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Particle Transport of Radionuclides Following a Radiological Event

A Literature Review and Summary

Office of Research and Development
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DISCLAIMER

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ABBREVIATIONS AND ACRONYMS

AGRICP	Agricultural Countermeasure Program
Am	Americium
AMAD	Activity Median Aerodynamic Diameter
Ba	Barium
CBRN	Chemical, biological, radiological, and nuclear
Ce	Cerium
Cf	Californium
Co	Cobalt
CONDO	CONsequences of Decontamination Options
Cs	Cesium
DIPCOT	DIsPersion over COmplex Terrain
EA	Environment agency
ERMIN	European Model for Inhabited Areas
Eu	Europium
FSA	Food Standards Agency
GIS	Geographic information system
I	Iodine
Ir	Iridium
IS	Information system
JAERI	Japan Atomic Energy Research Institute
MAA	Multi-Attribute value Analysis
Mo	Molybdenum
MOGRA	Migration Of GRound Additions
MOIRA	The MOdel based computerized system for management support to Identify optimal remedial strategies for Restoring radionuclide contaminated Aquatic ecosystems
NPP	Nuclear power plant
NW	Nuclear weapon
PARATI	Program for the Assessment of RAdiological consequences in a Town and of Intervention after a radioactive contamination
Po	Polonium
Pu	Plutonium
Ra	Radium
RDD	Radiological dispersal device
RESRAD	RESidual RADioactive
RODOS	The Real-time On-line DecisiOn Support
Ru	Ruthenium
Sr	Strontium
Te	Tellurium
Zr	Zirconium

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EXECUTIVE SUMMARY

With the prevalence of terrorism, the threat of an attack targeting densely populated urban areas is of increasing concern. One possible means of attack is a radiological dispersal device (RDD)—essentially, a dispersal device (e.g., an explosive) capable of spreading contaminants over a confined area. RDDs are unlikely to invoke mass casualties; instead, they contaminate people and surfaces with radioactivity. Although the activity levels of the resulting contamination may be low, chronic exposure could result in damaging health effects. Unlike other sources of radioactivity (i.e., nuclear power plant [NPP] accidents and nuclear weapon [NW] detonations), RDDs are extremely mobile and relatively simple to build. However, very little is known about the nature of contaminants produced by RDDs or their behavior in urban environments. In contrast, a considerable amount of research has been conducted on NPP accidents and NW detonations. This paper seeks to compare NPP and NW incidents and their derived contaminants to better understand RDDs and how they might interact with urban environments.

This literature review was conducted to address the current state of knowledge on particle transport relative to radiological sources and their host environments. More specifically, this review seeks to 1) determine whether empirical evidence exists for further characterizing RDDs according to literature pertaining to NW detonations and NPP accidents, 2) provide an overview and analysis of the current state of knowledge related to radiological sources with reference to particle transport, 3) contrast the behavior of radionuclides in urban and rural environments, and 4) explore the current state of radiological transport models, taking the above findings into consideration. The literature review concludes by discussing research gaps and research needs in order to improve response and recovery capabilities following a RDD incident.

Numerous knowledge gaps, as identified by this review, need to be addressed in order to better understand and predict the transport of radiological contaminants. The gaps include, but are not limited to, the impacts of natural and human-derived resuspension within urban environments and the necessary countermeasures to reduce the impacts of these mechanisms, water-soluble radioactive contaminant transport within urban areas, surface interaction of dispersed particles, and a thorough technical review of available radiological models with reference to particle transport.

1. INTRODUCTION

The release of radiological material from an incident has the potential for widespread contamination and public exposure. The magnitude of such an event may be augmented by the continued transport of radioactive material. In a relatively short time, contaminants may migrate to otherwise clean areas, increasing the extent of contamination. This phenomenon was recently observed near Fukushima, in which contaminants migrated to uncontaminated or decontaminated areas [1]. In essence, there are few options for sequestering atmospheric transport or surface migration. Short-term gross mitigation efforts, let alone long-term cleanup, would likely require a significant amount of resources and time.

In addition to the environment in which the radioactive contaminants are released, the source of contamination will influence the magnitude and overall behavior of radioactive material. Radiological dispersal devices (RDDs) are one such source.

RDDs are designed to disperse radioactive material in order to expose people and contaminate areas. Although their ability to contaminate large areas or expose vast numbers of people to radiation is limited compared to nuclear power plant (NPP) accidents or nuclear weapon (NWs) detonations, RDDs are capable of contaminating targeted areas of interest, disrupting normal activities, inflicting major economic implications, and invoking fear [2]. The radioactive material needed to construct a RDD can be easily appropriated. Such materials are often found in industrial, research, and medical wastes [3].

Large-scale tests assessing the dispersion and surface transport of radioactive particles associated with RDDs are limited due to their hazardous nature. Accordingly, there is very little literature documenting the probable outcome of such an event, especially regarding urban environments. There is, however, an abundance of literature addressing historical NW detonations and NPP accidents. This review assesses that literature, characterizing NPP accidents and NW detonations in order to facilitate conjectures about the transport of radionuclides analogous to RDDs in urban environments. Such data could promote more informed response and recovery decisions when responding to RDD incidents.

This document provides an overview and analysis of the current state of knowledge related to radiological sources with reference to radiological material transport in urban environments. More specifically, it seeks to 1) determine whether empirical evidence exists for further characterizing RDDs according to literature specific to NW detonations and NPP accidents, 2) provide an overview and analysis of the current state of literature related to radiological sources with reference to particle transport, 3) contrast the behaviors of radiological materials in urban and rural environments, and 4) explore the current state of radiological transport models, taking the above findings into consideration.

1.1. Methodology

To prepare this document, the authors aggregated literature and other information from the appropriate sources. These sources were queried using a set of predefined keywords. Each piece of literature was read, assessed, and documented based on a number of criteria (i.e., applicability, accuracy, clarity, and uncertainty and variability). Literature deemed at least moderately relevant, according to the above criteria, were then summarized. This document was synthesized by incorporating the main points presented by pertinent literature.

