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

Volume 11: Niobium-94

***National Low-Level Waste
Management Program***

April 1995

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National Low-Level Waste Management Program Radionuclide Report Series

Volume 11: Niobium-94

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ABSTRACT

This report, Volume 11 of the National Low-Level Waste Management Program Radionuclide Report Series, discusses the radiological and chemical characteristics of niobium-94 (^{94}Nb). This report also includes discussions about waste types and forms in which ^{94}Nb can be found and ^{94}Nb 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, and nickel-63. These radionuclides contribute significantly to the dose estimated during a performance assessment analysis.

This report is Volume 11 of the series. It outlines the basic radiological, chemical, and physical characteristics of niobium-94, 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.

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National Low-Level Waste Management Program Radionuclide Report Series

Volume 11: Niobium-94

INTRODUCTION

This report outlines the basic radiological, chemical, and physical characteristics of niobium-94 (^{94}Nb) and examines how these characteristics affect the behavior of ^{94}Nb in various environmental media, such as soils, groundwater, plants, animals, the atmosphere, and the human body. Discussions also include methods of ^{94}Nb production, waste types, and waste forms that contain ^{94}Nb .

All niobium atoms contain 41 protons ($Z=41$) and various numbers of neutrons (typically $N=47$ to 65 neutrons) within the atom's nucleus. There is only one stable isotope of niobium, namely ^{93}Nb . All other niobium isotopes, including ^{94}Nb , are radioactive. The radioactive isotopes of niobium have half-lives ranging from a few seconds (^{104}Nb , 1.0 seconds) to millions of years (^{92}Nb , 37,000,000 years). ^{94}Nb has a 20,000 year half-life.¹ The radioactive isotopes of niobium are not a normal constituent of the natural environment and are generated as a result of human activities.

The primary source of ^{94}Nb in the environment has been low-level radioactive waste material generated from the neutron activation of stable ^{93}Nb that is present in the structural components of nuclear reactor vessels, especially those constructed of Inconel. ^{94}Nb enters the environment from the dismantling activities associated with nuclear reactor decommissioning.

RADIOLOGICAL CHARACTERISTICS

Confusion regarding the half-life of ^{94}Nb may occur because of an excited state ($T_{1/2} = 6.6 \text{ min}$) that decays to the ground state of the nuclide by ejection of an atomic electron.² The most recent and best available information concerning ^{94}Nb reports a half-life of 20,000 years.^{1,3} ^{94}Nb can be formed as a fission product. However, the principal means of production is via neutron capture (n, γ) of ^{93}Nb , namely

^{94}Nb undergoes radioactive decay via negative beta particle (β^-) emission (i.e., 100% of all decays result in an electron being emitted from the nucleus) leading to the creation of a stable molybdenum-94 (^{94}Mo) nucleus.

The maximum beta particle energy is 500 keV (thousand-electron volts). However, the average beta particle energy is only 156 keV per ^{94}Nb disintegration.⁴ Because the released beta particle is usually emitted with an energy less than its maximum theoretical (e.g., 500 keV for ^{94}Nb decay), an antineutrino particle is simultaneously emitted, which carries off the energy difference between 500 keV and that of the released beta particle. Consequently, beta particles are emitted with a continuous energy spectrum ranging from 0 to 500 keV. Because neutrinos (or antineutrinos) very 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 niobium will be absorbed by a ^{93}Nb nucleus is very small. However, even with the relatively small amount of ^{93}Nb in the Inconel in a nuclear reactor vessel, the extremely long half-life of ^{94}Nb means that the total amount of this radioactive nuclide present in the vessel will continue to increase during the reactor lifetime. By the time the reactor is decommissioned, a significant amount of ^{94}Nb will be generated in those reactor vessels with large amounts of Inconel (and, to a lesser extent, in those reactor vessels with stainless steels containing niobium) and will pose special problems when the reactor is decommissioned. Large quantities of ^{94}Nb can pose significant radiological hazards. For example, under some conditions (especially after several decades when the shorter-lived nuclides have largely decayed away) ^{94}Nb can contribute a large fraction of the total radioactive dose received by persons who dismantle nuclear reactors. This situation can occur if the reactor has been operated for a long time (e.g., >30 years). In other words, ^{94}Nb does not normally represent a major concern in shielding, but can be an important contributor to the overall radioactivity from activation nuclides and can affect the classification of certain reactor hardware as low-level radioactive waste material.

The 500 keV maximum energy beta particle emitted by the ^{94}Nb nucleus is relatively strong. Table 1 lists the estimated maximum ranges for a 150 keV (average energy) beta particle emitted from ^{94}Nb decay. Note that the maximum particle ranges are large, and because it requires only 70 keV for an electron to penetrate the protective layer of human skin, the ^{94}Nb beta particles have plenty of energy to penetrate the 0.07 mm (dead layer) of human skin. Therefore, exposure to the 500 keV maximum energy beta particles from the decay of ^{94}Nb can result in a beta dose to some internal organs.

Table 1. Comparison of the estimated maximum ranges for a 156 keV average energy beta particle emitted from ^{94}Nb decay for various materials.

Material (description)	Estimated maximum range for a 156 keV β^- (mm) ^a
Air (1 atmosphere pressure)	250
Water	0.30
Plastic (Lucite)	0.24
Concrete	0.15
Glass	0.13
Aluminum	0.11
Iron	0.033
Copper	0.028
Lead	0.025

a. Estimates are based on the maximum beta particle range data shown in References 4 and 5 as a function of energy and materials.

