Preliminary Scoping and Assessment Study of the Potential Impacts of Community-wide Radiological Events and Subsequent Decontamination Activities on Drinking Water and Wastewater Systems

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ABSTRACT

Since the terrorist attacks of September 11, 2001, there has been a great deal of concern about further attacks within the United States, particularly attacks using weapons of mass destruction (WMD) or other unconventional weapons, such as a radiological dispersal device (RDD) or “dirty bomb,” which is a type of RDD. During all phases of an RDD event, secondary impacts on drinking water and wastewater systems would be possible. Secondary impacts refer to those impacts that would occur when the water systems were not the direct or intended target of the specific event. Secondary impacts would include (1) fallout from an event occurring elsewhere on water supply reservoirs and (2) runoff into storm water and sewer systems during precipitation events or as a result of cleanup and decontamination activities. To help address potential secondary impacts, a scoping and assessment study was conducted for the U.S. Environmental Protection Agency’s National Homeland Security Research Center to support its water security program. The study addresses the potential impacts on water resources and infrastructure that could result from the use of an RDD, including potential impacts from the initial attack as well as from subsequent cleanup efforts. Eight radionuclides are considered in the assessment: Am-241, Cf-252, Cs-137, Co-60, Ir-192, Pu-238, Ra-226, and Sr-90.

INTRODUCTION

A scoping report that addresses the potential impacts on drinking water and wastewater resources and infrastructure that could result from the use of a radiological dispersal device (RDD) was prepared for the U.S. Environmental Protection Agency’s (EPA’s) National Homeland Security Research Center to support its water security program [1]. This paper presents a brief summary of the issues addressed in the report and preliminary conclusions.

The term “radiological dispersal device” or RDD refers to any method used to deliberately disperse radioactive material into the environment in order to cause harm. A “dirty bomb,” which is produced by packaging explosives, such as dynamite, with radioactive material, which would be dispersed when the bomb went off, is one type of RDD. Recognizing the complexity of the subject and the large number of uncertainties involved, the study presents screening-level analyses and discusses issues in a broad sense.

The study addresses four major topics: (1) estimated secondary effects on drinking water and wastewater treatment systems from a range of hypothetical large-scale urban radiological incidents; (2) potential impacts of radiological decontamination activities on drinking water and wastewater systems following an RDD event; (3) a survey of water treatment technologies and their application to an RDD event; and (4) a survey of site remediation and restoration technologies and their implications with regard to water systems. Secondary impacts are those that occur under circumstances in which the systems of interest are not the intended target of the attack. The impacts are therefore limited to those that result from (1) direct fallout (i.e., deposition) of radioactive contamination on drinking water supply sources from an RDD event occurring elsewhere and (2) runoff from radioactively contaminated ground and property into sewer systems during precipitation events or as a result of cleanup activities. Impacts from direct radiological attacks on water systems, such as the introduction of radioactive material directly into treated water storage or distribution systems, are *not* considered in the report.

The scope of the report is limited to secondary impacts on drinking water and wastewater systems from an RDD event occurring in an urban environment and from subsequent decontamination and cleanup activities. Three representative drinking water systems and three representative wastewater treatment plants are considered. The assessment scope and major assumptions are summarized in Table I.

SECONDARY CONTAMINATION OF WATER AND WASTEWATER SYSTEMS

An RDD attack could result in the dispersal of radioactive material over a considerable area. It is likely that the radioactive material would be initially dispersed mechanically, such as by an explosion or sprayer. In an explosion, a large fraction of the material, consisting of the larger pieces and fragments, would settle to the ground very near the point of the blast. Smaller particles, not subject to immediate gravitational settling, would remain airborne and move downwind in what is commonly referred to as a “plume.” As the plume moved downwind, radioactive material would settle out, contaminating the ground, building surfaces, vehicles, and other property. A conceptual representation of how drinking water and wastewater systems could become contaminated from an RDD event is shown in Fig. 1.

