and end pieces of the fuel rods and not in the fuel itself. Removal of the fuel will not eliminate this nuclide from the nuclear waste. In addition, corrosion of cobalt-bearing materials can create special problems for decommissioning and dismantling activities. Although the materials that contain cobalt are largely corrosion resistant, some corrosion does occur. If the material is part of the reactor vessel (high neutron flux area), the activated ⁶⁰Co is transported with the reactor coolant to other parts of the plant where it can be deposited in low flow velocity volumes such as elbows and valves. This creates "hot spots" that must be specially shielded to prevent excessive personnel exposure during plant maintenance and decommissioning activities. If the structural material is outside the reactor vessel (low neutron flux areas), the corrosion products are transported into the reactor vessel where the cobalt is irradiated. The, now activated, ⁶⁰Co is then transported outside the vessel where it follows the same deposition patterns.

Although ⁶⁰Co has a relatively short half-life, compared with other nuclides studied in this series of reports (e.g. ¹³⁷Cs,²⁰ which has a half-life of 30.2 years and ⁶³Ni,⁴ which has a half-life of 100 years), it still persists well into expected plant decommissioning/decontamination activities.

Medical, Academic Institutions, and Commercial Waste

There are a number of commercial applications for ⁶⁰Co. The transportation industry uses this nuclide as a radiation source to measure the thickness of automobile sheet steel.²¹ This nuclide has found extensive use in the metals industry as a radiography source to detect flaws in welded joints and castings. The electrical industry uses ⁶⁰Co to preionize gases in electronic tubes. There are several applications in the chemical-processing industry, including gauging of liquid or solid levels, a catalyst in flow studies, drug-metabolism studies, sterilization of medical supplies, and measuring the effects of polymerization in the initiating chemical reactions. This nuclide is used in the consumer-products industry to sterilize and pasteurize food and to control solid and liquid levels in foods and beverages. It is used to measure pipeline flow, level, and density gauging for the crude-petroleum and natural gas

industries. Utilities also use ^{60}Co to measure snowpack densities for water resource management. In the agriculture industry, this nuclide is used to study the movement of insect larvae through soil, study mineral metabolism in animals, and to sterilize insects for control. Uses in the aerospace industry include radiographic inspection of parts and as a power source for locations remote from utility resources [^{60}Co has been considered for application as fuel for the Systems for Nuclear Auxiliary Power reactor, but it is not clear whether it has ever actually been used in this application].

Because of its high-energy gamma radiation, ^{60}Co has been used extensively as a radiation source for both commercial and medical uses. It is used in place of x-rays or radium in materials inspection to reveal internal structure, flaws, or foreign objects.⁹ Its use is enhanced by its relatively long half-life that enables production of a reproducible gamma radiation field for a long time and its penetrating, high-energy gamma-rays. It is also used as a standard spectroscopic calibration source for gamma-ray energies in the 1 to 2 MeV range.

Because of the high gamma-ray energy associated with this nuclide, extreme care must be exercised when using a source. A rule of thumb for external exposure is 1.32 R/h per Ci (3.56×10^{-7} Gy/h per MBq) of ^{60}Co for a source 1 m from a person.²²

For example, an employee at the Nevada Test Site was attempting to manually replace the shield plug on a ^{60}Co shipping cask when he accidentally received a 1,200 rem (12 Sv) radiation dose to his right hand and a 42.5 rem (0.43 Sv) dose to his pelvis. This was due to his mistakenly thinking the source was still in the cask when it actually had been removed and was unshielded during the operation.²³

In another incident, the U.S. Nuclear Regulatory Commission reported high levels of ^{60}Co in the ash generated during sewer sludge incineration at a treatment plant in Cleveland, Ohio.²⁴ The contamination was caused by the disposal methods of a company licensed to manufacture radiation sources for cancer therapy.

^{60}Co is commercially available in multiple forms. It is available as the element dissolved in hydrogen chloride (HCl) with concentrations ranging from 10^{-5} to 2,000 $\mu\text{Ci/mL}$ (0.7 to 7×10^7 Bq/mL) and as CoCl_2 dissolved in HCl with concentrations ranging from 1 to 1,000 $\mu\text{Ci/mL}$ (3.7×10^4 to 3.7×10^7 Bq/mL).²⁵ ^{60}Co is also available as a beta source (with thin-walled encapsulation to minimize attenuation of the beta-rays) in either aluminum or stainless steel backing materials with activities ranging from 8×10^{-4} to 0.1 μCi (30 to 37,000 Bq). Finally, it is available as a gamma source in a variety of encapsulation materials (plastic, aluminum, polystyrene, plexiglas, and epoxy resin) with activities ranging from 0.01 to 100,000 μCi (370 to 3.7×10^9 Bq). Some suppliers, however, provide sources in multiple curies. ^{60}Co is commercially produced in the United States by the U.S. Department of Energy (DOE) in the Advanced Test Reactor at the Idaho National Engineering Laboratory (INEL) by irradiating cobalt rods or wire or nickel-plated pellets. It is then shipped in welded stainless steel containers.²⁶ Thus, there is a variety of material types associated with this nuclide as a commercial gamma source, and the waste treatment/storage methods used to isolate it from the environment must take this variety into account.

BEHAVIOR OF COBALT-60 IN THE ENVIRONMENT

Cobalt in Soils

Understanding the behavior of radioactive materials such as ^{60}Co in the soil is important in assessing the possibility of transport of these radionuclides through the biosphere.²⁷ It is important to understand the interactions between radionuclides and various media along the path to the biosphere, whether disposal is in deep or shallow rock caverns or in shallow overburden facilities.

