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Results of Literature Review and Technology Survey of Source Reduction and Waste Minimization Techniques Applied to a Wide Area Radiological Incident

Office of Research and Development
National Homeland Security Research Center

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for

U.S. Environmental Protection Agency
National Homeland Security Research Center
Decontamination and Consequence Management Division
Research Triangle Park, NC

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TABLE OF CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

Acronyms

^{137}Cs	cesium-137
AC	Activated Carbon
AMS	Aerial Measuring System
ASPECT	Airborne Spectral Photometric Environmental Collection Technology
CBR	chemical, biological, or radiological
CBRNIAC	Chemical, Biological, Radiological & Nuclear Defense Information Analysis Center
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CI/KR	critical infrastructure/key resources
DHS	U.S. Department of Homeland Security
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EBCT	empty bed contact time
ED/EDR	Electrodialysis/Electrodialysis Reversal
EPA	U.S. Environmental Protection Agency
FAST	FIELDS Analysis and Sampling Tools
FIELDS	Field EnvironmentaL Decision Support
FWHM	full width at half maximum
GAC	granular activated carbon
GEM	Gamma Emergency Mapper
GIS	geographic information system
GM	Geiger-Müller
GPS	global positioning system
HazMat	hazardous material
HDIAC	Homeland Defense and Information Analysis Center
HEPA	high efficiency particulate air
HPGe	high-purity germanium
ICEM	International Conference on Environmental Remediation and Radioactive Waste Management
IND	Improvised Nuclear Device
INMM	Institute of Nuclear Materials Management
IOC	isotope of concern
ICV	in-container vitrification
ISV	in-situ vitrification
IX	ion exchange
KIWI	An array of eight-2-inch x 4-inch x 16-inch sodium iodide detectors
LAGS	large area gamma spectroscopy
LLRW	low-level radioactive waste
NCP	National Contingency Plan
NPP	Nuclear Power Plant
NTIS	National Technical Information Service
RCRA	Resource Conservation and Recovery Act
RDD	Radiological Dispersal Device
RID	radionuclide identifier
RO	reverse osmosis
SAM	Surveillance and Measurement

SCI	Science Citation Index®
SGS	Segmented Gate System
S/S	stabilization/solidification
SME	subject matter expert
SSCT	Small System Compliance Technology
UASI	Urban Areas Security Initiative
WAC	Waste Acceptance Criteria
WARRP	Wide Area Recovery and Resiliency Program

Abbreviations

cm	centimeter(s)
cps	counts per second
Cs	cesium
Ge	Germanium
h	hour(s)
keV	kiloelectron volt(s)
$LaBr_3$	Lanthanum Bromide
lb	pound(s)
MeV	megaelectron volt(s)
mrem	micro roentgen equivalent man
NaI	Sodium Iodide
µSv	microsievert(s)

BACKGROUND AND PURPOSE

The threat of a wide-area urban event with the potential for significant public health and economic impact is of national concern. A joint agency effort occurred in 2012 and 2013 to understand the state of national readiness more fully and prepare better for improved response capabilities in the area of remediation and recovery following such an event. This effort involved the U.S. Environmental Protection Agency (EPA), the U.S. Department of Energy (DOE), the U.S. Department of Homeland Security (DHS), the U.S. Department of Defense (DoD), and the U.S. Department of Health and Human Services (HHS). Two of the agencies, EPA and DHS, took concrete steps to lead this effort that was part of the Wide Area Recovery and Resiliency Program (WARRP).

WARRP was designed to develop guidance to reduce the time and resources required to recover a wide urban area (specifically, the Denver Urban Areas Security Initiative [UASI]) following a chemical, biological, or radiological (CBR) incident, including meeting public health requirements and restoring critical infrastructure (CI), and key resources (KR) (both civilian and military) and high-traffic areas. WARRP planning documents generated for the Denver UASI could potentially be used as templates and adapted by other urban areas to plan for recovery from wide-area all-hazards incidents.

It was anticipated that a wide-area Radiological Dispersal Device (RDD) ("dirty bomb" attack) under the parameters of the WARRP-developed RDD scenario, could result in tens of millions of tons of contaminated solid waste and billions of gallons of contaminated liquid waste. Generally, physical damage outside the blast zone of a radiological dispersal device (i.e., dirty bomb) is expected to be minimal; the amount of blast-related debris is likely to be relatively small compared to the amount of undamaged contaminated materials. It may be possible to systematically segregate contaminated waste, which includes debris, from uncontaminated waste from an RDD incident (the meaning of the terms "contaminated" and "uncontaminated" will be decided by the cleanup goals and waste acceptance criteria [WAC] of the disposal facilities). Cesium-137 (^{137}Cs) is a radioactive source that could be used in the construction of an RDD, and was the primary isotope of interest for the WARRP radiological scenario, a Subject Matter Expert workshop held in Denver in August 2012 (*1*), a subsequent Standard Operating Guideline (SOG) document with technical recommendations (*2*), and therefore this literature survey.

It should be recognized that safety is the overarching objective for a radiological cleanup. It should not be implied that limiting cost is an end in itself. Once a strategy (or potentially more than one) has been identified that will meet the appropriate safety criteria, cost is an important discriminator and may be critical to the ability to actually implement the chosen strategy in a way that preserves the desired level of safety. There are three primary objectives for waste management to help manage RDD cleanup costs: (1) waste minimization, (2) waste segregation by material and radiological activity, and (3) cost-effective treatment and disposal of each waste stream.

- Waste minimization. Examples of waste minimization are: (1) removing two inches of soil rather than five inches when ^{137}Cs contamination resides mainly in the top two inches (sod cutting); (2) composting organic wastes and vegetative wastes to reduce waste volume; and (3) employing surface scarification techniques from buildings or other surfaces to remove surface contamination without removing the whole substrate.
- Waste segregation. Examples of waste segregation are: (1) removing and managing vegetation, soils, and contaminated structures separately; and (2) handling and staging waste from cleanup of the area of highest contamination ("hot zone") separately from waste with lower levels of -radioactivity (separate by activity). Segregation will minimize wastes and enable alternate disposal pathways to be used for the lightly contaminated materials. Waste segregation has the potential to achieve

significant efficiencies in time and cost while at the same time ensuring long-term protectiveness of the waste managed.