In addition to beta particle radiation, each ^{94}Nb decay results in two high-energy gamma rays, 700 and 870 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 fact by listing the "half-value layers," or the thicknesses of various materials required to attenuate a beam of 870 keV gamma rays to one-half the original intensity. As shown, shielding the environment from ^{94}Nb requires a substantial thickness, as opposed to some of the nuclides in this series, such as ^{63}Ni , which is only a beta emitter.⁶

The decay sequence for ^{94}Nb showing the emission of a negative beta particle (e.g., an electron) and the two gamma rays is illustrated in the following nuclear transformation:

Table 3 lists the radiotoxicity of several important radionuclides, and Table 4 compares the average and maximum electron energies associated with ^{94}Nb decay with other well-known electron (beta particle) emitters. Notice that ^{94}Nb is shown in the same radiological group as cobalt-60 (^{60}Co) and strontium-90 (^{90}Sr). ^{94}Nb decay results in both a lower beta energy emission and gamma energy emission than either ^{60}Co or ^{90}Sr . [Note: the high-energy gamma radiation from ^{90}Sr is from the decay of its relatively short-lived ($T_{1/2} = 64 \text{ h}$) daughter, yttrium-90 (^{90}Y)].

Table 2. Half-value layers for the 870 keV gamma ray emitted from the decay of a ^{94}Nb nucleus.^a

Material	Half-value layer thickness (cm) ^b
Lead	0.70
Iron	1.4
Aluminum	3.9
Stone concrete	4.3
Water	9.2
Air	7.9×10^3

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 its intensity.

b. These values were interpolated from Table 6.2 of Reference 4.

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

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, 3, 4, 8, 9, and 10)

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
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.	806.0 ^c
Cesium-137 (¹³⁷ Cs)	195.0	1176.0
Potassium-40 (⁴⁰ K)	541.0	1330.0
Phosphorous-32 (³² P)	694.0	1710.0

a. 1000 keV = 1 MeV (million electron volts). 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 cobalt-59 (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 iodine-131 (¹³¹I) occurs at 606 keV, and only 0.6% occurs at 806 keV.

CHEMICAL AND PHYSICAL CHARACTERISTICS

Niobium is a member of the fifth group of the periodic table, which includes zirconium, molybdenum, technetium, ruthenium, rhodium, palladium, and silver.¹¹ Commercially pure niobium is ductile, easy to fabricate at room temperature by conventional forming practices, and used extensively in aerospace applications. It is a lustrous platinum-white metal that is relatively light in weight and has good high-temperature strength. In combination with zirconium, it is used in nuclear applications because it resists corrosion and radiation damage well and has a small probability for absorption of neutrons.¹² Most niobium is used in special stainless steels, Inconels, high-temperature alloys, and superconducting alloys.

Niobium was originally called "columbium" in the United States and is still sometimes referred to by this name in the metallurgist and metals industry. It is chemically very similar to tantalum and is often found in nature in combination with this element. Niobium, which is 10 times more abundant than tantalum, composes approximately $2.4 \times 10^{-3}\%$ of the earth's crust.¹³

Niobium forms an oxide coating in most acid environments, which provides excellent protection against acid attack, especially for nitric and hydrochloric acids. However, hydrofluoric acid and strong alkaline solutions can attack niobium severely. At elevated temperatures, the metal reacts with halogens, oxygen, nitrogen, carbon, hydrogen, and sulfur. It forms high-melting-point compounds with light elements such as carbon, boron, silicon, and nitrogen.

The mechanical properties of niobium are very dependent on the purity of the metal. Often, high-temperature strength is compromised by other alloying materials that are added for increased fabricability. Niobium and its alloys are readily machined; the characteristics of machining vary in ease from those of copper to those of stainless steel. However, special attention should be paid to lubrication to avoid galling. Niobium and its alloys are easily forged, rolled, or otherwise worked directly from ingots at room temperature.

Niobium typically forms compounds with an oxidation state of +5. Its most common oxide is Nb_2O_5 , which is produced by heating the metal in an oxygen environment. This oxide forms a white powder, which is a dense, relatively inert substance. The oxide dissolves readily in concentrated alkali, but does not appreciably dissolve in common acids such as nitric or hydrochloric acids.¹⁴ Dissolving the oxide in acids can produce compounds with halogens such as fluorine and chlorine. Again, the most common halides are formed with niobium in an oxidation state of +5. The resulting fluorides are volatile white solids. Other halides, such as iodine and chlorine, form yellow to brown or purple-red solids by direct reaction of the metal with excess halogen. Reduction of this oxide by hydrogen results in oxides with lower oxidation states, such as NbO_2 and NbO .

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

Table 5. Chemical and physical characteristics of niobium. Obtained from References 12, 13, 15, and 16.

Physical property (units)	Niobium data
Melting point (K) ^a	2,741
Boiling point (K) ^a	5,200
Solid density (g/cm ³)	8.6
Crystal form	Body-centered cubic

a. Note that zero Kelvin equals -273.15°C and -459.67°F.

NIOBIUM-94 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, found primarily in stainless steel and other important alloys (e.g., Inconel). Depending upon the amount of time these materials are irradiated and the integrated neutron flux, any of these nuclides may become the critical activation product affecting the dismantling activities of the reactor.

Though not a principal structural material based on total mass, niobium does form an important constituent of some materials, especially stainless steels and Inconels. Typical amounts of niobium in stainless steel range from a few to as much as several hundred parts per million (ppm) mass. The amount of niobium in Inconels can be as high as a few percent.^{17,18}

The principal means of producing ^{94}Nb is through neutron capture of ^{93}Nb , the only stable isotope of niobium. The total niobium mass is relatively small. However, because ^{93}Nb constitutes the only stable isotope, all of the niobium mass is available for activation, which increases the total amount of ^{94}Nb that can be produced.