Four parameters were reported to be essential in accurately predicting soil concentrations from either contaminated ground water or irrigation water.²⁷ The four parameters, in order of decreasing importance, are (1) soil retention, (2) annual precipitation, (3) soil texture, and (4) depth to the water table. The soil retention parameter represents the solid/liquid partition coefficient and is denoted by the symbol K_d . K_d is defined by $K_d = C_s/C_l$, where C_s is the cobalt concentration in the soil ($\mu\text{g Co/gram of soil}$), and C_l is the cobalt concentration in the groundwater ($\mu\text{g Co/mL of liquid}$). Therefore, the units of K_d are mL/g (i.e., $\text{mL of water per gram of soil}$). This empirical model combines all soil retention mechanisms into a simple linear partition relation between the soil and surrounding groundwater. This model assumes that the cobalt concentrations in groundwater and soil are in equilibrium with each other. Using this definition for K_d , it follows that the larger the value (i.e., the higher the radionuclide concentration in the soil relative to that in the groundwater), the slower the migration of the radionuclide relative to groundwater flow. Therefore, K_d can be thought of as a measure of the amount of "fixing" or holdup in the soil.

Typically, K_d is measured under laboratory conditions, using samples that are relatively homogenous, and where it can be ensured that equilibrium conditions are met. Applying these values to specific soils in the field can be difficult because actual soils are generally inhomogeneous and there are uncertainties as to how long it takes for the cobalt concentrations in the soil and groundwater (C_s and C_l) to reach equilibrium with each other. Therefore, soil samples used in laboratory studies should be representative of the field as possible. Even though the soil samples do not precisely match conditions in the field, K_d values from laboratory studies can be used in computer models that extrapolate data from laboratory experiments and field studies. In addition, some experiments are conducted using intact field samples to validate the laboratory K_d values and to study the effects associated with soil inhomogeneity.

The range of K_d for ^{60}Co has been reported in Reference 28 to be from 0.2 to 3,800 mL/g . The mean value is 55. This illustrates the large variation of soil properties as well as variations of the tendency of ^{60}Co to be adsorbed depending on chemical form. This reference also indicates the effects of this nuclide on microorganisms in the soil. For ^{60}Co soil concentrations ranging from 10 to 100 ppm, there is a decrease of 4 to 23% in the respiration of loamy sand.

In another experimental study of the soil retention of ^{60}Co , the effect of complexing agents was measured.²⁹ K_d values for ^{60}Co were measured to be in the range of 1.2×10^3 to 7.0×10^4 for Conasauga shale with pH 12 and 6.7, respectively. These values were reduced to between 0.8 and 2.9 with the addition of EDTA, an organic complexing agent often used for decontamination of nuclear plants. These K_d values were corroborated by in situ measurements of soil and water ^{60}Co concentrations in wells near the Oak Ridge National Laboratory. The K_d values averaged 35, which

was close to but somewhat larger than those in the experiment for the measured EDTA concentrations of 3.4×10^{-7} M. Similar reductions in K_d were also measured for conditions including other chelating agents such as diethylenetriaminepentaacetic acid (DTPA), CDTA, and natural organics such as humic and fulvic acids.

In a separate study, these results were qualitatively corroborated in the short term (for experiments lasting a few days).³⁰ However, in the long term (for experiments lasting up to 500 days), the amount of cobalt remaining in solution decreased from 90% to less than 10%. These results were corroborated with field tests at the Savannah River burial grounds where water concentrations of $^{60}\text{Co}/\text{EDTA}$ decreased from 30% in 5 days to less than 1% after 15 days. This suggests that cobalt/EDTA has a tendency to dissociate, leaving uncomplexed cobalt, which is readily adsorbed by the soil. The implication to waste management is that the potential for transport of cobalt by EDTA may not be as serious at all burial sites as previously thought.

Reference 31 includes a good summary of the soil characteristics of elemental cobalt in general and ^{60}Co in particular. Soil concentrations of ^{60}Co have been measured to be in the range of 0.1 to 50 pCi/g (3.7 to 1,900 Bq/g) in surface soils and from 0.05 to 5 pCi/g (2 to 180 Bq/g) in subsurface (11 to 15 cm) soils in the vicinity of a liquid disposal trench. Elemental cobalt and many of the simple compounds involving this element tend to be easily deposited in soil. Generally speaking, it appears that cobalt is adsorbed to the surface of clay materials in the soil through iron and manganese oxides. Only a small fraction is adsorbed onto the mineral lattice. Therefore, it would be expected that removal of cobalt from the soil could be achieved using extracting solutions such as acetic acid, dilute HCl, and chelating compounds such as EDTA. Much of the information regarding the soil characteristics of cobalt were derived using different soil-extraction solutions. In this respect, acetic acid and EDTA compounds have been shown to extract a major proportion of cobalt from soil.

Because of the fixing ability of soils to remove cobalt from solutions, ^{60}Co tends to be found in the top 5 cm of soils. In addition, the activity of this nuclide was measured to decrease by 99% within 5 m of a waste disposal trench at DOE's Hanford, Washington, reservation. In a separate study, also reported in Reference 31, it was shown that ^{60}Co penetrated soil very little and that 78% of the total activity was within the top 3-cm layer of soil. In percolation tests, simulating rainfall, cobalt was shown to be removed from the soil at a slow rate of 5% per year.

The retention of ^{60}Co is strongly dependent on the type of soil and amount of rainfall. For example, a study was made of the effect of both of these parameters on cobalt retention, where it was shown that for low rain intensity (2 mm/h), the organic (humic layer) top layer of soil retained nearly all of the percolating cobalt whereas for high rainfall (30 mm/h) intensity, up to 10% was released from this layer. In the mineral soil layer, ^{60}Co was much more mobile. This type of information is important to determine initial distribution of fallout during rain and can affect the initial soil-to-plant transfer, initial outdoor radiation exposure, and subsequent transport in the groundwater. The humic layer consisted of 82% organic material while the mineral layer was primarily sand with up to 17% silt and only a few percent of clay. The ^{60}Co was introduced as CoCl_2 .

A study was made of the speed with which ^{60}Co moved in sandy soils.³² The chemical form of cobalt was CoCl_2 and positively charged (cationic) cobalt was eliminated so that the noncationic behavior could be studied and rapid groundwater conditions were replicated. Some of the results of

this study were that the noncationic species migrated independently from cationic species and that the noncationic cobalt was not adsorbed much by the sandy soil.