- Treatment and disposal. Examples of potentially cost-effective treatment or disposal options are: (1) developing in-state disposal options for lower-activity contaminated materials; and (2) employing effective techniques for separating, concentrating, or removing the specific radiological contaminant from wastewater.

It is possible that most, if not all, of the waste generated from an RDD incident will likely be classified as Low-Level Radioactive Waste (LLRW), although the legal categorization of this waste is by no means assured. LLRW is radioactive waste not classified as high-level radioactive waste, transuranic waste, spent nuclear fuel, or by-product material as defined in paragraphs (2), (3) or (4) of the definition of by-product material set forth in 10 CFR 20.1003 (per 10 CFR 61.2). LLRW may contain varying amounts of radioactivity. In general practice, LLRW does not include naturally occurring radioactive material but does include man-made material. The cost of the disposal of massive quantities of waste in an LLRW repository and the impact on the available future capacity for the facility may make implementation of such a strategy unrealistic.

A key component of effective waste handling and cost savings will be to identify which waste will need to go to a LLRW repository versus a local disposal facility and to identify recommended minimization/disposal/treatment pathways. The amount of waste that needs LLRW disposal will need to be minimized by screening activity level and proper segregation.

Waste screening technologies could be tied to the WAC levels. WAC should take into account the radiological, physical, and hazardous (if present) characteristics of the waste. For example, free liquids could be an issue in the case of sludges and with soil/debris where water was used for dust suppression. Because of the potentially massive amount of waste that may be generated, WAC for municipal solid waste landfills (regulated under Subtitle D of the Resource Conservation and Recovery Act [RCRA]) may be considered because not all waste may be classified as contaminated material that needs to be shipped to a low-level waste facility.

A systems approach that includes waste management, in addition to decontamination, is needed to develop effective and efficient cleanup strategies. Contaminated item (and radionuclide) characteristics and types will generally dictate the cleanup method used. Waste can be minimized by identifying waste with an activity level below a site-specified level that would allow it to be sent to a non-LLRW disposal facility, such as a RCRA Subtitle C or Subtitle D landfill, or even allow it to be recycled.

This report describes the details of a literature search for source reduction and waste minimization technologies that could be used for a radiological incident. The general approach was to gather information on existing packaging, segregation, and screening technologies directed at radiologically contaminated waste and debris.

SEARCH STRATEGY

A very broad-based literature and internet search was conducted for potentially applicable technologies using a list of key words directed at radiologically contaminated waste, debris, and wastewater. The literature search was conducted using the database provider Dialog, which searches more than 500 databases of comprehensive published scientific and engineering articles. The search also included the Nuclear Plant Journal and Japan Atomic Energy Agency.

As part of the Dialog search, the following specific databases were searched because they were most likely to describe technologies that would address the consequences of an RDD incident.

- **Energy Science & Technology** (formerly DOE ENERGY) is a multidisciplinary file containing references to basic and applied scientific and technical research literature. The information is collected for use by government managers, researchers at the national laboratories, and other research efforts sponsored by DOE.

- The **Inspec** database provides more than 11 million abstract and index records from more than 4,000 journals and serials; more than 2,200 conference proceedings; and thousands of books and book chapters, reports, and dissertations. More than 20,000 U.S. and United Kingdom patents published between 1968 and 1976 are included. **Inspec** content is obtained from quality- or peer-reviewed scientific and engineering literature written in any language that falls within the subject scope of the database.
- The **NTIS: National Technical Information Service** database consists of summaries of U.S. government-sponsored research, development, and engineering, plus analyses prepared by federal agencies or their contractors. Unclassified, publicly available, unlimited distribution reports are made available from agencies such as the National Aeronautics and Space Administration, DoD, DOE, U.S. Department of Housing and Urban Development, U.S. Department of Transportation, U.S. Department of Commerce, and some 240 other agencies. Additionally, some state and local government agencies contribute summaries of their reports to the database. NTIS also receives information from the National Aerospace Laboratory in Japan and Micromedia in Canada, among others.
- The **Ei Compendex®** database is a version of *Engineering Index*, which provides information from the world's engineering and technological literature. Ei Compendex provides coverage of more than 4,500 journals and selected government reports and books worldwide. Subjects that are part of Ei Compendex include: civil, energy, environmental, geological, and biological engineering; electrical, electronics, and control engineering; chemical, mining, metals, and fuel engineering; mechanical, automotive, nuclear, and aerospace engineering; and computers, robotics, and industrial robots. In addition to journal literature, this database contains more than 480,000 records of published proceedings of engineering and technical conferences formerly indexed in *Ei Engineering Meetings*.
- **SciSearch®** contains all of the records published in the *Science Citation Index®* (SCI®), plus additional records in engineering technology, physical sciences, agriculture, biology, environmental sciences, clinical medicine, and the life sciences. SciSearch® indexes all significant items (articles, review papers, meeting abstracts, letters, editorials, book reviews, correction notices, etc.) from more than 6,100 international scientific and technical journals.
- **Wilson Applied Science & Technology Abstracts** provides comprehensive information of more than 400 English-language scientific and technical publications. Non-English-language periodicals are indexed if English abstracts are provided. Content includes trade and industrial publications, journals issued by professional and technical societies, and specialized subject periodicals, as well as special issues such as buyers' guides, directories, and conference proceedings.
- **Solid State and Superconductivity Abstracts** provides information on research and applications across the field of physics and conductivity. The database covers all aspects of theory, production, and application of solid state materials and development, as well as the new high- and low-temperature superconductivity technology.
- **Inside Conferences** is produced by the *British Library*. The database contains details of all papers given at every congress, symposium, conference, exposition, workshop, and meeting received at the British Library Document Supply Centre since October 1993. Each year, over 16,000 proceedings are indexed, covering a range of subjects published as serials or monographs. Over 500,000 bibliographic citations for individual conference papers are added annually. Most records are in English, with many languages represented in the source documents.

The search also accessed information in the Chemical, Biological, Radiological, and Nuclear Defense

Information Analysis Center [(CBRNIAC, now Homeland Defense and Information Analysis Center (HDIAC)], (*3*) which contains over 3.5 million documents. Hundreds of technical articles were identified in the search. The titles (and often the abstracts) for all items found in the search were examined. Those articles with the most likely relevance to the project (based on broad applicability to reduction of waste volumes from a radiological incident) were further examined and are listed below.

