Volume 1: Task 2.1 Report

Radiological Risk Assessment for King County Wastewater Treatment Division

D. J. Strom

August 2005

Prepared for King County, Washington, under a grant from the Department of Homeland Security as a work for others project under U.S. Department of Energy contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

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Executive Summary

Staff of the King County Wastewater Treatment Division (WTD) have concern about the aftermath of a radiological dispersion event (RDE) leading to the introduction of significant quantities of radioactive material into the combined sanitary and storm sewer system in King County, Washington. Radioactive material could come from the use of a radiological dispersion device (RDD). RDDs include "dirty bombs" that are not nuclear detonations but are explosives designed to spread radioactive material (National Council on Radiation Protection and Measurements (NCRP) 2001). Radioactive material also could come from deliberate introduction or dispersion of radioactive material into the environment, including waterways and water supply systems.

This document develops plausible, likely scenarios, including the identification of likely radioactive materials and quantities of those radioactive materials to be involved. These include ^{60}Co, ^{90}Sr, ^{137}Cs, ^{192}Ir, ^{226}Ra, Pu, and ^{241}Am.

Two broad categories of scenarios are considered. The first category includes events that may be suspected from the outset, such as an explosion of a dirty bomb in downtown Seattle. The explosion would most likely be heard, but the type of explosion (e.g., natural gas, industrial explosion, or terrorist RDD) may not be immediately known. Emergency first responders must be able to quickly detect the radioisotopes previously listed, assess the situation, and deploy a response to contain and mitigate (if possible) detrimental effects resulting from the incident. In such scenarios, advance notice of 3 to 4 hours might be available before any contaminated wastewater reaches a treatment plant.

The second category includes events that could go initially undetected by emergency personnel. Examples of such a scenario would be the inadvertent or surreptitious introduction of radioactive material into the sewer system. Intact rogue radioactive sources from industrial radiography devices, well-logging apparatus, or moisture density gages may get into wastewater and be carried to a treatment plant. Other scenarios might include a terrorist deliberately putting a dispersible radioactive material into wastewater. Alternatively, a botched terrorism preparation of an RDD may result in radioactive material entering wastewater without anyone's knowledge. Drinking water supplies, bottled or packaged beverages, and foodstuffs may also be contaminated, with the result that some or most of the radioactivity ends up in wastewater. In some of these scenarios, the first evidence that an incident has occurred may be detection of radioactive material in wastewater.

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1.0 Introduction

> *In the United States there are no identified cases in which radioactive materials in sewage systems are a threat to the health and safety of publicly-owned treatment works (POTW) workers or the general public. However, there have been a small number of facilities where elevated levels of man-made radioactive materials were detected. Based upon this past experience, there is a concern that radioactive material could concentrate in sewage sludge and ash and could pose a threat to the health and safety of workers or the public.*
>
> (Interagency Steering Committee on Radiation Standards 2003c).

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This document only briefly covers the event of the detonation of an improvised nuclear device (IND), the Department of Homeland Security's term for a home-made nuclear weapon. Also, it does not address accidents at nuclear power reactors since there are none near Seattle. Finally, the report does not address sabotage of spent nuclear fuel shipments, since there is no commerce in nuclear power reactor fuel in the Puget Sound area.

2.0 Radiation and Radioactive Materials

This section provides background information on radioactive materials and the radiation they emit, and identifies the radioactive materials that are widely regarded to be of interest in the context of radiological terrorism.

2.1 Ionizing Radiation

Radiation includes ionizing and non-ionizing radiation. Examples of non-ionizing radiation are radio waves, microwaves, infrared light (radiant heat), visible light, and ultraviolet light.

Ionizing radiation includes x-rays, and high-energy radiation emitted by radioactive materials and nuclear reactions such as a nuclear reactor or nuclear explosion. Ionizing radiation includes alpha, beta, gamma, and x-radiation, and neutrons. Each of these types of radiation differs in its penetrating power and the nature of its interactions with matter. Each type of radiation poses its own challenges for detection and protection.

From here on, the term "radiation" is used to mean "ionizing radiation."

Excellent guides to radiation are available on-line (U.S. Environmental Protection Agency (EPA) 2004b; Centers for Disease Control and Prevention 2003b).

2.1.1 Alpha Radiation

Alpha radiation, sometimes denoted by the Greek letter α, is the least penetrating kind of radiation. Alpha radiation can be completely absorbed and stopped by 2" of air or a thin sheet of paper, and will not penetrate the outermost, dead layer of human skin (Figure 1). However, if alpha radiation is emitted from radioactive material inside the body, it is more damaging than other types of radiation. Alpha radiation is composed of γ-particles, another name for the nucleus of a helium atom containing 2 protons and 2 neutrons.

2.1.2 Beta Radiation

Beta radiation, sometimes denoted by the Greek letter β, is more penetrating than α-radiation. Beta radiation can be completely absorbed and stopped by 1/2" or less of plastic or water (Figure 1). Beta radiation may penetrate up to 1/2" of skin and muscle, and if emitted from radioactive material inside the body, it can cause tissue damage. Beta radiation is composed of electrons, which behave as high-speed particles.

2.1.3 Gamma Radiation and X-Radiation

Gamma radiation, sometimes denoted by the Greek letter γ, is physically identical to x-rays, but originates in nuclear reactions such as radioactive decay. Gamma and x-radiation can be highly penetrating, with some of it passing all the way through the body and some being absorbed within the body. Gamma and x-radiation can be reduced by shielding with materials such as water, earth, concrete, iron, and lead (Figure 1). The amount of shielding needed depends on the energy and intensity of the radiation. If

emitted from radioactive material inside the body, gamma radiation can cause tissue damage. Gamma and x-radiation are electromagnetic radiation, like radio waves and light.

2.1.4 Neutron Radiation

Neutron radiation only occurs in nuclear reactors, nuclear weapons detonations, and at high-energy accelerators. It is only mentioned for completeness and is not discussed further.

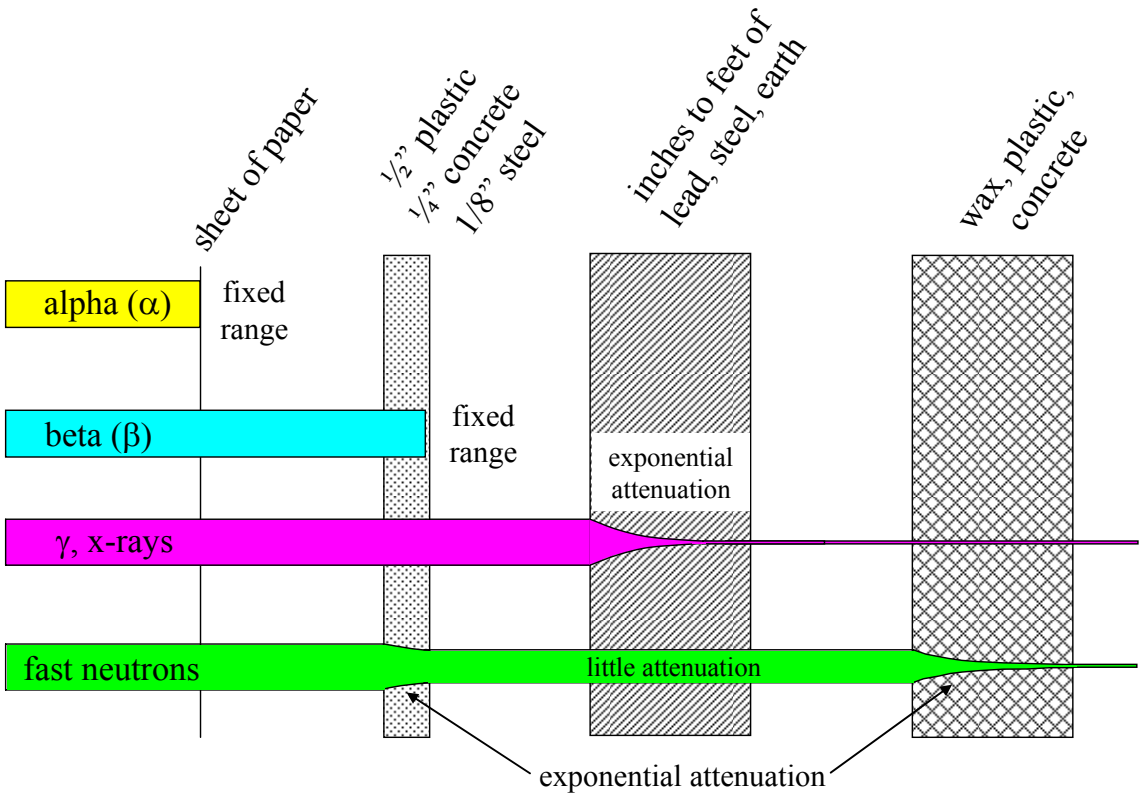

Figure 1. Interactions of various kinds of radiation with matter. The width of each bar indicates the intensity of the radiation. Alpha radiation is absorbed by even a thin sheet of paper. Beta radiation is more penetrating, but can be stopped by 1/2" or less of a material like plastic or water, 1/4" of concrete, or 1/8" of steel. Gamma and x-radiation pass easily through plastic, but are stopped by massive shields of water, earth, concrete, iron, or lead. Fast neutrons can penetrate modest amounts of lead, but are stopped by materials containing hydrogen, such as water, concrete, plastic, oil, or wax.