A Japanese study was conducted where the sorption and migration of ^{60}Co (and other nuclides ^{85}Sr and ^{137}Cs) in coastal sandy soil were measured.³³ In particular, the effects of added humic acid (a complexing agent) on the sorption/migration behavior were studied. This study modeled the presence of dissolved organic substances in natural waters, which originate from the decay of organic matter in soils and waters. The resultant humic acid tends to be stable and complex in molecular structure. Since it is widely present in many soil structures, it is important to understand how it would affect the ability of waste disposal sites to retain radioactive nuclides, especially in the presence of rain or other sources of groundwater. It should be noted that sandy soil has little sorbing capacity for humic acid. Therefore, the results were not masked by any sorption of the acid independent of the radionuclides. Some geological materials, however, do adsorb humic acid and the results from this study should only be applied with care to these other conditions. All of the nuclides studied in this experiment, including ^{60}Co , were chlorides in chemical form (e.g., CoCl_2). The results from this study indicate that the sorption ratio (related to K_d) of ^{60}Co decreased from 300 mL/g for the case with no humic acid, to approximately 20 mL/g for the case of 35 ppm humic acid. The other two nuclides did not exhibit any significant decrease in sorption ratio.

The Yankee Rowe Nuclear Power Plant has been shutdown and is in the planning stage for decommissioning and decontamination activities. Reference 34 summarizes remediation plans for this site. Based on measurements taken in 1993 and 1994 (after final shutdown in 1992), it was concluded that the primary radionuclide that migrated beyond the reactor control area of the plant was ^{60}Co , which was measured in a few areas immediately adjacent to the plant. Additionally, since most of the site was covered with asphalt, the ability of this material to minimize migration of nuclides was also assessed. It was concluded that asphalt is porous, at least as related to the nuclides of interest. In some instances, the ^{60}Co concentrations immediately below the asphalt were higher than those in the asphalt samples. Approximately 98% of the activity resides within 6 in. from the surface, independent of which specific nuclide was being measured. The dose rate for a person exposed to the highest levels of radiation at the site would be 100 mrem/year, leaving soil removal as the only realistic option for decommissioning. If the locations of high concentration could be administratively averaged with adjacent areas, it was concluded that little remediation would be required other than waiting a few years for the levels to decrease.

The last two references in this section summarize in situ studies of ^{60}Co in soil samples. Reference 35 summarizes the sampling in areas surrounding the Browns Ferry Nuclear Power Plant and included samples taken of various substances including air, water, milk, foods, vegetation, fish, sediment, and soil. This study is a direct measure of the soil contamination due to the operation of this commercial nuclear reactor. There were no measurable radioactivities in the soils that could be identified with operation of this plant (there was measurable ^{137}Cs activity, but this was identified with fallout, not plant operations). There was some ^{60}Co activity measured in sediment samples, but the activity levels were low and did not represent a hazard to the public.

Reference 36 summarizes sampling conducted at the Maxey Flats, Kentucky, shallow land burial site and involved measuring several radionuclides, including ^{60}Co . This reference concluded that some ^{60}Co was measured in sediment samples adjacent to the site. This was due to surface runoff of rain into the adjacent woods, rather than subsurface migration. The only nuclide activity that

exceeded expected nuclear fallout levels was ^{60}Co , and its level was low [approximately 1 to 2 pCi (0.04 to 0.07 Bq) of ^{60}Co /gm of soil] in areas outside of the waste disposal site.

Cobalt in Groundwater

Reference 31 discusses cobalt in aquatic ecosystems, including both water and sediments. According to this reference, there are relatively few data relating to ^{60}Co concentrations in sediments. One study reported that the sediment concentration of ^{60}Co was 20 times higher than the concentration in the surrounding water. This indicates that the soil in these sediments does a good job of extracting the ^{60}Co from the water, consistent with much of the data in the preceding section. Other studies summarized by this reference (including measurements taken in the White Oak Lake and in water near the Humboldt Bay Power Reactor) corroborate these findings, namely that ^{60}Co in water tends to be readily adsorbed by the sediment. One included study concluded that the accumulation ratios for sediments would be expected to differ in short-term studies compared to long-term studies because they tend to be cyclic in nature. The cyclic behavior would be affected by sediment accumulation cycles, which tend to peak in spring and early summer due to runoff of winter snow. This reference concluded that the distribution of ^{60}Co between water and bottom sediments can be assumed, in general, to be 5% in the water and 95% in the sediment and that this balance can be expected to be achieved rapidly. The concentration ratios for marine and freshwater aquatic systems are expected to be of the order of 10^4 and 10^3 , respectively.

Reference 35 included measurements of radioactive concentrations in river and reservoir water as well as from wells in the vicinity of the Browns Ferry Nuclear Power Plant. This indicates contamination of the surrounding surface and groundwaters because of operation of this plant. All radioactivity in surface water samples was below the lower level of detectability for all species except the gross beta activity and naturally occurring nuclides. Similar results were reported for groundwater samples. Therefore, there were no measurable concentrations of ^{60}Co in any of the water samples. However, ^{60}Co was measured in some sediment samples. Because of the low levels of measured activities of this nuclide, sediment samples were taken both upstream and downstream of the plant so that the effects of fallout could be determined. The upstream (fallout dominated) concentrations were 0.02 pCi/g (7×10^{-4} Bq/g) compared with 0.05 pCi/g (2×10^{-3} Bq/g) in the downstream (fallout plus plant release) samples. Thus, there is a measurable difference, although the levels of ^{60}Co are extremely low.

The remediation plan, summarized by Reference 34, also included groundwater sampling. The groundwater in the vicinity of the Yankee Rowe Nuclear Power Plant lies between 3 and 18 ft below the ground surface. There was no measurable ^{60}Co in any of the groundwater samples taken for this study.