The following search strategies were used for the initial technical literature search. The search methodology involved looking at broad search terms such as: "radioactive screening waste minimization," "radioactive segregation waste minimization," and "radioactive soil segregation." These terms were coupled with more-focused search terms such as: "CANBERRA Falcon 5000," "segmented gate system," and "Berkeley SAM-940." Output from these searches is listed in Section 3, Results. The search strategy was also broad in a geographic sense as it was not limited to studies conducted in the United States but also included studies conducted worldwide.

Draft results from the literature search were organized in an Excel file and distributed to participants of the WARRP Subject Matter Expert (SME) Meeting, hosted by EPA's National Homeland Security Research Center in Denver, Colorado, on August 14-15, 2012 (*1*). One purpose of the SME Meeting was to identify existing radiological waste screening and segregation technologies that might be brought to bear under the RDD scenario to identify potential ways to adapt the technologies to the situation. During the SME Meeting, additional feedback was solicited on the technology features from government (state and federal), military (regional), and industry experts in the area of radiological waste to ensure that all types of technologies covering a variety of waste streams were considered in the literature review.

Therefore, in addition to the primary technology search conducted before the meeting, additional literature searches were conducted based on SME feedback following the meeting. Examples of search terms are shown in Table 1 below.

Table 1. Examples of Search Terms based on SME Meeting Feedback

Additional Search Terms	
turf or sod cutters	high efficiency particulate air (HEPA) vacuums
soil washing + radioactive	parking lot washer or street sweeping of sweepers
removal + vegetation + radioactive	grass cutting or lawn mowing or mower
biomass + radioactive + waste minimization	"triple" dig or plow + radioactive
soil removal + radioactive + waste minimization	detection + radioactive + waste minimization
gamma spectroscopy	plasma arc + vitrification
mechanical + radioactive + waste minimization	dust suppression

The additional search strategy considered radiologically contaminated materials, particularly soils; however, other matrices were considered. These potential waste streams include: soil, biomass, building interior contents, building exterior materials, concrete, asphalt, and asbestos or lead-contaminated waste. Attempts were made to identify technologies that currently exist for soil screening and segregation, but were adaptable or developed for other types of matrices.

In addition to the search strategies presented above, the following key words were added for waste and debris technologies as part of the final literature review:

- Manual survey
- Automated survey
- Composting of organic matter (for biosolids)
- Dig and haul
- Scarification
- High-pressure washing
- Incineration
- Cementitious stabilization/Solidification
- Waste repository
- Waste analysis plan
- Waste acceptance criteria
- Scabble/scabbling
- Strippable coating
- Chelating Agents
- Ion Exchange (IX)
- Reverse Osmosis
- Electrodialysis/Electrodialysis Reversal (ED/EDR)
- Membrane Filtration
- Conventional Filtration
- Activated Carbon (AC)
- Evaporation (Passive or Active)

RESULTS

One conclusion that was reached at the SME Meeting was that rather than focusing on a single technology or two, a technology toolbox approach or "waste minimization scheme" should be followed to identify different methods and technology options, realizing that each one might potentially be used depending on the situation.

Relevant literature articles are grouped below according to the associated radiological technology identified. The technologies are each classified into four categories:

- Screening and characterization: Determining the identity, location, physical characteristics, and initial quantity of contamination of the radioactive material through the use of survey equipment. These technologies include:
  - Manual Survey
  - Automated Survey
- Mitigation: Removing contamination from an original location, fixing contamination in place, or covering contamination. Contamination removal often requires removal of the substrate on which the contamination exists. These technologies include:
  - Dig (plow)
  - Lawn Mowing and Removal of Cuttings
  - Dust Suppression
  - Composting of Organic Matter
  - Sod Cutter
  - Selective Removal of Vegetation
  - HEPA-Filtered Vacuum Cleaning

    - High Pressure Washing
    - Street Sweeping
    - Scarification
- Segregation and waste management: Sorting and processing waste (to separate contaminated from uncontaminated material and low-activity from high-activity material), reducing waste volumes, and ultimately treating and disposing of waste. These technologies include:
    - Soil Washing
    - Segmented Gate System
    - Plasma Arc Vitrification
    - Cementitious Stabilization/Solidification
    - Large-Scale Dig and Haul
    - incineration
- Wastewater cleanup technologies: cleanup, particularly aqueous-based cleanup techniques, may generate large volumes of water that present treatment, storage, and disposal issues. Techniques such as ion exchange, filtration, reverse osmosis, and evaporation may potentially separate, concentrate, or remove the specific radiological contaminant or its decay products from wastewater that is produced as a secondary waste. These technologies include:
    - Chelating Agents
    - Ion Exchange
    - Reverse Osmosis
    - Electrodialysis/Electrodialysis Reversal
    - Membrane Filtration
    - Conventional Filtration
    - Activated Carbon
    - Evaporation

It was not the goal of this literature review to focus on decontamination methods or method variations for radiological decontamination of hard surfaces. The literature covers RDDs, nuclear power plant (NPP) accidents, and improvised nuclear device (IND) fallout type contamination and therefore the specific performance of the technology will not only vary due to site specific conditions but also the type of contamination.

Table 2 lists the various source reduction, mitigation, and waste minimization technologies and associated published literature.