Concrete sewer pipes often have walls that may be 1" thick for each foot of diameter. Thus, a large diameter pipe may provide significant shielding for its radioactive contents. As shown in Figure 8, 10" of concrete absorbs 90% of the most energetic radiation that may be emitted from contaminated wastewater. Since earth is a good shielding material, radiation from buried pipes will be mostly or entirely absorbed by a thick covering of dirt.

2.2 Radioactive Materials

Radioactive materials are simply chemicals or substances containing some radioactive atoms. Radioactive materials may be solid (metal, crystalline, ceramic, powder, salt); liquid (dissolved or suspended); or gaseous (including gases, vapors, mists, and airborne dust) depending on the particular chemical and physical form. Radioactive materials may or may not be water soluble.

2.2.1 Radioactive Atoms

Radioactive atoms are unstable and undergo spontaneous changes in their atomic nuclei. These changes result in the emission of ionizing radiation such as alpha particles, beta particles, and gamma or x-radiation. The transition of each atomic nucleus results in a new nucleus, generally of a different chemical element. Radioactive materials are identified as a chemical element, such as cobalt, and the number of particles in its nucleus, such as 60. Such a combination, for example, cobalt-60 (^{60}Co), is called a radionuclide. A ^{60}Co atom emits a beta particle and two gamma rays when it transitions into a non-radioactive nickel-60 atom.

Radioactivity is the phenomenon of these spontaneous changes with the resulting emission of ionizing radiation. Radioactive atoms that undergo decay may turn into stable, non-radioactive atoms, or they may turn into new, different radioactive atoms. An example of the latter is the transition of radioactive strontium-90 (^{90}Sr) into radioactive yttrium-90 (^{90}Y), which in turn transitions into stable zirconium-90.

2.2.2 Amount of Radioactivity: the Activity in Curies (or Becquerels)

The amount of radioactivity that a sample of radioactive material contains is called the *activity* and is traditionally measured in units called curies (unit symbol: Ci)[1]. One curie is 37,000,000,000 nuclear transitions per second. A curie is generally a lot of radioactivity, so smaller units are often used, such as the millicurie (mCi), which is 0.001 Ci, and the microcurie (μCi), which is 0.000 001 Ci. A smoke detector typically contains 0.9 μCi of americium-241 (^{241}Am).

2.2.3 Radioactive Decay and Half-Life

As radioactive atoms transition to new atoms with the emission of radiation, the amount of radioactivity is said to decay. This means that there is less and less of it over time. The rate at which radioactivity decreases is expressed in terms of the half-life of the material, which is a characteristic of each radionuclide.

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1 Most countries, and the U.S. Department of Transportation, use the becquerel (Bq) as the unit of activity. 1 Bq is one radioactive transition per second, so 1 Ci = 37,000,000,000 Bq. Packages marked with for DOT shipping labels are commonly marked in megabecquerels (1 MBq ~ 27 μCi), gigabecquerels (1 GBq ~ 27 mCi) or terabecquerels (1 TBq ~ 27 Ci).

2.2.4 Exposure to Radiation Emitted by Radioactive Materials

Radioactive materials emit radiation. A person may be exposed to this radiation by coming near a source that emits penetrating radiation such as gamma radiation (bottom row in Figure 2), or if the person inhales or ingests the material, or gets the material on the skin (Figure 2). Following intakes via ingestion or inhalation, some of the radioactive material will remain in the human body the same way a non-radioactive chemical would remain in the body. Usually, most inhaled or ingested material is cleared out of the body in a few days, but this is not always the case. While the radioactive material is in the body, radiation it emits can be absorbed in the body, leading to radiation dose.

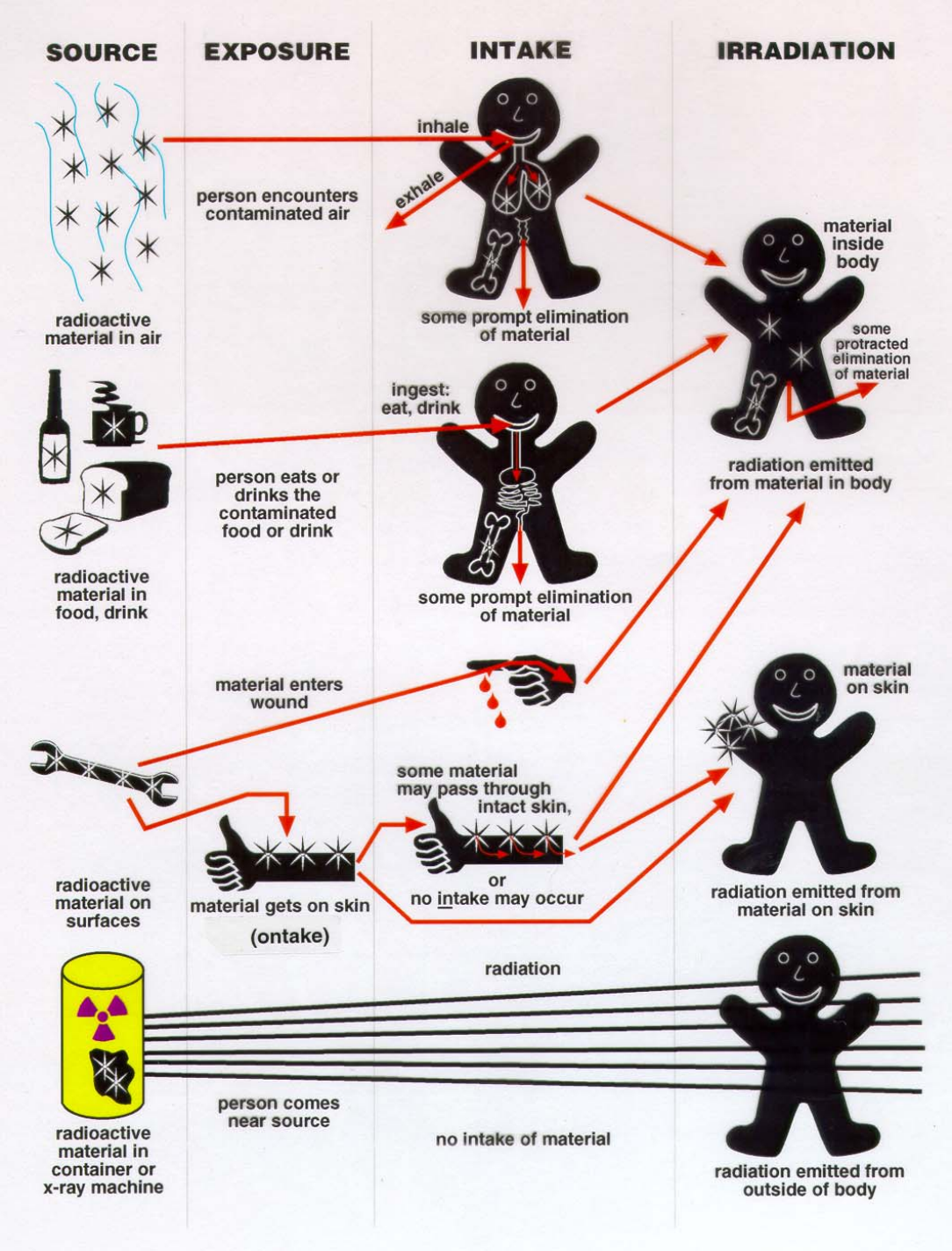

Figure 2. Sources of radioactive material, exposures to radioactive materials, intakes and ontakes of radioactive materials, and irradiation by radioactive materials (Strom and Watson 2002).

2.3 Characteristics of Radioactive Materials that May Be Used for Malicious Purposes

The characteristics of selected radionuclides are given in the Table 1. These are of particular interest because they are plentiful in relatively large amounts. Half-lives and principal radiation types are shown. The D-values are internationally-recognized dangerous amounts of these radionuclides (International Atomic Energy Agency (IAEA) 2003) in units of curies or terabecquerels (TBq), where 1 Ci = 0.037 TBq. For the most common chemical forms of these radionuclides, note the incredibly small mass associated with a dangerous amount of radioactivity. As shown in the last three columns, these radioactive materials may have industrial, medical, or defense uses.

Table 1. List of radionuclides of concern. Some emit more than one kind of radiation. D-values are threshold values for dangerous amounts in curies, terabecquerels, and milligrams (mg) if the radionuclide is not diluted with non-radioactive material. Use or origin indicates where the radionuclides may be in use.

