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

Volume 13: Curium-242

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

Volume 13: Curium-242

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ABSTRACT

This report, Volume 13 of the National Low-Level Waste Management Program Radionuclide Report Series, discusses the radiological and chemical characteristics of curium-242 (^{242}Cm). This report also includes discussions about waste types and forms in which ^{242}Cm can be found and ^{242}Cm behavior in the environment and in the human body.

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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, niobium-94, and cobalt-60. These radionuclides contribute significantly to the dose estimated during a performance assessment analysis.

This report is Volume 13 of the series. It outlines the basic radiological and chemical characteristics of curium-242, waste types and forms that contain it, and its behavior in environmental media such as soils, plants, water, air, animals, and the human body. Additional reports will be generated for other radionuclides.

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National Low-Level Waste Management Program Radionuclide Report Series

Volume 13: Curium-242

INTRODUCTION

This report outlines the basic radiological and chemical characteristics of curium-242 (^{242}Cm) and examines how these characteristics affect the behavior of ^{242}Cm in various environmental media, such as soils, water, plants, animals, the atmosphere, and the human body. Discussions also include methods of ^{242}Cm production, waste types, and waste forms that contain ^{242}Cm .

^{242}Cm is important from the point of view of low-level radioactive waste disposal primarily because of the radiological daughters produced through the ^{242}Cm decay scheme. Although ^{242}Cm decays with a relatively short half-life (163 days), its radiological daughters, such as plutonium-238 (^{238}Pu) with a half-life of 86 years, can persist for much longer in radioactive waste.

All curium atoms contain 96 protons ($Z = 96$) and various numbers of neutrons (typically $N = 142$ to 155 neutrons) within the atom's nucleus. There are no stable isotopes of curium and all are radioactive. The radioactive isotopes of curium have half-lives ranging from a few minutes to millions of years.¹ Despite the extremely long half-life of some curium isotopes, they do not exist naturally in the environment but may be produced artificially. The first curium isotope to be synthesized, ^{242}Cm , was produced in 1944 by G. T. Seaborg, R. A. James, and A. Ghiorso. They effected the synthesis by bombarding ^{239}Pu with high energy helium nuclei (alpha-particles), according to the following reaction:²

Larger amounts of this nuclide, produced by the prolonged neutron irradiation of americium-241 (^{241}Am), provided material for the first isolation of visible amounts of curium by L. B. Werner and I. Perlman in 1947 according to

The original metallurgy and chemistry research on this manmade element was performed using ^{242}Cm , which has a half-life of 163 days. However, higher mass and longer-lived isotopes, especially ^{244}Cm (half-life of 18 years), ^{247}Cm (half-life of 15.6 million years), and ^{248}Cm (half-life of 370,000 years), are now the principal sources of this element.

The primary source of ^{242}Cm in the environment has been radioactive waste material generated from neutron irradiation of ^{241}Am [ultimately from neutron irradiation of uranium-238 (^{238}U)] in nuclear reactor fuel. This is the principal direct source of this nuclide. However, a metastable state of americium, ^{242m}Am , is also produced by neutron irradiation of fuel materials. This nuclide has a

half-life of more than 150 years and ultimately decays to ^{242}Cm . Therefore, ^{242}Cm is continually produced as a decay product for several hundred years after the fuel from a reactor has been removed and can, at least theoretically, enter the environment during this time. ^{242}Cm enters the environment from the activities associated with nuclear reactor operations and decommissioning and when the sources (such as sources used for remote electric power generation) are being used, manufactured, or disposed.

RADIOLOGICAL CHARACTERISTICS

The most recent and best available information concerning ^{242}Cm reports a half-life of 163 days.^{1,3} The principal means of ^{242}Cm production is via neutron capture (n, γ) interactions with ^{241}Am or multiple neutron capture interactions with ^{238}U or ^{239}Pu .

The decay of ^{242}Cm and its radiological daughters is complex. The principal decay chain from ^{242}Cm to the stable nuclide lead-206 (^{206}Pb) is

This is the most likely decay process based on the principal branch for the decay of each nuclide ground state. For several of these decay processes, there is a competing process. Many of the alpha-decay processes also result in the emission of various energy gamma-rays, and the beta-decay processes result in the emission of various energy beta particles and gamma-rays. In addition, there is a small but finite probability that this nuclide will spontaneously undergo fission, resulting in fission products and neutron emission. Thus, due to the complexity of the decay of ^{242}Cm , the resultant alpha-, beta-, and gamma-spectra (and also neutron spectrum) are also complex and do not lend themselves to a simple presentation. With the possible exception of the ^{241}Pu decay scheme, this is the most complex decay scheme of all of the nuclides included in this report series. With the exception of ^{241}Pu , all of the other nuclides decay either directly to a stable nuclide or reach a stable nuclide with two decays.

No attempt has been made in this study to correlate the potential effects of radiation associated with the nuclide decay listed in Equation (3). Only the effects associated with the direct decay of ^{242}Cm will be included. The types and energies of the radiation associated with the subsequent decay are provided in the references.

The decay of ^{242}Cm results in alpha particles of two principal energies, 6.12 and 6.07 million electron volts (MeV).⁴ Approximately 75% of the time, the higher energy alpha particle is emitted, and 25% of the time, the lower energy particle is emitted. There have been at least four additional alpha energies measured from the decay of this nuclide, but they represent less than 1% of the decay. There are also gamma-rays that result from the decay of this nuclide, with energies ranging from 44 to 890 thousand electron volts (keV). Finally, electron emissions with maximum energies ranging from 22 to 39 keV are also associated with the decay of this nuclide.³ Again, these emissions are only from the direct decay of ^{242}Cm and do not include the emissions from the subsequent decay of the ground states of resultant nuclides, as shown in Equation (3).

Since the released beta particle is usually emitted with an energy less than its theoretical maximum, an antineutrino particle is simultaneously emitted and this particle carries off the energy difference between the released beta particle and the total energy given off by the decay process. Consequently, beta particles are emitted with a continuous energy spectrum ranging from zero to the maximum energy. 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.

As stated above, approximately 75% of the decays of ^{242}Cm result in the emission of an alpha particle with an energy of 6.12 MeV. The range of these alpha particles is approximately 4.7 cm in air. Thus, even a small distance removed from a ^{242}Cm source is sufficient to be shielded from the alpha radiation. The maximum energy beta-ray would be stopped within a range of 2.5 mg/cm² (to get the linear range in a given material, divide this value by the density of the material). Table 1 lists the approximate range of a 39 keV beta particle in various common materials. As seen, it does not require much of these materials to shield the environment from the beta particles associated with the direct decay of ^{242}Cm .