An RDD event occurring elsewhere in three general ways could contaminate drinking water supply systems. First, radioactive material from an RDD plume could be

Table I. Summary of Assessment Scope and Major Assumptions for an RDD Event in an Urban Environment

Parameter	Scope/Assumption	
Representative systems	Drinking water	– 100 million, 250 million, and 500 million gallons per day (gpd) of surface water
	Wastewater	– Water treatment of 100 million, 250 million, and 500 million gpd – Sludge production of 20,000, 50,000, and 100,000 dry tons/yr
RDD sources	– 8 relevant radionuclides from industry, medicine, and research/education evaluated – 3 activity sizes from low to high considered for each radionuclide – Range of physical/chemical forms considered for each radionuclide	
Potential impacts	Drinking water	– Radionuclide concentrations in treated water
	Wastewater	– Radionuclide concentrations in water and sludge – Treatment plant worker risks
Treatment technologies	Water	– Review of current and developmental water treatment technologies
	Urban environment	– Survey of site remediation and restoration technologies and potential implications with regard to water systems

directly deposited on a drinking water source used by the system (e.g., river or lake). Second, radioactive material could be washed off of contaminated ground surfaces by precipitation or decontamination procedures and run off into a system source. Third, radioactive material could be discharged into a drinking water source from a wastewater treatment system that was affected by an RDD somewhere upstream.

Wastewater treatment systems could become contaminated by an RDD event from radioactive material being washed off of contaminated ground surfaces by precipitation or decontamination procedures. In an urban area, it is likely that a large percentage of the surface area would be impermeable, resulting in a considerable fraction of water running off into storm water collection systems. This runoff would be transported, usually by gravity, to retention/evaporation ponds, wetlands, infiltration basins and trenches, or a wastewater treatment plant, or directly discharged to nearby surface water. In combined systems, storm water and sanitary wastes are collected and conveyed in the same pipe to a treatment plant. Contaminated runoff could also infiltrate sanitary sewer systems and be transported to a wastewater treatment plant.

The fraction of radioactive contamination washed from surfaces into drinking water sources or storm water or wastewater collection systems would be a function of the physical and chemical properties of the contamination, properties of the contaminated surfaces (e.g., pavement versus landscaped land), and properties of the precipitation event. Loosely adhered particles or soluble particles would have a high likelihood of being “flushed” from contaminated surfaces. Radioactive material either could be dissolved in the water or be in the form of suspended solids. Some contamination might chemically adhere to surfaces and would not be removed by the application of water. In addition, larger, insoluble particles might remain on surfaces or be washed into storm water catch basins.