			Radiation			**D-value**			**Use or Origin**		
Radionuclide	Symbol	Half-life	alpha	beta	gamma	Ci	TBq	mg	Industrial	Medical	Defense
cobalt-60	^{60}Co	5 years		β	γ	0.8	0.03	0.7	x	x	
strontium-90	^{90}Sr	28 years		β		30	1	450	x	x	
molybdenum-99	^{99}Mo	66 hours		β	γ	8	0.3	0.017		x	
iodine-131	^{131}I	8 days		β	γ	5	0.2	0.04		x	
cesium-137	^{137}Cs	30 years		β	γ	3	0.1	44	x	x	
iridium-192	^{192}Ir	75 days		β	γ	2	0.08	0.2	x	x	
radium-226	^{226}Ra	1600 years	α	β	γ	1	0.04	1,000	x		
uranium	U	4.5 billion years	α	β	weak			-	x		x
americium-241	^{241}Am	432 years	α		γ	2	0.06	580	x		x
plutonium	Pu	24,000 years	α	β	weak	2	0.06	-	x		x

2.4 Amounts that affect humans

Radiation is like money in one sense: you can't talk meaningfully about it unless you know how much you're talking about! There are amounts of radioactive material that are so small that they are of no concern.

Furthermore, radioactive materials exist in nature. Radioactive uranium, thorium and potassium-40 are primordial radioactive materials that have been on earth since the dawn of time. They are found everywhere and occur in trace amounts in all food and beverage. All human beings have eaten these trace amounts all of their lives, and all contain traces of these radioactive materials.

2.4.1 Normal Levels of Radioactive Materials in Sewage

Medical-use radionuclides are legally discharged[2] into sanitary sewers every day as they are passed out of patients who have received them for diagnosis and treatment (Nakamura et al. 2005; Hilton, Harvey, and Simmonds 2004; Hotte and Sokolek 2001; Brennan 1997; Miller et al. 1996; Ainsworth et al. 1994; Kennedy Jr. et al. 1992; Larsen et al. 1992; Prichard, Gesell, and Davis 1981; Sodd, Velten, and Saenger 1975; Blake and Rapley 1972).

A recent survey conduced by the Nuclear Regulatory Commission (NRC), Environmental Protection Agency (EPA), and Department of Energy (DOE) revealed very low levels of natural and human-made radionuclides in sewage sludge and ash (Interagency Steering Committee on Radiation Standards 2003b):

The survey obtained sewage sludge and incinerator ash samples from 313 POTWs across the country. A total of 45 radionuclides were detected, with eight radionuclides (Be-7, Bi-214, I-131, K-40, Pb-212, Pb-214, Ra-226, and Ra-228) reported in more than 200 samples. Highest concentrations were observed for I-131, Tl-201, and Sr-89 (all short half-lived medical isotopes). Many samples contained radium and uranium.

Three overall conclusions arose.

1) Elevated levels of radioactive materials were found in some sewage sludge and ash samples, but did not indicate a wide-spread problem;
2) Estimated doses to potentially exposed individuals are generally well below levels requiring radiation protection actions; and
3) For limited POTW worker and on-site resident scenarios, doses above protective standards could occur. This was primarily due to indoor radon generated as a decay product of naturally occurring radionuclides, such as Ra-226 and Th-228.

How much radioactive material, then, would be of concern? The D-values given in the Table 1 above are amounts of radioactivity that are likely to cause injury or death from a couple of days' exposure under some circumstances.

To answer the "How much?" question, we must have a "currency" for radiation dose.

2.4.2 Amount of Radiation Absorbed: Dose in Rems

Radioactive materials are chemicals that emit radiation. When the body absorbs radiation, the radiation can cause change, damage, or harm, depending on the amount. An amount of radiation is called a dose. In

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2 See, for example, Washington State Department of Health, *Radiation Protection Standards*. Chapter 246-221 Washington Administrative Code; specifically, 246-221-190, "Disposal by release into sanitary sewerage systems" which states, "(2) Excreta from individuals undergoing medical diagnosis or therapy with radioactive material shall be exempt from any limitations contained in this section." For a federal perspective, see Title 10, Code of Federal Regulations, Part 20.2003 (10 CFR 20.2003), "Disposal by release into sanitary sewerage" and 10 CFR 35.75, "Release of individuals containing unsealed byproduct material or implants containing byproduct material" for sample federal regulations.

the U.S., radiation dose is measured in a unit called a rem.[3] Often, dose is measured in millirems, where 1 mrem = 1/1,000 rem.

2.4.3 Everyday Radiation Doses

For perspective, each of us receives around 0.2 to 0.3 rems (200 to 300 millirems) each year from natural radionuclides and other natural sources of radiation.

Many medical procedures (x-rays, CT scans, or nuclear medicine exams), produce doses in the range of 0.01 rem (chest x-ray) to 5 rems (CT, nuclear medicine) to part or all of the body.

2.4.4 Dose Limits for Workers and the Public

Federal agencies such as theNRC (1993), the Occupational Safety and Health Administration (1971) and state agencies such as the Washington State Department of Health (2005) have adopted regulatory limits for exposures of the public and for radiation workers.

2.4.4.1 Worker Dose Limits

A radiation worker is a person who normally works with radiation or radioactive materials as part of his or her job, and who has received training in radiation protection and the biological effects of radiation.

The dose limit for workers is 5 rems per year from human-made sources, and employers are required to keep doses as low as is reasonably achievable (ALARA) below this limit. In emergencies, workers are generally allowed to receive 25 rems while conducting critical or life-saving activities. There are unlikely to be any clinical symptoms at this dose level.

2.4.4.2 Public Dose Limits

Radiation dose limits for the public are lower than for radiation workers, because

- the public does not gain the benefit of a paycheck from radiation doses (other than medical exposures)
- the public includes the very young, children, and the elderly, all of whom may be more sensitive to radiation than adults who are healthy enough to work.

King County WTD workers are currently considered members of the public, and not radiation workers[4].

3In Europe and the most of the rest of the world, radiation dose is measured in a unit called the sievert (Sv), where 1 Sv = 100 rems. Common sub-multiples of the sievert are the millisieverts (1 mSv = 1/1,000 Sv = 100 mrem), and the microsieverts (1 μSv = 1/1,000,000 Sv = 0.1 mrem).

4 It is legitimate to ask whether, in the event of an act of war or an emergency such as a radiological dispersion event, all public servants such as firefighters, emergency medical technicians, police, HAZMAT teams, and even WTD employees become radiation workers.

The dose limit to the public is 0.1 rems (100 millirems) per year from human-made sources (excluding medical).

2.4.4.3 EPA Drinking Water Radionuclide Concentration Limits

Under the Safe Drinking Water Act, the EPA has drinking water standards that are expressed as concentrations of radionuclides in water, usually in units of picocuries per liter (pCi/L). One picocurie is one trillionth of a curie. These maximum contaminant levels are found in 40 CFR Part 141.16, "Maximum contaminant levels for beta particle and photon radioactivity from man-made radionuclides in community water systems." The EPA limits are for ingestion of drinking water, and are shown in Table 2.

Table 2. EPA limits from 40 CFR 141, National Primary Drinking Water Regulations

Radionuclide	Value	Unit
$^{226}Ra + ^{228}Ra$	5	pCi/L
Gross alpha	15	pCi/L
^{3}H	20,000	pCi/L
^{90}Sr	8	pCi/L
U	30	µg/L
Other □□ emitters	4	mrem/year

2.4.5 The Health Effects of Short-Term Irradiation

Low doses of radiation, such as those received from natural sources every year, do not produce any clinical symptoms in people. However, low doses of radiation may lead to a slight increase in cancer risk later in life. For purposes of radiation protection in peacetime, it is assumed that 1 rem leads to a 0.05% increase in cancer risk (International Commission on Radiological Protection (ICRP) 1991). Since over 40% of people get a serious cancer at some point in their lives, and about 23% of us die from cancer, a 1-rem dose would lead to a lifetime risk of 23% + 0.05%, or 23.05% lifetime fatal cancer risk.

Higher doses produce clinical symptoms (Strom 2003). At 100 rems, some people will feel tired and perhaps nauseous, and have a lowered white blood cell count for a few weeks, but will recover completely. Doses of 200 rems or more received over a period of hours lead to clinical symptoms. With no medical care, 300 rems is a lethal dose for about 50 % of people, while intensive medical care can save most people at this dose level. Few people can survive a dose of 600 rems delivered in a few hours, even with good medical care. If the dose is protracted over weeks, months, or years, there would be few or no symptoms (Strom 2005).

Excellent, readable information on health effects of radiation is available from the NRC (U.S. Nuclear Regulatory Commission (NRC) 1996; U.S. Nuclear Regulatory Commission (NRC) 1999), the EPA (U.S. Environmental Protection Agency (EPA) 2004a), and the Centers for Disease Control and Prevention (Centers for Disease Control and Prevention 2003a).

3.0 Scenarios for Entry, Transport, and Fate of Radionuclides in Wastewater

This section describes radioactive sources that may be available to persons with malicious intent, and scenarios for entry, transport, and fate of radionuclides in wastewater.