In addition to beta particle radiation, each ^{242}Cm decay results in several relatively high-energy gamma-rays with energies ranging from 44 to 890 keV. This is more energetic than the 660 keV gamma-ray associated with the decay of cesium-137 (^{137}Cs) but less than the 1,330 keV gamma-ray associated with the decay of ^{60}Co . Table 2 illustrates this by listing the half-value layers, or the thicknesses of various materials required to attenuate a beam of 890 keV gamma-rays to one-half of the original intensity. As shown, shielding the environment from ^{242}Cm requires a substantial thickness, as opposed to some of the nuclides in this series, such as nickel-63 (^{63}Ni), which is only a beta emitter that emits x-rays of significantly lower energy.⁵ These results are from Reference 3. Reference 6 lists a large number of gamma-rays resulting from the ^{242}Cm decay, with an energy range from 44 to 1,220 keV and the most probable energy being 44 keV. The high energy x-rays are low probability, which should be taken into account in any disposal analysis.

The decay sequence for ^{242}Cm showing the emission of an alpha particle (principal emission) and associated gamma-rays and beta-rays is illustrated in the following nuclear transformation:

The beta energy is maximum energy listed by Reference 3 as being major radiation. This does not represent the maximum beta energy associated with this decay. The maximum energy was not found in the literature search for this report.

Table 3 lists the radiotoxicity of several important radionuclides, and Table 4 compares the electron energy associated with ^{242}Cm decay together with the maximum and average electron energies associated with electron (beta particle) emitters. Notice that ^{242}Cm is shown in the same radiological group as ^{241}Pu , ^{241}Am , and neptunium-237 (^{237}Np). All of these are actinide metals and each primarily decays by alpha decay. The principal radiological danger for these nuclides results from the high-energy alpha particles emitted during decay. The 6.12 MeV alpha particle, emitted by the decay

Table 1. Comparison of the estimated maximum ranges for a 39 keV average energy beta particle emitted from ^{242}Cm decay for various materials.

Material (description)	Estimated maximum range for a 39 keV β^- (mm) ^a
Air (1 atmosphere pressure)	2
Water	0.0025
Paper	0.002
Wood	0.013
Glass	0.0009
Aluminum	0.0009
Iron	0.0003
Copper	0.0003
Lead	0.0002

a. Estimates are based on the maximum beta particle range data shown in Reference 4 as a function of energy and materials.

Table 2. Half-value layers for the 890 keV gamma-ray emitted from the decay of a ^{242}Cm nucleus.^a

Material	Half-value layer thickness (cm) ^b
Lead	0.73
Iron	1.4
Aluminum	4.0
Stone concrete	5.1
Water	9.3
Air	8.0×10^3

a. The half-value layer for a given material is the thickness of the 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 4.

Table 3. Comparison of the radiotoxicity of several important radionuclides (from Appendix 2 of Reference 7).

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

Table 4. Average and maximum kinetic energies of beta particles and atomic electrons released during decay of several important radionuclides. (Information compiled from data presented in References 1, 3, 4, 8, and 9.)

Radionuclide	Released electron energy	
	Average energy (keV) ^a	Maximum energy (keV)
Nickel-59 (⁵⁹ Ni)	4.1 ^b	~7.7 ^b
Tritium (³ H)	5.7	19.0
Nickel-63 (⁶³ Ni)	17.1	67.0
Curium-242 (²⁴²Cm)	39^c	—
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 ^d
Cesium-137 (¹³⁷ Cs)	195.0	1176.0
Potassium-40 (⁴⁰ K)	541.0	1330.0
Cobalt-60 (⁶⁰ Co)	94.0	1480.0
Phosphorous-32 (³² P)	694.0	1710.0

a. 1,000 keV = 1 MeV. 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. The beta particle energy for ²⁴²Cm is the highest energy, major emission beta group and may not represent either the average or maximum energy.

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

of ^{242}Cm , is more energetic than that emitted by ^{241}Am (5.49 MeV), ^{241}Pu (4.85 MeV), and ^{237}Np (4.78 MeV). Because of the radiological danger resulting from ingestion or inhalation of these actinides, this group is assigned the highest radiological risk. The specific activity of ^{242}Cm is 3,300 Ci/g. The maximum concentration of ^{242}Cm that is acceptable for near-surface disposal without specific U.S. Nuclear Regulatory Commission authorization is 20,000 Ci/g (this corresponds to Class C waste). Class A waste is limited to a 2,000 Ci/g concentration.¹⁰

CHEMICAL AND PHYSICAL CHARACTERISTICS

Curium is a member of the actinide series of the periodic table, which includes actinium, thorium, protactinium, and uranium and the transuranium elements, neptunium, plutonium, americium, berkelium, californium, einsteinium, fermium, mendelevium, nobelium, and lawrencium.^{11,12,13} This series lies between radium and rutherfordium and is chemically similar to the lanthanide series, which is the group of elements between barium and hafnium. In both cases, the series consists of elements whose inner electron shell of 14 "f" electrons is being filled. In the case of the actinides, the 5f shell is being filled, and in the case of the lanthanides, the 4f shell is being filled. This results in two series, each of whose members are chemically similar to a member of the other series. For the case of curium, it is chemically similar to gadolinium in that in both cases the inner "f" shell is half filled. In fact, it is so similar to gadolinium that in the absence of its radioactivity, it could easily be mistaken for this lanthanide element.

All of the actinide elements are chemically similar. They typically form trivalent ions; complex ions and organic chelates; soluble sulfates, nitrates, halides, perchlorates; and sulfides and acid-insoluble fluorides and oxalates.

Curium is unlike any of the lighter elements included in this series in that all of its isotopes are manmade, with none appearing naturally in the environment. Of the 16 curium isotopes, either discovered or postulated, ²⁴²Cm was the first to actually be produced and isolated in the laboratory. This was done by the bombarding ²³⁹Pu with high energy helium-4 (⁴He). Curium was first isolated in 1947 using the isotope ²⁴²Cm in the form of a pure hydroxide.

Curium exists primarily in the +3 oxidation state, with colors ranging from colorless to yellow, in a water environment. Solid compounds include Cm₂O₃, CmO₂, (and oxides of intermediate composition), CmF₃, CmF₄, CmCl₃, CmBr₃, and CmI₃. The +4 oxide ion is unstable in water.

The metal is silvery and shiny in appearance, is chemically reactive, and has two crystalline structures depending on the temperature. The low-temperature crystal structure is a close-packed double hexagonal (alpha state at temperatures less than 1,176°C) and face-centered cubic (beta state at a temperature higher than 1,176°C).¹⁴ The metal may be produced by reducing CmF₃ with barium vapor at high temperature. This metal tarnishes in air and dissolves readily in common mineral acids with the formation of the +3 oxidation state ion. This is an exoergic reaction and evolves approximately 140 kilocalories of heat per mole of dissolved curium.