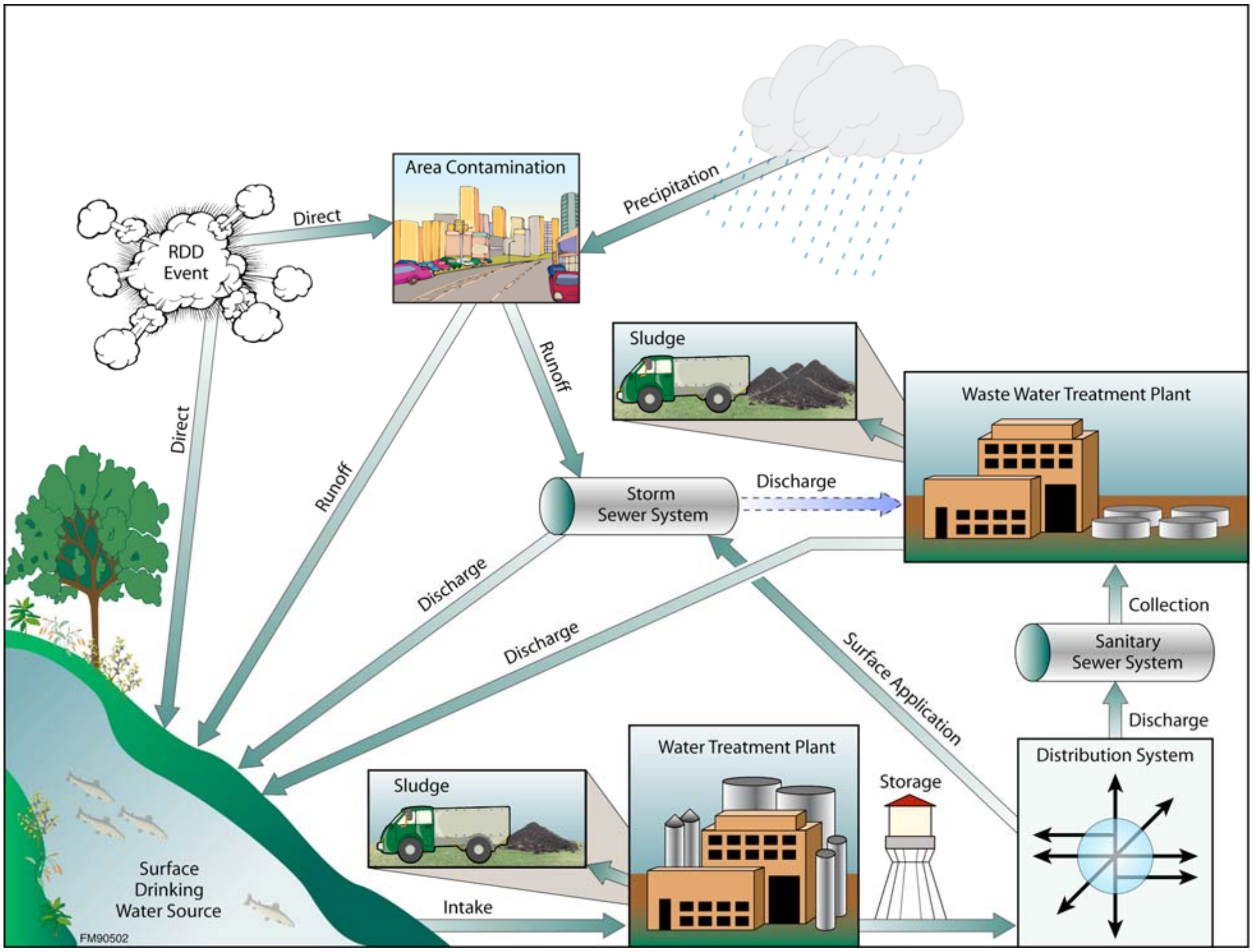

Fig. 1. Secondary effect of an RRD event, which could be the contamination of drinking water and wastewater systems through various pathways

If water or wastewater contaminated with radionuclides entered a drinking water or wastewater treatment plant, some fraction of the radioactivity entering the plant would be removed by the treatment train and concentrated in the sludge. Residual radioactivity not removed by the treatment train would remain in the treated water and enter the distribution and storage system (for drinking water treatment plants) or be discharged to a receiving water body (for wastewater treatment plants). The amount removed in the sludge would depend on the physical and chemical characteristics of the contamination and the specific type of treatment used.

Water and wastewater system workers could be exposed to elevated levels of radioactive materials (1) when they came into contact with residual wastes from various processes, filter backwash, and sludge; (2) during maintenance of contaminated pumps or piping; or (3) when they moved or transported wastes and filter media for disposal. Possible sources of radiation would be pumps and piping where mineral scales accumulate; sedimentation basins where residual sludges accumulate; filters, pumping stations, and storage tanks where scales and sludges accumulate; and holding tanks where filter backwash, brines, or other contaminated residuals are collected for disposal or recycle. Exposure to radiation could also occur at processing or handling areas where residuals are shoveled, transported, or disposed of, both at system locations and at off-site locations, such as landfills.

IMPORTANT CHARACTERISTICS OF POTENTIAL RDD SOURCE MATERIAL

Although dozens of radionuclides are in use in the world, only a relatively small set of them is considered particularly attractive for producing an RDD, either because they are currently or were historically used in concentrated amounts or because they are widely available. The radionuclides of interest in this study are Am-241, Cf-252, Cs-137, Co-60, Ir-192, Pu-238, Ra-226, and Sr-90.