3.1 Radioactive Materials that May Fall into the Wrong Hands

A variety of radionuclides in a number of physical and chemical forms may become available to persons with malicious intent, as listed in Table 1. Common chemical and physical forms are found in Table 3.

Many of the larger radionuclide sources are found doubly encapsulated in tough stainless steel canisters that are seamlessly welded shut. Parts of typical ^{60}Co teletherapy sources are shown in Figures 3 and 4. A dummy "pigtail" source of ^{192}Ir is shown in Figure 5.

Figure 3. Parts of a dummy 60Co teletherapy source. All of the radioactive materials are in the pellets, made of cobalt and nickel metal. At the right are spacers, with the inner capsule (center) and outer capsule (left). Each capsule is welded shut. The outer capsule is placed in a rugged source holder.

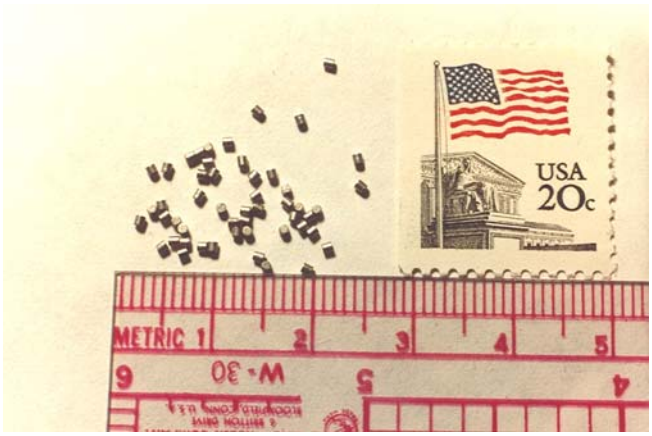

Figure 4. Photograph of metal 60Co pellets such as those involved in the 1983 Juarez, Mexico, incident. Such pellets, if dispersed in wastewater, would be negligibly soluble and would follow large sand grains. Some may wind up in grit or be entrained in rags and debris. Each pellet may be several curies of activity, and the collection shown would produce very dangerous levels of radiation.

Table 3. Initial Chemical and Physical Forms of Radionuclides.

Radionuclide	Initial Chemical and Physical Forms
cobalt-60	metal (solid) or metal pieces (grains of rice) encapsulated in stainless steel; see Figures 3 and 4
strontium-90	ceramic $SrTiO_3$ (strontium titanate) in strong metal container
molybdenum-99	adsorbed to an ion exchange resin inside a lead radiation shield
iodine-131	liquid or NaI capsule
cesium-137	CsCl encapsulated in stainless steel
iridium-192	metal (solid) encapsulated in stainless steel (Figure 5), or as tiny needles or metal seeds
radium-226	$RaCl_2$ encapsulated in various holders
uranium	metal, salts
americium-241	metal, possibly mixed with beryllium and encapsulated in stainless steel
plutonium	metal or oxide

Figure 5. A typical [dummy] gamma radiography source that may contain up to 200 curies (7.4 terabecquerels) of ^{60}Co or ^{192}Ir (177 or 22 mg, respectively, if at 100% radionuclide purity). The radioactive material is encapsulated at the very tip of the cable. Touching a real source like this would cause severe radiation burns to the finger tips in seconds. Such sources are stored and shipped in locked, sturdy, heavy, shielded containers with warning labels.

Although handling multiples of D-value quantities of these radionuclides may very rapidly lead to radiation burns, other severe irreversible injury, and even death, terrorists have shown themselves willing to risk life and limb. Thus, despite the fact that handling such sources may be immediately dangerous to life and health, it is not prudent to believe that terrorists will be deterred by such dangers.

3.2 Dispersal Scenarios

Individuals with malicious intent may find ways to disperse sources. The popular press and technical sources (National Council on Radiation Protection and Measurements (NCRP) 2001) have reported that explosive dispersal may occur, or that material may be distributed in the air by other means of generating an aerosol. If the radioactive material can be dissolved, it could be sprayed in solution or added to food, beverage, or municipal water supplies.

Radioactive material may enter the wastewater stream in effluents from any drain entering the sewer system, and, in the case of King County's WTD, through the storm sewer. If radioactive material is discovered to have been dispersed, one of the first responses may be to have the fire department wash it into the sewers. Certainly this tactic has always been part of plans for recovery from nuclear attack (Sartor 1982).

3.3 Benchmark Cases

Two limiting cases will be developed in some detail: a case of mostly insoluble ^{60}Co pellets entering the system, and a case of completely soluble $^{137}CsCl$ entering the system.

3.3.1 The Insoluble Scenario: Cobalt-60 (^{60}Co) Pellets

The ^{60}Co pellets scenario can be used to represent $^{90}SrTiO_3$ (a ceramic); ^{192}Ir; uranium, americium, or plutonium metal fragments; and other insoluble forms such as an intact sealed source.

3.3.2 The Soluble Scenario: Cesium Chloride ($^{137}CsCl$)

The $^{137}CsCl$ scenario can be used to represent any soluble material such as ^{99}Mo, $Na^{131}I$, or $^{226}RaCl_2$.

3.4 Fate of Radioactive Material in the Wastewater System

The fate of radioactive material in the wastewater system depends on its chemical and physical form (Table 4). Radioactive materials in wastewater would not be expected to be present in sufficient quantities to affect pipes, pumps, valves, or microorganisms in digesters, given the relatively large dilution factors. In 1994, an NRC study showed that radioactive materials may concentrate in sewage sludge (Ainsworth et al. 1994). Few measurements are available for retention of specific radionuclides in the various waste streams. The only data available for cobalt and cesium are from Stetar et al. (1993), while two sources report values for ^{131}I (Prichard, Gesell, and Davis 1981). Sewage system processes that reduce the volume of sludge through dewatering, incineration, and other technologies result in the further reconcentration of radionuclides. After being dispersed in wastewater, radioactive materials may reconcentrated in rags, grit or biosolids. Radioactive material in biosolids can become further concentrated as biosolids are dried or burned. Under normal conditions, radioactive materials found in biosolids are not considered an exposure risk (Interagency Steering Committee on Radiation Standards 2003c; Interagency Steering Committee on Radiation Standards 2003b; Interagency Steering Committee on Radiation Standards 2003a). The concentration of radioactive material in sewage sludge and ash is a topic of concern that has not been fully addressed (Interagency Steering Committee on Radiation Standards 2003c).

Under the off-normal conditions of a radiological accident or attack, unprecedented amounts of material (*activities* measured in *curies*) may be present in wastewater. In these cases, potentially dangerous levels of radiation may be present if the radioactive materials reconcentrate in rags, stones or grit, biosolids, or may adhere to surfaces of pipes and other equipment.

Table 4. Estimates (in italics) of low and high ranges of percent of radioactive material entering a combined sanitary and storm sewer system that will appear in various waste streams or be retained for some time on surfaces within the system (based on Ainsworth et al. 1994). Boldface values are measurements.

Form Entering Sewer	Material	Screenings		Rocks or Grit		Biosolids		Treated Water		Surfaces[c]	
		Low	High	Low	High	Low	High	Low	High	Low	High
metal pieces	^{60}Co, ^{192}Ir, U, ^{238}Pu, ^{241}Am	*trace*	*?*	*50%*	*100%*	*10%*	*50%*	*trace*	*trace*	*trace*	*20%*
fine particles	^{60}Co, ^{90}Sr, ^{192}Ir, ^{226}Ra, U, ^{238}Pu, ^{241}Am	*trace*	*?*	*trace*	*10%*	*80%*	*90%*	*trace*	*10%*	*trace*	*20%*
dissolved[a]	^{60}Co	-	-	-	-	**31%**		**69%**		-	-
dissolved or soluble	^{90}Sr, ^{192}Ir, ^{226}Ra, U, ^{238}Pu, ^{241}Am	*trace*	*?*	*trace*	*10%*	*10%*	*50%*	*20%*	*80%*	*trace*	*20%*
metal, ceramic	^{90}Sr, ^{226}Ra	*trace*	*?*	*50%*	*100%*	*10%*	*50%*	*trace*	*trace*	*trace*	*20%*
bound to resin	^{99}Mo	*trace*	*?*	*50%*	*90%*	*10%*	*50%*	*trace*	*trace*	*trace*	*20%*
dissolved[a]	^{131}I	-	-	-	-	**2%**		**98%**		-	-
dissolved[b]	^{131}I	-	-	-	-	**23%**		**77%**		-	-
dissolved[a]	^{137}Cs	-	-	-	-	**12%**		**88%**		-	-

[a]Stetar et al. 1993.

[b]Prichard et al. 1981.

[c]Some material may adhere to the slime layer on pipes and equipment, and other material may precipate with phosphates, recovered from sewage as struvite (magnesium ammonium phosphate).

It is clear from **Table 4** that a great deal of uncertainty exists on the efficacy of treatment of wastewater for the removal of radioactive material, and that even rough estimates of radiological hazards in various parts of the wastewater treatment process must be tempered with statements that they are uncertain. It must be concluded that protective actions should be based on extensive, ongoing measurements of radiation and radioactive material following an incident.