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

Table 5. Chemical and physical characteristics of curium (from References 15, 16, and 17).

Physical property (units)	Curium data
Melting point (K) ^a	1,615
Boiling point (K) ^a	3,570 ^b
Solid density (g/cm ³)	13.5
Crystal form ^c	alpha—close-packed double hexagonal (lt) beta—face-centered cubic (ht)

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

b. The boiling point is not listed in any of the references as a measured value. Instead, this value was calculated from the thermodynamic data for this element, using the computer program HSC Chemistry for Windows.¹⁸

c. (lt) refers to low temperature or the crystal structure for temperatures below 1,176°C; (ht) refers to high temperature or the crystal structure for temperatures above 1,176°C.

CURIUM-242 PRODUCTION

The structural and fuel 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. Usually, it is the structural materials that are of concern relative to activation by irradiation. However, although the vast majority of the radioactivity associated with the reactor fuel is a direct result of the fissioning process, activation can and does occur in these materials as well. A practical result of this activation is the breeding of fuel (transmutation of nonfissile fuel materials, such as ^{238}U , into fissile material such as ^{239}Pu). Another byproduct of the irradiation of fuel materials is the production of ^{242}Cm by the multiple neutron absorption of ^{238}U , with appropriate subsequent decay. This is the principal production means of this nuclide.

When the neutron source is stopped, the directly produced ^{242}Cm decays with a half-life of 163 days and within a few years is essentially gone. However, there can still be a significant source of this nuclide in spent nuclear fuel due to the presence of $^{242\text{m}}\text{Am}$, also a product of multiple neutron absorption of ^{238}U . $^{242\text{m}}\text{Am}$ is a long-lived isomeric state of ^{242}Am that decays to ^{242}Cm via the following reaction:

Since $^{242\text{m}}\text{Am}$ has such a long half-life (relative to that for either ^{241}Am or ^{242}Cm), after a few weeks following termination of the neutron source, these three nuclides will be in secular equilibrium, where for every disintegration of an americium nucleus, there will be a corresponding disintegration of a curium nucleus. Thus, ^{242}Cm can persist for hundreds of years following reactor shutdown. Also, as mentioned in the introduction and an important aspect of low-level waste, the radiological daughters of ^{242}Cm can persist for long periods of time.

In addition to the production of this nuclide in nuclear reactors, it can also be produced in an accelerator. In fact, the first production of ^{242}Cm was in the University of California's 60-in. cyclotron. Helium-ions were used to bombard ^{239}Pu , forming ^{242}Cm via the following reaction:

Early chemical studies of this manmade element principally used two isotopes, ^{242}Cm (half-life of 163 days) and ^{244}Cm (half-life of 18 years). Subsequent chemical studies were conducted using isotopes with much longer half-lives such as ^{247}Cm and ^{248}Cm , which have half-lives of 1.6×10^7 and 3.5×10^5 years, respectively.¹¹

A study conducted at the Commission of the European Communities - Joint Research Center and the Reactor Research Center in Karlsruhe characterized spent fuel using nondestructive assay.¹⁹ It was concluded that this could be effected by measuring the neutron flux caused by spontaneous fission of the fuel, due mainly to the presence of ^{242}Cm and ^{244}Cm .

Finally, significant quantities of ^{242}Cm were produced and released to the environment during nuclear weapon testing activities.²⁰ However, atmospheric testing was halted in the early 1970s, and due to the relatively short half-life, essentially all of the direct residual activity of this nuclide from weapons testing has decayed away. The underground testing-associated activity of this nuclide is essentially gone, so it is expected that the direct, weapons-associated ^{242}Cm is no longer in the environment. However, as stated above, residual ^{242}Cm may exist from the weapons program due to the decay of $^{242\text{m}}\text{Am}$.

WASTE TYPES AND FORMS THAT CONTAIN CURIUM-242

The total activity of ^{242}Cm that has been deposited in U.S. disposal sites is shown in Figure 1.^a This figure contains data for 1986–1994, inclusive. The disposal of this nuclide peaked in the late 1980s and early 1990s, and more than half of the total activity of this nuclide was deposited during 2 years, 1989 and 1991. Less than 1 Ci has been deposited since 1992 in these sites. This section includes a discussion of the sources of ^{242}Cm that make up these deposits.

Nuclear Reactors

Although not as wide-spread as for some nuclides (for example ^{60}Co)²¹, there are some applications of ^{242}Cm . For example, this nuclide has been used as the power source for an isotopic power reactor.²² In this application, a practical power density of 150 watts/cm³ can be achieved, which is among the highest densities for this type of application. This nuclide was used in the design of the SNAP-11 (Systems for Nuclear Auxiliary Power) generator, which was to be used in the Surveyor experiment (lunar surface use). However, the rapid development of solar cell technology superseded the use of this generator.

The principal production means for this nuclide is in nuclear reactors, where the actinides in the fuel (principally ^{238}U and ^{239}Pu) are transmuted into ^{242}Cm by multiple neutron absorption. In general, this nuclide is retained in the fuel rods and does not enter the environment. However, entry into the environment can occur if a severe reactor accident occurs, such as the one at the Chernobyl reactor, or if some of the fuel rods develop leaks and the curium enters the primary coolant. In the latter case, ^{242}Cm can be removed from the primary coolant by filters and/or cleanup resins and enter the environment coupled with these media. Then, this nuclide can contaminate various environmental ecosystems until it has decayed away.

Other historical uses of this nuclide may exist, but none were found in the literature search. In any case, the short half-life of this nuclide means that it will decay to insignificant levels within a relatively short time.

Medical, Academic Institutions, and Commercial Waste

There are no known medical uses for this nuclide, either for diagnosis or treatment of diseases (this was confirmed by a communication with personnel at the American College of Radiologists).^b This nuclide has been used in some laboratory studies (for example, in early laboratory studies of the chemistry of curium), although these are limited. If sources of $^{242\text{m}}\text{Am}$ were made for laboratory/medical use, these would also be a source of ^{242}Cm . Although another curium isotope is available from standard commercial sources (^{244}Cm is available from two commercial sources^{23,24}), no listing for ^{242}Cm was located.

a. Data taken from the Manifest Information Management System data base monitored by the National Low-Level Waste Management Program, December 1994.

b. Private communication between C. Sperry (American College of Radiologists) and J. P. Adams (Idaho National Engineering Laboratory), May 15, 1995.

Cm-242 Disposed at All Disposal Sites

Figure 1. Total activity of ²⁴²Cm deposited in U.S. disposal sites.