Radionuclide concentrations are periodically measured for systems in the vicinity of the Calvert Cliffs Nuclear Power Plant.³⁷ Low concentrations of ^{60}Co were measured in most of the sediment samples in the vicinity of this power plant. The samples were taken from the shoreline of the Chesapeake Bay, in marine water locations. The report concludes that 227 mCi (8.40×10^9 Bq) of ^{60}Co were released during 1985 and 1986 into the bay via cooling water discharge. The maximum ^{60}Co concentration measured in the (sandy) sediment samples was 280 pCi/kg (10 Bq/kg).

A study was made of the groundwater contamination in the vicinity of the Oak Ridge National Laboratory.³⁸ A seep has developed near one of the burial trenches associated with the laboratory. Water samples taken from this seep showed ^{60}Co concentrations above normal background levels, and it was decided to attempt to correlate these findings with the water chemistry in the trench. Specifically, the effect of the presence of complexing agents, such as EDTA, in the water was studied. EDTA is used in cleanup and decontamination operations at the laboratory and is found in liquid waste. However, the presence of EDTA in the groundwater could not be verified. The principal conclusions of the report are that uncomplexed ^{60}Co is expected to be bound with the soil and not be transported with the groundwater; the principal adsorbents in the (Conasauga shale) soil are manganese oxides; and complexed ^{60}Co (with, for example, EDTA) is the principal chemical form of cobalt that did migrate to the seep.

The corrosion of ^{60}Co -laden stainless steel samples by seawater and the subsequent fate of the release nuclide were the subject of a study conducted by the Pacific Northwest Laboratory.³⁹ In this study, irradiated stainless steel samples were placed in the flowstream of seawater. The flow carried the ^{60}Co into another chamber where marine animals and sediment absorbed the nuclide and the final concentrations in the animals, seawater, and sediment were measured. This study simulated what would be expected to occur as a result of disposal of activated stainless steel components in the oceans. It was concluded that most of the activity absorbed by the animals was from the interstitial water in the sediment and not from the bulk water.

Groundwater contamination patterns beneath the Hanford Project reservation have been studied periodically throughout the history of the site. Two studies are summarized here, the one for the period up to 1972⁴⁰ and the one for the period of January to December 1976.⁴¹ In the first report, the principal radionuclides (other than naturally-occurring radionuclides) detected in the groundwater were ^{60}Co and ruthenium-106 (^{106}Ru). Reactor coolant had been discharged directly into the Columbia River but had been terminated before this first report. As a result, although the ^{60}Co levels were detectable, they were decreasing. Maximum ^{60}Co concentrations in either river or groundwater were less than 12 pCi/L (0.4 Bq/L).

In the second report, the extent of underground "plumes" were measured. Although not specifically stated, the mobility of the ^{60}Co with the groundwater suggests the presence of complexing agents. The only Hanford-related nuclide that was measured in the Columbia River water was ^{60}Co . The presence of this nuclide is attributed to reactor coolant discharge into the river. Therefore, no contamination of the river due to underground migration was detected.

The leaching of ^{60}Co from soil was measured in an experiment conducted by personnel of the Belgium Department of Radioprotection.⁴² In this study, homogeneously contaminated sandy soils were exposed to water flows, simulating rain water. The study concluded that up to 1.7% of the 15 mCi/m² (5.3 MBq/m²) ^{60}Co was leached over a 2-year period.

An experimental study was made by the Japan Atomic Energy Research Institute (JAERI) of the migration of ^{60}Co under steady-state water flow conditions.⁴³ Two different coastal sand soils were used in this experiment. The study concluded that most of the ^{60}Co was adsorbed on the soil near the injection point. This adsorption was believed to be due to ion exchange. A small fraction of the ^{60}Co did migrate beyond the injection point, primarily as particulates.

A separate JAERI study was made of the effects of nonsteady state water flow conditions on the migration of ^{60}Co .⁴⁴ This was done to simulate intermittent rainfall and evaporation cycles. This study concluded that there were two natural chemical forms for cobalt under these conditions. First, cationic ^{60}Co was postulated, which readily adsorbed on the soil and remained fixed. Second, $^{60}\text{Co}(\text{OH})_2$ was postulated, which was generated as a result of hydrolysis in the interstitial water during the evaporation phases and which was more mobile. The migration of this hydroxide form was sensitive to the cycling of the water flow and comprised approximately 1% of the total ^{60}Co injected during the test.

Cobalt in Plants

In addition to the previously summarized results, Reference 31 also contains a summary of the uptake of ^{60}Co into terrestrial plants. For example, one study, summarized in this reference, reported ^{60}Co concentrations ranging from 4.22 to $13.2 \times 10^{-3} \mu\text{Ci/g}$ (156 to 490 Bq/g) in the roots and from 1.1 to 3.0 pCi/g (39 to 112 Bq/g) in aboveground parts of plants growing near a trench storage site. Another study reported between 0.002 and 2 pCi/g (0.074 and 7.4 Bq/g) of ^{60}Co in plants from the Enewetak Atoll, which lies close to the site of numerous aboveground nuclear explosion tests. This study further states that the fraction of ^{60}Co fixed to magnesium oxides in the soil is not available for uptake by plants. Other factors affecting plant uptake include soil pH (decreasing cobalt uptake with increasing pH) and soil type (plants grown on coarse textured soils tend to have higher concentrations of cobalt than those grown on heavy textured soils containing high amounts of organic matter).

In an experiment involving maize and bushbeans, it was found that most of the ^{60}Co in maize was retained by the roots (> 95%) and the rest was in the aboveground parts of the plant. For bushbeans, the roots also exhibited the highest concentrations, although the total fraction in the roots was less than for maize.

In a study involving rice, it was determined that the rice plant could accumulate 0.3% of the ^{60}Co in the soil. Again, the roots exhibited most of the storage of ^{60}Co (68%). In summary, for the plants considered in the Reference 31 report, the fraction of soil-applied ^{60}Co that remained in the roots, relative to that absorbed by the entire plant, was 68%, 70%, and 96% for rice, bushbeans, and corn.