4.0 Exposure Pathways from Radioactive Materials in Wastewater Systems

Radioactive materials in wastewater may potentially expose members of the public, WTD workers, WTD microorganisms in the digesters, and the flora and fauna in the environment through a variety of routes. These may be

- direct irradiation, as shown at the bottom of Figure 2
- by getting radioactive material on the skin
- by getting radioactive material in the body via ingestion
- by getting radioactive material in the body via inhalation, as shown in the rest of Figure 2.

This section examines the routes of exposure in sequence for each of several logically distinct points or processes. These are

- wastewater in pipes on the way to the plant
- pumping stations
- wastewater in the treatment plant
- slime and coated surfaces in treatment plant
- screenings in plant
- screenings in dumpster at disposal site
- grit in plant
- grit in dumpster at disposal site
- biosolids in digesters
- biosolids in trucks
- biosolids applied to crops
- crops eaten
- resuspended dust from biosolids
- treated water
- untreated water (WTD bypass).

It is important to note that *all pathways leading to exposure of the public are also potential pathways leading to exposure of WTD workers, who are often more likely than members of the public to be near WTD facilities and infrastructure.*

The exposure pathways evaluated below are discussed in the absence of any protective measures for public, workers, microorganisms, or the environment, and in the absence of any security measures that might prevent entry of radioactive materials into the wastewater system.

4.1 Direct Irradiation

Direct irradiation of wastewater workers and the public from radioactive material is possible. Radioactive materials may be found

- in influent (untreated wastewater)
- in sediment in wastewater pipes
- on surfaces of pipes and equipment that contacts wastewater
- in screenings
- in grit
- in biosolids
- in treated effluent.

While in wastewater, the huge wastewater volumes work both to dilute the radioactive material and to shield (absorb) the radiation it emits before it can get to people. Earth is an excellent radiation shield, and buried sewer lines are shielded depending on their depth. Even an intense radiation source would be undetectable on the other side of ten feet of concrete or packed earth!

Of the radionuclides listed in Table 1, ^{60}Co, ^{99}Mo, ^{131}I, ^{137}Cs, ^{192}Ir, and ^{226}Ra are strong emitters of gamma radiation. Strontium-90, with its decay product ^{90}Y, emits energetic beta particles with limited range that are stopped by 1/2 inch of water. The other materials, U, ^{241}Am, and Pu are not primarily *external* radiation hazards; they are hazardous when they are taken into the human body by inhalation, ingestion, or entry through an open wound or injection.

4.1.1 Factors Affecting Radiation Intensity (Dose Rate) from Direct Irradiation

Radiation dose from direct irradiation varies with characteristics of both the source and the person or object being exposed. Reducing radiation intensity (called the radiation "dose rate") can be done by minimizing the amount of the material, minimizing the time a person is near the source, maximizing the distance from the source, and maximizing the amount of shielding around the source to absorb the radiation.

The intensity of the radiation at a particular point in the plant depends on source variables including

- amount of radioactive material (activity)
- how long it is there or how long it takes to pass through that point in the plant (residence time of the radioactive material)
- configuration and shielding of the radioactive material
- distance.

These variables can be controlled when the source is known to be present. For example, removal of radioactive material and its proper disposal as radioactive waste can reduce or eliminate the amount radioactive material that is producing radiation, thereby reducing radiation dose rates. Moving a source away reduces the radiation intensity, so that, if a source is moving with wastewater, a stationary person experiences a reduction in radiation intensity as the source moves away. Placing radiation-absorbing

barriers (shielding materials) between a location to be protected and the source reduces radiation intensity. Setting up exclusion zones and evacuation can be used to maximize distance and minimize radiation intensity.

The predominant personal variable is exposure time. This variable can be controlled when the source is known to be present by spending as little time near it as possible.

4.1.1.1 Radiation Intensity (Dose Rate) and Amount of Radiation (Rate)

For unshielded radioactive sources, radiation intensity (dose rate) depends on the source strength (its activity in curies) and diminishes rapidly with increasing distance from the source. The amount of radiation (dose) is proportional to how much time one spends in a radiation field. See Figure 6 for a comparison with speed and distance.

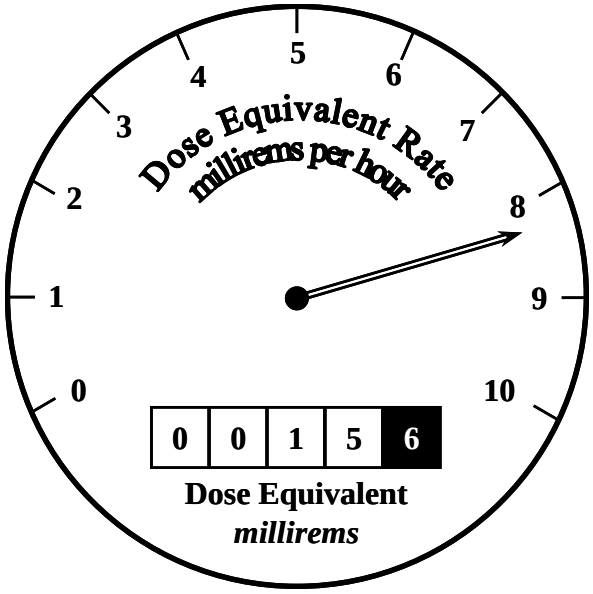

Figure 6. Amount of radiation (dose in millirems) is like distance measured on an odometer, while radiation intensity (dose rate in millirems per hour) is like speed measured on a speedometer. Just like *distance* in miles = (*speed* in miles per hour) × (*driving time* in hours), *dose* in millirems = (*dose rate* in millirems per hour) × (*exposure time* in hours).

4.1.1.2 Unshielded Sources

If radioactive material becomes concentrated and separated from water, it may produce much higher radiation intensities than if it is mixed with or covered with water. For example, when new, each tiny pellet of ^{60}Co shown in Figures 3 and 4 could have an activity of up to 1 Ci, leading to a dose rate of 12.5 rems per hour at one foot, a serious but not immediately dangerous dose rate. Dose rate constants for selected radionuclides are given in Table 5.

Table 5. Dose rate constants for radionuclides emitting significant gamma radiation.

Nuclide	Effective Dose Equivalent (rem/hour at 1 ft. from 1 Ci)[a]	Exposure (R/hour at 1 ft. from 1 Ci)[b]	Effective Dose Equivalent (rem/hour at 1 m from 1 Ci)[c]	Exposure (R/hour at 1 m from 1 Ci)[d]
^{60}Co	12.5	14.0	1.16	1.30
^{131}I	2.25	2.37	0.21	0.22
^{137}Cs	3.21	3.53	0.30	0.33
^{192}Ir	4.81	5.00	0.45	0.46
^{226}Ra	9.02	13.2	0.84	1.23
^{241}Am	0.25	2.38	0.023	0.22

[a]Technically, the units are (rem/hour)(ft.^{2}/Ci)
[b]Technically, the units are (R/hour)(ft.^{2}/Ci), where R denotes "roentgens"
[a]Technically, the units are (rem/hour)(m^2/Ci)
[b]Technically, the units are (R/hour)(m^2/Ci), where R denotes "roentgens"

For sources that are small with respect to the distance one is away from the source, the radiation intensity (dose rate) decreases inversely with the square of the distance. So the dose rate at 2 feet from the ^{60}Co source is $1/2^2 = 1/4$ of the dose rate at 1 foot, and the dose rate at 3 feet is $1/3^2 = 1/9$ of the dose rate at 1 foot. A simple formula relates dose rate to activity:

$$\text{Dose Rate(rems/hour)} = \frac{(\text{Dose Rate Constant})(\text{Activity in curies})}{(\text{Distance in feet})^2}. \quad (1)$$

This formula can be used to determine the activity of a source if the dose rate can be measured at a known distance:

$$\text{Activity in curies} = \frac{(\text{Distance in feet})^2(\text{Dose Rate in rems/hour})}{(\text{Dose Rate Constant})}. \quad (2)$$

For example, if one measured 0.1 rem per hour at 100 feet from a ^{60}Co source, the activity would be

$$\text{Activity in curies} = \frac{(100)^2(0.1\,\text{rems/hour})}{(12.5\,\text{rems/hour at 1 foot from 1 curie})} = 80\ \text{curies}. \quad (3)$$

This is a possible value for a ^{60}Co industrial radiography source such as the pigtail source shown in Figure 5 if it were removed from its storage shield.

4.1.1.3 Shielded Sources

Water, concrete, earth, and iron or steel all are used for shielding ionizing radiation. All are found in the infrastructure of the WTD! Figure 7 shows the fraction of radiation from ^{60}Co that is transmitted through a given thickness of water. Of all of the radionuclides in Table 1 (except ^{226}Ra), ^{60}Co emits the most penetrating gamma radiation. A source of ^{60}Co under 27" of water has 90% of its radiation absorbed by

the water; another 19” of water will absorb 99% of the radiation; 62” will cut the radiation level by 99.9%; and 79” of water will absorb 99.99% of the radiation. For ^{137}Cs and ^{192}Ir, the absorbed fractions are much greater.