An older reference discussed general guidelines for fabrication of laboratory equipment.²⁵ This reference included guidelines for handling ^{242}Cm in a laboratory. The use of stainless steel and rounded corners is recommended and a comparison between the handling of this nuclide and that of ^{238}U (both alpha emitters) is made. The point is made that ^{242}Cm has a much higher specific activity (for example, a 1 mCi source of ^{238}U would comprise of the order of 1 kg of mass whereas a 1 mCi source of ^{242}Cm would comprise only 0.25 mg) and that, therefore, the handling techniques would be much different.

BEHAVIOR OF CURIUM-242 IN THE ENVIRONMENT

Curium in Soils

Understanding the behavior of radioactive materials such as ^{242}Cm in the soil is important in assessing the possibility of transport of these radionuclides through the biosphere.²⁶ 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.²⁶ The four parameters, in order of decreasing importance, are (a) soil retention, (b) annual precipitation, (c) soil texture, and (d) 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 curium concentration in the soil (microgram centimeters per gram of soil), and C_l is the curium concentration in the groundwater (microgram centimeters per milliliters of liquid). Therefore, the units of K_d are milliliters per gram (i.e., milliliters 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 curium 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 curium 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 as closely 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.

One study measured the diffusion of curium in various types of soils, including silt/loam, loamy sand, and sand.²⁰ There was a wide range in K_d values in these experiments. The values ranged from 98 to 51,900 mL/g. The authors state that this range is not solely due to variations in the physical and chemical properties of the soils but also partially due to variations in the experimental technique. (In a separate study, also included in this reference, the range of K_d values was from 71 to 11,000 mL/g—this time for the clay fraction of Miami silt loam.) The authors further state that there are no available data of the distribution and mobility of curium in soil under field conditions. However, it is expected that curium will act identically to americium and the other higher actinides so much of its behavior can be inferred from the behavior of these other elements. In this study, the diffusion coefficients of curium were also inferred from the data. These values were more uniform, ranging from 6×10^{-10} to 2.1×10^{-11} cm²/s. Based on these diffusion coefficients, the movement of

curium in soil, due to diffusion, is calculated to be of the order of 1 cm every 1,000 years. Curium, thus, does not diffuse much and movement in soils is likely to be dominated by adsorption on the soils and the mobilities of the soil particles to which it is adsorbed. The formation of soluble complexes and adsorption onto relatively mobile particles would increase its mobility.

Curium chemistry in soils is dominated by the +3 oxidation state. Its soil chemistry is similar to both americium and neodymium, which could be used to infer the long-term behavior and distribution of curium. Curium forms stable complexes with EDTA as well as with organic acids such as citric, tartaric, and lactic acids.²⁰

There are few studies of the adsorption behavior of curium in soils. Of those which do exist, none are field studies and the majority are in the form of batch equilibrium experiments. In one study, conducted using ^{242}Cm , the adsorption of curium by several clays was measured in a NaCl solution at neutral pH. This study indicated that adsorption was dominated by precipitation rather than by ion exchange. A second study, using silt loam, also indicated that ion exchange was not an important adsorption mechanism.²⁰ This was further confirmed by a study conducted at the Oak Ridge Laboratory.²⁷ The authors indicated that the behavior of curium in laboratory studies of clay slurries was dominated by complexes of curium. The movement of curium through these slurries indicated that its mobility in soils would be dominated by filtration and surface adsorption rather than by ion exchange processes.

A study was made of the effects of the nuclear reactor accident in Chernobyl in 1986 by the Finnish Center for Radiation and Nuclear Safety.²⁸ This study concluded that although ^{242}Cm was the dominant alpha-emitting transuranic nuclide in the fallout from Chernobyl, it represented only 0.02% of the fallout due to ^{137}Cs , a dominant gamma emitter. Samples were taken over several periods in the vicinity of Helsinki (south-central Finland). Most of the deposition of ^{242}Cm occurred during the time between May 23 and June 2, resulting in a surface contamination of 210 mBq/m² [1 becquerel (Bq) is equal to 1 disintegration per second (d/s) as compared to 1 curie (Ci), which is equal to 3.7×10^{10} d/s]. Other samples were taken in the Kuhmo region (east-central Finland—nearer to the reactor) between April 1 and May 5, and this sample had a surface contamination of 14,000 mBq/m². The report concluded that the distribution of fallout in Finland was uneven. Even within this conclusion, the distribution of ^{242}Cm was not uniform (i.e., the ratio of this nuclide to other nuclides, either other actinides or other nonactinides, varied greatly from site to site). For example, the ratio of surface contamination by ^{242}Cm to that by $^{239,240}\text{Pu}$ varied from 0.42 to 160, a range of nearly 400. The ratio of ^{242}Cm to ^{137}Cs contamination varied from 0.017 to 0.02%.

Another study was directed to the classification of radioactive fallout in the immediate vicinity of the Chernobyl reactor.²⁹ Approximately 50 soil samples were taken and analyzed for several radionuclides from the reactor and there was a relatively wide range of contamination levels in the soil. The range of ^{242}Cm activity was 0.01 to 6.9 Bq/g, a range of more than 50.

A study of the fallout in Germany from the accident in Chernobyl was jointly sponsored by the University of Mainz and Institute for Heavy Ion Research of the Federal Republic of Germany.³⁰ Based on the measurements from this study, it was estimated that about 3% of the actinide elements were released from the fuel, with most of the nuclides released in the form of dispersed fuel. Although no actual numbers were presented, it was stated that ^{242}Cm was the most dominant alpha emitter of the material released from the reactor.

The Department of Radiation Physics at the University of Lund studied the fallout in Scandinavia caused by the Chernobyl accident.³¹ The dominant alpha emitter in the fallout from this accident was identified to be ^{242}Cm , which was more than 14 times the activity due to $^{239,240}\text{Pu}$. It was concluded that all of the curium was due to the accident at Chernobyl.

In addition to the other mentioned soil contamination studies associated with the Chernobyl accident, one study also looked at the particle size distribution for the various fallout products.³² In this study, soil samples were taken, in the northwest direction from the reactor, from five different regions. The soil layers from 0.005 to 0.01 m in depth were collected and separated into particle size fraction. The soils were sandy and had little humus. In general, the highest activities of actinides, including ^{242}Cm , were found in the smallest particles, which would be expected to be the most mobile soil particles. The results from all five soil samples were listed in the reference and in every case the ^{242}Cm activity peaked for particle sizes in the range from 0.005 to 0.05 mm.