Based on the mass number for ^{94}Nb , one might suppose that nuclear fission would also be a major source of this nuclide, as illustrated in Figure 1, which shows the fission yield for uranium-235 (^{235}U). This figure shows that mass number 94 is near the maximum yield for fission products. However, when ^{235}U fissions, the fission products are produced with a large number of excess neutrons and usually decay, via beta-decay, to stable isotopes. For mass number 94, a typical fission product is bromine-94 (^{94}Br), which comprises 3.2% of all fission products (or 6.4% on Figure 1). As this fission product beta-decays, it will eventually transmute into zirconium-94 (^{94}Zr). However, ^{94}Zr is a stable isotope and does not decay to ^{94}Nb . Therefore, essentially no ^{94}Nb is produced by fissioning and ^{93}Nb produced by neutron activation. This information was obtained from the fission yield data from the ORIGEN2¹⁹ computer code cross-section data.

Because ^{94}Nb atoms do not readily absorb thermal neutrons, and because niobium comprises only a small fraction of the total structural mass in a nuclear reactor, it generally takes many years of neutron irradiation to produce a significant quantity of ^{94}Nb . However, ^{94}Nb has a half-life that is much longer than the normal life of a nuclear reactor (e.g., 20,000 years versus ~30 years for most reactors). Therefore, essentially all of the ^{94}Nb that is produced within the reactor structure remains with the reactor until it is dismantled. A small fraction of ^{94}Nb can be released from the corrosion of structural components and transported to other sites via the reactor coolant system. In other words, the ^{94}Nb inventory increases linearly with reactor operation and does not significantly decrease with time. 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.

There are two groups in Figure 2: those that build up relatively rapidly and reach a saturated condition, such as ^{60}Co and iron-55 (^{55}Fe); and those, whose half-lives are long compared with the relevant reactor life time, that never reach saturated conditions, such as ^{94}Nb

and ^{63}Ni . Significantly, the nuclides in the first category also tend to decay more rapidly. In fact, after 100 years subsequent to reactor shutdown, these nuclides have effectively disappeared from the structural materials and ^{94}Nb represents the principal potential contributor to personnel exposure.¹⁷ Once this condition has been established, ^{94}Nb remains the dominant gamma-emitting nuclide for any time scale of human interest.

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.

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 . (Obtained from References 20 and 21).

WASTE TYPES AND FORMS THAT CONTAIN NIOBIUM-94

Nuclear Reactors

The quantity of ^{94}Nb generated within the structural components of a nuclear reactor increases linearly with burnup; that is, double the reactor operation and the ^{94}Nb inventory doubles. Because the half-life of ^{94}Nb is much longer than the life of the reactor ($T_{1/2} = 20,000$ -year versus 30-year lifetime for a reactor) no process effectively decreases the ^{94}Nb inventory over the reactor's useful life time. If decommissioning is delayed for several decades after reactor shutdown, the residual gamma flux may be dominated by ^{94}Nb .

The U.S. Nuclear Regulatory Commission (NRC) has adopted formal guidelines for classification of waste for shallow-land disposal of radioactive waste.²² These guidelines specify three different class definitions, with increasing activity inventory limits and commensurately increasing disposal requirements. Class C is the classification with the highest inventory limits, allowing 0.2 Ci/m^3 inventory for ^{94}Nb . (The lowest classification, Class A, allows only 0.02 Ci/m^3 inventory for ^{94}Nb .) Radioactive waste with inventories exceeding the Class C limits cannot be placed in a shallow-land disposal without specific authorization by the NRC.

The Department of Energy has published a program document, DOE/LLW-114, that includes information concerning the difficulty of measuring some nuclides that are very important for waste classification from nuclear power plants.²³ Most of the total activity in activated reactor parts results from short-lived nuclides such as ^{60}Co (a gamma emitter) and ^{55}Fe (a beta emitter). However, because these are short-lived, the waste disposal classification for these parts is dominated by longer-lived nuclides, primarily ^{63}Ni and ^{94}Nb . Because of the high background radiation caused by the presence of the short-lived nuclides, it is very difficult to measure these latter nuclides. Therefore, in most cases, the inventories of the long-lived nuclides are correlated with the inventories of the more dominant nuclides, usually ^{60}Co . Measurements that determine ^{60}Co content are then used in conjunction with scaling factors to estimate the activities of ^{59}Ni , ^{63}Ni , and ^{94}Nb . This technique introduces uncertainties in the expected amount of ^{94}Nb because of the uncertainties associated with the amounts of ^{93}Nb in the various stainless steels and Inconels in the reactors. For example, the actual quantity of Nb in a given component can vary by as much as $\pm 50\%$ from the value used in the analysis.

Reference 17 documents a study of the activities of several activation products in nuclear reactors, including ^{94}Nb . This reference includes both theoretical and experimental results. The experimental results were based on analysis of samples from eight reactors. The measured activities were less than $1 \mu\text{Ci/g}$ for stainless steels but up to $60 \mu\text{Ci/g}$ for Inconel. This study also included analysis of concrete samples for activation products. While ^{94}Nb was found in measurable amounts, its contribution to the overall activity was relatively small. One interesting conclusion of this report is that while most of the samples resulted in activities close to calculated values, one specific datum was considerably higher than calculated. This sample was from the core of a reactor where there is a large flux of epithermal neutrons (neutrons that have not yet been slowed down to thermal energies). Stable niobium (^{93}Nb) has a relatively high probability for absorption of these more energetic neutrons (a phenomena known as "resonance" absorption), and small uncertainties in the epithermal neutron flux can result in large errors in the calculated absorption.