2. SOURCES OF RADIATION

The detonation of Trinity, the first atomic bomb, began the Atomic Age [4]. The era promised revelations in defense and energy, many of which came to bear. Over the past 60 years, radioactive materials have introduced a wide range of beneficial uses, especially in the areas of medicine, industry, and research. With this modernization came great power—and responsibility, because conventional and unconventional radioactive sources can adversely impact human health and the environment for decades or longer. Radiological incidents can be propagated through natural and man-made causes and are derived from an array of sources such as NW detonations, NPP accidents, transportation incidents, sabotage, improvised nuclear devises, and RDDs. Each radiological incident varies in terms of release mechanism, release dimensions, deposition behaviors, isotopic compositions of source materials, and subsequent impact [5].

Radionuclides released into the air may be in a gaseous, particulate, or multi-phase (i.e., gaseous and particle) form [6]. In particle form, radionuclides can be characterized by particle size, shape, elemental composition, structure (e.g., crystalline and amorphous phases), and valence and oxidation conditions [7]. The mobility, environmental behavior, bioavailability, and ecological impact are determined by the physiochemical properties of the particles themselves. As particles coagulate or condense onto atmospheric aerosols, their physiochemical form may change, thus altering their behavior [8]. In short, radioactive particles are distinguished by their source and formation mechanisms [8]. These characteristics will later influence particle dispersion, deposition, migration, and remobilization.

For the purpose of this paper, radiological sources are limited to NWs, NPPs, and RDDs. The following variables have the greatest influence on the physiochemical characteristics, size, and structure of particles in regard to the source:

- NWs: device yield, detonation environment, and height of detonation.
- NPPs: oxidative stress, fuel matrix, and release characteristics.
- RDDs: elemental and physiochemical properties of radioactive sources, packaging material/method, and explosive yield [9].

There are stark differences between the radiological sources listed above. Disparities are most apparent in incident magnitude, with impacts ranging from small (e.g., RDDs) to large (e.g., NWs). The area of contamination increases with incident magnitude. Regardless of meteorological conditions, the height of detonation and the distance radioactive material is ejected into the atmosphere will be the main factors that decide the extent of contamination. For instance, NW detonations can insert particles into the stratosphere by means of extreme explosive force, where they may traverse the globe in a number of days; particulate originating from an NPP accident will predominantly reside within the troposphere. Other disparities include available fuel matrix, activity, and physicochemical characteristics of particles. More information on this topic is provided in the following sections.

Similarities also exist, especially between NPP accidents and NW detonations. According to studies that took place near NPPs and NWs, ignoring the destructive nature and extent of contamination of NW detonations, concentration and deposition values did not vary by more than one order of magnitude between the two [10]. Similar resuspension values have also been reported [11]. Furthermore, fallout from NW detonations and NPP accidents is more likely to produce homogeneous boundaries of contamination, while RDDs are more likely to generate heterogeneous boundaries[9]. This is based on the assumption that NW detonations and NPP accidents are more likely to deposit contaminants in a uniform, yet violent manner. The compositions (i.e., fuel) of NWs and NPPs are somewhat consistent, and therefore are more likely to produce analogous particle sizes and physiochemical properties. For instance, deposited contaminants from Fukushima are reportedly similar in isotopic makeup to those from Chernobyl [12]. As such, these types of incidents are more predictable. On the other hand, RDDs are more likely to consist of a heterogeneous mixture of fuel and construction material that, when detonated, will produce a mixture of fragments and particles of variable size and shape leading to heterogeneous deposition [13].

2.1. Nuclear Weapons

An NW can be described as an explosive device capable of releasing a vast amount of energy in a limited time and space by means of nuclear interactions [4]. This sudden release of energy causes extreme increases in pressure and temperature, in turn causing the rapid expanse of compressed gases (i.e., a shock wave) in addition to the emission of initial, thermal, and residual radiation [4]. Consequences of NWs may differ greatly in terms of detonation mechanism (i.e., fusion vs. fission), composition, and design.

Following detonation of an NW, a large amount of energy is released within a short period of time. Enveloped weapon residues, nearby aerosols, and ground material are heated to extremely high temperatures (i.e., ~5,000°C), creating a luminous mass of gaseous material (i.e., a fireball) [4]. The gaseous particles are eventually solidified by means of nucleation and condensation [4]. As the fireball expands, it engulfs secondary materials (e.g., nearby aerosols and debris). Once the contents of the fireball cool, these secondary materials can serve as nuclei for condensation of smaller molecules and gas particles [4]. Accordingly, surface area availability is a major factor in determining particle size distribution, which in turn is influenced by detonation altitude, device yield, and the surrounding environment. For instance, ground detonations can produce very large particle sizes (i.e., up to a few cm in diameter), whereas high-altitude detonations produce much smaller particle size ranges (i.e., approximately 0.01–20 μm) [4].

Literature describes four common types of radioactive particles that are characteristic of NW detonations: 1) condensation of vapors of fission and activation products producing particles about 1 μm in diameter; 2) precipitation of the molten components of the bomb and materials absorbed by the fireball (e.g., soil, rocks, and staging equipment) producing spherical shaped particles of about 0.2–2 mm in diameter; 3) irregularly shaped solid or partially molten components of ground material; and 4) agglomerates of radioactive particles of types 1 and 2 [4]. The physiochemical properties of particles are shot and device dependent. For instance, spherical particles are formed at high altitudes whereas ground detonations create vitrified materials with affixed soil compartments.

The duration and horizontal extent of fallout largely depends on the distance of the detonation from the ground surface, meteorological conditions, and to a lesser extent the yield of the weapon [4]. Surface bursts, when exposed to an increased inventory of surface area, are more likely to produce local fallout and, therefore, limit the extent of horizontal contamination when compared to atmospheric bursts. Nonetheless, the effects of nuclear weapons may extend great distances within a short period of time, and under the right conditions can circumnavigate the earth in a matter of days [14]. Fallout settling time—or the duration of time it takes for particles to deposit on the ground—is largely a function of particle size, as demonstrated in Table 1.

Table 1. Particle Characteristics According to Fallout Type [7]

Fallout Type	Description	Radius (µm)	Settling Time
Local fallout	Large particles	> 100	Minutes–hours
Intermediate fallout	Medium-size particles	10–100	Days–hours
Global fallout	Small particles	< 10	Years

The radioactivity of particles is attributed to fissionable material (i.e., uranium (U) or plutonium (Pu)) in addition to the generation of fission products. Radionuclides most commonly attributed to nuclear weapons fallout are [15-17]:

- Fission products—cesium-137 (^{137}Cs), iodine-129 (^{129}I), and strontium-90 (^{90}Sr).
- Activation products—cobalt-60 (^{60}Co), europium-154 (^{154}Eu), and ^{152}Eu.
- Components of nuclear fuel—plutonium-238 (^{238}Pu), ^{240}Pu, and americium-241 (^{241}Am).