Table 2. List of Technologies from Literature Survey	
Technology	**Notes/Abstract**
Manual Survey	The CANBERRA Falcon 5000 (*4*), a portable radionuclide identifier (RID) based on a high-purity germanium (HPGe) detector (energy range of 20 kiloelectron volts [keV] to 3.0 megaelectron volts [MeV]). The CANBERRA Falcon 5000 uses a high-purity germanium (HPGe) detector paired with a low-noise electrical cooler using Pulse Tube cooling technology that can achieve the energy resolution needed for isotopic measurement. The unit is field-portable, does not require liquid nitrogen cooling, and covers a wide energy range (*5*). The Falcon 5000 gamma analysis software is designed to suggest radionuclides from the library as soon as a significant peak is found in the spectrum (*6*) and can distinguish gamma rays that are within approximately 1.5 keV of each other (*7*). Test measurements have concluded that the Falcon 5000 can be used successfully for isotopic measurements of uranium and plutonium in sealed sources such as waste drums filled with various matrix materials. The Falcon 5000 comes pre-configured with a default nuclide library, but it can be edited or loaded with a different library as the application requires. The library can be managed in the field and can be tailored to specific applications by defining the type of analysis and then adjusting the parameters of the calculation. This device has been purchased by EPA and is available through EPA/Office of Radiation and Indoor Air in Las Vegas. Operational Energy Range: 20 keV to 3.0 MeV Sensitivity: Not Reported Precision: full width at half maximum (FWHM) – resolution: ≤ 2.0 keV at 1332 keV; ≤1.0 keV at 122 keV
Manual Survey	The Surveillance and Measurement (SAM)-940 system is a radioactive isotope identification device used to support remedial activities by pairing its ability to identify isotopes of concern (IOCs) with its sensitive detection capability. A built-in alarm informs the user of the presence of activity above a set threshold. The system is suggested to reduce disposal costs for radioactive waste by allowing prompt remediation of targeted areas that have been identified as having IOCs and eliminating multiple visits to sites by declaring an excavation site clear of IOCs before demobilizing from the site. The unit can be modified to display isotopes instantly as they are detected in the environment (*8*). The SAM Defender (standard resolution) and SAM Resolver (high resolution) are portable systems, developed to provide simple operation for Emergency Response, Law Enforcement, Homeland Security applications (*9*). The SAM-940 system is owned by several EPA Regions. Operational Energy Range: 18 keV – 3 MeV Minimum Detectable Amount (MDA): 2x2 inch NaI detector is 0.00299 µSv/h Sensitivity: Not Reported Accuracy: 97 % Identification confidence level in 2 seconds Precision: 7 % resolution

Table 2. List of Technologies from Literature Survey	
Technology	**Notes/Abstract**
Manual Survey	The FLIR Systems identiFINDER is a hand-held digital signal-processing gamma spectrometer used for the location, measurement, and identification of sources or contamination of gamma radiation. Many models of the identiFINDER are available, and every version is portable, lightweight, and able to rapidly detect, quickly locate, accurately measure, and precisely identify gamma- emitting radionuclides. The identiFINDER is equipped with two battery packs for both rechargeable and non-rechargeable batteries and download and analysis software. In a comparison with two other commonly used hand-held radioisotope identifiers, the identiFINDER did not perform as well in certain performance parameters such as accuracy and sensitivity at greater distances (i.e., lower ^{137}Cs radiation levels). However, the identiFINDER reported the best gamma energy response range (15 keV to 3 MeV) (*10*). The identiFINDER has been deployed worldwide; a next-generation instrument, the identiFINDER 2, is also commercially available (*11*). Operational Energy Range (gamma) 20 keV – 3 MeV Sensitivity: (^{137}Cs) >500 cps per µSv/h (100 µrem/h) Precision: Gamma Sodium Iodide (NaI): typical resolution ≤8 % at 662 keV; Gamma Lanthanum Bromide ($LaBr_3$): typical resolution ≤4 % at 662 keV
Manual Survey	The ORTEC Micro-Detective-HX is a portable hand-held HPGe-based radioisotope identifier (*12*). The unit weighs less than 16 lb (7.3 kg), is water resistant, and has a larger nuclide library than its heavier predecessor, the Detective-EX (25.9 lb [11.7 kg]). Two detectors determine the gamma dose rate over a wide range from <0.05 µSv/h to >10000 µSv/h, a dose-rate range of approximately six decades. For lower dose rates, below ~20 µSv/h, the dose rate is determined from the Germanium (Ge) detector spectrum. For dose rates above this value, the internal Geiger-Müller (GM) tube is used. The dose rate uncertainty is greater than (–50 % to +100 %), and the unit alarms at dose rates >10,000 µSv/h (fixed maximum threshold). The predecessor of this technology was developed at Lawrence Livermore National Laboratory. In 2006, DHS awarded a contract to AMETEK (*13*) to develop a high-resolution portable radiation detection system (i.e., the Micro-Detective-HX) to be used by U.S. Customs and Border Protection, public safety officials, and other first responders to screen vehicles and search public facilities for radioactive materials.
Manual Survey	The BetaCage is a low-background atmospheric-pressure neon drift chamber with a high degree sensitivity to emitters of low-energy electrons and alpha particles. The BetaCage fills a gap in existing screening technologies that are insufficiently sensitive to such particles. The BetaCage design accepts nearly all alphas and low-energy electrons from the sample surface while allowing rejection of residual background (*14*). The design involves an atmospheric-pressure neon time-projection chamber optimized for the detection of <200 keV electrons and multi-megaelectron volt alpha particles. The BetaCage is still in prototype form (*15*).

Table 2. List of Technologies from Literature Survey	
Technology	**Notes/Abstract**
Manual Survey	Large Area Gamma Spectroscopy (LAGS) utilizes a gamma spectral analyzer suspended over a slab upon which soil is spread out to a uniform depth. A counting period of approximately 30 minutes is used to obtain a full-spectrum analysis for the isotopes of interest. This technology may be useful to detect isotopes in low-level waste and low-level mixed waste (*16*).
Automated Survey	Survey tools, like Field EnvironmentaL Decision Support (FIELDS) Analysis and Sampling Tools (FAST), can perform real-time continuous field data collection and assessment, integrating data from portable hazardous material (HazMat) field instruments, global positioning system (GPS) data, geographic information system (GIS), mapping, database storage, and analysis (*17*). FAST is a Windows PC application that can map the relevant data for viewing within ArcGIS, Google Maps, or other applications for further data processing.
Automated Survey	A more sophisticated technology in this field is the Airborne Spectral Photometric Environmental Collection Technology (ASPECT) system developed for the EPA. ASPECT, a remote sensing technology that employs standoff radiological (and chemical) detection, can screen the surface area for gamma and neutron sources at high speeds and return quality-assured data within minutes to the decision-makers. Based on the ASPECT system, EPA has a ground-based survey technology used to detect and measure radioactivity. This ground-based survey, the "Asphalt" system, is utilized on the ground through a survey via all-terrain vehicle, pickup truck, sport utility vehicle, or other type of vehicle. The system utilizes eight 2 inch x 4 inch x 16 inch sodium iodide crystals (with ability to add four more), and up to three 3 inch x 3 inch lanthanum bromide crystals. This ground-based system has greater resolution and sensitivity than other systems, including hand-held devices, due to the size of the crystals. The products are the same from either the air or the ground. However, this ground-based technology is more effective than airborne systems because readings are collected closer to the source, so the system can obtain more sensitive readings. Both systems are tied to a central computer and modem, allowing data to be produced and transmitted while the survey is still in progress (*18*). Some of the most common applications for airborne gamma-ray spectrometry surveys include contamination mapping and detection (i.e., ^{137}Cs) and emergency response (*19*). More than 140 deployments have been made since 2001. These deployments have included responses to natural disasters (e.g., Hurricanes Katrina, Rita, Gustav, and Ike) and environmental emergencies (e.g., BP oil spill, Las Chonchas wildfires, site characterizations for Superfund sites) (*18*), which were primarily for detection of chemicals rather than radiological contamination.