Curium in Water

Reference 20 includes a summary of the behavior of curium, including ^{242}Cm , in aquatic ecosystems. The concentration of curium isotopes in water depends on several parameters, concentration of the nuclide in the radioactive waste, distance from the point of discharge, and speed of removal from the water (which, in turn, depends on the physical and chemical characteristics of the released curium and of the water). ^{242}Cm is of greater relative importance in aquatic ecosystems than in terrestrial ecosystems because more of this nuclide is discharged to the environment in liquid wastes. Typically, curium is present in water in insoluble form, which means that it may be transported with the water or may deposit out, depending on the size of the particles and fluid velocities. However, sometimes it will be in soluble form, usually due to having formed soluble curium complexes. Although not confirmed in experimental studies, the chemical form of curium in seawater is usually assumed to be in the +3 oxidation state. The adsorption behavior of curium strongly depends on pH. The log of the K_d values increases linearly between pH = 4 and 7, plateaus, and then increases between pH = 8 and 10. The concentration of curium in waters can change seasonally, with a significant decline in concentration in spring and early summer. This behavior may have been due to uptake by algae in the water, although identification of a specific mechanism was not possible.

A study was made of the activity of certain actinides and beta emitters in the process water used in the Loviisa VVER-440-design nuclear power plant in Finland.³³ This study concluded that curium is approximately evenly distributed between the cation and anion resins in the normal operation state. The total radioactivity of ^{242}Cm in the process water was 0.7 MBq, compared with 3.1 MBq for $^{239,240}\text{Pu}$. ^{242}Cm was detected in two of the three primary coolant samples taken from this plant in this study. The concentrations ranged from < 2 to 1.0 kBq/m³ in these samples, taken during 1983 and 1984. The concentration range for the anion exchange resin samples was from < 2 to 1,050 kBq/m³ and in the cation exchange resin samples, from 3 to 380 kBq/m³. The concentrations in the mixed resin bed samples ranged from 63 to 1,420 kBq/m³. This report also includes a determination of the ratio of ^{242}Cm to $^{239,240}\text{Pu}$ in the ion exchange resin bed samples. This ratio ranged from 0.03 to 2.33, indicating a two-order of magnitude range in the relative concentrations. These values are much lower than other reported ratios, which ranged from 1.5 to 127 for VVER-440 reactors.³⁴

A similar study was made of the Doel II and III pressurized water reactors.³⁵ Evidence was found for the presence of ^{242}Cm in samples obtained during steady state operations, after reactor shutdown, and during the soluble activity peak. However, most of the alpha-emitting activity had an energy of 5.3 MeV, as opposed to that for ^{242}Cm , which has a 6.13 MeV alpha energy. Overall, the total alpha activity concentration ranged from 3×10^{-11} to $1.6 \times 10^{-9} \mu\text{Ci/mL}$ during normal operations where there was no evidence of failed fuel. If failed fuel was present, the levels raised to a range of 2.2×10^{-9} to $6.3 \times 10^{-9} \mu\text{Ci/mL}$. The majority of this activity was found to be insoluble under normal operating conditions. The solubility increased during shutdown, when the concentrations of gamma-emitting species also increased. The shutdown concentration of ^{242}Cm ranged from 1.57×10^{-10} to $1.73 \times 10^{-8} \mu\text{Ci/mL}$ and the normal operations concentrations varied from 1.26×10^{-10} to $4.0 \times 10^{-9} \mu\text{Ci/L}$.

Scientists at the Woods Hole Oceanographic Institute performed an environmental study of the releases of radionuclides from three pressurized water reactors, Millstone Point 1 and 2 and Maine Yankee, including the release of ^{242}Cm .³⁶ The Millstone Point 1 reactor discharged this nuclide at a rate of 30 to 100 nCi/month, with the exception of a brief time in early 1977 when more than 3,000 nCi/month were discharged. A new waste treatment process was installed at Millstone Point, which greatly reduced the discharge. Millstone Point 2 discharged at a rate of a few to 40 nCi/month. There were no measurable discharges of this nuclide from Maine Yankee.

The concentrations of various actinides in the primary coolant of a boiling water reactor was the subject of a study by the Institute for Radiation Protection in Neuherberg, Germany.³⁷ The ratio of ^{242}Cm to $^{239+240}\text{Pu}$ ranged from 0.13 to 100. The principal concern is that if there are actinides in the primary coolant of a reactor, it may be expected that they will be transported via primary leakage into waste water and airborne effluents and injected into the environment.

An environmental study was made of the radionuclides in the effluent from the Argonne National Laboratory that was discharged into streams in the vicinity.³⁸ The maximum concentration of ^{242}Cm in the Sawmill Creek was $< 1 \times 10^{-17} \text{ Ci/cm}^3$.

Personnel at the Woods Hole Oceanographic Institute conducted an investigation into the presence of fission products and actinides in the Black Sea caused by the accident at the Chernobyl RBMK reactor.³⁹ Among the nuclides included in this study was ^{242}Cm . One hundred to one thousand liter seawater samples were taken from a variety of locations in the Black Sea and analyzed for alpha emitters using standard spectrometric analysis techniques. The range of ^{242}Cm concentrations was 0.4 to 34 mBq/m³. This study concluded that the measured curium originated from the Chernobyl reactor accident.

Scientists from the German Hydrographical Institute, Hamburg, Germany, performed a study of the transfer of actinides from the English Channel into the North Sea.⁴⁰ Large volume (60 to 200 L) samples of seawater were collected from 13 different locations in the channel and North Sea in 1975. Only a small fraction of these samples contained detectable concentrations of ^{242}Cm and a typical concentration was 7 fCi/kg. The ratio of ^{242}Cm to $^{239+240}\text{Pu}$ activities was of the order of 0.2 to 0.7 and the paper concluded that these actinides originated from the La Hague fuel reprocessing plant.

During the era of atmospheric testing, studies were initiated of the behavior of transuranic radionuclides in Lake Ontario. Following the termination of the atmospheric testing, these studies

were continued because of the recognized potential for leakage from the nuclear fuel reprocessing facility at Springville, New York. An update to these studies was performed by scientists at the Woods Hole Oceanographic Institute in the late 1970s.⁴¹ Sediment samples were taken and analyzed for the presence of the actinides. The concentration of ²⁴²Cm ranged from < 0.05 to 0.11 pCi/kg of sediment.

A summary of several studies of curium behavior in sediments is included in Reference 20. Curium is believed to be rapidly removed from a water column by deposition in sediments. The values for K_d vary widely, depending on the specific conditions for the experiment. Some values are of the order of 100 mL/g and others as high as 10,000 mg/L. The reason for the different units is not discussed. The equilibrium K_d values increase significantly with increasing pH.