2.2. Nuclear Power Plants

NPPs make use of fission to heat water that in return produces steam that actuates steam-driven turbines. Nuclear fission is achieved by means of U or Pu isotopes [18]. In addition to heat, fission produces a number of radioactive byproducts. Because of the immense heat generated during fission, NPP require advanced cooling systems. In the event that these cooling systems fail, the core containing the fuel and fission products can be compromised. This excessive heating causes melting of the cores and protective casing (i.e., meltdown). If not remedied, pressures within the containment structure may exceed safe levels, causing the structure to either leak radioactive contaminants or explode—dispersing radioactive materials [18].

Nuclear reactors contain a myriad of radioactive materials. The Chernobyl accident in 1986 released condensed aerosols, fuel particles, and radioactive gases, with the latter contributing around 50% of the total release. Dobrovolsky and Lyalko assigned Chernobyl particles to four categories: 1) fuel particles (i.e., fuel particles consisting of U oxide fuel fragments containing a range of fission and activation products), 2) fuel construction particles (i.e., particles consisting of a matrix of nuclear fuel), 3) construction particles (i.e., reactor construction materials that serve as carriers), 4) and hybrid particles or condensation particles (i.e., particles that were mainly formed from interaction of reactor fuel, construction materials, and fire suppressant materials) [7, 19]. Two groups of radionuclides were identified within areas contaminated in the Chernobyl incident:

- The volatile group: tellurium-132 (^{132}Te), ^{134}Cs, ^{137}Cs, molybdenum-99 (^{99}Mo), ruthenium-103 (^{103}Ru), and ^{106}Ru, with an activity median aerodynamic diameter (AMAD) on the order of 1 µm.
- The refractory group: barium-140 (^{140}Ba), zirconium-95 (^{95}Zr), cerium-141 (^{141}Ce), ^{144}Ce, ^{89}Sr, and ^{90}Sr, with an AMAD of 4 µm [8, 14].

Before Chernobyl, very little ^{134}Cs was present in the environment (i.e., nuclear weapons tests did not produce a large amount of ^{134}Cs).

Although the effects of Chernobyl fallout had global implications, it was estimated that $2x10^{18}$ Bq of fission and activation products were deposited within 30 km of the power plant. Heightened contamination levels remained within the atmosphere years following initial release [16]. As with NW detonations, environmental and meteorological conditions and source material (i.e., fuel) are influential in determining the overall source characteristics. For instance, the stratospheric residence times of radiocesium were approximately 770 and 150 days for Chernobyl and Fukushima, respectively [20]. This disparity is likely linked to higher amounts of refractory elements being dispersed from Chernobyl, and in the case of Fukushima, a reduction in resuspension because of contaminates being transported offshore. Similarities were also observed. The AMAD of volatile nuclides from Chernobyl was approximately 0.51 µm, compared to 0.43 µm for Fukushima [21].

2.3. Radiological Dispersion Devices

RDDs are designed to disseminate radioactive material in an attempt to inflict casualties, cause destruction, invoke fear, and ultimately contaminate people and surfaces. The primary effects of RDDs are twofold. First, although not effective in inflicting mass causalities, RDDs are capable of exposing bystanders to dangerous levels of radiation. Second, RDDs are capable of dispersing and depositing contaminants that will likely require extensive efforts and resources to remediate.

RDDs consist of a dispersal source and radioactive material. The dispersal source will typically involve an explosive device; however, this may not always be the case. The yield of the dispersal source is proportional to the extent of contamination. Radioactive materials are chosen based on their portability, ease of access, level of activity, and physiochemical forms. The following radionuclides are of greatest concern: ^{241}Am, californium-252 (^{252}Cf), ^{137}Cs, ^{60}Co, iridium-192 (^{192}Ir), ^{238}Pu, polonium-210 (^{210}Po), radium-226 (^{226}Ra), and ^{90}Sr [3]. It is suspected that the following factors will be considered by those building RDDs: 1) availability of a particular isotope, 2) availability of an isotope in large quantities, 3) ability to shield, 4) high activity level, and 5) sufficiently long half-life [2]. Literature has suggested that beta/gamma sources between 0.1 and 100 TBq would be best suited for strength and mobility purposes [22]. There have been 300 attempted radioactive substance smuggling incidents over the past decade [2].

RDD composition and geometry can greatly affect the aerosolization properties of the radioactive material [13]. For explosive detonations, fine particulate matter can undergo a phase change to either a liquid or a vapor. This will result in lower deposition velocities at the surface. Particles will remain airborne for longer periods of time and contaminate a larger area, even with limited explosive force [22]. Upon detonation, two important phenomena take place: 1) radionuclides agglomerate with inert material inside the fireball, and 2) secondary oxidation of the radiological material occurs. In the event of agglomeration, small particles of inert material in the vicinity of the fireball may be entrained into the turbulent eddies within the fireball. These particles then interact with the radiological material, assisted by varying velocities within the eddies [13]. As a result of this interaction, radiological particles increase in size, causing rapid settling. According to Harper, Musolino, and Wente, the opposite was observed when radiological materials conducive to oxidation (i.e., with a high Bibbs energy of formation) were used [13]. Particle size decreased significantly resulting in a reduced rate of deposition. RDDs will likely produce uneven radioactive fragments and particles of varying sizes, resulting in heterogeneous patterns and areas of contamination [9]. Studies have indicated that particles are closely associated with nearby materials (i.e., soil matrix). Moreover, these materials influenced the morphology and chemical composition of particles [23].

RDDs have the potential to contribute a significant amount of exposure; however, the spatial extent of contamination, by means of explosives, may be limited. The extent and spread of contamination is dependent upon particle size, height of release, and ambient weather conditions [24]. Unlike NW detonations and NPP accidents (which can produce either spherical or fragmented particles, depending on their source and surrounding materials), RDDs will likely produce particles in a fractured state with moderate particle size distributions. RDDs are less predictable than NW detonations or NPP accidents in terms of magnitude and extent of contamination. Where NPP accidents are closely associated with fuel and NW detonations with the height of detonation, RDDs are a direct product of their construction materials. These materials will determine the overall physiochemical characteristics of the contaminants and, most importantly, the efficiency of aerosolization.