The potential impacts on water and wastewater systems would depend highly on the radiological, physical, and chemical properties of the dispersed radioactive material. For example, large chunks of a radionuclide in metallic form would be very unlikely to enter the water system infrastructure because they would not be very soluble and thus would be relatively immobile. Conversely, a radionuclide dispersed as a very fine powder in a soluble chemical form would be expected to dissolve in or be entrained by runoff water, readily entering the water collection and treatment systems. The radiological characteristics of radionuclides, such as half-life, type of radiation emitted, and the energy of the emissions, are fundamental properties of each radionuclide and cannot be altered. The physical and chemical properties of the dispersed material would depend on the initial form of the material, any processing done to the material before incorporation into an RDD device, and the method of dispersal. A summary of key properties of the radionuclides considered in this assessment is presented in Table II.

The radioactive material in sources is generally encapsulated, or sealed, in metal — such as stainless steel, titanium, or platinum — to prevent its dispersal. The form of the radioactive material within these sources ranges from solid metals to fine powders. Cobalt and iridium are generally used in solid metallic form and therefore are not readily dispersible. Several radionuclides, such as americium, californium, and plutonium, are most often oxides and may be in powdered form. Cesium is typically used as cesium chloride (CsCl), which is a soluble powder. Radium and strontium are used in various forms, including chlorides. Historically, radium was also used in luminous paints. In general, powdered forms would be most effectively dispersed by an RDD, and soluble chemical forms would be most likely to impact water systems.

Considerable uncertainty is associated with the physical and chemical characteristics of radioactive materials following dispersal by an RDD. The dispersal method, such as the explosion produced in a dirty bomb, would likely physically and chemically alter the source material, producing a mixture of different chemical forms, such as oxides and nitrates, with a spectrum of particle sizes. In addition, it is conceivable that a terrorist with only rudimentary chemistry skills could chemically or physically alter the source material before incorporating it into an RDD in order to maximize dispersal.

Table II. Basic Properties of the Radionuclides of Interest [2]

Isotope	Half-Life	Specific Activity (Ci/g)[a]	Primary Radiation Emitted	Typical Form
Am-241	430 yr	3.5	Alpha (α)	Americium oxide; americium-beryllium (AmBe) sources are typically compressed powders
Cf-252	2.6 yr	540	Alpha (α), neutron (n)	Californium oxide
Cs-137[b]	30 yr	88	Beta (β), gamma (γ)	Cesium chloride (CsCl)
Co-60	5.3 yr	1,100	Beta (β), gamma (γ)	Metallic cobalt or cobalt-nickel alloy
Ir-192	74 d	9,400	Beta (β), gamma (γ)	Metallic iridium
Pu-238	88 yr	17	Alpha (α)	Plutonium dioxide, generally pressed into a ceramic-like material
Ra-226	1,600 yr	1	Alpha (α)	Radium bromide or radium chloride
Sr-90[c]	29 yr	140	Beta (β)	Metallic strontium, strontium chloride, strontium fluoride, strontium titanate

[a] To convert Ci to Bq, multiply by 3.7×10^{10}.

[b] Includes Ba-137m.

[c] Includes Y-90.

ESTIMATED POTENTIAL IMPACTS TO DRINKING WATER AND WASTEWATER TREATMENT PLANTS

Wastewater Treatment Plant Impacts -- Sludge

A wastewater treatment facility could become contaminated by an RDD event from radioactive material being washed off of contaminated ground surfaces by precipitation or decontamination procedures. Some fraction of the radioactivity entering the plant would be removed by the treatment train and concentrated in the sludge. The residual radioactivity not removed by the treatment train would remain in the treated water and be discharged to a receiving water body. The radioactive concentrations in wastewater treatment plant sludge and discharge would depend on the concentration in the water entering the treatment plant and the removal efficiency of the treatment process.