This conclusion that most of ^{60}Co absorbed by plants remains in the roots was also noted in a separate study performed by the Atomic Energy Authority of Egypt.⁴⁵ Approximately 70% of the absorbed nuclide remained in the roots. The soil used in the experiments was sandy loam soil and clover was used as the plant. This experiment was designed to investigate the ability of clover to extract ^{60}Co from soil as part of a decontamination effort. Several complexing agents were also introduced to measure their effects on cobalt extraction. Of the complexing agents used in this study, it was concluded that Fe-DTPA enhanced ^{60}Co extraction the most.

A different type study was performed by scientists at the Institute for Radiation and Botany of the Organization for Radiation and Environmental Research, Ltd.⁴⁶ In the study, partially grown grasses were brought into contact with ^{60}Co -contaminated slime. The nuclide surface contamination (from the direct contact of the slime with the plant parts) as well as the internal contamination (uptake from the soil) were measured. The mean value for the transfer coefficient (the ratio of the

concentration of ^{60}Co in the plant to that in the soil) was about 2×10^{-2} pCi/kg (plant) per pCi/kg (soil).

The influence of residence time on the uptake of ^{60}Co from soil to barley plants was measured in an experiment conducted at the Institute of Radioagronomy in Juelich, Germany.⁴⁷ Two different soil types were used: parabraunerde (mixture of fine sand, silt, and clay) and podsol (primarily fine and coarse sand). The chemical form for cobalt was CoCl_2 . The transfer factor (concentration in plants divided by the concentration in the soil) was approximately 0.04 for podsol and 0.02 for parabraunerde. In both cases, only limited amounts of ^{60}Co could be extracted from the soils.

A similar experiment extended the results to a number of other plants, including winter wheat, summer barley, radishes, and lettuce.⁴⁸ This study used the same soils as did Reference 47. The transfer factors varied from 0.004 to 0.01 in the parabraunerde soil and from 0.007 to 0.26 in the podsol soil. In each case, the winter wheat exhibited the largest transfer factor and lettuce exhibited the smallest.

A large data base of soil/plant transfer factors has been developed by the International Union of Radioecologists.⁴⁹ This data base contains approximately 2,000 soil-to-plant transfer factors and this reference contains an update to this data base. Included in the data base are soil/plant transfer factors for ^{60}Co for a variety of plants and for four soils, sand, loam, clay, and silt. Ten different crop types are included: cereal (both grain and flour), fodder (maize, clover, alfalfa), grass, leaves of root crops, pods (pods and seeds of peas and beans), roots of root crops (beets, radishes), shoots (stems and shoots of cereals, pears, beans, potatoes, and bran), tubers, green vegetables (cabbage, spinach, leek, lettuce), and nonedible roots. The transfer factors for ^{60}Co range from 0.04 to 0.3 for sand soil, 0.001 to 0.18 for loam, 0.001 to 0.19 for clay, and 0.003 to 0.53 for silt. In each case, the highest transfer factor was measured for green vegetables and the lowest for cereal. There were no data for roots, which in some earlier-mentioned studies exhibited the highest concentrations.

The uptake of ^{60}Co in the vicinity of the Hanford Reach of the Columbia River (near the DOE's Hanford site) was measured for several types of wild plants and farm crops.⁵⁰ The wild plants were the mulberry tree, willows, and reed canary grass. The ^{60}Co concentrations were about 0.03 pCi/g (0.001 Bq/g) in the mulberry foliage and ranged from 0.02 to 0.1 pCi/g (0.0007 to 0.004 Bq/g) in the fruit. Of the farm crops collected in the survey (asparagus, pumpkin, and tomatoes), only tomatoes had measurable concentrations of ^{60}Co . The nuclide concentration for this vegetable was approximately 0.02 pCi/g (0.0007 Bq/g), which would result in an estimated dose of 3×10^{-5} mrem (3×10^{-7} mSv) if 1 kg were consumed.

The final study included in this report was performed by personnel at the Institute for Radioactivity and Agronomy of the Nuclear Research Laboratory in Juelich on the influence of aging on ^{60}Co -uptake by young barley plants.⁵¹ In this study, the same ^{60}Co -contaminated soil samples were used to raise three successive plantings of barley. There was a significant dropoff in the uptake of ^{60}Co by the plants with succeeding plantings, indicating some "aging" effects on the soil/plant transfer. There was no clear indication of what aging phenomena caused the decrease in the transfer factor.

Cobalt in Air

The injection of ^{60}Co into air can occur as a result of either atmospheric nuclear weapons testing activities or a severe core damage accident. In either case, since ^{60}Co is not a fission product, the production occurs as a result of the neutron irradiation of structural materials associated with either the weapon or the reactor. Atmospheric weapons testing was terminated several half-lives ago, and the residual ^{60}Co contamination has been reduced significantly by radioactive decay. Thus, only small amounts would be expected to persist from this activity. For example, Reference 35 includes an assessment of the persistent fallout activity in the region of the Browns Ferry Nuclear Plant. This report concluded that the only measurable fallout activity at this time (1992) is ^{137}Cs . However, comparison of ^{60}Co activities in water upstream and downstream of the plant indicate some source of this nuclide external to the plant.

In an earlier study of the Maxey Flats (Kentucky) burial site contamination (1984), measurable amounts of ^{60}Co were detected whose distribution clearly suggested fallout as a source.³⁶ This conclusion is based on comparison of ^{60}Co concentrations (in the soil and in the groundwater) in samples taken near and far from the burial site. The fallout-originated soil contamination levels are not specifically stated in the report, but the implication is that these levels are less than or approximately 0.1 pCi/g (0.004 Bq/g). Since this report predates the nuclear reactor accident at Chernobyl, these contamination levels are presumably due to atmospheric testing of nuclear weapons.