3. SPREADING MECHANISMS

3.1. Deposition

Deposition can be described as the process in which atmospheric material is dispersed through the air, eventually settling on surfaces [25]. The settling of particles consists of two unique sub-processes: dry and wet deposition. Dry deposition is the direct interaction of a surface with the material excluding the direct incorporation into precipitation [26]. Dry deposition is determined by a combination of factors such as surface and particle characteristics and meteorological conditions [8]. During transit, precipitation may lead to a significant depletion of contaminants [27]. This scavenging process is known as wet deposition. Wet deposition is described as the transfer of material from the atmosphere to the surface by means of precipitation (i.e., rain or snow) [25]. Important factors affecting wet deposition are the proximity of the dispersed material to an area of precipitation, height of the rain-producing layer, amount and rate of precipitation, and particle size distribution [15, 28-30].

Deposition values may fluctuate considerably due to a number of factors including meteorological conditions, heterogeneous mixing, and particle size distribution of the passing plume. This phenomenon was particularly evident following the Chernobyl incident, when areas near the NPP experienced lower rates of deposition in comparison to outlying areas. Wet deposition was most prevalent during Chernobyl and was correlated with geographic areas reporting increased levels of contamination [16, 17]. Surface elevation may also play an important role in deposition. This is likely due to the presence of orographic precipitation found at high-altitude locations [31, 32].

3.2. Surface Transport

The migration of contaminants across a given surface is a function of the initial physiochemical characteristics of the contaminant as well as the composition, orientation, and condition of the residing surface [25]. These characteristics may vary depending on the environment in which the contaminant was deposited. The particle's environment (e.g., urban areas) and that environment's components (e.g., sewers) greatly influence the extent and magnitude of radioactive contaminant transport. The purpose of this section is to highlight the significance of urban and rural environments to radioactive contaminant transport as contaminants traverse these environments via various mechanisms.

3.2.1. Urban Environments

Literature originating from Chernobyl and RDD dispersion modeling have shown that dispersion and deposition in urban areas are largely influenced by the presence of tall buildings that divert surface airflow patterns around buildings and through city streets [33]. Accordingly, deposition patterns can vary greatly by city depending on the geometry of the infrastructure [33]. For instance, following deposition, radioactive material either penetrates into urban surfaces, migrates by means of fluvial transport, pools in low-lying areas, enters sewer systems, or is resuspended, restarting the process.

The transport of radionuclides will vary depending on their physiochemical characteristics. For example, ^{137}Cs, a radioactive isotope of cesium, is highly mobile during periods of precipitation because of its high water solubility [34]. Surface migration of contaminants due to runoff is promoted by presence of tall buildings and sewer or drainage systems [25]. Dose rate information from aerial surveys conducted in the Fukushima evacuation areas have shown a faster than expected reduction in the overall dose rate [35]. Empirical studies have attributed this reduction to surface runoff of ^{137}Cs. However, this collective runoff has the potential to create large areas of pooling containing high concentrations of radionuclides [35]. Decades following initial deposition from the Chernobyl incident, low-lying urban areas have been found to contain activity levels as high as 540 Bq/kg when compared to low-lying areas [36]. Very little is known about the distribution, resuspension, and migration of radionuclides in urban environments [37]. Despite this, their ability to expand contamination in an area has been well documented in literature [37].

3.2.2. Buildings

Buildings account for a majority of the surface area within urban environments. Depending on a number of factors, buildings have the potential to collect or promote the migration of radionuclides. As with the radionuclide itself, this is highly dependent on the physiochemical properties of the building construction materials. Studies assessing the distribution of contaminants from Chernobyl in nearby urban areas have suggested that building orientation in regard to release point and building height may influence the distribution of radionuclides on building surfaces, with the upper floors containing higher levels of contamination [37]. This is likely a result of inadequate shielding of nearby buildings of increased heights coupled with the effects of urban airflow. However, to what extent these characteristics influence the deposition and migration of radionuclides is still unknown.

3.2.3. Streets and Sidewalks

Levels of contamination of the streets of Pripyat, an urban area approximately 100 km from Chernobyl, were an order of magnitude or more lower than in buildings [33, 38]. Contamination levels of streets are known to rapidly decrease over time because of weathering and mechanical agitation; however, less traveled streets tend to retain contaminants for longer periods of time [34, 38]. One study in particular reported contamination remaining on roadways for up to 7 years [34]. A majority of the contamination resides on a thin layer of street dust and is removed as a result of resuspension or migrates to neighboring surfaces by way of runoff [34].

Due to the type of materials commonly used in their construction and their proximity to buildings and streets, sidewalks present activity levels similar to streets following a radiological incident [39]. Cement, a material often used in the construction of sidewalks, is conducive to the entrapment of radionuclides, such as ^{137}Cs, due to the presence of silica and the micro-porosity of the cement matrices [39]. Because of this, sidewalks may retain contaminants for longer periods of time than other urban surfaces.

3.2.4. Sewers

Following initial deposition, wash-off mechanisms such as runoff from precipitation or wash-water from decontamination activities are capable of transporting radionuclides throughout urban areas. This phenomenon is augmented by the presence of drainage systems and the increased distribution of impermeable surfaces [25]. Contaminated effluents subjected to runoff by means of wash-off will either 1) migrate through urban drainage systems, risking redistribution in water courses elsewhere, or 2) enter sewer treatment systems where they may be trapped in sewer sediment or sludge, treated and disposed of, or recirculated for reuse [25]. It is assumed that the transport of radionuclides is largely dependent on the species, physiochemical characteristics, construction material, and status of sewerage systems. Species may be the most influential factor. In two separate studies, a mass balance of effluence entering the sewage treatment plant showed

10% of ^{137}Cs and 20% of ^{90}Sr being trapped in sewage sludge, with the remaining fraction being discharged [40, 41]. Urban drainage systems and treatment systems are likely the most efficient mechanisms at transferring contaminants to clean areas or exposing inhabitants to moderate levels of radiation. Nonetheless, very little information exists on the fate of radionuclides in sewer systems.