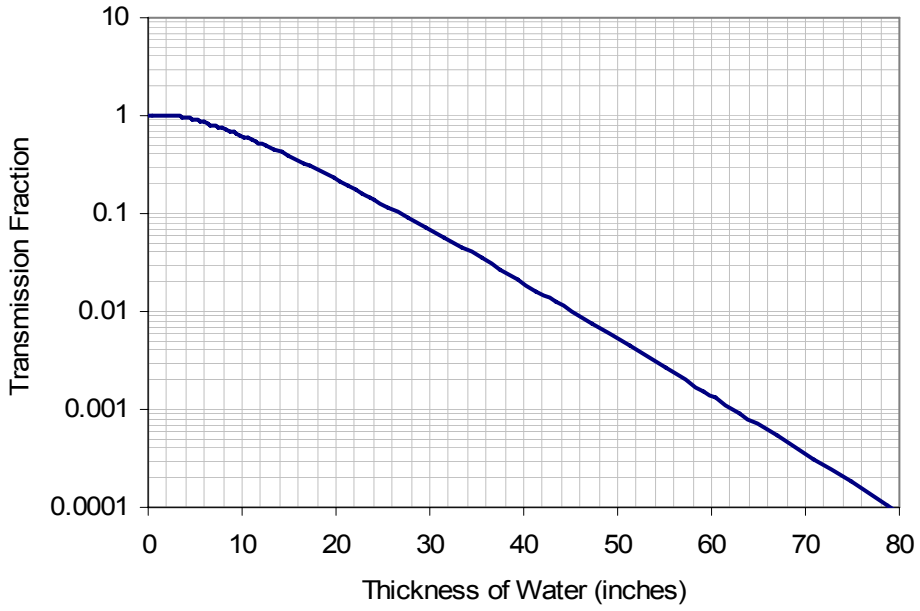

Figure 7. Transmission through water of ^{60}Co radiation.

The fractional transmission shown in Figure 7 and Table 6 leads to the conclusion that, if a radioactive source is underwater, the farther away a radioactive source is from a detector, the less radiation will reach the detector because of absorption, making it very difficult to detect at any significant distance. For example, 12’ of water transmits only about 1/100,000,000 of ^{60}Co radiation, so that even a massive source separated from a detector by 12’ of water would deliver little radiation to a detector.

Figure 8 shows that concrete and iron are even more effective as shields than water, a phenomenon that is due to their higher density and higher atomic number constituents. It can be seen on the graph that a 10”-thick concrete wall of a pipe will transmit only about 10% of ^{60}Co gamma radiation, absorbing the other 90%. It can be seen on the right-hand graph that a 2”-thick iron pipe wall transmits only about 25% of ^{60}Co gamma radiation, absorbing the other 75%.

Table 6. Percent or fraction of ^{60}Co radiation transmitted through various depths of water.

Water Depth (in.)	% Transmitted	Fraction Transmitted
12.5	50%	1/2
27	10%	1/10
45	1%	1/100
62	0.1%	1/1,000
79	0.01%	1/10,000
96	0.001%	1/100,000
112	0.0001%	1/1,000,000
128	0.00001%	1/10,000,000
144	0.000001%	1/100,000,000
160	0.0000001%	1/1,000,000,000
176	0.00000001%	1/10,000,000,000
192	0.000000001%	1/100,000,000,000

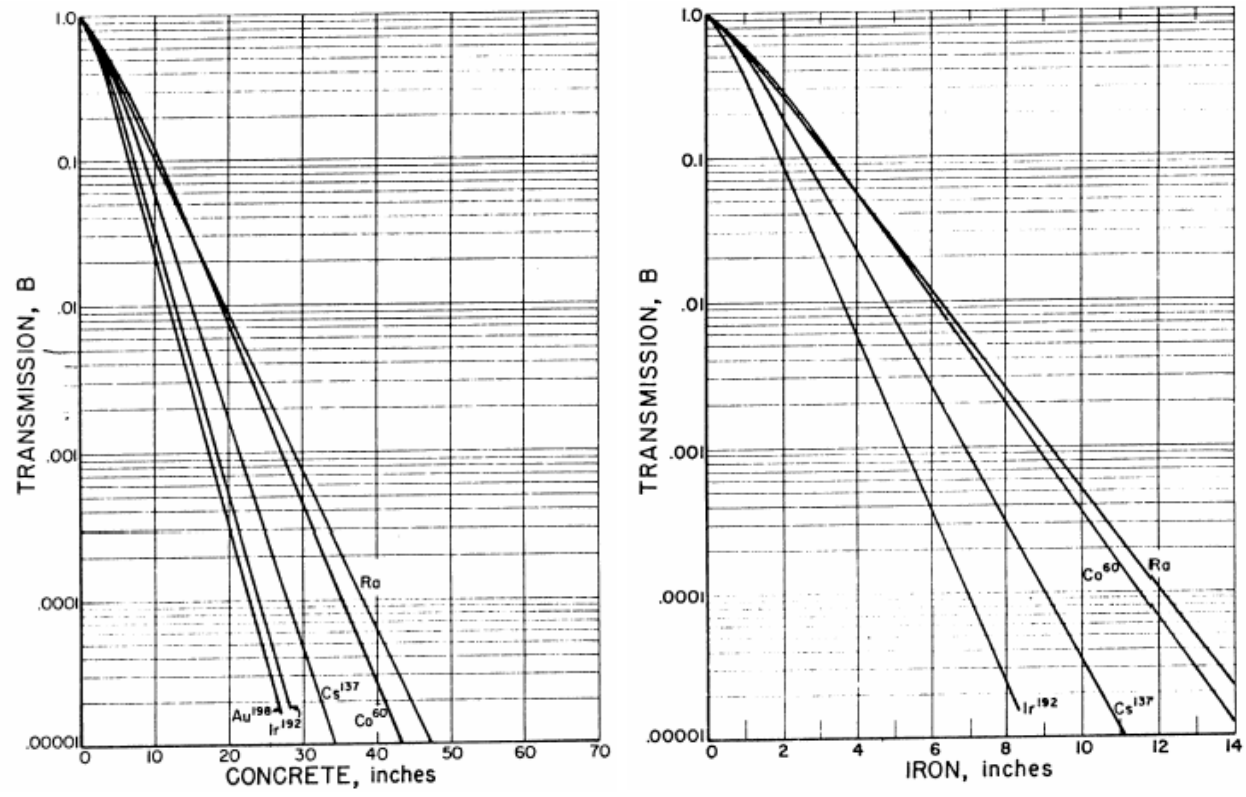

Figure 8. (Left) Transmission of gamma radiation from several radionuclides of interest through concrete (147 lb/ft^3 = 2.35 g/cm^3). (Right) Transmission of gamma radiation from several radionuclides of interest through iron (492 lb/ft^3 = 7.87 g/cm^3). Graphs from (Bureau of Radiological Health 1970).

The shielding effect can be looked at in a different way, as reducing dose from radioactive materials dissolved in water. Figure 9 shows the percent of dose received from ^{60}Co above various depths in a uniform solution. Again, ^{60}Co is used because it is a worst case, meaning that the radiation from ^{60}Co is more penetrating than from all other likely sources except ^{226}Ra. The top 7.5" of water delivers fully half of the dose, while 90% of the dose comes from the top 22" of water.

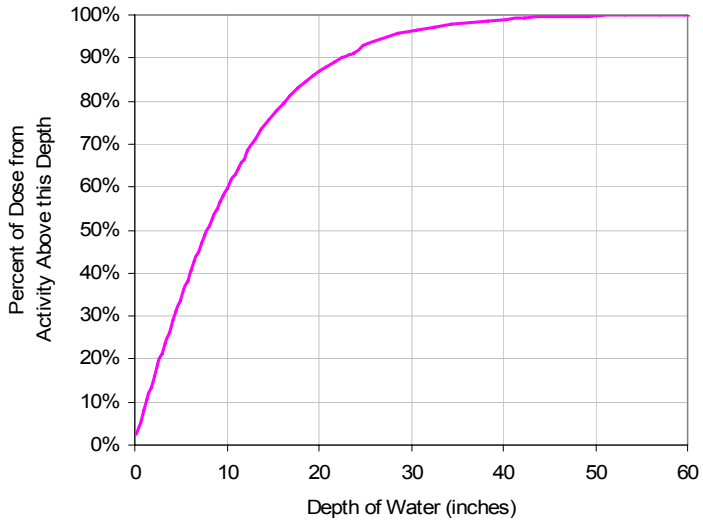

Figure 9. Percent of dose from ^{60}Co dissolved in water above a given depth in the water.

The EPA has published cancer risk coefficients for radioactive contamination (Eckerman et al. 1999). These coefficients do not give dose from radioactive contamination in the environment, but rather go directly to risk for comparison with chemical carcinogen risk coefficients.

4.1.1.4 Dilution

Table 7 shows NRC concentration limits for discharge *to* sanitary sewers. These numbers are based on soluble materials and their relative toxicity.