Reference 24 documents a study of the nature of the radioactive contamination and distribution expected to be encountered during light water power reactor decommissioning. A principal conclusion of this study is that ^{94}Nb and ^{63}Ni concentrations in Inconel and stainless steel components in these components exceed Class C low-level waste limits for shallow land burial and are the radionuclides that determine waste-class for these components (for many samples, ^{94}Nb and ^{63}Ni were the only radionuclides that exceeded the Class C limits). In fact, for some samples, the ^{94}Nb activity levels exceeded the Class C limits by a factor of several hundred to several thousand, especially for fuel assembly hardware and grids and springs in the core. The highest ^{94}Nb levels were measured in pressurized water reactor components. The levels in boiling water reactor components were much lower, but did exceed the Class C limits for some fuel assembly parts. Separate studies also concluded that some of the stainless steel reactor vessel components are expected to exceed the Class C waste limits for ^{94}Nb (as well as those limits for ^{59}Ni and ^{63}Ni).^{25,26,27,28}

Low-level radioactive wastes usually contain small quantities of fission products or activation products, including ^{94}Nb . During the operation of a light water reactor, oxide corrosion films form on the surfaces of piping, pumps, valves, steam generator tubing, and many other components in contact with the primary coolant. Some of these corrosion products dissolve or erode in the circulating coolant, are deposited on the fuel cladding, and become activated by the neutron flux. The principal radionuclides formed by this activation process are ^{58}Co , ^{60}Co , ^{55}Fe , ^{59}Fe , manganese-54 (^{54}Mn), chromium-51 (^{51}Cr), ^{65}Zn , ^{63}Ni , and ^{94}Nb . These radionuclides are eventually released from the core region of the reactor and are carried by the coolant and incorporated into oxide films on the surfaces of the primary coolant system (PCS) components.²⁹ The primary waste types that can contain radionuclides produced as a result of nuclear reactor operations are contaminated scrub water and decontamination solutions; contaminated clothing; contaminated tools and equipment used in radioactive areas; pumps, valves, seals, bearings, and scrap materials; ion-exchange resins; and filters. However, none of these waste types contain radiologically significant quantities of ^{94}Nb . Only very small quantities of ^{94}Nb are found in the primary coolant system of operating reactors. This small amount results from activation of suspended metals or crud. Most of the niobium in reactor systems is found in Inconel structures, which are very corrosion resistant. The equipment and systems used to clean this water will contain much higher concentrations of ^{94}Nb , as well as other radionuclides. The types of safeguards to be used in the disposal of decommissioned reactor parts and the long-term safety of the disposal of these parts are dictated by the amount of radionuclides, including ^{94}Nb , contained in the parts. In some cases, ^{94}Nb may be the limiting radionuclide that determines handling and storage requirements.¹⁷

The primary low-level radioactive wastes containing ^{94}Nb are solid waste forms produced by activation of structural materials, mainly Inconel and, to a lesser extent, stainless steel components. When these components are decommissioned and dismantled, low-level radioactive wastes are produced that contain ^{94}Nb . For example, it is possible that structural components from decommissioned nuclear power plants will be melted down for recycling. Especially if the reactor contained Inconel structures, residual amounts of ^{94}Nb will either end up in new structures or, more probably, be processed out of the metals and enter the waste stream. Depending on the mode of reprocessing, the ^{94}Nb could take either the elemental form or become an oxide or halide. The exact form would depend on the processing procedure.

One study investigated the presence of ^{94}Nb in corrosion films deposited on the insides of pipes in nuclear power plants.³⁰ In this study, samples of corrosion product depositions were taken from the insides of pipes exposed to reactor coolant in several pressurized and boiling water reactors. Though ^{94}Nb was measured in several of the samples, the concentration range was very low, from $<1.2 \times 10^{-5}$ to $5.0 \times 10^{-4} \mu\text{Ci}/\text{cm}^2$. These concentrations were very small compared with the principal corrosion product constituents such as ^{60}Co and ^{63}Ni . The ^{94}Nb concentrations measured in this study were much lower than the Class A shallow-land burial criterion for this nuclide. This study indicated that ^{60}Co , ^{55}Fe , ^{63}Ni , and ^{137}Cs were the most abundant radionuclides associated with the contaminated piping, hardware, and concrete for a up to 20 years after reactor shutdown.

Medical, Academic Institutions, and Commercial Waste

Because ^{94}Nb has such a long half-life (compared with most radioactive applications), it is unlikely that this nuclide would be injected or ingested for either medical diagnosis or treatment. The relatively strong gamma ray emission (700 and 870 keV), together with the long half-life, could make it an ideal external radiation source for medical treatment. However, personnel at the American College of Radiologists stated that ^{94}Nb is not used either for the diagnosis of disease or for medical treatments.^a

This nuclide is used in laboratory work and is included in Reference 31, which is a list of certified reference materials of radioactivity. ^{94}Nb is available from the National Bureau of Standards, Office of Standard Reference Materials in activities ranging from 0.1 to 0.2 μCi . These sources are packaged in aluminum/plastic cases. Because of the long half-life, the sources will not decay within a human time scale.

a. Private communication between C. Sperry (ACR) and J. Adams (INEL) on January 26, 1995.

BEHAVIOR OF NIOBIUM-94 IN THE ENVIRONMENT

Niobium in Soils

Understanding the behavior of radioactive materials such as ^{94}Nb in the soil is important in assessing the possibility of transport of these radionuclides through the biosphere.³² 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.³² 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 niobium concentration in the soil ($\mu\text{g Nb/g}$ of soil) and C_l is the niobium concentration in the groundwater ($\mu\text{g Nb/mL}$ of liquid). Therefore, the units of K_d are mL/g (i.e., 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 the surrounding groundwater. This model assumes that the niobium concentrations in groundwater and soil are in equilibrium with each other. Using this definition for K_d , it follows that the larger the value (that is, 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 with 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 nonhomogeneous and there are uncertainties as to how long it takes for the niobium concentrations in the soil and groundwater (C_s and C_l) to reach equilibrium with each other. Therefore, one must be careful to ensure that soil samples used in laboratory studies are 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 nonhomogeneity.