Residents of Bikini Island were contaminated by radionuclides from fallout of atmospheric testing, and in 1978, they were removed from their homes and relocated to the Marshall Islands to avoid additional contamination.⁵² At the time the residents were moved, exposure was estimated to result in annual doses in excess of 0.5 rem (0.005 Sv) in some cases (this was due to the total exposure and not just that of ^{60}Co). Body burdens of ^{60}Co ranged from 1.6 to 3.0 pCi (60 to 110 Bq) in a sample of the population.

Reference 53 is a summary of the radionuclide concentrations found in game birds that frequent the area within and surrounding the Hanford site. This report concludes that "radionuclide concentrations attributable to Hanford operations were only slightly greater than (within a factor of 10) or indistinguishable from expected levels attributed to worldwide fallout." Concentrations of ^{60}Co in duck meat were as high as 1.8 pCi/g (0.07 Bq/g), which would imply that at least one-tenth of this contamination would be due to fallout. This study was conducted during the period of atmospheric testing when the ^{60}Co levels due to fallout would be highest.

In summary, ^{60}Co can enter the air from atmospheric testing of nuclear weapons (this practice was ended 30 years ago) or from a severe core damage accident in a nuclear plant.

BEHAVIOR OF COBALT-60 IN THE HUMAN BODY AND IN ANIMALS

This section summarizes several studies of the behavior of ^{60}Co in the body. This behavior is complex and depends on whether the nuclide is taken into the body (either by ingestion or inhalation) or irradiates the body externally. There are numerous such studies and only a small number are included here. First, the behavior of this nuclide in animals is discussed, followed by a discussion of the behavior in humans.

Behavior of Cobalt-60 in Animals

Cobalt is required in small amounts by plants and animals and is part of vitamin B_{12} . Cobalt compounds are typically added to salt licks in those areas of the world where it is naturally deficient to avoid serious cattle and sheep diseases.⁸

Retention of radionuclides has been measured in various game birds that reside in or around the Hanford site.⁵³ Various birds, including coots, ducks, geese, and pheasants, were collected from areas on the site and along the adjacent stretch of the Columbia River during the period from 1971 to 1975. These birds were selected because they represent a potential route for ^{60}Co to get from the environment into the human food chain. Of these birds, ^{60}Co was found mainly in ducks and was found more frequently in pond ducks (ducks that were harvested from ponds on the Hanford site) than for river ducks (ducks that were harvested from the Columbia River). This is not unexpected because the ^{60}Co water concentrations were higher in the ponds than in the river. The highest concentration of ^{60}Co in the meat was 1.8 pCi/g (0.07 Bq/g) and the range of concentrations was from 0.01 to 1.8 pCi/g (0.0004 to 0.07 Bq/g). It is estimated that ingestion of 500 g of duck meat contaminated with 1.8 pCi/g (0.07 Bq/g) of ^{60}Co would result in a whole body dose of 0.004 mrem (40 μSv). The ^{60}Co concentrations in the sampled pheasant, coot, and geese populations were much less and were near the lower level of detectability.

A similar study was performed on various animals that reside on the INEL near Idaho Falls, Idaho.⁵⁴ Barn swallows were collected in this study and exhibited levels of ^{60}Co in all adult and most of the immature birds analyzed. Concentrations ranged from 4 to 8 pCi/g (0.1 to 0.3 Bq/g) for immature birds to 50 pCi/g (2 Bq/g) for adult birds. Relative to filtered pond water on the site, the concentration factor [ratio of the ^{60}Co concentration in the bird (pCi/g) to that in the water (pCi/mL)] for ^{60}Co was 1.3 to 2.7 for immature birds and 17 for adult birds. Other birds included in the study included ducks and coots that were harvested from the leaching pond at the Test Reactor Area at the INEL. This study included an analysis of the distribution of ^{60}Co between the various body parts. The edible parts of the bird (muscle) contained ^{60}Co concentrations approximately 35 pCi/g (1.3 Bq/g), where nonedible parts contained concentrations of 1,879 pCi/g (70.5 Bq/g) and 540 pCi/g (20.0 Bq/g) for gut and feathers, respectively. Thus, the ^{60}Co tended to not concentrate in the edible parts as much as in the nonedible parts. Similar, although not quite as dramatic, differences in ^{60}Co concentrations between edible and nonedible parts were also measured in sage grouse collected near the same area.

Reference 31 lists concentration factors for ^{60}Co for various animals, such as mice, dogs, and monkeys. There is a wide range of concentration factors (including distribution among body parts) too numerous to be included in this document.

Reference 39 was a experimental study of the transfer of ^{60}Co from activated stainless steel to marine animals. In this study, activated stainless steel was exposed to seawater, which contained various common marine animals. The uptake of the radionuclide into these animals was measured. The results showed that the concentration factor for ^{60}Co varied widely among the various animals. For mollusks, the concentration factor ranged from 1 to 210, for crustacea, from 300 to 4,000, and for fish, from 20 to 5,000.

Reference 37 summarizes radionuclide concentrations in marine animals attributable to emissions from the Calvert Cliffs Nuclear Power Plant. This report concludes that there are measurable amounts of ^{60}Co in oysters harvested from the Chesapeake Bay in the vicinity of the plant. The ^{60}Co ranged in concentration from 2 to 5 pCi/kg (0.07 to 0.2 Bq/kg) and was only found in a couple of the samples. No measurable concentrations of ^{60}Co were found in samples of blue crabs, grass shrimp, or finfish.

Behavior of Cobalt-60 in Humans

The fractional absorption of ^{60}Co from the gastrointestinal tract after ingestion is variable and depends on the mass of cobalt ingested and whether ingestion takes place with a meal or after a period of fasting.³¹ The assumption of a fractional absorption of 0.2 is conservatively high and may overestimate the actual value by as much as a factor of 10 in some cases. For most animals, the inhalation classification is W (Week) for any cobalt compound. However, for humans, the recommended classification is Y (Year) for oxides, hydroxides, halides, and nitrates and W for all other compounds. The reason for this difference is that cobalt tends to reside longer in the lungs for humans than for animals. According to this reference, cobalt distributes itself relatively uniformly throughout a human with the possible exception of the liver, which tends to have a higher concentration. Reference 55 was a study of ^{60}Co uptake in various soil, plant, and animal materials due to fallout from atmospheric testing. This study showed higher concentrations in both the liver and kidneys of rats. Reference 21 also indicates that ^{60}Co tends to concentrate in the liver.