3.2.5. Parks

Gardens and parks tend to act as sinks for radiological contaminants in urban environments and are widely reported as contributors to the overall dose [42, 43]. This is likely due to the abundance of permeable surfaces (e.g., soil) within these areas. This phenomenon may be augmented by runoff from surrounding impermeable urban surfaces. Surface transport mechanisms in gardens and parks are similar to those found in rural environments.

3.3. Rural Environments

Permeable surfaces are more prominent in rural areas than urban ones, due to the abundance of soil matrices. Accordingly, either radionuclides are captured or migration is greatly reduced. Nonetheless, rural environments will likely retain radionuclides for extended periods of time, act as sources of radiation, or contaminate foodstuffs.

3.3.1. Forests

Forests near Chernobyl and Fukushima greatly reduced the overall mobility of radionuclides [44, 45]. Forests with litter layers present tend to not only slow migration, but also reduce levels of resuspension [44]. Over time, forests tend to homogenously distribute contaminants throughout the ecosystem. Very little radioactive ^{137}Cs is lost from the system by runoff, with more than 90% of the total deposition residing in the upper organic horizons. The underlying litter layer constitutes as a major regulator of forest systems [46]. Given their use for resources, natural habitats, and recreation, and their proximity to populated areas, forests should be a major deciding factor when considering decontamination.

Trees are a predominant plant of forest ecosystems and are extremely efficient at collecting pollutants [46]. Dry deposition on trees may be 10 times higher than in adjacent grasslands [9]. Scavenging efficiency and subsequent migration is a function of species, season, and environmental conditions [27]. Scavenging efficiency greatly varies by species. For instance, conifers have a greater interception capacity than broad-leaved deciduous trees. Upon deposition trees may translocate radionuclides from the underlying soil matrix or the atmosphere. Contaminants are either absorbed by leaves and needles or migrated by means of root uptake or translocation [47]. Younger trees may lack the more extensive canopy afforded to older trees [48]. Therefore, the translocation of contaminants for small trees is less likely. The absorption of contamination by root uptake has been described as limited due to the retention qualities of soil. Emerging tissue contains very little radioactivity; this suggests that it is not easily absorbed and transferred to other tissue, with a large portion residing in the needles, twigs, and leaves versus the core wood [49]. Over time, contamination will continue to accumulate in the core wood [50].

Water availability is described as a major factor in determining retention rates (i.e., more water, higher retention) [49].

Contamination of trees was found to be roughly three times higher than that of grassed surfaces. One study in particular reported forest canopies intercepting as much as 60%–80% of radionuclide deposits [27, 44]. This is likely due to the abundant surface area of leaves/needles [27]. Contamination eventually migrates to the litter layer by means of runoff during periods of rain or leaf shedding [44]. Radionuclide redistribution in a forest canopy may be enhanced by the following mechanisms: 1) removal via wash-off or wind erosion; 2) foliar penetration or root uptake; and 3) leaf/needle removal [48]. Wash-off was found to account for approximately 80% of migration [51]. When tree growth is active (i.e., spring, summer), the removal of contaminants found in the forest canopy is accelerated. This acceleration is likely due to shedding of epidermal layers of leaves and bark. This phenomenon typically occurs within the first couple of warm months [44].

Literature once presented the hewing of heavily contaminated areas of land as a productive countermeasure [44]. The reduction of activity by pruning and removal was later proven to be inefficient [52]. It is now assumed that leaves and branches may act as shields of radiation, especially for urban areas adjacent to dense forests [52]. However, the removal of topsoil, immediately following deposition, was found as a productive countermeasure in reducing the air dose rate [52]. There may be areas in which public perception may require forests to be culled, as in Chernobyl's "Red Forest" [44]. If hewing of large portions of forest areas is desired, it is highly recommended that these activities take place during winter months preferably when snow cover is present, in order to limit the disturbance of the litter layer [44].

3.3.2. Soil

As a result of NW testing and nuclear NPP accidents (e.g., Chernobyl), the migration of radionuclides in soils is well documented throughout literature. Studies have consistently described soil as a major pathway for radionuclides entering the food chain and water supply. Furthermore, the contamination of soil has the potential to retain radiological materials for extended periods of time and to transfer contaminants to otherwise clean areas. Radionuclides' vertical migration is gradual. It is reported that some radionuclides take years to migrate just a few centimeters [53]. The rate of migration varies by radionuclide. The most commonly studied radionuclides according to rate of migration in soil are as follows: ^{131}I > ^{239}Pu, ^{240}Pu > ^{90}Sr > ^{137}Cs [5, 15, 34, 42, 53-58]. Table 2 below shows the mean depth profiles for ^{240}Pu and ^{239}Pu, ^{90}Sr, and ^{137}Cs from various radiological sources.

Table 2. Mean Depth Profiles for ^{240}Pu and ^{239}Pu, ^{90}Sr, and ^{137}Cs [53, 59-61]

Radionuclide	Source	Mean Depth	Years Since Deposition
$^{240+239}$Pu	Nuclear weapon	0–2 cm	>50 years
^{90}Sr	Chernobyl	5–10 cm	14 years
^{90}Sr	Fukushima	0–5 cm	<1 year
^{137}Cs	Chernobyl	0–5 cm	12 years
^{137}Cs	Fukushima	0–5 cm	<1 year

A number of variables influence to the mobility of radionuclides in soil. The most commonly attributed are soil solution, physiochemical properties of soil, microorganisms, the radionuclide involved, and moisture level [42, 47, 56, 58, 59, 62]. Accordingly, lower pH-values, clay content, and cation exchange capacities result in higher mobility rates [47, 56, 59, 62]. Migration is most apparent when contrasting ecosystems and climates. Radionuclides such as ^{137}Cs have a stronger affinity for semi-natural ecosystems than for agricultural ecosystems, with forest ecosystems having a prolonged rate of attenuation [12]. Radionuclide efflux is minimal during winter months and at its maximum during summer months. This is likely due to the increased presence of biomass in soil during winter [63].

3.3.3. Aquatic Environments

Effluent from the source to surface waters is an important pathway for further contamination and exposure (e.g., drinking water, irrigation systems) [64]. Migration is typically facilitated by wash-down and surface runoff. Groundwater contamination resulting from rainwater infiltration from soil is not expected. Rather, considering the slow migration rate of most radionuclides, the odds of exposure from other environments are higher [65].