The potential range of radionuclide concentrations in wastewater treatment plant sludge was estimated as a function of the amount of radioactivity flushed to the treatment plant and the efficiency of the treatment train. The results are presented graphically in Fig. 2. The amount of radioactive material entering the plant was assumed to span six orders of magnitude, ranging from 0.001 Ci (37 MBq) up to 1,000 Ci (37 TBq). (The radioactivity flushed to the plant would in actuality be a fraction of the total amount released by the RDD, and it would be a function of the characteristics of the material released and the potential flow paths to the wastewater treatment plant). The treatment efficiency was assumed to range from 0.01% to 99%. The results shown in Fig. 2 are independent of the specific radionuclide.

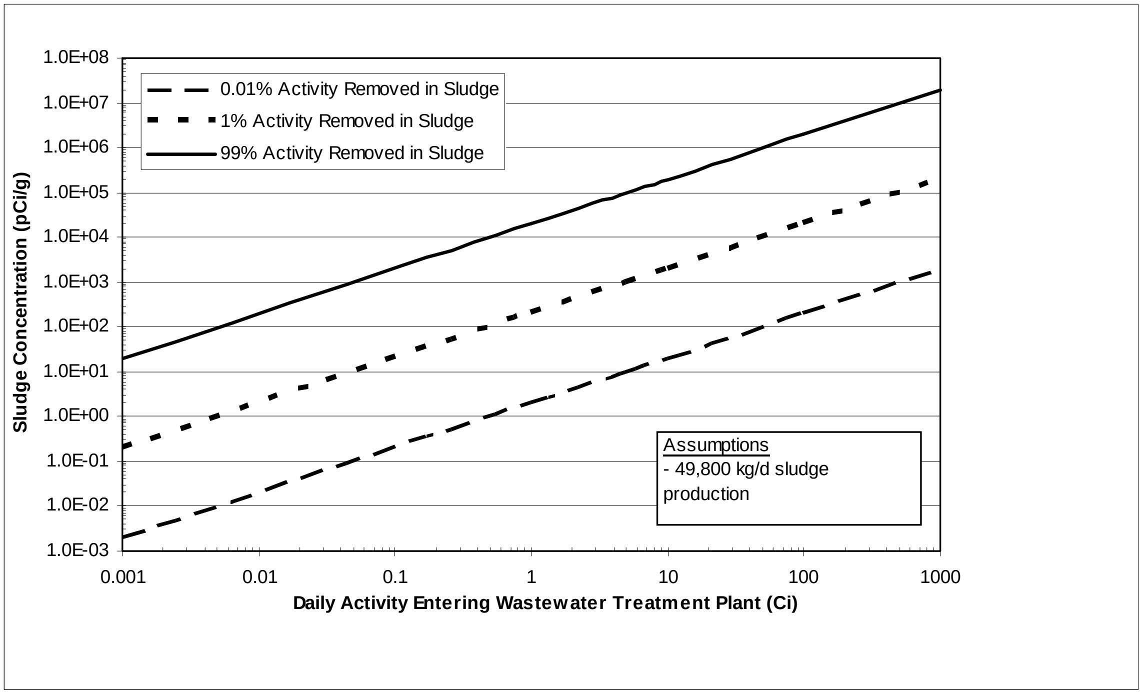

Fig. 2. Potential wastewater treatment plant sludge concentrations as a function of radioactivity entering the plant and treatment train removal efficiency (to convert from Ci to Bq, multiply by 3.7×10^{10})

As shown in Fig. 2, potential sludge concentrations increase with both removal efficiency and the amount of radioactivity entering the treatment plant. For example, if 1 Ci (37 GBq) of a radionuclide was flushed to the plant, the concentration in the sludge could range from about 2 pCi/g (0.074 Bq/g) if 0.01% was removed by the treatment process to about 20,000 pCi/g (740 Bq/g) if 99% was removed. This dependence underscores the importance of understanding the chemistry and environmental transport of the radioactive material released by an RDD and the specific characteristics of a treatment train in order to accurately predict potential impacts.

The sludge concentrations would increase linearly with the amount of radioactivity entering the plant. The radiation dose and resulting risk associated with any concentration would depend on the specific radionuclide involved (discussed further below). Because the sludge would be contaminated with radionuclides, it could require handling and disposal as low-level radioactive waste. Special handling procedures might be required, and traditional sludge disposal methods, such as land spreading or land filling, might not be appropriate or acceptable.