Curium in Plants

Published information on the occurrence and distribution of curium in plants is restricted in scope. There are few data from field studies. Most of the relevant data are derived from experiments where the only method of uptake is via the roots. Often, experiments designed to investigate the effects of different factors (e.g., soil chemistry, plant species) have experienced analytical problems and, therefore, the results are not conclusive.²⁰

A couple of field studies are included in this reference. During the 1960s, the curium content of lichen was measured on a regular basis in Sweden. This was during the period of intensive atmospheric testing of nuclear weapons and the purpose of this testing was to determine the effects of fallout. Typical concentrations of ²⁴²Cm were from 0.003 to 0.015 pCi/kg for this nuclide. Another study was conducted, this time using vegetation growing on the shore of radioactive waste ponds near a test reactor at the Idaho National Engineering Laboratory. The concentrations ranged from 0.1 to 14 mBq/g, depending on the species studied. Additionally, it was concluded that the dominant contamination mechanism was from surface deposition, not root uptake.

Reference 20 includes a discussion of the effects of various soil factors on the uptake of curium into various types of plants. For example, the presence of large amounts of organic matter in the soil will greatly reduce the plant concentration levels of curium because the curium preferentially is adsorbed to the organic matter, reducing the amount available for plant uptake. The presence of lime in the soil also reduced the uptake into plants. The lime increased the pH of the soil, resulting in nearly complete hydrolysis and adsorption of curium onto soil solids or the formation of insoluble carbonate complexes that were not taken up into the plants. However, adding a complexing agent, either DTPA or, to a much lesser extent, EDTA, with the lime increased the concentration factor significantly, sometimes more than two orders of magnitude. However, these were laboratory experiments where the DTPA was added to the curium nitrate solution before it was added to the soil. If the DTPA were applied to curium-laden soil, the effects would probably be much less. Plants used in these studies include tumbleweed, rice, barley, bush bean, soybean, wheat, corn, and clover.

The studies included in Reference 20 also drew conclusions regarding the distribution of curium among the various (aboveground) plant parts. Measurements of curium concentration in the roots were not included. In general, the concentrations were highest in the leaves, followed by the stems, chaff, and seed. Thus, ingestion of leafy vegetables would result in the highest transfer of curium to humans and grains, the least. Fruits are also believed to have high curium concentrations. Where

curium is chemically bonded with a complexing agent, more of the curium is available for uptake into plants.

A fairly early study of the behavior of curium in plants was conducted by the Oak Ridge National Laboratory.²⁷ This study used both beans and grass. The study concluded that the curium concentrations in the grass samples did not exceed the control sample concentrations (which were grown with no curium contamination). However, the bean plants exhibited significant activity in the foliage and stem tissues. An additional observation was made by relocating bean plants from the soil directly into the curium-laded solution. Some of the plants had their roots severed before being placed into the solution. The uptake of curium into the plants was actually enhanced in those plants without roots. The authors concluded that any mechanism to discriminate against curium uptake in plants is probably in the roots and that removal of the roots also removes this mechanism.

Researchers at the Pacific Northwest Laboratory have investigated the effects of aging on the uptake of curium into various plants.⁴² In this lysimeter experiment, cheat grass, peas, barley, and alfalfa plants were grown in an environment that included curium. (Note, this experiment was conducted using ^{244}Cm , rather than ^{242}Cm , but since chemical effects should dominate, the behavior of both nuclides should be similar.) The uptake ratio [ratio of vegetation concentration of curium (picocuries/gram) to the curium in the lysimeter (millicuries)] was 65 to 80 for cheat grass; 0.16 to 0.9 for barley seed and 10 to 39 for barley stem-leaf; 3.0 to 4.7 for pea seed and 4.8 to 6.3 for pea stem-leaf-pod; and from 1.5 to 7.8 for alfalfa. Overall, the uptake ratio was approximately 10 times higher for curium than for plutonium.

A study was recently conducted by scientists at the Westinghouse Savannah River Company to investigate the uptake of curium into vegetation adjacent to the seepage basins at the laboratory.⁴³ This report concluded that the concentration of curium decreased significantly with distance from the surface of the soil, indicating that curium is relatively immobile in this soil. There was a slight difference in concentrations between the leaves and wood in the trees, with higher concentrations in the wood. Also, curium concentrations in hardwood trees were about twice as high as in pine. The concentration factors ranged from 0.005 to 0.02, which values are in the range of previously reported numbers in the literature.

The accident in the Chernobyl reactor prompted numerous scientific investigations into fallout phenomena, including one conducted by the Institute for Radiation Protection in Neuherberg, Germany.⁴⁴ This study looked at the uptake of various radioactive reactor byproducts in grass growing in South Bavaria, Germany, where the deposition of Chernobyl-derived radionuclides was comparatively high. Grass samples were collected in May 1986 in an area near Boeblingen, approximately 60 km west of Munich. The activity of ^{242}Cm in these samples was 3.0 Bq/kg. This activity was 20 times higher than that for $^{239+240}\text{Pu}$ and was nearly 40 times higher than that for ^{238}Pu .

The global fallout of curium was studied by scientists in 1978 at the University of Lund in Sweden.⁴⁵ Their study involved measuring the concentration of ^{242}Cm in a specific lichen (*Cladonia alpestris*), collected from various locations in central Sweden. The ^{242}Cm activity measured in these samples is actually that produced by the decay of $^{242\text{m}}\text{Am}$, which decays with a two-step decay process and a half-life of 152 years to ^{242}Cm . The concentrations of ^{242}Cm in lichen varied about an average value of 0.006 pCi/kg during measurements taken in the 1960s.

Curium in Air

From a biological hazard standpoint, the most important pathway for actinides to contaminate humans is inhalation. For example, the maximum dose to any body organ (rem) per microcurie inhaled is 57. The maximum external dose range from a point source (rem per hour) per microcurie source is $<1 \times 10^{-8}$.²² Ingestion is less hazardous than inhalation because the uptake from the gastrointestinal tract is relatively small.³¹ Fallout from the Chernobyl reactor accident was studied by scientists at the Lund University in Sweden. They concluded that ^{242}Cm was the principal alpha emitter in the fallout from this accident. Precipitation concentrations were measured in Southern Europe (4,000 mBq/m³) and in South Sweden (500 mBq/m³). Air samples were taken and measured for this nuclide. The concentrations were as high as 3,000 $\mu\text{Bq}/\text{m}^3$ in South Finland, compared to 250 $\mu\text{Bq}/\text{m}^3$ for Denmark and South Sweden. The mean residence time for this nuclide was generally one to three days in air and 24 days in rain. There was some question as to whether the measured concentrations were due to Chernobyl fallout or residual ^{242}Cm from the decay of $^{242\text{m}}\text{Am}$ from the fallout of earlier atmospheric tests. However, the ratio of ^{242}Cm to $^{239+240}\text{Pu}$ would be expected to be in the range of 0.004. In these tests, the ratio was 14, indicating the presence of original ^{242}Cm .