Upon entering aquatic environments, radionuclides accumulate in bottom sediments and organic matter [71]. Factors influencing level of contamination include subsurface contamination levels, time of inundation, and volumetric flow rate [66]. Contamination levels decrease in a relatively short period of time by means of flushing, burying, and radioactive decay [12]. Attenuation is most noticeable in oceans, rivers, and lakes (with tributaries); closed areas of water tend to decrease at a slower rate. This is likely from the lack of discharge resulting in minimal sedimentation (i.e., burying).

Contaminants may be remobilized due to precipitation and flooding events [67, 68]. Concentrations are closely correlated with increasing volumetric flow rate. Flow rate is a function of precipitation and flooding. As water flow and water levels increase, so does the likelihood of remobilization [67]. Many studies have demonstrated that this phenomenon, particularly for ^{90}Sr and ^{137}Cs, is closely correlated with flooding events [69]. River banks and flood plains near large rivers have been of particular concern with regard to the Fukushima incident. These areas appear to collect high concentrations of ^{137}Cs following significant precipitation events and continue to act as a transport mechanism years following initial deposition [35].

4. RESUSPENSION

Resuspension is defined as the re-entrainment of atmospherically deposited material into the atmosphere [70, 71]. Resuspension is the primary source of lateral spreading of radioactive material outside the initial contaminated area [72]. This lateral spreading serves as a persistent source of both dose and contamination. Inhalation of resuspended particles, within the first few weeks of initial deposition, may have the same impact as directly inhaling the initial contaminating cloud [73]. Literature has consistently defined resuspension as a potential concern following a radiological release. During Chernobyl, recently cleaned areas were often re-contaminated, regaining initial levels of contamination [74]. Following the end of weapons testing, the primary mechanism leading to increased atmospheric concentrations was the resuspension of previously deposited material; this is still considered the most significant contributor for both air and ground activity [11, 17].

Historically, the effects of resuspension were not considered a major threat [75]. During nuclear weapons testing in the 1950s and 1960s, the dose of field observers were drastically underestimated as a result of resuspension [73]. What little data resulted from these assessments originated from tests conducted in arid regions where there was a strong dependence on resuspension by wind [76]. Furthermore, historical resuspension measurements were often delayed until months or years after the initial event. Until the advent of Chernobyl, there had been a limited number of studies investigating resuspension [77].

Literature has defined a number of factors that may influence resuspension. The most prominent are 1) surface properties, 2) meteorological conditions, 3) size distribution of contaminant particles, 4) chemical properties of contaminant, and 5) time since initial deposition [62, 70, 76, 78-82]. Particles are more likely to resuspend when attached to a (larger) host particle [74, 83]. The act of resuspension may be initiated by a number of mechanical influences [77]. Resuspension can be initiated by human or natural mechanisms [70, 82]. Figure 1 below shows a list of common resuspension mechanisms according to natural and human activities.

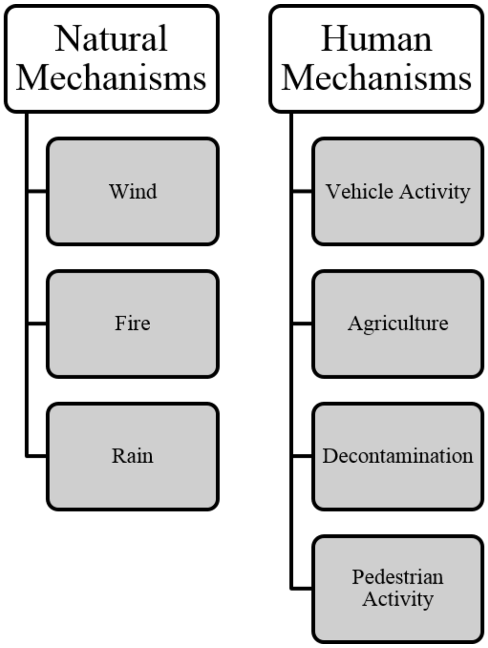

Figure 1. Resuspension Mechanisms According to Natural and Human Activities

4.1. Natural Resuspension Causing Mechanisms

4.1.1. Wind

The influence of wind on resuspension in not certain, and literature is conflicting [84]. A majority of studies have indicated that resuspension will increase with wind speed and particle size (i.e., area), which in return promotes aerodynamic lift [72, 75, 82, 85, 86]. However, a few studies found correlations with wind direction instead [76, 78]. For wind-driven resuspension, particles of 1,000–2,000 µm roll or slide across a surface depending on wind direction (i.e., surface creep). Particles smaller than 50–1,000 µm in diameter may be lifted by wind and subsequently return to earth as a result of saltation [86, 87]. Once the particle strikes the ground, it may resuspend smaller particles [72, 87]. Studies have shown that most radioactive material transported by wind is a result of saltation [86]. Under similar conditions, particles less than 50 µm may be suspended for extended periods of time. The resuspension of small particles less than 0.1 µm is unlikely. Nonetheless, over time, contamination levels are rapidly diluted in the presence of heightened wind speeds [75, 85].

It has been historically assumed that trees may act as sources of resuspended material secondary to wind transfer [79]. Early studies out of Chernobyl indicated that, once contaminated, trees could serve as a spreading mechanism. It was hypothesized that vegetation induces resuspension due to the friction of leaves and disturbances in turbulence [72]. Recent literature indicated that contaminants deposited on tree canopies (specifically of coniferous trees) near Chernobyl remained for an extended period of time. Furthermore, some studies showed higher levels of contamination at the edge of forests, indicating that trees near the forest's edge were, in effect, capturing a majority of contaminants before they entered the forest [44, 48]. The rate of resuspension of small particles from surfaces of trees due to wind has been described as minimal and decreased over time [79]. In fact, the presence of vegetation may minimize the effects of resuspension and reduce atmospheric concentrations of radionuclides over the long term [79, 88].

4.1.2. Rain

Literature suggests rain is capable of causing both mechanical and surface agitation, which can lead to resuspension. This phenomenon is temporary: as rain saturates the surface, the rate of resuspension is greatly reduced. This mechanism has been described as a largely ineffective resuspension mechanism [80, 89].

4.1.3. Fire

Following a radiological incident, access to forested areas will likely be restricted, significantly reducing human influence on wildfires. Rather, natural mechanisms such as lightning are more likely to cause wildfires. Therefore, for the purposes of this report, wildfires are deemed as a natural mechanism of resuspension.