Table 7. Concentration limits for discharge to sanitary sewage from 10 CFR 20 Appendix B, expressed in microcuries per 1,000 L (metric tonne) and per 1,000 gallons.

Radionuclide	Soluble Chemical Form(s)	Conc. (µCi/ 1,000 L)	Conc. (µCi/1,000 gal.)
^{60}Co	All compounds except oxides, hydroxides, halides, and nitrates	3	11.4
^{90}Sr	All soluble compounds including $SrTiO_3$	0.5	1.89
^{99}Mo	All compounds except oxides, hydroxides, and MoS_2	20	75.7

^{131}I	All compounds	1	3.79
^{137}Cs	All compounds	1	3.79
^{192}Ir	All compounds except halides, nitrates, metallic iridium, oxides, and hydroxides	10	37.9
^{226}Ra	All compounds	0.06	0.23
Uranium	DU, UF_6, UO_2F_2, $UO_2(NO_3)_2$	0.3	1.14
Plutonium	All compounds except PuO_2	0.02	0.076
^{241}Am	All compounds	0.02	0.076

Direct irradiation from water containing these concentrations is utterly trivial, since the concentrations are limited by considerations of ingestion, not direct irradiation.

Because of the countless numbers of pipe shapes and sizes, and volumes of water that occur in the WTD system, some simplification must be made. One conceptual means of simplifying is to look at an overall worst-case. Because the dose rate to a person cannot exceed the dose rate to the wastewater itself, upper limits on dose rates can be calculated for the case when all the radiation energy emitted in the water is absorbed in the water (this would occur for an infinite volume or simply large volume). Half this value is not a bad approximation for the dose rate in air at the surface of a large, deep pool of uniformly contaminated water. As shown in Table 8, adapted from (Eckerman 2004), the radionuclide with the highest total energy emitted is ^{60}Co, and it consequently has the most limiting concentration to yield a dose rate of 1 rem/h. These values are in the ballpark of 1,000 μCi/gallon or 1 mCi/gallon. The largest credible source is 10,000 Ci or 10,000,000 mCi. If this was diluted in 10,000,000 gallons of water, it would produce a maximum dose rate of 1 rem per hour with no shielding. If diluted by less water, the unshielded dose rates on contact with the water could be higher. If there was less activity, the dose rate would be proportionately lower.

Table 8. Concentrations of selected radionuclides that would deliver 1 rem per hour to an infinite volume (an upper limit on dose rate) (Eckerman 2004).

Nuclide	Dose coefficient for immersion in water [rem hr^{-1} $(mCi\ gal^{-1})^{-1}$]	Dose coefficient at surface of water [rem hr^{-1} $(mCi\ gal^{-1})^{-1}$]
^{60}Co	0.904	0.452
^{90}Sr + ^{90}Y	0.00386	0.00193
^{99}Mo	0.0524	0.0262
^{131}I	0.129	0.0646
^{137}Cs + ^{137m}Ba	0.206	0.103
^{192}Ir	0.277	0.138
^{226}Ra	0.00220	0.00110
^{235}U	0.0503	0.0252
^{239}Pu	0.0000276	0.0000138
^{241}Am	0.00542	0.00271

At 100 million gallons per day (MGD), 10 million gallons flows past any point in 1/10 day, or 2.4 hours. Thus a ball-park estimated exposure to someone in close proximity to such water is 1 rem/hour for 2.4 hours, or 2.4 rems. That is above the public dose limit, but below the limit for workers, and certainly not a dose that would be life-threatening. If the concentration were higher, the transit time would be proportionately shorter, so, once the dissolved radioactive material is diluted, doses will be limited. If there was shielding, doses would be lower. If the exposed person was at some distance away, doses would be lower.

When radioactivity is reconcentrated in screenings, grit, or biosolids, potential doses are much higher.

4.1.2 Direct Irradiation: Public

The various sources are evaluated for who among the public is at risk, and qualitatively what the risk might be. These are shown in Table 9.

Table 9. Direct Irradiation of the Public.

Source	Who's at Risk?	Qualitative Risk Assessment
Wastewater in pipes on the way to the plant	People near manholes	Pipes are heavily shielded; only "shine" through manholes with or without covers would be significant
Pumping stations	People near the station	Most pipes and equipment underground or below grade
Wastewater in the treatment plant	People near the plant	Plant is shielded with earthen barriers; only "skyshine" could deliver any dose
Screenings in plant	People near the plant	Very low because of distance from public areas
Screenings in dumpster off-site	People near the dumpster	Could be very significant to nearby people
Grit in plant	People near the plant	Distant from public access
Grit in dumpster off-site	People near the dumpster	Could be very significant to nearby people
Biosolids in digesters	People near the plant	Distant from public access
Biosolids in trucks	People near the truck	Could be very significant to nearby people
Biosolids applied to crops	Farmers	Could be significant during application; less so after application
Crops eaten	Consumers	Likely to be very dilute
Resuspended dust from biosolids	Persons downwind of farm	Likely to be very dilute
Treated water	Scuba divers near discharge point	Direct irradiation of the public from water discharged 240' below Puget Sound will be effectively zero due to shielding and dilution
Untreated water (WTD bypass)	Scuba divers near discharge point	Direct irradiation of the public from water discharged 80' below Puget Sound will be very low due to shielding and dilution

4.1.3 Direct Irradiation: WTD Workers

It is important to remember that all pathways leading to exposure of the public are also potential pathways leading to exposure of WTD workers, who are often more likely than members of the public to be near WTD facilities and infrastructure (Table 10). This section deals with additional exposure pathways.

WTD workers will be closer to wastewater bearing radioactive material than the public, and will spend more time at close distances. They will also be in situations where direct irradiation from radioactive material in or under wastewater will have less, or even no, shielding.

Table 10. Direct Irradiation of WTD Workers

Source	Who's at Risk?	Qualitative Risk Assessment
Wastewater in pipes on the way to the plant	Workers in pipes	Direct irradiation potentially of concern. Irradiation times from material in sediment or wastewater depends on movement and amount of time worker is present. Dose depends on distance from radioactive material, and is proportional to activity concentration (Ci/gal. in wastewater) or activity (Ci in sediment)
Pumping stations	Workers in the station	See first entry, above
Wastewater in the treatment plant	Workers in the plant	See first entry, above. Wastewater becomes more and more dilute with time; suspended activity (if any) settles, reducing dose rate
Screenings in plant	Workers in the screening area	Potentially high radiation levels if material is entrained in something screenable. Screenings will be radioactive waste
Screenings in dumpster off-site	Workers near screenings dumpster	Potentially high radiation levels if material is entrained in something screenable. Screenings will be radioactive waste
Grit in plant	Workers near grit separator	Potentially the highest radiation levels if material is solid pellets (e.g., ^{60}Co) or chunks or small intact source. Grit will be radioactive waste
Grit in dumpster on or off-site	Workers near grit dumpster	Potentially the highest radiation levels if material is solid pellets (e.g., ^{60}Co) or chunks or small intact source. Grit will be radioactive waste
Biosolids in digesters	Workers near the digesters	Shielded by water layer; not expected to be significant
Biosolids concentrating area and truck loading area	Workers in loading area near the truck; drivers	Could be very significant to nearby workers for materials concentrating in biosolids. Biosolids will be radioactive waste
Biosolids transport	Drivers	Could be significant
Treated water	Workers in the plant	Some direct irradiation of workers from treated water on its way out of plant; significant shielding expected
Untreated water (WTD bypass)	Workers in the plant	Some direct irradiation of workers untreated water on its way out of plant; significant shielding expected

4.1.4 Direct Irradiation: Microorganisms in Digesters

Microorganisms in digesters are not expected to receive doses that would be lethal to them.

4.1.5 Direct Irradiation: Environmental Concerns

There are no scenarios in which flora or fauna would receive doses from direct irradiation that would threaten a species. There may be localized places where dose rates could be high enough to affect local plant or animal communities.

4.2 Skin Contamination

Considerations of skin contamination will be limited to members of the public and WTD workers.

4.2.1 Skin Contamination: Public

Skin contamination is not expected to be a significant exposure pathway for members of the public because a sanitary sewer system keeps wastewater away from the public once it enters the system.

4.2.2 Skin Contamination: WTD Workers

Skin contamination could occur for WTD workers if they make dermal contact with wastewater, screenings, grit, or biosolids. Since simple sanitation is practiced by WTD workers, the skin contamination exposure pathway is not expected to be significant.

4.3 Ingestion

Considerations of the ingestion pathway include the public, WTD workers, microorganisms, and the environment.

4.3.1 Ingestion: Public

Ingestion of radioactive materials from WTD operations by the public can occur via two routes, consumption of seafood and anything that feeds on seafood, and consumption of crops grown on soil to which has been added contaminated biosolids.

An undetected radioactive contamination event could lead to the production, delivery, and application to farmland of contaminated biosolids. Depending on the crops involved, there may be potential for doses somewhat above limits for the public, but this requires detailed modeling beyond the scope of the current project.