To provide an indication of the potential impacts on wastewater treatment plant workers, radiation doses to workers who process the contaminated sludge were estimated. Doses were estimated based on dose factors presented in NUREG-1783, a comprehensive evaluation of potential doses from radioactivity in sewer sludge for a number of radionuclides and exposure scenarios [3]. The resulting worker dose estimates as a function of the amount of radioactivity entering the treatment plant are shown in Fig. 3, assuming that 99% of the contamination was removed in the sludge (representative of a fairly effective treatment system). As shown in Fig. 3, the particular radionuclide involved has a significant impact on potential worker risk. For a given concentration in the sludge, Ra-226 would result in the highest worker doses and risks, partly because the dose factor for Ra-226 includes exposure to radioactive radon gas generated by decay (this is primarily a problem only for enclosed treatment facilities). The remaining radionuclides ranked from highest dose per unit sludge concentration to lowest are Co-60, Cs-137, Am-241, Pu-238, and Sr-90. With the exception of Ra-226, the gamma emitters Co-60 and Cs-137 result in the highest risks to treatment plant workers because of the penetrating nature of the gamma radiation. (Ir-192 and Cf-252 are not included in Fig. 3 because dose factors were not developed in NUREG 1783 for these radionuclides).

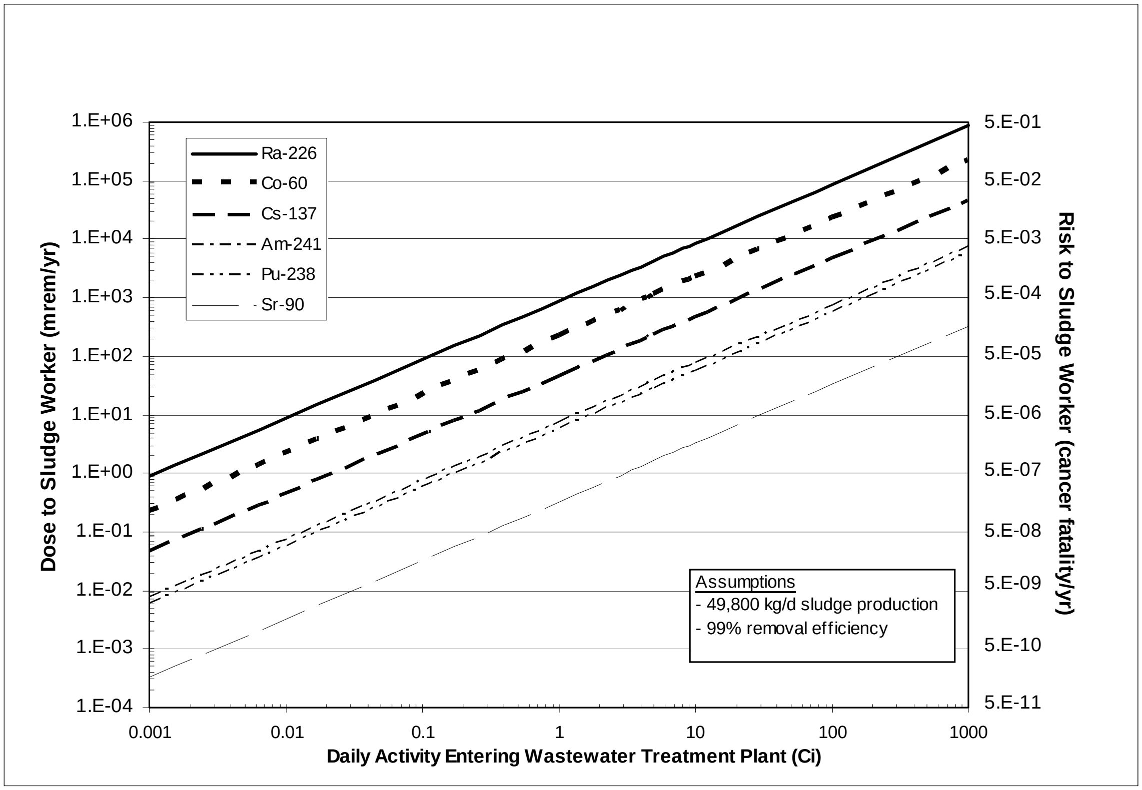

Fig. 3. Potential dose to wastewater treatment plant workers who are processing sludge, as a function of radioactivity entering the plant and assuming 99% removal efficiency (to convert from: Ci to Bq, multiply by 3.7×10^{10}; rem to Sv, divide by 100)