Biomass, particularly in forested areas, is extremely efficient at collecting radionuclides by means of aerosol capture or absorption. Biomass may retain high levels of radiation over many years or decades. The presence of combustible vegetation increases the risk of fire in any forested area; literature has shown that radionuclides may resuspend during forest fires and are a significant inhalation hazard [90, 91]. This is particularly true in the presence of alpha emitters, where exposures can quickly exceed safe levels [90]. During burning, atmospheric concentrations may increase by several orders of magnitude [92].

Atmospheric concentrations are a function of a fire’s phase. Concentrations can be several hundred times higher during active burning, up to 10 times higher when a fire is smoldering, and up to several times higher post-fire [90]. Accordingly, the rate of resuspension is a function of fire temperature and local weather conditions [46]. The burning process may modify the aerodynamic properties of particles, thus increasing their risk of resuspending [90]. A study conducted by Horrill, Kennedy, Paterson, and Mcgowan estimated that between 10% and 40% of radiocesium was released from forest fires near Chernobyl [46]. Moreover, a recent study by Mousseau, Milinevsky, Kenney-Hunt, and Møller suggested that, in highly contaminated forest areas, litter loss may be depressed by reductions in soil invertebrates, thereby increasing the risk of forest fires [93]. Overall, the range of particles resuspended due to forest fires is limited. Estimates range between several kilometers and up to 20 kilometers [90, 92]. Although concentrations of radionuclides are high in close proximity, fire events will only impact a very small area downwind [92].

4.2. Human Resuspension-Causing Mechanisms

Anthropogenic resuspension has been associated with a wide range of activities [76, 78, 82]. These can reach greater depths, and thus resuspend a larger number of particles [87]. Historically, the effects of resuspension in urban environments are poorly understood, though Chernobyl and Fukushima brought marginal advancements in understanding [75].

4.2.1. Vehicles

The resuspension of material from roadways could lead to increased inhalation dose and serves as an important factor in the (re)contamination of localized areas [94]. Literature addressing the resuspension of radionuclides in urban environments as a result of vehicle activity is severely lacking. What limited work has been conducted clearly indicated that material could be resuspended by vehicle traffic. This was demonstrated in a widely cited study by Garland, who correlated high concentrations of resuspended pollutants during periods of increased vehicle activity [76].

Vehicles primarily cause resuspension through particle abrasion by tire sheer and induced turbulence [70, 72]. The resuspension of particles from vehicle traffic is highly dependent upon particle size, vehicle size, road surface type, time since initial deposition, and vehicle speed, with the latter being the biggest contributor [74, 76, 80, 94-96]. A study by Nicholson, Branson, Giess, and Cannell showed that the rate of resuspension increases with particle size [94]. Resuspension from vehicle-induced turbulence requires that the threshold value exceed the surface stresses on the particle [95]. This threshold value is determined by the surface area of the passing vehicle (i.e., the larger the vehicle, the greater the displacement of air); therefore, trucks will likely resuspend more material than cars. Vehicle speed is also an import factor. As vehicle speed increases, so does the rate of resuspension (i.e., proportional to turbulence generated by the vehicle). The difference in vehicle surface area is less evident at speeds above 20 mph [96].

Roadway surface type is a major factor in determining the surface particle matrix. For instance, particles may behave differently on dirt roads due to the increased presence of dust particles that may act as carriers [95]. Furthermore, literature has indicated a reduction in resuspension when vehicles were driven over vegetative surfaces rather than paved surfaces [74, 96]. Particles residing on roadways have a fairly short residence time in that a majority of the material is displaced within the first few vehicle passes. This is likely due to a reduction in particle inventory resulting from resuspension or fixation of particles to the road surface. Literature is conflicting in the amount of time for which material is readily resuspended. Estimates range from five days to a year [76, 80, 95, 96]. Generally, the rate in which material is resuspended is reduced by an order of magnitude within the first week, and several orders of magnitude within 30 days [80].

There are a number of outlying risks associated with vehicle-induced resuspension. In some instances, larger particles may be resuspended without the tire itself being introduced directly to the material [70, 74]. Furthermore, once mechanically agitated, particles may separate into smaller sub-particles, possibly increasing their atmospheric residence time [81]. Although most prominent in dry conditions, tire spray was reportedly a significant contributor during wet surface conditions and is capable of transferring particles to adjacent surfaces or passing vehicles [74, 94]. Vehicles are likely the primary source of resuspension in urban areas. Vehicle activity should be limited following initial deposition at the risk of remobilizing contaminants and thus increasing the extent of contamination.

4.2.2. Pedestrians

Very little literature on pedestrian-driven resuspension exists. A study by Linsley showed that bicycle and foot traffic caused more resuspension than wind, but only about a quarter as much as vehicle traffic [96-98]. Overall, pedestrian-generated resuspension is not considered a significant contributor of radiological particle resuspension.

4.2.3. Agricultural Activities

Literature is conflicting as to the degree of resuspension generated by agricultural activities. A number of studies have assessed particle resuspension as a result of Chernobyl and Fukushima. They collectively found that agricultural practices such as tilling have the potential to increase atmospheric dust levels and concentrations of radionuclides [82, 84, 99]. However, the resuspended particles were very limited in lateral spreading. This is likely because of agglomeration, in which smaller particles affix to larger particles originating from the soil matrix. Only those individuals operating farm machinery or within close proximity of agricultural areas would be at risk. Resuspension because of agricultural activities is considered a moderate spreading mechanism, capable of redistributing material up to a few hundred meters [82].

4.2.4. Decontamination Activities

Decontamination activities have shown to significantly increase radionuclide concentrations, particularly downwind [88]. The rate at which particles are resuspended is dependent on a number of variables including decontamination technology being used and meteorological conditions. More research is needed to determine the impact of resuspension as a result of decontamination activities; however, preliminary Fukushima studies suggest that nearby outdoor decontamination activities correlate with increased concentration levels of ^{137}Cs in indoor areas [100].