Reference 56 includes a detailed listing of the equivalent dose per unit intake of various radionuclides by inhalation, including ^{60}Co . This reference indicates that the dose, which is class dependent, is approximately 2,700 rem/Ci (1×10^{-8} Sv/Bq) for Class W and 16,000 rem/Ci (6×10^{-8} Sv/Bq) for Class Y. For ingestion, the equivalent dose per unit intake, is approximately 800 to 1,900 rem/Ci (3×10^{-9} to 7×10^{-9} Sv/Bq), depending on the gastrointestinal uptake fraction, f_1 (0.05 to 0.3). In both cases, the dose is relatively uniform for all included organs. In this reference, Class Y and $f_1 = 0.05$ are for oxides, hydroxides, and trace inorganics. Class W and $f_1 = 0.3$ are for organic complexed compounds and all other inorganics.

^{60}Co is also used extensively in the medical industry to treat various types of cancer. Standard treatments have been developed for cancers of various organs including the bladder,⁵⁷ kidney,⁵⁸ and ovary.⁵⁹ Each of these treatments involves exposure of the affected area with the gamma radiation from ^{60}Co to achieve a specific dose: 5,000, 6,000, and 4,000 rad [50, 60, and 40 Gray (Gy)] for cancer of the bladder, kidney, and ovary, respectively. Another paper reported the use of ^{60}Co for treatment of cancer of the eye.⁶⁰ The typical dose to the cancer was 10,000 rad (100 Gy) and of the 116 patients in the study, only 20 had recurrences of the cancer. While other gamma sources could be used instead, if ^{60}Co is to be used, it is typically done as an external source.

This nuclide is also used outside of the United States for cancer treatment. Reference 61 summarizes experience in the use of ^{60}Co for the treatment of cervical, endometrial, and vaginal cancers in Yugoslavia. Doses were in the thousands of rad for each of these cancers and for either cervical or endometrial cancers, the survival rates were approximately 75%. Some of the short-term side effects were diarrhea, abdominal pain, rectal bleeding, and vaginal stenosis.

Reference 52 reports the results of a study of ^{60}Co removal rates for residents of the Bikini Atoll. These residents were internally contaminated by ingestion of food that contained ^{60}Co from fallout by atmospheric testing. The biological half-life of ^{60}Co has three components, short, intermediate, and long. Based on this population, the long half-life is 124 days for adult males, 160 days for adult females, and 217 days for adolescents. Approximately 90% of the ingested cobalt was estimated to exhibit the long-term biological half-life. In another study, three accidentally contaminated radiation workers were used to measure the elimination rate of various nuclides.⁶² The contamination by ^{60}Co was $1.8 \mu\text{Ci}$ ($6.7 \times 10^7 \text{ Bq}$) of $^{60}\text{CoCl}_2$, ingested by mouth. Analysis of the whole-body scan data indicated a three-component biological removal rate of 0.5 days (33%); 2.7 days (4%); and 59 days (63%), where the numbers in parentheses indicate the relative amount of ^{60}Co in each half-life group. The calculated whole body dose due to this ingestion was 3.2 mrem (0.03 mSv).

In a report by the International Commission on Radiological Protection, a four component biological removal rate equation is presented.⁶³ First, cobalt is assumed to be retained in a transfer compartment with a half-life of 0.5 days. Then, 60%, 20%, and 20% are assumed to be eliminated from the body with biological half-lives of 6, 60, and 800 days, respectively. This same reference indicates that 50% of ingested cobalt will be immediately excreted from the body without absorption. Of the rest, 10% is concentrated in the liver and the rest is uniformly distributed throughout the body.

Elimination rates for inhaled ^{60}Co were reported by Reference 64. Four components for the biological removal rate were measured: 0.5 days (50%); 6 days (30%); 60 days (10%); and 800 days (10%). This report also includes calculated doses for given amounts of ^{60}Co that were inhaled. These were of the order of 0.01 mrem for 540 pCi (1 mSv for 20 kBq) of ^{60}Co intake. Reference 3 lists the inhalation dose factors for various ages of humans. These factors (expected dose per unit inhaled activity) are 32, 19, 11, and 7.5×10^{-4} mrem/pCi for infants, children, teenagers, and adults, respectively.

As a final source for the biological removal rate information, Reference 21 lists the biological half-life for cobalt to be 9.5 days, independent on the body part. This reference also lists 0.021 rem/ μCi (0.0007 Sv/Bq) as the maximum dose to any body organ for inhaled ^{60}Co .

The high gamma radiation strength of ^{60}Co results in relatively large doses due to external exposure to this nuclide. For example, the exposure rates in millirad per hour for a 100 mCi ($3.7 \times 10^9 \text{ Bq}$) ^{60}Co source are 520, 130, 33, and 14 (0.0052, 0.0013, 0.00033, and 0.00014 Gy/h) for an individual who is situated 50 cm, 1 m, 2 m, and 3 m from the source.⁶⁵ For comparison, the exposure rates for ^{137}Cs , another nuclide included in the National Low-Level Waste Management Program Radionuclide Report Series,²⁰ is 130, 33, 8.3, and 3.8 mR/h (0.0013, 0.00033, 0.000083, and 0.000038 Gy/h) for an individual situated 50 cm, 1 m, 2 m, and 3 m from the source.

^{60}Co is also used as an industrial irradiation source for testing the effects of radiation on animals.⁶⁶ In this reference, a radiation research facility is described where ^{60}Co was used to study the effects of low-level, continuous, whole body exposure to mammals. The irradiation took place outside and concern was raised as to whether people in the surrounding areas might have been excessively irradiated due to lack of shielding. The report concluded that the worst case exposure to the public due to use of an encapsulated 190 Ci (7.0×10^{12} Bq) ^{60}Co source was approximately 200 mrem/y (2 mSv/y), which is well within the DOE regulatory limits at the time of facility operation.