Table 2. List of Technologies from Literature Survey	
Technology	**Notes/Abstract**
Automated Survey	Another robust aerial measurement system is the U.S. Department of Energy (DOE) Aerial Measuring System (AMS) airplane- and helicopter-based automated survey of gamma-emitting radionuclides. This system consists of five fixed-wing aircraft and three helicopters stationed at three locations in the United States. The detector systems can be mounted on other aircraft (e.g., U.S. military aircraft in Japan) or ground vehicles (KIWI configuration of an array of eight-2-inch x 4-inch x 16-inch sodium iodide detectors). The KIWI uses the same system used on a helicopter but is mounted on a four-wheel drive vehicle instead. Unlike the AMS helicopter, the KIWI is about three feet above the ground and has a detector field of view approximately 10 feet in diameter. The KIWI gives a high-spatial resolution mapping of contamination (*20*). This system must return to base and land; then the data must be downloaded and then processed and analyzed.
Dig (plow)	Plowing (*21, 22*) puts contaminated soil deep enough into the ground that exposure is limited, including to the lower boundaries of crop root systems. Deep plowing digs down to 90 centimeters (cm) or more beneath the surface. A similar concept uses hand-held tools (i.e., shovels) to dig up the surface dirt and rebury it well below the surface while bringing fresh topsoil to the surface. “Triple-Digging” (practiced in areas around Chernobyl in the 1990s) involves a simple, manual (shovel)-based approach that reburies contaminated soil deeper in the ground and replaces it with uncontaminated soil. Placing contamination at depth may also result in contaminant transport to groundwater and ultimately surface water and may also make contaminants available for plant uptake. This method can be effective in reducing the potential for direct contact with contaminated materials on the soil surface, external radiation from surface contamination, and pickup by shallow-rooted crops. Deep plowing in particular may be more effective, with a report showing that uptake from deeper placement of contaminated soil was one-tenth of the uptake from shallow placement over a period of four years. The same report also shows that deep plowing to 50 cm in contaminated soil reduced the uptake of radiation by oats up to 60 %, while plowing up to 30 cm had little effect. However, this method can be costly and ineffective in reducing the uptake of radioactivity for deep-rooted crops. Many deep-plowed soils can also produce poor crops because of low fertility, high acidity, soluble salts, or poor texture, which would take years of nutrient and sand addition for remediation.

Table 2. List of Technologies from Literature Survey	
Technology	**Notes/Abstract**
Lawn Mowing & Removal of Cuttings	The effectiveness of removing contaminated ground cover (such as grass) or agricultural crops is highly dependent on the partitioning of the contaminant between the plants, the roots, and the soil. Generally, no mowing or crop removal methods have removed more than 75 % of fallout from a contaminated area. Sod cutting and soil removal might, therefore, be follow-on actions. However, mowing can be useful as it typically removes ground cover plants, which tend to carry greater amounts of radioactivity once removed (*21*). Assuming soil removal is not necessary, removing contaminated crops via lawn mowing may not be as effective as removal via forage chopper or direct-cut forage harvester. Removing ground cover or crops also raises the question of where to dispose of the contaminated plant material, which has not received substantial study to this point. In an RDD event, some urban areas will have a large amount of contaminated grass. Mowing the lawn to remove the adhered contamination with the grass clippings has been shown to be an effective means of reducing radioactive dose (*23*). However, most lawn mowers would be unsuitable for this kind of cleanup because they have no way to capture the contamination particles; the contamination would simply be resuspended and not removed for disposal. However, at least one method was developed to help deal with mowing contaminated lawns. Thermo Nuclear Services developed a lawn-mowing system that is equipped with a gamma-ray detection system on the mower discharge chute (*24*). When the detection system senses a contaminated section of grass clippings, it actuates a gate (similar to the larger segmented gate system [SGS] soil conveyer) and diverts the contaminated clippings to a secure, HEPA-filtered container.
Dust Suppression	Many different dust suppression techniques are available to control the resuspension of contaminated particles within an urban environment. Some of these techniques have been adapted from the asbestos remediation industry, such as using a water-misting spray cannon to control airborne radioactive contamination during facility demolition (*25*). Other more advanced methodologies make use of sticky substances such as glycerin or latex, to fix contamination in place (*26*). One novel method of dust control uses an engineered wax to trap and control contamination (*27*). These techniques can be effective at reducing airborne contamination and resuspension of contamination during manipulation of contaminated debris such as mowing lawns, pruning contaminated trees, or removing contaminated facility sections.