Reference 28 discusses the fallout from the Chernobyl accident. The authors concluded that ^{242}Cm was the dominant alpha-emitting transuranic nuclide in the fallout from this accident. However, they also concluded that overall the concentrations of these transuranic elements comprised only a small fraction of the total fallout—the total activity of ^{242}Cm in the fallout was only 0.01% of that due to ^{137}Cs . Most of the ^{242}Cm deposition occurred between May 23 and June 2, 1986, and resulted in a surface contamination level of 210 mBq/m².

An environmental study was made of the radionuclide releases from the Savannah River Plant in 1981.⁴⁶ During 1981, approximately 1.6×10^{-4} Ci of $^{242+244}\text{Cm}$ were released, primarily in particulate form, into the atmosphere. The study included a dose assessment of all of the radionuclides released from the plant and concluded that less than 0.03 mrem/year of dose would result from the release of the curium nuclides (actually, the dose due to the curium nuclides was grouped into the dose from several of the released radioactive species and this number represents the dose from all of these except ^3H , ^{14}C , and argon-41 (^{41}Ar), which were the principal airborne release components).

BEHAVIOR OF CURIUM-242 IN THE HUMAN BODY AND IN ANIMALS

This section summarizes several studies of the behavior of ^{242}Cm in the human body and in animals. Since ^{242}Cm is principally an alpha emitter, the human hazard from this nuclide is dominated by internal dose when the nuclide is either ingested or inhaled. Of these two, inhalation is the more important method.⁴⁷ A number of factors may influence the dose to the lung and other tissues and the subsequent biological effects, including chemical form, specific activity, and particle size distribution.

Reference 20 contains an extensive summary of the behavior of curium isotopes, including ^{242}Cm in animals and humans. One conclusion is that the isotopes of curium are metabolized in humans in a manner similar to americium. Thus, much can be inferred about curium behavior in the human body based on the extensive data base for americium. Some general observations mentioned in this reference include (a) the fractional gastrointestinal absorption is low, typically less than 10^{-3} in adults (both humans and animals); (b) curium and the higher actinides (e.g., berkelium, californium, fermium, einsteinium) behave more like americium than like plutonium; (c) and data indicate that curium initially deposits on bone surfaces and is only slowly redistributed into the volume of mineral bone. Specific information in this reference to ^{242}Cm indicates that the fractional gastrointestinal absorption is approximately 3×10^{-4} for both soluble and oxide forms. After inhalation of ^{242}Cm (in the nitrate form), the percent that was redistributed to the bone grew from 6% after 1 day to 20% after 3 months. The removal rate data for rats (following inhalation of monodisperse aerosols) indicate that up to 85% of the initial body burden is eliminated in feces with a half-life of 1 day and the rest is eliminated with a half-life of about 20 days. Other studies, also summarized in this reference, indicate half-lives between 0.8 and 4.0 for the initial reduction, followed by 47 to 94 days for the longer value. The fractions corresponding to these two components are approximately 85 and 15%, respectively.

Reference 20 also discusses distribution of curium isotopes within the body. In rats, at 1 day following intermuscular injection, less than 10% of the total injected curium had been transported from the injection site. Of that transported, approximately 50% was located in the liver, and 20% in the bones. The remainder was removed via urine. After 45 days over half of the original injected curium had been transported from the injection site. Of this, 41% was in the bone, 30% in the urine, 6% in the liver, and 20% in feces. Other animals included in curium studies are baboons, goats, and cows. In these animals, the initial concentration seemed to favor the liver, kidneys, and skeleton. Only limited data were reported on the behavior of curium in humans due to accidental exposure.

Scientists at the Nuclear Research Center in Karlsruhe, Germany, performed a study into the effectiveness of two chelates in removing ^{242}Cm from contaminated rats. Specifically, this study examined the relative effectiveness of CaDTPA and ZnDTPA in curium removal. This was done because at the time using CaDTPA was the preferred method of curium removal and this chelate was relatively toxic. If ZnDTPA could be shown to be effective in curium removal, this would be preferred because it is less toxic. The experimental approach involved injecting rats with ^{242}Cm in the form of a citrate. After various delay times, either CaDTPA or ZnDTPA were injected and the rats were monitored as to the curium removal rate. The initial curium distribution in the rats was determined to be primarily in the skeleton and liver, with approximately equal amounts in each. For the time frame immediately following injection of the chelates, CaDTPA was shown to be superior in removing curium from the body. However, this advantage was only transitory and for prolonged

treatment, ZnDTPA is equally as good. The study also showed that even after the curium has been deposited in the liver, it can still be removed using either chelate.

Reference 20 also includes some information regarding the distribution of ^{242}Cm in rats following intravenous injection. The curium is located primarily in the liver and skeleton 6 days after injection and with no specific treatment to remove the nuclide. By day 13, a significant fraction of the liver burden was removed by natural body processes assisted with a saline injection. If the rats were treated with a chelate (either CaDTPA or ZnDTPA), the liver burden was significantly reduced (by more than 90%), but the skeleton burden remained nearly constant. There was not significant deposition in other tissues.

Another study using rats was performed by researchers of the National Radiological Protection Board in Harwell, England.⁴⁸ In this study, the retention and translocation of two forms of curium (nitrate and citrate) were measured after deposition in the three anatomical regions of the respiratory system, namely, the nasopharyngeal, tracheobronchial, and pulmonary regions. These two chemical forms are classed as "W" compounds (i.e., retention in the pulmonary compartment is of the order of weeks). The study concluded that there is significant translocation out of the lung, especially for the citrate form. The nitrate form remained in the lung in significant amounts, even after 1 week following deposition. However, in another study, it was determined that curium nitrate cleared the lungs much more rapidly than plutonium nitrates.⁴⁹

Concentrations of various radionuclides were measured in duck populations that stayed for prolonged times on radioactive leaching ponds on the Idaho National Engineering Laboratory.⁵⁰ First, the ^{242}Cm concentrations were measured in the water, plankton, periphyton, and sediments. These concentrations were 4.8×10^{-5} , 0.12, 1.1, and 0.02 Bq/g, respectively. Fourteen mallard ducks were used in this controlled study. After letting the ducks feed on the pond for either 75 or 145 days, they were killed and samples were taken from the bones, gastrointestinal (GI) tracts, muscles, lungs, livers, and feathers and analyzed for ^{242}Cm content. Measurable concentrations of this nuclide were found only in bone, GI tract, and feather samples, with the highest concentration in the GI tract and feather samples. All other samples were below the detectable limits for this nuclide.

Reference 36 includes a study of the uptake of various radionuclides due to the effluent released from the Millstone Point reactors. The researchers measured between 3 and 9 dpm/kg of radioactivity in oysters harvested in the vicinity of this plant.