An experimental study of K_d values for niobium in an oxalate complex and in various rock forms was performed in Sweden.³³ The results from this study indicated a range of K_d from $8\text{--}11 \text{ m}^3/\text{kg}$.

Niobium occurs naturally in many soils. In fact, on an elemental basis, the naturally occurring forms of niobium can be much more prevalent than the trace amounts of ^{94}Nb found in typical waste streams.³⁴ In a study of surface soil samples from Bull Island, South Carolina, the typical range for naturally occurring niobium concentrations in soils was measured to be from <2 to 7 ppm .³⁵ In a similar study of Polish soils, the baseline concentrations of several

elements, including niobium, were measured in approximately 130 representative samples of arable soils.³⁶ Areas of expected pollution were avoided. The measured average concentration of niobium was 3.2 mg/kg, which was significantly smaller than all of the other elements except beryllium and arsenic. All elements included in this study had significantly higher concentrations in silty and loamy soils than in sandy soils. These concentrations are much lower than many other constituents. For example, the aluminum and potassium concentrations in the same samples ranged from 930,000 to 1,700,000 and from 330,000 to 840,000 ppm, respectively.

Reference 37 lists niobium concentrations in various soil types as igneous rocks—20 µg/g; shales—11 µg/g; sandstones—0.05 µg/g; and limestones—0.30 µg/g. Concentrations, either expected or actual, for radionuclides, including ⁹⁴Nb, are much lower.

A water-saturated soil system with a relatively high organic content in the presence of buried waste nuclides could lead to effective complex formation and increased solubility and mobility of the buried waste nuclides. Some of these organic complexing agents include EDTA, DTPA, NTA, HEDTA, and organic acids that are used in laboratories for processing and decontaminating radioactivity. These conditions may enhance the mobility of nuclides because of complex formation with organics, which in turn may be a dominant mechanism of nuclide transportation in soils and groundwater. For example, the organic molecules can bond very strongly with the nuclide and form a variety of charged and uncharged complexed species. Uncharged and negatively charged complexes will tend not to be attached to negatively charged soil sites, and positively charged complexes will not attach to positively charged soil sites. In any case, these complexes will be transported more easily through the soil with the groundwater than would have been the case if the nuclide were not complexed.

For this reason, the U.S. Department of Energy commissioned the Pacific Northwest Laboratory to study the effects of complex formation on the mobility of various nuclides.³⁸ (Note: in this study, one of the radioactive isotopes of niobium, ^{93m}Nb, was used as a tracer. This nuclide has a much shorter half-life than ⁹⁴Nb and is, therefore, a more desirable nuclide to be used for such studies. However, because the study involved the chemistry of niobium, rather than the radioactivity or physics of this element, the results should be directly applicable to ⁹⁴Nb.) EDTA and some of the organic acid complexes form the most stable complexes with niobium, while other organic acids, such as α-hydroxy carboxylic acids, are less stable. Overall, however, and in the absence of extensive experimental data, Reference 38 predicts that the mobility of niobium is not significantly affected by any of these complexes (because interaction of the complexed niobium with water forms an insoluble hydrated form of niobium oxide, which precipitates out of the water and is fixed in the soil) and that niobium, either in elemental form or as a complex, would be readily adsorbed by soils and not travel very far with the groundwater.

The Savannah River Laboratory conducted experiments into the adsorption of niobium in soils, on behalf of the U.S. Atomic Energy Commission.³⁹ One should exercise care in interpreting the results from this study because the experimenters used a combination of zirconium and niobium in their tests (based, presumably, on the observation that ⁹⁵Nb is a decay daughter of ⁹⁵Zr and is often found in combination with it). However, zirconium and niobium chemistries are fairly similar (though by no means identical) because both are in the second transition series of the periodic table. The results from this study indicate that niobium is readily

adsorbed in the soil, even when complexed with an oxalate ion, so long as the pH of the soil was in the range of 4 to 8 (this is the range studied and the results may still be true for pH > 8).

A more recent study also used the ^{95}Zr - ^{95}Nb combination. This study, conducted by the University of Manchester in Great Britain, examined the desorption behavior of nuclides adsorbed onto silt.⁴⁰ In this study, silt contaminated with radioactive waste from the Sellafield fuel reprocessing plant was used to study the desorption of the Zr-Nb pair. Even though the chemistries of these two elements are similar, the study attempted to separate the desorption characteristics of the two. Various chemicals were used in an attempt to remove the niobium from the soil samples. Some of these chemicals successfully removed a significant amount of niobium, namely, oxalic acid, citric acid, and concentrated hydrochloric acid. The other chemicals were generally not successful, namely, water, potassium chloride, sodium phosphate tribasic, sodium fluoride, more dilute hydrochloric acid, sodium hydroxide, and concentrated nitric acid.

By contrast, one study was made of the mobility of radioactive niobium in the soil surrounding the Chernobyl Nuclear Power Plant.⁴¹ In this study, various stable and radioactive species were studied and their solubility and mobility in the soil samples were measured. For example, researchers concluded that radioactive cesium and strontium nuclides do not necessarily behave like their stable isotopes in that the radioactive nuclides tend to be more mobile, apparently because of the much larger concentrations of the stable isotopes in the soil and groundwater. The study did not include a similar conclusion regarding radioactive isotopes of niobium. However, ^{95}Nb was categorized as being as mobile as the radioactive cesium isotopes (actually lying between ^{134}Cs and ^{137}Cs).