Wastewater Treatment Plant Impacts -- Wastewater Discharge

Radioactive contaminants not removed by the treatment train would remain in the treated water and be discharged to a receiving water body. Radionuclide concentrations in wastewater treatment plant discharge water were calculated as a function of the amount of radioactivity flushed to the treatment plant and the efficiency of the treatment train. Potential discharge water concentrations increase with activity entering the treatment plant and decrease with treatment removal efficiency. The higher the treatment train removal efficiency, the greater is the amount of radioactive contaminants removed from the water and concentrated in the sludge, resulting in lower concentrations in the discharged water. For example, if 1 Ci (37 GBq) of a radionuclide was flushed to the plant, the concentration in the wastewater discharge could range from about 3 pCi/L (0.11 Bq/L) if 99.9% was removed by the treatment process to about 3,000 pCi/L (110 Bq/L) if only 1% was removed. As stated for sludge, this dependence underscores the importance of understanding the chemistry and environmental transport of the radioactive material released by an RDD and the specific characteristics of a treatment train in order to accurately predict potential impacts. Discharge concentrations could exceed drinking water maximum contaminant levels (MCLs) for radionuclides specified by the EPA over a wide range of conditions. The dose and resulting risk associated with ingestion of contaminated wastewater treatment plant discharge would depend on the specific radionuclide involved.

Drinking Water Supply System Impacts

Indirect contamination of a drinking water supply source could occur from (1) deposition onto the source itself, (2) runoff from contaminated land, (3) contaminated discharge from a wastewater treatment plant, and (4) contaminated discharge directly from a storm water collection system (untreated). The radionuclide concentration in a water source would depend on the amount of activity entering the water, the fraction of the activity that was dissolved or suspended in the water, the volume of the reservoir, and the degree of mixing that occurred.

Radiological impacts on a drinking water supply system from an RDD event could occur if the water source for the system was contaminated. Potential radionuclide concentrations were estimated for three sizes of water supply reservoirs: those with volumes of 1 billion gallons, 100 billion gallons, and 500 billion gallons (4 billion L, 380 billion L, and 1,900 billion L). The results indicate that, under certain conditions, even smaller radiation sources could be of concern with regard to reservoirs of 1 billion gallons or less by causing water concentrations that exceeded the MCLs. Large radiation sources could result in water concentrations that were orders of magnitude greater than the MCLs, even for very large reservoirs. If contaminated water was used as a source for drinking water, treatment would be required to remove radionuclides to achieve compliance with the MCLs. Exceedance of the MCLs does not necessarily imply that the water would be unsafe to drink over a short period; the MCLs are set at conservative levels to ensure public safety from long-term chronic exposure.

POTENTIAL IMPACTS OF DECONTAMINATION ON WATER SYSTEMS

Decontamination is defined as the removal of contamination from surfaces, facilities, or equipment by washing, heating, chemical or electrochemical action, mechanical cleaning, or other techniques. The objectives of decontamination are to reduce radiation exposure; salvage equipment and materials; restore buildings and land, or parts thereof, to an unrestricted use condition; and reduce the magnitude of residual radioactive contamination for public health and safety reasons.