Reference 49 is a study of the biological effects of, among other nuclides, ^{242}Cm in rats and dogs. This study concluded that all of the transuranics, including the curium isotopes, tend to translocate from the lung to the bone and liver, and to a lesser extent, to the spleen and kidney. For example, in dogs that inhaled curium oxide aerosols, the curium was relatively uniformly distributed among the lung, liver, bone, and muscle 1 month after exposure. Additionally, in studies of pregnant rats, it was shown that the placenta and placental membranes are an effective barrier to the transfer of curium from the mother to the fetus. It would take high quantities of curium in the mother before appreciable contamination of the fetus would occur. The biological hazard of curium isotopes seems to be greatest in the bone. Osteogenic sarcomas were measured as a direct result of curium exposure in mice, rats, and dogs. However, these studies used ^{244}Cm instead of ^{242}Cm and these results may not be directly applicable to the latter.

As stated earlier, studies of the behavior of ^{242}Cm in the human body are not numerous. However, a few do exist and are discussed here. A human-based study was performed by researchers at the National Radiological Protection Board in Chilton, United Kingdom.⁵¹ Five human volunteers were administered small amounts of ^{242}Cm in citrate form and the GI absorption was measured. The fractional absorption was measured to be approximately 2×10^{-4} . The authors conclude that the fractional absorption is somewhat less in humans than in rats.

An accident resulted in contamination of a technician at the European Institute for Transuranium Elements in Karlsruhe, Germany.⁵² The technician was preparing targets for a mass spectrometer when some ^{242}Cm escaped, contaminating the laboratory air. The average concentration of the curium in the air was of the order of 10^{-9} Ci/m³. Measurable activities of curium were detected in the feces and urine samples, ranging from <0.1 to 50 pCi/g. Measured contamination of the nose and pulmonary tract were 500 and $<6,000$ pCi, respectively. The authors further stated that the biological half-life is 360 days, which combined with the radiological half-life of 163 days results in an overall half-life of 110 days.

Scientists at the National Radiological Protection Board in Harwell, United Kingdom, have conducted an investigation into the development of chromosome changes caused by alpha exposure.⁵³ In this study, human blood samples were irradiated by alpha particles from ^{242}Cm , and the average number of mutations (dicentric) per blood cell were measured as a function of dose. It was shown that the dose-effect curve is linear up to 400 rad exposure.

Reference 54 contains interesting information regarding the distribution of and subsequent dose to various human body parts caused to the intake of ^{242}Cm . The principal doses due to inhalation are in the bones and lungs. If the nuclide is ingested, the principal dose is in the bones and the lungs are not affected appreciably.

The annual limits for intake (ALI) on ^{242}Cm and the derived air concentration (DAC) for ^{242}Cm are shown in Table 6. The ALI is defined as that annual intake of a radionuclide that would result 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, thus, 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 ^{242}Cm . In the case of multiple radionuclides released in a mixture, additional guidelines outlined in the Code of Federal Regulations, Part 20 of Title 10⁵⁵ must be followed.

Table 6. Annual limits on intake and the derived air concentrations for ^{242}Cm (from Reference 56).

Radionuclide	Component	Ingestion	Inhalation ^a
^{242}Cm	ALI (μCi)	54 (5×10^{-4}) ^b	0.3/W
		81 (5×10^{-4}) (bone)	0.3/W
	DAC ($\mu\text{Ci/mL}$)	— ^c	1.1E-10/W ^d

a. Clearance from the lung directly to the blood stream or to the GI tract depends on 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 ^{242}Cm , the classification is W.

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 insoluble activity is cleared from the upper respiratory tract and then swallowed; a fraction (f_1) enters the blood stream via the GI tract. In the case of ^{242}Cm , $f_1 = 5 \times 10^{-4}$. Additional details of this model are described in References 57 and 55.

c. Data not available.

d. 8E-8 denotes 8×10^{-8} .

CONCLUSIONS

^{242}Cm has a half-life of 163 days and decays by alpha particle emission to ^{238}Pu . After a combination of 13 alpha and beta decays, the stable ^{206}Pb nucleus finally results. High energy alpha particles, medium energy gamma-rays, and low energy beta particles are emitted when this nuclide decays. The total particle and photon spectrum is complex because of the complex decay scheme.

^{242}Cm is important from the point of view of low-level waste disposal primarily because of the radiological daughters produced through the ^{242}Cm decay scheme. Although ^{242}Cm decays with a relatively short half-life (163 days), its radiological daughters, such as ^{238}Pu with a half-life of 86 years, can persist for much longer in radioactive waste.

The principal source of ^{242}Cm generation is in nuclear reactors, where it is produced by multiple-neutron absorption of nuclear fuel constituents such as ^{238}U and ^{239}Pu . Upon reactor shutdown, this nuclide quickly decays away and the original inventory disappears. However, this nuclide is also the decay daughter of ^{242}Am , which has a half-life of 152 years and, therefore, ^{242}Cm will persist in spent nuclear fuel for a long time.

There are no naturally occurring isotopes of curium as it is a totally manmade element. Although ^{242}Cm was the original curium isotope produced, several other isotopes have been produced and are also available.

Some laboratory usage of ^{242}Cm has occurred (for example, early laboratory studies of the chemistry of this manmade element), but currently there are no known medical uses for this nuclide, either for diagnosis or treatment of diseases.

There are some applications of ^{242}Cm . For example, this nuclide has been used as the power source for an isotopic power reactor.²² In this application, a practical power density of 150 watts/cm³ can be achieved, which is among the highest densities for this type of application. This nuclide was used in the design of the SNAP-11 (Systems for Nuclear Auxiliary Power) generator, which was to be used in the Surveyor experiment (lunar surface use). However, the rapid development of solar cell technology superseded the use of this generator.

The chemistry of curium is dominated by the half-filled inner 5f subshell. The principal oxidation state is +3, although a limited number of compounds exist with other oxidation states. This element has an analogue in the lanthanum series of the periodic table. The lanthanide most similar to curium is gadolinium, which has a half-filled 4f subshell.

The ability of soil to adsorb ^{242}Cm out of the groundwater depends on a number of factors, including pH and the presence or absence of complexing agents. However, in general, curium is easily adsorbed by soils and is not easily leached into the groundwater.

The principal radiological hazard associated with this nuclide is due to its high energy alpha particles. Since these alpha particles do not penetrate materials easily, external exposure to this nuclide does not pose a high risk. The principal risk is due to inhalation of this nuclide. When inhaled, curium tends to concentrate in either the lung or bone tissues and is removed from the body with an overall half-life of approximately 110 days.

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