In summary, niobium will tend to become fixed in soils and not be significantly transported with the groundwater. There are some decontamination solutions that can alter this characteristic and cause the niobium to be more mobile, but most will not. There may be differences in soil mobility between radioactive and stable niobium isotopes.

Niobium in Groundwater

Niobium tends to be easily adsorbed by soils, removing it from groundwater. However, this may be dependent on a number of parameters, such as the groundwater pH and whether or not complexing agents are present. For example, in Savannah River silt, niobium pre-adsorbed in the soil could be complexed and removed from the soil by some agents but not others.³⁹ Thus, the presence of complexing agents can significantly slow removal of niobium from groundwater.

A theoretical study was underwritten by Ontario Hydro to investigate the potential for on-site burial of decommissioned waste at a nuclear reactor site to contaminate groundwater.⁴² Specifically, this study involved an option to bury all radioactive waste associated with decommissioning the Bruce Nuclear Generating Station A nuclear power plants. The plan envisioned excavating 55-m deep pits for each of the four nuclear reactors, placing all contaminated primary components in the pits, backfilling the pits with the excavated rock plus concrete, and capping the pits. Assumptions regarding this analysis included no credit for the backfill in the pits (that is, the groundwater was assumed to be in immediate and intimate contact with the contaminated components) and conservatively high corrosion and leaching rates for the activation products. The principal sources for ^{94}Nb are the pressure and cladding tubes, which

have a large initial inventory of stable zirconium and niobium. After leaching the ^{94}Nb from the tubes, the groundwater was assumed to transport the radioactivity to Lake Huron, where it would contaminate the water, fish, and crops irrigated by the lake. Transport to the lake was calculated to be 100 years after leaching from the components. The maximum dose to the public from ^{94}Nb was 2×10^{-8} Sv/year (2×10^{-6} rem/year) and occurred 4,700 years after burial of the reactor components. This dose is insignificant compared with the allowable public dose rate of 5×10^{-3} Sv/year (0.5 rem/year).

A similar study was made of an underground rock repository currently being considered in Sweden.³³ In this case, the activated and contaminated metal parts of a reactor would be buried in a deep tunnel excavated in granitic rock. The components would be encapsulated in concrete blocks, placed in the tunnels, and the tunnels would be backfilled by a bentonite/quartz mixture. Only the very long-lived radionuclides were included in the study, including carbon-14 (^{14}C), ^{59}Ni , ^{63}Ni , ^{93}Zr , $^{93\text{m}}\text{Nb}$, and ^{94}Nb . Chemical effects were modeled, and it was concluded that in the groundwater Nb would probably have oxidation states of either +3 or +5. The formation of fluorides and niobates was also considered, and the solubility of the most probable chemical forms was modeled. Unlike the study in Reference 42, the diffusion of the niobium species through the concrete and bentonite/quartz was modeled, which resulted in a much longer release time from the tunnel. The shortest time to release all niobium into the groundwater is 400 million years. The best estimate time was more than four times longer. Even if the backfill material were somehow removed, the release time (from the tunnel into the groundwater) would be 200 million years (this is the best estimate; the most conservative [low] time is 40 million years).

The Finnish nuclear power companies, Imatran Voima Oy and Teollisuuden Voima Oy, plan to dispose of their nuclear power plant components in repositories located near their respective power plant sites. In preparation for this, these companies commissioned a study of the behavior of activation products, ^{59}Ni , ^{93}Zr , and ^{94}Nb in the cement/bentonite/crush-rock environment expected to exist surrounding the components. Specifically, the study was designed to estimate the most realistic solubilities of these nuclides in the environment and to calculate the rate of migration of the nuclides through this environment. The solubility and chemical speciation of these nuclides will be dependent on water pH, solubility is expected to be lower for lower pH. The results from the analysis indicate essentially no migration beyond the boundary of the repositories for at least 300,000 years.

In summary, the studies included in this report indicate that it would take from hundreds of thousands to hundreds of millions of years for niobium to be significantly leached from geologic repositories and transported to where exposure to the public would take place.

Niobium in Plants

Most of the information regarding the behavior of niobium in plants consists of data regarding the uptake of this element from soil and groundwater into various types of vegetation. Reference 35 reports the investigation into the uptake of various elements from soil to plants in the Bull Island, South Carolina, Cape Romain National Wildlife Refuge. This study was commissioned by the U.S. Geological Survey as part of their responsibility to determine the effects of atmospheric pollutants in wildlife refuges through the U.S. Specifically, the researchers took soil samples and measured trace element contamination levels. They also took samples of

two vegetation types, Spanish moss and loblolly pine, and measured their uptake of the soil constituents. Niobium was measured in 7 of the 16 soil samples with concentrations up to 7 ppm, which meant that a complete statistical analysis of the concentration could not be performed (because fewer than 70% of the samples contained measurable amounts of this element). Niobium was detected in 16 of the 38 Spanish moss samples and in 2 of the 59 loblolly pine needle samples with concentrations up to 0.58 ppm. The plants appeared to not have concentrated the niobium as they extracted it from the soil. This study used stable isotopes.

Another study also used stable isotopes.³⁷ This study listed a transfer factor of 0.11 from soil to plants. Based on a comparison of uptake factors for zirconium and niobium, this study concluded that for the case of $^{95}\text{Zr}/^{95}\text{Nb}$ from soil to plants, the uptake would be dominated by the effects of the niobium, rather than the zirconium, nuclide. This study also indicated that of the niobium that is taken up into plants, approximately 10–15% is absorbed by the plant shoots and nearly one-half of this remains in the grain of cereals at harvest.