Potential impacts on drinking water and wastewater systems from decontamination activities following an RDD event were examined. Water was considered a decontamination agent because it is commonly used for decontamination and its use would probably have the most direct impacts on drinking water and wastewater systems. Water used to decontaminate surfaces impacted by an RDD event would be contaminated with radionuclides. This decontamination water could enter the storm water and/or sanitary sewer collection system. The radionuclide concentration in the decontamination wastewater would depend on the initial contamination levels, the effectiveness of the decontamination, and the amount of water used. Large volumes of contaminated water would be problematic and could lead to spreading of the radiation farther and the creation of a large volume of secondary waste. Some of the contamination could lodge or react with material in the sewer system, contaminating the collection system piping. Contamination of the sewer system could represent a long-term risk, primarily to sewer workers. Impacts to the sewer system could be reduced or eliminated by using vacuuming or other “dry” decontamination techniques in lieu of water, or by using water combined with some type of local water collection and treatment system (e.g., a mobile system).

WATER TREATMENT TECHNOLOGY SURVEY

Both water and wastewater in the United States undergo treatment processes. In the case of drinking water, raw water is treated to remove potential contaminants and make it fit for human consumption. Drinking water quality is defined by EPA regulations and is frequently expressed in MCLs. Like drinking water, wastewater must be treated to remove contaminants before it can be released to the environment under EPA regulatory constraints (National Pollutant Discharge Elimination System permits). Cleanup goals for wastewater prior to release to the environment can be less stringent than those required for drinking water purposes, and drinking water standards (e.g., MCLs) may not apply.

Existing drinking water and wastewater treatment facilities can be used to reduce the concentrations of certain radionuclides (e.g., radium), if they use appropriate softening or coagulating compounds in their treatment train, if the concentrations of the radionuclides in the water are low, and if cleanup goals are defined by MCLs. Such conditions might exist following a small RDD event that contaminated a limited area with low levels of radioactivity. Drinking supply systems that do not use some form of filtration are more vulnerable to impacts from an RDD event, and retrofitting filtration units for some of these systems could be very costly. Systems that use ion exchange, activated alumina, reverse osmosis, and electrodialysis can effectively deal with the radionuclides of concern for this study, if the concentrations in water are low and if cleanup goals are defined by MCLs.

For large radionuclide sources, it is unlikely that existing drinking water treatment facilities would be able to meet MCLs for single-pass treatments for an RDD event if significant contamination of the source water occurred. Multiple passes through a treatment process or combined treatment processes could be used to improve the overall effectiveness of the treatment system; however, this could be a time-consuming process. This method is currently being used in zero-liquid discharge facilities.

Because each drinking water treatment utility is designed for conditions specific to its location and water source, there is no universal technology improvement that could be recommended to reduce each one’s vulnerability to an RDD event. Each system would have to be analyzed independently to determine an optimum approach to system improvement.

SITE REMEDIATION AND RESTORATION TECHNOLOGY SURVEY

The report also provides a survey of site remediation and restoration technologies and potential implications with regard to water systems. Past experiences were examined to identify issues that were raised and cleanup methods that were used in remediation efforts following the Goiania, Brazil, and Chernobyl, Ukraine, accidents. On the basis of these cleanup methods and other technologies used in the nuclear industry, potential cleanup techniques for urban restoration were summarized. Ideally, cleanup technologies that can be applied quickly and cost-effectively over a large urban area (e.g., a few city blocks) would be the technologies of choice. However, at this time, there is no one technology that can address all types of contamination, contamination levels, and surface types without incurring problems associated with secondary effects, secondary wastes, and/or a labor-intensive effort. Thus, all potential cleanup technologies were considered because even the most labor-intensive methods could be the most practical for hot spot areas in a given situation. The report also discusses current methods for cleaning drinking water and wastewater/storm water system infrastructure. The aggressiveness of these methods covers a wide range, which might be suitable for remediating a range of potential radiological hazards in pipeline systems.

CONCLUSION

The results presented in the report indicate that the potential impacts at wastewater treatment plants from an RDD event could range from levels below concern to quite significant levels, depending on the size of the radiation source involved and possible mechanisms of migration and transport in the environment. If a large source was used and the contamination was very mobile, significant impacts could occur at wastewater and water treatment plants. Of particular concern would be impacts related to the processing of sludge, because contamination could be concentrated within sludge. A more precise method for such analysis is needed.

ACKNOWLEDGMENT

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