Table 2. List of Technologies from Literature Survey	
Technology	**Notes/Abstract**
Composting of Organic Matter	Composting may also be a viable alternative for some niche waste streams from an RDD incident such as food waste (*28*). The U.S. military and others have found that through composting soils, some organic contaminants can be destroyed from munitions-contaminated soils, providing evidence that the composting of this type of contaminated soil is a cost-effective and environmentally sound method for volume reduction of some waste streams (*29*). Note that composting reduces volume of the overall matrix (not really the contaminants in the case of radiological contaminants).
Sod Cutter	A sod-cutting machine was tested to evaluate its usefulness in the radiological reclamation of small lawn areas. Reclamation effectiveness was determined to be dependent on blade depth, soil moisture content, and mass loading of fallout constituents (*30*). Other studies addressing decontamination of soil and prevention of radionuclide runoff have involved methods such as deep plowing, placement of a sorbing layer under contaminated soil, and the construction of the Vector Industrial Complex for treatment and disposal of radioactive wastes generated by various decontamination procedures (*31*). Turf cutting in the zone close to Chernobyl showed a clear distinction in the effectiveness of radionuclide decontamination between podzolic and peaty soils. Removal of the upper five centimeters of soil was substantially more effective in peaty soils (*32*). An Agricultural Research Service study found that removing two inches of soil was effective in removing 80-90 % of radioactive surface contamination (*21*). However, individual sod cutters cannot remove huge quantities of soil/vegetation and are also dependent on the soil type and local geology characteristics such as surface unevenness, presence of rocks, soil texture, moisture content, and vegetation cover (*33*).
Selective Removal of Vegetation	Certain species of plants and vegetation absorb higher concentrations of radioactivity, partly due to their physical characteristics (*21*). Removing certain types of vegetation or selected parts can aid in remediation efforts. For example, lichen in the Fukushima area was found to contain higher radioactive concentrations and, therefore, needed to be removed from tree bark by high-pressure washing (*33*). Removing contaminated mulches or vegetation varieties by type can be quite effective overall. For example, when contaminated wheat-straw mulch was removed, over 90 % of the contamination was removed with the mulch. As part of the same study, the removal of contaminated Bermuda grass mulch removed 30 % of the contamination when two tons per acre of mulch were removed and 60 % when five tons per acre were removed.

Table 2. List of Technologies from Literature Survey	
Technology	**Notes/Abstract**
Soil Washing	Soil washing separates the fine silt and clay particles from coarser sand and gravel, with contaminants adhering to the silt or clay particles. The process facilitates the transfer of chemical contaminants from the soil surface to the water, which can be separated and treated further (*34*). Soil washing is most appropriate when soils consist of less than 25 % silt and clay and at least 50 % sand and gravel (*35*). Depending upon soil matrix characteristics, soil washing can allow for the return of the clean coarse fractions of soils to the site (*36*). Soil washing will generally not be cost effective for soils with fines (silt/clay) content in excess of 30 to 50 % (*36*). Completion of pilot-scale treatability studies for soil washing to reduce contaminated soil volumes demonstrated that this treatment process is not cost-effective for liquid radioactive effluent sites and, therefore, is not considered a treatment option for soil volume reduction prior to disposal (*37*).
HEPA Filtered Vacuum Cleaning	HEPA vacuum cleaning is an effective method of removing contaminated particles. Vacuuming is often used to remove the debris left behind by high-pressure washing and street sweeping (*33*). This method is particularly effective if the material has not interacted with the matrix (via leaching, adsorption, or cation exchange, for instance). In one case, a small vacuum street sweeper was used to remove contamination from a clipped meadow, resulting in the removal of approximately half the contamination (after sweeping twice). After the initial two sweeps, further sweeping/vacuuming was ineffective (*21*). Some studies have shown a consistently high (typically 95 %) removal of contamination using vacuum cleaning alone for a simulated nuclear fallout particle from concrete (*38*). Other projects have shown effective use of vacuum cleaning for streets and other large flat surfaces (*23, 39*). Vacuum cleaning has also been practiced as part of a more extensive cleaning system - for example, scabbling, shot peening, water blasting, or grit blasting tools-with greater success than vacuum cleaning alone (*40, 41*).
High-Pressure Washing	High-pressure washing is largely effective in removing contamination from some surfaces, particularly surfaces of a nonporous nature. However, high-pressure washing requires the use of prodigious amounts of water and can generate similarly prodigious amounts of contaminated wastewater, which must be effectively collected and disposed of. Methods that collect wastewater, such as spin-jet devices, are currently being assessed as a way to address this limitation (*33*). Recent EPA testing of a rotating water jet technology (3-Way Decontamination System, River Technologies, LLC, Forest, VA) on concrete surfaces revealed modest removal levels (36 %) of ^{137}Cs applied as an aqueous solution (*42*).

Table 2. List of Technologies from Literature Survey	
Technology	**Notes/Abstract**
Street Sweeping	Street sweeping is a practical method for cleaning widespread contamination because street sweeping uses equipment that is already available and does not damage the surface (*43*). Street sweeping can leave the majority of radioactive particles behind unless vacuuming or washing occurs simultaneously (*22*). Sweeper dust can have a high concentration of radioactivity (*44*). This high concentration of radioactivity causes a significant issue from the resuspension of contamination. Another study used a sweeper on soil, with its steel bristles removing 75 % of the contamination from moist soil with a thin layer of contamination. Another sweep removed up to 90 % of the contamination. The same sweep with plastic bristles would have been less effective because the plastic bristles could not cut as well through vegetation (*21*).
Segmented Gate System (SGS)	An SGS is a radioactive soil waste minimization system. The SGS uses a series of conveyer belts that pass excavated soil under radiation detectors. Uncontaminated soil passes through the conveyer without activating a "gate." The conveyer is timed and instrumented so that when the system detects a contaminated soil area among a large number of uncontaminated areas, it activates a "gate" at the end of the conveyer belt to remove only that area or section of the whole (*45*). The SGS potentially could be modified for other well-subdivided media such as asphalt or extruded concrete. Several projects have shown that the SGS may provide a significant waste reduction, with an average soil waste reduction of 97 % shown in most projects (*46*). However, the SGS provided significantly less efficiency under two conditions: when the soil was thoroughly contaminated (very uniform contamination throughout the section of soil removed), such as with windblown contamination on soil, and when the soil contained large amounts of vegetation (*45*). The SGS has been useful for processing plutonium-contaminated soil at Johnson Atoll (*47*), the Painesville, Ohio, Metal Recycling Project (*48*), and several DOE sites (*49*). By providing area-specific "pictures" of contamination levels, excavation could be performed in a manner that would not mix highly contaminated soil with low to moderately contaminated soil. This procedure has minimized the effect of mixing all soil together during the excavation process and has resulted in a higher overall volume reduction of contaminated soil. Use of the SGS has been shown to be cost-effective at segregating (rather than removing and disposing) some soil matrices (*50*). The SGS can function as a stand-alone technology, or it can be coupled with other soil treatment technologies. The SGS is currently offered by Eberline Services (*51*).
Scarification	While scarifiers and scabblers are effective in removing layers of contaminated concrete, the process is repetitious and can generate airborne contaminants (*52*). One test using scabbling and cutting, completed approximately 11 years after the Chernobyl event, removed two 1-cm layers from an asphalt roadway to reduce contamination and dose in the area (*53*).