4.3.2 Ingestion: WTD Workers

Waste Treatment Division workers are unlikely to ingest significant amounts of wastewater, so the EPA limits described in Table 2 are not relevant for worker protection.

4.3.3 Ingestion: Microorganisms in Digesters

Microorganisms in digesters may absorb and even bioconcentrate certain radioactive materials in certain chemical forms. These materials are then part of the cell structure, and can produce radiation dose to the

microorganisms. Due to diluting and mixing, there are no credible scenarios in which significant harm is expected to occur to microorganisms.

4.3.4 Ingestion: Flora and Fauna in the Environment

Treated water discharged into Puget Sound will be rapidly diluted, but plants and animals in the vicinity will ingest contaminated water and incorporate some of the contamination into their tissues. Bioconcentration is known to occur for some radionuclides in some chemical forms. Discharge of contaminated water either treated or untreated (due to bypass) could negatively impact the market for seafood harvested due to public perception of contamination rather than significant expected doses to the public.

4.4 Inhalation

Some wastewater may become airborne as mist, carrying dissolved or very fine particulate radioactive materials in the mist. Anywhere that one can smell wastewater there is a potential for intakes via inhalation. Given the enormous volumes of water generally treated, from hundreds of thousands to hundreds of millions of gallons per day, airborne concentrations are likely to be trivial.

4.4.1 Inhalation: Public

Inhalation is not expected to be a significant intake route for the public from WTD operations in King County. However, wind-borne contamination that becomes resuspended following application of biosolids to cropland could be a significant exposure pathway for the public.

4.4.2 Inhalation: WTD Workers

Workers may experience inhalation intakes of radionuclides, but it is difficult to imagine a scenario in which these would be great. Resuspended contamination in the form of mist is not likely to contain enough activity to result in significant intakes. Resuspension from screenings or grit, if dried, may be significant. Resuspension of biosolids in the air may occur to a small extent in the truck loading area, and could potentially be an intake route.

4.4.3 Inhalation: Biosolids Applicators and Farmers

Those applying biosolids to cropland, and farm workers would be expected to experience inhalation intakes of radionuclides. Depending on the scenario, this could be a very significant pathway, especially for high-radiotoxicity materials like plutonium and ^{241}Am.

5.0 Detection

Detection of radioactive material is beyond the scope of this document. Clearly, placement of sensitive gamma radiation detectors with central alarms

- upstream from the plant
- at the screenings conveyor
- at the grit collection point, and
- at the biosolids collection points

would be a good plan. Some considerations for detection are given in Table 11.

Table 11. Direct radiation and aliquot radiation detection considerations

Radionuclide	Direct Detection In Wastewater	Detection in Water Sample
cobalt-60	sensitive gamma detector	sensitive gamma detector
strontium-90	difficult	precipitate Sr+2, filter, count filter with Geiger-Muller or liquid scintillation
molybdenum-99	sensitive gamma detector	sensitive gamma detector
iodine-131	sensitive gamma detector	sensitive gamma detector
cesium-137	sensitive gamma detector	sensitive gamma detector
iridium-192	sensitive gamma detector	sensitive gamma detector
radium-226	sensitive gamma detector	sensitive gamma detector
uranium	impossible	precipitate U, filter, count filter with liquid scintillation or alpha spectrometry
americium-241	difficult	precipitate Am, filter, count filter with Geiger-Muller, liquid scintillation or alpha spectrometry
plutonium	impossible	precipitate Pu, filter, count filter with liquid scintillation or alpha spectrometry

6.0 Conclusions and Recommendations

This radiological risk assessment for the King County Wastewater Treatment Division reveals that a radiological dispersion event (RDE) that goes initially undetected can have consequences for WTD workers and biosolids truckers, the public, farmers, and the environment. Workers can receive radiation doses via direct exposure and possibly inhalation. The public can be irradiated by ingestion of seafood and crops grown on soil to which contaminated biosolids have been added as well as by inhalation of resuspended biosolids dust from treated cropland. Farm workers can be directly irradiated and exposed to resuspended biosolids dust. Finally, discharge of treated or untreated wastewater to Puget Sound can result in measurable radioactive contamination that could negatively impact the economics of seafood and recreation.

The emergency preparedness and response program should incorporate the lessons and implications of the findings given above. Once an RDE is detected, the use of protective measures can greatly reduce doses to workers, biosolids truckers, the public, farmers, and the environment.

It is particularly important that plans be made in advance to segregate, safely store, and dispose of radioactive waste that would be generated by deliberately or inadvertently treating contaminated wastewater. Such a plan must involve state and federal government agencies.

A great deal of uncertainty exists on the efficacy of treatment of wastewater for the removal of radioactive material, and that even rough estimates of radiological hazards in various parts of the wastewater treatment process must be tempered with statements that they are uncertain. Protective actions should be based on extensive, ongoing measurements of radiation and radioactive material following an incident.

There are larger issues that should be considered. If an RDE occurs, is it an emergency? If so, what radiation protection standards apply? Are WTD workers still considered members of the public, or are they emergency first-responders? Will OSHA have emergency worker standards in place? Will the public, wastewater workers, and the environment be better off if radioactively contaminated wastewater is treated, or will they be better off if the plant is bypassed for some period of time? If bypassing makes sense, what criteria are used to trigger bypassing, and when can treatment of wastewater resume? What is the duty, if any, of WTD workers to protect the public by treating contaminated wastewater to reduce environmental consequences at the price of incurring major costs for management of radioactive waste and decontamination of the plant? If an RDE is an act of terrorism by a hostile country or group, does a state of war exist? If so, do wartime radiation protection standards apply? Are WTD then soldiers on the front lines of the war on terrorism? If so, what actions, radiation protection standards, and cleanup activities would be different than in peacetime?

These questions probably cannot be answered by WTD personnel alone, since they involve the public, policy-makers, and lawmakers at the local, state, and federal levels.

The U.S. Department of Homeland Security has published its National Response Plan (NRP) (U.S. Department of Homeland Security (DHS) 2004b). *There are no specifics in the NRP on the questions raised above.* The NRP assigns responsibility for wastewater to the Department of Health and Human Services (DHHS) with support from the U.S. Environmental Protection Agency and the U.S. Department of Defense (DoD). The DHHS "supplies engineering and environmental health personnel to assist in

assessing the status of wastewater and solid-waste facilities." The EPA "assists in identifying water and wastewater needs; supplies sanitary engineers to assess wastewater and solid-waste facilities; provides bio-surveillance, warning, and detection capabilities." The EPA also "assists in investigation and intelligence analysis for hazardous materials incidents involving contaminated wastewater or drinking water systems." The DHHS, in coordination with Public Works and Engineering and Oil and Hazardous Materials Response as appropriate, may task its components, and request assistance from other organizations as appropriate, to assist in assessing potable water, wastewater, solid waste disposal issues, and other environmental health issues; conducting field investigations, including collection and laboratory analysis of relevant samples; providing water purification and wastewater/solid waste disposal equipment and supplies; and providing technical assistance and consultation on potable water and wastewater/solid waste disposal issues." The DoD "Provides available military medical personnel to assist HHS in the protection of public health (such as food, water, wastewater, solid waste disposal, vectors, hygiene, and other environmental conditions)."

The DHS has outlined some research areas for wastewater, but only in very general terms (U.S. Department of Homeland Security (DHS) 2004a). It assigns to EPA the task of "working to produce effective and affordable methods, technologies, equipment, and other tools needed to protect drinking water and wastewater systems from purposeful attacks. Protection against contamination of 2004 National Critical Infrastructure Protection Research and Development Plan drinking water systems is the highest homeland security priority for EPA; physical and cyber security of the Nation's drinking water and wastewater systems are also addressed. The products of this R&D are designed for use by drinking water and wastewater utility personnel, emergency and follow-up responders, states, EPA regional offices, and others involved in protecting human health and the environment."

Based on the findings of this report and its companion volumes that address instrumentation and emergency response, it is recommended that the King County Wastewater Treatment Division seek funding from EPA for developing "effective and affordable methods, technologies, equipment, and other tools needed to protect wastewater systems from purposeful attacks." Research is needed on

- the transport and fate of radionuclides in wastewater
- the overall benefits, risks, and costs to public, workers, environment, and wastewater treatment authorities so that bypass/treat decisions can be made on a sound basis
- action levels to bypass and resume treatment of wastewater
- practical detection and measurement strategies and technologies using off-the-shelf equipment, and identifying needs and opportunities for innovation
- methods of enhancing the removal of radioactive material from wastewater, and sequestration and management of the subsequent radioactive waste
- methods of, and procedures for, decontaminating wastewater treatment plants in the aftermath of a radiological dispersion event
- developing a model radiation protection program to keep doses to wastewater treatment workers as low as is reasonably achievable

- determining the special training needs for wastewater workers involved with a radiological dispersion event
- methods of minimizing entry of radioactive materials into combined sanitary and storm sewer systems, perhaps by treatment in proximity to the radiological dispersion event.

Clearly, much work remains to be done.

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