A similar study was performed of the uptake of fission products from underground nuclear explosions at the Nevada Test Site into the local grass.⁴³ As previously stated, ^{94}Nb is not a fission product and this study did not include this particular niobium isotope. However, ^{95}Nb is a fission product (the daughter of ^{95}Zr) and this nuclide was included. Care must be taken in applying the results from this study to ^{94}Nb because of the potential perturbing effects of the zirconium precursor. The results from this study are consistent with those of Reference 35, in that the soil concentrations of niobium were larger than those in the plants, that is, there is no measurable concentrating effect. The niobium that was taken up into the plant tended to be distributed throughout the parts of the grass, though, on a mass basis, approximately twice as much niobium was found in the leaf as in the stem.

Following the Chernobyl reactor accident, a sampling program was instituted in Japan to monitor the fallout and uptake into the food chain. The results were documented in Reference 44. While trace amounts of radioactive niobium (specifically ^{95}Nb , a fission product) were found in soil samples, none were measured in plants or the milk supply. Of course, conclusions based on this "non-result" are at best tenuous. At least these results are consistent with other observations that niobium appears not to be concentrated to any significant degree by plants.

Finally, a study was made of the uptake of radioactive niobium into fruits and vegetables grown near Oak Ridge National Laboratory.⁴⁵ In this study, the researchers obtained samples of 22 types of fruits and vegetables from local grocery stores and analyzed them for radionuclide and trace element compositions. The purpose of the study was to determine the effects of the operation of the Oak Ridge National Laboratory on the population in the vicinity of the lab. As in the Reference 43 study, the researchers measured the ^{95}Nb uptake so care should be taken in applying these results to ^{94}Nb . Typical concentrations of ^{95}Nb in the fruits and vegetables were of the order of 10^{-15} Ci/g. The ^{95}Nb concentrations tended to be fairly uniform, and no specific fruit or vegetable exhibited an obvious preference for this nuclide.

Reference 37 summarizes several studies into the uptake of niobium from water to aquatic plants. These studies indicate an uptake factor ranging from 0.01 $\mu\text{g/g}$ for marine (ocean) plants to 0.8 $\mu\text{g/g}$ for freshwater plants. However, these data should be used with caution because they

are based on measurements involving the $^{95}\text{Zr}/^{95}\text{Nb}$ nuclide combination and the results may be influenced by the presence of the zirconium.

Niobium in Air

Niobium isotopes (radioactive or nonradioactive) are not normally found in air, except possibly for small amounts generated and released following an atmospheric test of a thermonuclear weapon.

Radioactive ^{94}Nb is produced entirely as an activation product in the reactor structural components (e.g., $^{93}\text{Nb}(n,\gamma) \rightarrow ^{94}\text{Nb}$) and does not appear as a fission product radionuclide. Therefore, even if a severe core damage accident occurred in a nuclear reactor and released significant amounts of fission products, the result would not necessarily be the release of significant amounts of ^{94}Nb into the air.

The presence of ^{95}Nb in soil and plant samples in Malaysia has been reported as a result of nuclear fallout.⁴⁶ However, this nuclide is a fission product, and ^{94}Nb is an activation product. Therefore, the presence of one does not necessarily imply the presence of the other. While the literature search represented in this study was not complete, no references were found that specifically addressed either the presence or behavior of ^{94}Nb in air.

BEHAVIOR OF NIOBIUM-94 IN THE HUMAN BODY AND IN ANIMALS

Radionuclides have been classified as to their relative toxicity in man.⁴⁷ In this study, radionuclides are grouped into four classifications: very high toxicity, high toxicity, medium toxicity, and low toxicity. ⁹⁴Nb is included in the high toxicity group.

The biological hazard associated with a radionuclide can be characterized by the equivalent dose per unit exposure. The exposure can be by either external radiation (primarily from gamma rays, neutron flux, or both, or to a lesser extent, from beta rays if they are sufficiently energetic) or internal radiation (from ingestion or inhalation). Reference 48 lists the equivalent dose (Sv or rem) per unit exposure (Bq or Ci) for the principal human organs of concern, gonad, breast, lung, red bone marrow, bone surface, thyroid, as well as the overall dose equivalent. For the case of ⁹⁴Nb, the equivalent doses are all in the range of 10⁻⁹ to 10⁻¹⁰ Sv/Bq (100 to 1000 rem/Ci). These doses are fairly uniform, that is, no one organ dominates the whole-body dose because niobium does not seem to concentrate in any single organ more than others, as opposed to iodine, which tends to concentrate in the thyroid. In addition, the dose values are fairly low, compared with ¹³⁷Cs, for example, which has dose equivalents of the order of 10⁻⁸ Sv/Bq (10,000 rem/Ci), also uniform across all listed organs.

Two independent means can remove any radionuclide from the human body. The first is radioactive decay, characterized by the radiological half-life, T_r , wherein the nuclide is transmuted into another nuclide. For the case of ⁹⁴Nb, the other nuclide is molybdenum-94 (⁹⁴Mo), which is a stable nuclide. After decay to ⁹⁴Mo, no further biological hazard is expected because the concentration usually is too small for chemical effects to be present. The second means is by normal biological processes, such as exhalation (for airborne nuclides) and excretion (for ingested nuclides). This second process is quantified by the "biological half-life," T_b , which is a measure of the time for removal of one-half of the nuclide from the affected organ(s) and can differ for different body parts. The total removal rate is characterized by the effective half-life, T_{eff} which is defined by:

$$T_{eff} = \frac{T_r \times T_b}{T_r + T_b} \quad (3)$$

The following ⁹⁴Nb biological half-lives are given for various body parts: spleen—950 days; liver—845 days; kidneys—760 days; bone—1000 days; and total body—760 days.⁴⁹ Thus, the radiological half-life for ⁹⁴Nb is much longer than any of the biological half-lives, and the only significant removal mechanism(s) is biological.