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Technology	**Notes/Abstract**
Plasma arc Vitrification	Vitrification uses a heat source to create a molten bath of glass-forming materials into which waste materials can be dissolved to become an integral part of the glass. During the process, organic compounds are destroyed by the high temperatures required for vitrification. Once the glass product cools and solidifies, any contaminants that were not destroyed or volatilized are immobilized (*54*). Different vitrification technologies include the Joule-heated melter furnace, plasma arc centrifuge treatment, plasma hearth process, plasma arc melter furnace, in-situ vitrification (ISV), and in-container vitrification (ICV). AMEC's GeoMelt ICV has been used to treat diverse types of mixed LLRW. The GeoMelt vitrification process immobilizes radionuclides in an extremely durable glass waste form. The process is flexible, allowing for treatment of aqueous, oily, and solid mixed waste, including contaminated soil (*55*). In 2004, the process was selected by DOE to further treat low-activity radioactive waste at the Hanford Nuclear Reservation. The ICV melter was integrated with a full-scale, 10,000-liter dryer. The performance of the process exceeded all disposal performance criteria (*56*). Plasma arc melting is a vitrification technology that uses an electric current to convert contaminated soil and wastes into stable glass and crystalline products. The process can accommodate a wide range of soil and waste types and debris, which eliminates the need for handling, sorting, and size-reduction of bulk radioactive waste (*57*). Common problems associated with vitrification systems include inadequate design considerations due to the complexity of such systems, leakage, clogging of melt, and corrosiveness of waste materials. In addition, due to the high temperature of the operation, thermal cycling could result in damage to refractory, expansion of melter joints, or even fire (*54*). Vitrification is most suitable for liquid radioactive waste. Drawbacks include high initial investment cost, high operational cost, complex technology requiring highly qualified personnel, and high specific energy consumption. ISV is not suitable for liquid wastes but is most effective with diverse bulk solid wastes. However, a considerable limitation in ISV is the need to pretreat the waste to be vitrified (*58*).
Cementitious Stabilization/ Solidification	Cementitious stabilization/solidification (S/S) is a widely used technique for treating and disposing of hazardous waste and LLRW (*59*). Cementitious materials may include cement, ground granulated blast furnace slag, fly ash, lime, and silica fume. Often, clays and additives are added to help immobilize contaminants or otherwise enhance the waste forms that are produced as a result of this process (*60*). Cement-based systems have been used to treat low-level waste from nuclear power plants for decades (*61*). This method can also be used to treat radioactive contaminated soils, sediment, or sludge. Soils or wastewater can be solidified, locking in contaminants in low-permeability, high-strength blocks

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Technology	**Notes/Abstract**
Large-scale Dig and Haul	Large-scale equipment versus the smaller-scale sod cutter, for example, can be used in larger areas in digging and hauling greater quantities of contaminated soils. This method can include equipment such as graders, bulldozers, and rotary, elevating, and pan-type scrapers (*21*). The contaminated earth is then moved with earth-moving machines into piles or buried in depressions or trenches (*62*). Large-scale wholesale use of this technique can be virtually 100 % effective at removing contaminated structures. However, the use of this technique typically limits the opportunity for waste minimization by destroying buildings and mixing contaminated and uncontaminated debris. Large-scale dig/haul may be a stand-alone method or may be used with another method like the SGS.
Incineration	Incineration has become a largely effective and efficient process at nuclear power plants for waste streams that have a combustible component, but further improvements still need to be made in some areas (e.g., control of ultrafine particles). Incineration can allow from 50 to 80 % or more of solid radioactive waste to be burned efficiently, greatly reducing the volume of waste (*63*).
Chelating Agents	Zeolites are well-established chelating agents that remove radioactive components from aqueous waste streams. Considerable research and some implementations have taken place using zeolites for radioactive waste site remediation and decontamination of waters containing radionuclides (*64*). Misaelides et al. (*65*) presented information with general environmental applications for zeolites, but also included information on the use of zeolites as radionuclide sorbents, including investigation of natural zeolites and nuclear waste management in the case of Yucca Mountain, Nevada, and the sorption of heavy metals and radionuclides on zeolites and clays. Clays are a popular choice for decontamination because they are inexpensive and widely available. Clays are ideal chelating agents for this purpose because cations with low hydration energy undergo dehydration in the interlayer and promote layer collapse, and are thus fixed in the clay's interlayers (*66, 67*). Just as the ability of zeolites to remove radionuclides varies with the specific zeolite, the characteristics of clays vary with type of clay and the locality from which the clay comes (*68*). Bentonite clay, in particular, has been considered an ideal material for a deep geological repository for its high swelling ability, low hydraulic conductivity, high cationic sorption capacity, and long-term stability (*69*). Campbell and Davies (*70*) investigated plant uptake of cesium from soils amended with clinoptilolite and calcium carbonate, based on the observation that ^{137}Cs from the Chernobyl accident remained in a bioavailable form in soils of Great Britain. As a potential remedial measure, the zeolite clinoptilolite was tested in a greenhouse pot experiment for its effectiveness in selectively taking up cesium from two British soils (a lowland loam and an upland peat).

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Technology	**Notes/Abstract**
Ion Exchange (IX)	Ion Exchange (IX) systems exist that effectively remove radioactive ^{137}Cs. An IX system assembled at the Fukushima Daiichi Nuclear Power Plant site was reported to achieve a cesium removal goal of 99.9 % and be responsible for 70 % of the radioactivity removed from the wastewater, although details of the exact process and IX resin were not provided (*71*). Care should be taken when relying purely on vendor-supplied data with insufficient background to assess the reliability of the data. Such effectiveness is not unexpected because IX was used to clean up legacy nuclear waste from an old reactor at the DOE's Savannah River Site with removal efficiencies up to 99 % (*72*).
Reverse Osmosis	Reverse Osmosis (RO) is an effective treatment method for the removal of cesium from contaminated wastewater and nuclear liquid wastes. Another study found that RO membrane removal performance of cesium reduced the concentration of cesium, strontium, and iodine by greater than 99% in high-salinity water (*73*). A number of commercially available products employ RO for control of strontium in drinking water. Four were tested in USEPA's Environmental Technology Verification program (*74*). Natural strontium was effectively removed (97 to greater than 99 %). RO has also been found to be effective in decontamination processes with a large number of radioisotopes (*75*).
Electrodialysis/ Electrodialysis Reversal (ED/EDR)	ED/EDR uses an IX membrane to separate ionic contaminants. EDR consists of stacks of EDR membranes arranged in lines that make up the stages in an EDR system. Unlike the nanofiltration and RO processes, the product from the prior stage is further treated in subsequent stages. The concentrate from each stage is blended and wasted. ED/EDR has been identified by EPA as a Small System Compliance Technology (SSCT) for radium and may also be effective in removing uranium. ED/EDR has also been identified as an option for ^{137}Cs removal (*76, 77*).