The annual limits on intake (ALI) and derived air concentration (DAC) for ^{60}Co are shown in Table 6. The ALI is defined as the annual intake of a radionuclide resulting in a radiation dose to a human (for calculational purposes, the characteristics of the Reference Man are used) equal to the allowable limit. The DAC is defined as that concentration of a radionuclide in air, which if breathed for a work-year would result in an intake corresponding to the ALI (or, in the case of submersion, to an external exposure corresponding to the primary guide for limiting annual dose). DACs are used for limiting radionuclide intake through the breathing of, or submersion in, contaminated air. ALIs are used primarily for assessing doses due to accidental ingestion of radionuclides.

Historically, maximum permissible concentrations (MPC) in air and water have been used to determine safety guidelines for released radionuclide concentrations. Currently, the derived guidelines are presented in terms of ALIs for inhalation or ingestion, and DACs for inhalation (or submersion). For a radionuclide whose derived value does not change from the old definition, the DAC is numerically equal to the MPC value in air. The information in Table 6 applies only to ^{60}Co . In the case of multiple radionuclides released in a mixture, additional guidelines outlined in Chapter 10 of the Code of Federal Regulations,⁶⁷ Part 20 must be followed.

Table 6. Annual limits on intake and the derived air concentrations for ^{60}Co (from Reference 56).

Radionuclide	Component	Ingestion (μCi)	Inhalation ^a
^{60}Co	ALI	500 (0.05) ^b	200/W
		200 (0.3)	30/Y
	DAC	— ^c	7E-8/W ^d 1E-8/Y

a. Clearance from the lung directly to the blood stream or to the gastrointestinal (GI) tract depends upon the chemical form of the radionuclide and is classified as D, W, and Y, respectively, for clearance times of the order of days, weeks, and years. For ^{60}Co , the two listed classifications are Y for oxides and hydroxides and W for all other compounds.⁶⁵

b. The removal class, f_1 for each ALI is in parenthesis. A simple model of the lung was used to describe the translocation and retention of material by the body after inhalation. In this model, 25% of the inhaled activity was exhaled and 25% was deposited in the lower respiratory tract. The 50% that was deposited in the upper respiratory tract was eventually cleared by means of mucociliary processes and swallowed. What happens then depends on whether the inhaled material was in either a soluble or insoluble chemical form. Any soluble material deposited in the lower respiratory tract is assumed to be transferred directly to the blood stream. The activity cleared from the upper respiratory tract and then swallowed, a fraction (f_1), and in the case of ^{60}Co , $f_1 = 0.05$ or 0.3 , depending on the ALI, entered the blood stream via the GI tract. Additional details of this model are described in References 56 and 67.

c. Data are not available.

d. 8E-8 denotes 8×10^{-8} .

CONCLUSIONS

Cobalt-60 has a half-life of 5.2 years and decays by beta particle emission to stable ^{60}Ni . Both high-energy beta particles (maximum energy 1,480 keV, average energy 94 keV) and gamma-ray (energies 1,170 and 1,330 keV) emissions characterize this nuclide.

^{60}Co is produced in the structural steels and other alloys of nuclear reactor vessel and internal components from neutron activation of ^{59}Co , the only stable isotope of cobalt. These reactor components serve as the primary low-level radioactive waste material containing ^{60}Co . However, wide use of ^{60}Co radiation sources also contribute to the low-level radioactive waste inventory for this nuclide. The principal concern surrounding ^{60}Co is in limiting the dose received by persons associated with the decommissioning and dismantling of the reactors, primarily for reactors in service for several decades. If decommissioning is delayed for a long time after reactor shutdown, this nuclide would significantly decay, reducing the personnel dose and making the decommissioning and decontamination activities easier to accomplish.

^{60}Co is commercially available and has been used as an external source of gamma-rays for laboratory use. This nuclide is one of the principal irradiation sources for treatment of cancer in humans.

The chemistry of cobalt is dominated by the outermost two 4s subshell electrons. The principal oxidation state is +2, although several compounds with an oxidation state of +3 can be formed, particularly with organic and other complexes. Cobalt is primarily used to form specific alloys that have good high-temperature strength and corrosion characteristics and that are hard and durable for use in the aerospace, medical, and nuclear industries.

The ability of soil to adsorb ^{60}Co out of the groundwater depends on a number of factors, including pH and the presence or absence of complexing agents. However, in general, cobalt is easily adsorbed by soils and is not easily leached into the groundwater.

The principal source of ^{60}Co generation is in nuclear reactors, where it is produced by neutron absorption via the $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ reaction. This nuclide can enter waste streams through corrosion of stainless steel and Inconel surfaces in nuclear power plants with subsequent discharge with the primary coolant. The amount of ^{60}Co that has reached the environment has been the subject of numerous studies, both experimental and in the field. Since ^{60}Co has such high gamma-ray energies, it is easily detected and has been used to indicate the corrosion and transport of other, less easily detected, radionuclides.

When ^{60}Co comes into contact with the soil and groundwater, most of it will become fixed in the soil and will not migrate appreciably from the original site. Plants and animals can absorb this nuclide from the soil and propagate it into the food chain and several studies of this phenomena have been conducted. Most plants tend to concentrate ^{60}Co in the root systems. When this nuclide is ingested in mammals, much of it is removed within a few days although a significant amount may persist in the body for several hundred days. The amount that remains is generally uniformly distributed in the body, with the exception of the liver, which tends to concentrate the nuclide. The effective removal half-life for this nuclide is dominated by the biological half-life. The biological half-life has been extensively studied, but values among the various studies vary widely. The

biological half-life is complex, indicating several competing mechanisms, and has been characterized with up to four components of different relative fractions and decay constants.

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