Studies summarized in Reference 50 indicate that inhalation is a major exposure route in humans. For this reason, deposition and retention of inhaled niobium aerosols (⁹⁵Nb) were studied in dogs. Although a nuclide other than ⁹⁴Nb was used in this study, the chemical processes would dominate the results and they should be applicable to ⁹⁴Nb as well. In this study, approximately one-half of the inhaled niobium (in aerosol form) was retained in the lungs, independent of whether an oxide or oxalate chemical form was used. For the oxide particles, most of the upper respiratory tract deposits were removed within a couple of days, and less than 1% were absorbed into the circulation system. The redistribution of the oxalate particles was very

different. About one-half was excreted in urine or feces. The rest was deposited in the skeleton, liver, and other soft tissues. The lung was projected to receive the largest dose of all the body organs, but both the skeleton and kidneys were also identified as being potential organs of concern for radiation exposure from the inhaled niobium nuclides.

Reference 37 indicates that the fractional absorption of niobium from the gastrointestinal tract of adult animals is in the range of 0.05–1%, with the best estimate of 0.2%. In very young animals (that is, those that are still nursing), the fractional absorption is somewhat higher, on the order of 5%. The results summarized in Reference 50 are consistent with this finding that young animals tend to retain more than mature ones. The highest retention was in the bone tissues, and the lowest retention, in the spleen for rats. The transfer from the body to the milk in lactating animals was not significant. Thus, it is probably justifiable to neglect milk as a route of exposure to ^{94}Nb .

Reference 37 also summarizes the distribution of niobium in aquatic invertebrates. However, these results are based on measurements involving the $^{95}\text{Zr}/^{95}\text{Nb}$ nuclide combination and are suspect regarding conclusions for niobium. Therefore, they are not included in this report. The interested reader is referred to Section 4.2.2 of Reference 37 for further details.

The uptake of several radionuclides by marine animals, prawns, mussels, and winkles was studied in the waters off the western coast of England, near the Sellafield nuclear reprocessing center.⁵¹ Among the nuclides studied was ^{95}Nb . No niobium was detected in the prawns. However, niobium was consistently measured in the mussels and winkles, primarily in the soft tissues, such as the viscera and gills.

The annual limits on ^{94}Nb intake (ALI) and the derived air concentration (DAC) for ^{94}Nb 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 man (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 that result from 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 ^{94}Nb . In the case of multiple radionuclides released in a mixture, additional guidelines outlined in Title 10 of the Code of Federal Regulations,⁵² Part 20 must be followed.

The potential use of fusion power to generate electricity in the next century has generated considerable interest in the potential biological hazards associated with the energy source. One of the principal concerns involves activation of structural components followed by spalling off the walls and transport of the activation products into the environment. One of the nuclides of

concern is ^{94}Nb . An analysis was performed to assess the environmental impact of fusion energy.⁵³ This study summarized terrestrial and aquatic environmental effects of the production of radioactive niobium. Terrestrial effects include absorption of niobium, which places it into the food chain. Niobium was found to decrease growth rates in mice, particularly female mice, and to concentrate in the major organs of mammals. Aquatic effects include the concentration of radioactive niobium in the shell and byssus of shellfish.

Table 6. Annual limits on intake (ALI) and the derived air concentrations (DAC) for ^{94}Nb (data obtained from Reference 54).

Radionuclide	Component	Ingestion (μCi)	Inhalation ^a
^{94}Nb	ALI	900 ^b	200/W 20/Y
	DAC	— ^c	$8 \times 10^{-8}/\text{W}$ $6 \times 10^{-9}/\text{Y}$

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 ^{94}Nb , the two listed classifications are Y for oxides and hydroxides and W for all other compounds.⁵⁵

b. Removal class is $f^1 = 0.01$. 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 ^{94}Nb , $f_1 = 0.01$, entered the blood-stream via the GI tract. Additional details of this model are described in Reference 48, 54.

c. Data not available.

CONCLUSIONS

^{94}Nb has a half-life of 20,000 years and decays by beta particle emission to stable ^{94}Mo . Both high-energy beta particles (maximum energy 500 keV, average energy 150 keV) and gamma-ray (energies 700 and 870 keV) emissions characterize this nuclide.

^{94}Nb is produced in the structural steels and other alloys of nuclear reactor vessels and internal components from the neutron activation of ^{93}Nb , the only stable isotope of niobium. These reactor components serve as the primary low-level radioactive waste material containing ^{94}Nb . The major concern surrounding ^{94}Nb 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 provide the dominant, long-term source of gamma radiation from these components.

^{94}Nb is commercially available and has been used as an external source of gamma rays for laboratory use. No medical uses for this nuclide have been identified.

The chemistry of niobium is dominated by the outermost five 5s subshell electrons. The principal oxidation state is +5. The metal has good high-temperature strength and corrosion characteristics and is used in the aerospace and nuclear industries.

The ability of soil to adsorb ^{94}Nb out of the groundwater depends on a number of factors, including pH and the presence or absence of complexing agents. However, in general, niobium is easily adsorbed by soils and is not easily leached into the groundwater.

The greatest source of ^{94}Nb generation is in nuclear reactors, where it is produced by neutron absorption via the $^{93}\text{Nb}(n,\gamma)^{94}\text{Nb}$ 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 ^{94}Nb that has reached the environment is very small, and most studies of its hazard have been theoretical.

When ^{94}Nb 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. When this nuclide is ingested in mammals, most of it is removed within a few days. The part that remains is generally uniformly distributed in the body. The effective removal half-life for this nuclide is dominated by the biological half-life, which is approximately 760 days, though individual organs may have different values.

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