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Technology	**Notes/Abstract**
Membrane Filtration	Membrane filtration is often used as a pretreatment for surface water, sea water, or contaminated effluent before other processes such as RO or other membrane systems. More specifically, nanofiltration and ultrafiltration have been investigated for the removal of radioactive species from aqueous waste streams as an ultra-low-level analytical tool to separate actinides from other ionic species in high-level radioactive waste solutions, and as a possible treatment option for waste streams from the Los Alamos National Laboratory Plutonium Treatment Facility (*78*). In these applications, the nanofiltration and ultrafiltration membranes were coupled with water-soluble chelating polymers (such as IX resins), but did not have the disadvantage of using organic solvent-based extractants. A small study was undertaken to evaluate the separation of ^{137}Cs from a sodium salt excess medium utilizing nanofiltration. The removal efficiency of cesium was found to be between 75 and 95 %, depending on the concentration of a specific ligand, resorcinarene. Semi-permeable membranes have been demonstrated to be effective in reducing the volume of wastewater containing cesium and cobalt (*79, 80*). An inorganic nanofiltration membrane was used to treat LLRW and found to be effective (*81*).
Conventional Filtration	Standard coagulation/flocculation was found to be an ineffective treatment technique for the removal of ^{137}Cs from water; however, sequential precipitation, using copper ferrocyanide, was found to be an effective treatment method for removing ^{137}Cs and other radionuclides from liquid wastes (*79, 82*). This small-scale study was undertaken to treat low to intermediate-level nuclear liquid wastes in India by means of sequential precipitation using a copper ferrocyanide solution (created by adding potassium ferrocyanide, copper sulfate, and ferric nitrate together). The experiment used samples of contaminated groundwater, contaminated deionized water, and also synthetic alkaline water.

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Technology	**Notes/Abstract**
Activated Carbon (AC)	AC is made from organic materials with high carbon content such as wood, coconut, lignite, and coal, and the type of source material significantly impacts the adsorptive properties of the resulting AC (*79, 82*). In applying AC for contaminant removal, it is important to consider the properties of carbon utilized in preliminary testing and in actual operation. As many radionuclides are ionic, their potential for removal by many ACs can be limited unless the radionuclides are complexed to an appropriate organic substance. However, some ACs, based on the source, may have some IX character, and AC may be pretreated to enhance its ability to remove ionic compounds. Based on limited bench-scale and isotherm tests (*83, 84*), granular AC (GAC) was found to be effective for cobalt removal [up to 99 %, but at pH below typical drinking water treatment and at two-hour empty bed contact times (EBCTs)]. The studies did not provide sufficient data to indicate whether GAC would be feasible on a full-scale level. Based on study findings, cobalt removal by GAC is dependent on contaminant concentration, EBCT, and media type. Based on another article, removal of radium from water by GAC alone is not very effective (approximately 1 to 23 %) (*85*). The article suggests that radium was not adsorbed onto the GAC. As a filter medium (for conventional filtration), GAC would not be expected to be effective. Finally, based on isotherm studies, adsorption of uranium in water by GAC can be very effective. One study showed that treating the GAC with hydrophobic aerogels would enhance GAC adsorption. The type of GAC used in the studies was not mentioned, so no conclusions could be drawn about the effectiveness of the GAC material type (*79, 82*).
Evaporation (Passive or Active)	"Passive" evaporation draws its energy source to vaporize water from a natural source such as solar or wind. For example, an evaporation pond will be warmed by solar radiation, and unsaturated air blowing over the pond surface may speed the evaporation. “Active" evaporation employs an engineered source of energy, such as fossil fuel or nuclear power. Common thermal evaporation systems can include vacuum distillation or spray-drying. Evaporation could be used to achieve two different endpoints. First, nonvolatile solute contaminants (metals and most radionuclides) could be greatly concentrated (e.g., 100:1), and the low-volume concentrate could be combined with other liquid radioactive wastes in the separations area for subsequent treatment and disposal. The condensate stream, comprising 99 % of the feed stream, would be clean except for volatile radionuclides. Thus, the bulk of the extracted groundwater could likely be more easily disposed. Second, the concentrated waste stream could be reduced to dry solids and disposed of as solid radioactive waste (*86*).

CONCLUSIONS

Many effective methods of characterizing and reducing the volume of waste from a widespread radiological contamination event have been developed and are commercially available. Some of the well-known published methods include the SGS and simple and advanced identification and characterization methods such as the CANBERRA Falcon 5000 or ASPECT systems. These methods are well documented and supported by the literature. Other methods, such as removal of vegetation and the use of fixatives and sod cutters, are intuitively practical methods of waste mitigation from a radiological contamination event but are not as well-documented in the literature. Also, data on their effectiveness (or at least a conceptual approach) may be available but not published at this time.

In many cases, literature searches revealed that many of the technologies and methodologies identified have undergone preliminary evaluation or have been used for DOE legacy sites (e.g., segmented gate system) but would have to be field-tested during an RDD, IND, or NPP accident response to fully evaluate their effectiveness and application. Some of these methods deserve additional investigation since they could be deployed rapidly during an RDD incident. In addition, opportunities exist for technology development as well as the integration of existing equipment and techniques into a "toolbox approach" to facilitate waste minimization activities during an RDD incident.

This literature search has been used to develop the SOG Document (*2*) and is being used to inform future research plans. One observation that arose from this effort was that source reduction, mitigation, containment, and waste minimization are concepts that are inextricably linked when dealing with a wide-area radiological remediation effort, and this knowledge is an important concept to keep in mind as research, planning, and response efforts move forward.

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