4.3. Factors Influencing Resuspension

4.3.1. Particle Size

It is suspected that resuspension rate is a function of particle size due to an increase in aerodynamic lift force that increases with cross-sectional area [80]. Nonetheless, small particles are less subject to gravitational forces and may be carried over long distances. For instance, particles that originated from NW testing can typically be divided into three different categories: 1) large particles that are deposited onto the surface within a matter of hours, 2) small particles that remain in the atmosphere for days, 3) minute particles (i.e., the remaining fraction) that can remain in the atmosphere for months to years [28]. Particles 10 µm and smaller are subject to atmospheric transport, whereas particles 20 µm or larger are deposited near the source [101].

4.3.2. Range

The range of resuspended material is fairly limited [76, 78, 96]. Literature has reported a few instances where resuspended material traveled long distances (i.e., 50–60 km); however, very little deviation of contaminated areas has been reported [75]. For instance, while characterizing contaminated areas in Goiania, Brazil, following an accidental release of ^{137}Cs, Pires Rio and

Paretzke noted that the remaining activity was still confined to within 200 meters of the initial deposition site [102]. In this location, resuspension did not contribute to the overall exposure. Significant contamination of agricultural products, equipment, and structures was reported however. Furthermore, a study by Garland indicated that 60% of particles between 10 and 30 μm were removed from grass and redistributed within 4 meters by means of wind-driven resuspension [80, 89]. Regardless of particle size, literature disagrees in terms of range. Estimates vary from a few meters to up to 60 kilometers [76, 80, 89]. This disparity is likely a result of variations in climates across research locations.

4.3.3. Timeline

Resuspension will be particularly high during the early phases of a radiological incident [22, 72, 81]. These levels decline linearly with time. As previously deposited small particles are removed by weathering and resuspension, only those particles that are firmly bound to the surface remain [103]. Areas contaminated some 10–20 years ago may still serve as a primary source for resuspension; however, the majority of available literature is in agreement that resuspension may be possible at least three years following initial deposition [70, 76-78, 94, 102].

4.3.4. Limiting Factors

Ignoring the physicochemical properties of the particle and the surface-substrate, there are a number of factors that influence the availability of particles, at the surface, for resuspension. These variables vary by location. The most prominent are as follows:

- Weathering: As a result of weathering, particles are either captured by sorption or are washed away [98, 104]. The rate of resuspension is greatly reduced after the first precipitation event [72].
- Displacement: Both human and natural disturbances may transport contaminants to sheltered locations that are less prone to resuspension [98].
- Migration: The vertical migration of radionuclides, albeit slow, will ultimately reduce the amount of particles available for resuspension in the distant future and may act as a shielding mechanism as the contaminant penetrates to greater depths [35, 59].
- Proximity: Larger particles have a higher likelihood of depositing near their source and are more susceptible to resuspension; smaller particles, located near the periphery, are less susceptible to resuspension [76].
- Time: The rate of resuspension declines linearly with time [98].

4.3.5. Climates

Climate is a major factor in resuspension. In arid climates, resuspension is prominent by virtue of decreased precipitation, low humidity, and minimal vegetation [75, 105]. In humid climates with pronounced vegetation and precipitation, resuspension may be limited [80].

4.3.6. Seasons

There is a noticeable uptick in atmospheric concentrations of radionuclides during the spring and summer months [70]. Peaks in concentration in autumn and winter can be attributed to a limited vegetation matrix [75]. Increased wind speed during spring and autumn may also increase the rate of resuspension [75].

5. MODELING AND SIMULATION

Computational methods for estimating the effects of radiological material on people and the environment originated from NWs testing in the 1950s and 1960s [106]. These models, although simplistic in nature, were adequate for predicting the homogenous spreading of radionuclides produced by NW detonations and were well suited for the terrestrial geometries presented by arid environments. The Chernobyl era ushered in a need for more complex computational methods for modeling the spreading of radionuclides outside arid environments [106]. Predicting exposure pathways became increasingly complex when considering urban geometries: unlike arid environments, urban areas aid in the heterogeneous spreading of contaminants, which required complex computational codes. Nevertheless, as Chernobyl beckoned international attention, significant intellectual and financial resources followed [9, 106]. More capable calculation methods soon became available (e.g., Monte Carlo simulations).

Today, decision-makers can exercise a variety of tools for modeling the dispersion, transport, and overall fate of radionuclides for the purpose of predicting exposure, assessment, and remedial activities [9]. In the absence of monitoring or sampling measurements, these tools enable decision-makers to assess current or future conditions or implications according to a set of established parameters or environmental conditions. With the occurrence of the Fukushima accident, modeling capabilities are again challenged with the need for increased spatial scale. Population densities and overall urbanization are higher than in the Chernobyl area, requiring more precise modeling capabilities that can account for the effects urban environments and their surrounding rural areas might impose on particle transport. Therefore, as with the post-Chernobyl period, an assessment of current technology is necessary in order to determine the current capability to model small- and large-scale radiological incidents in urban areas. Although a high-level assessment of radiological models is beyond the scope of this report, an inventory of publically available radiological models was conducted in order to assess their current state so that recommendations pertaining to future research can be made. A literature review was conducted to identify the most widely cited radiological models. Sections 5.1–5.8 provide an overview of those models.

5.1. ARGOS

Summary: ARGOS is an information system (IS) for enhancing crisis management for incidents involving chemical, biological, radiological, and nuclear (CBRN) releases. ARGOS was designed to address a range of CBRN incidents. ARGOS is a prognostic tool as well as a database system for the collection and presentation of data for use in emergencies in an easily understandable form. ARGOS facilitates decision support, improving of situation awareness, and information sharing among emergency response organizations. As a simulation instrument, ARGOS is a valuable training tool for use by emergency response organizations.

Affiliated organization: Prolog Development Center A/S, Risø National Laboratory, Danish Emergency Management Agency

Model type: Decision support system

Model algorithm:

- Source model: Initially developed by Risø, the Source Calculation Model predicts gas releases from industrial storage or transport containers. The Source Calculation Model also calculates the initial dispersion until a stage where other dispersion models of the ARGOS system are able to take over.
- Atmospheric dispersion: ARGOS is divided into a small- and mid-scale dispersion model (called LSMC/RIMPUFF), a model for dispersion in urban environments, a model for dispersion of heavy gases, and a system for coupling to long-range models: DERMA (Danish), MLDP (Canada), SNAP (Norway), and MATCH (Sweden).
- CBRN scenarios: ARGOS incorporates an urban dispersion model capable of accounting for urban and street canyon geometries.
- Nuclear scenarios: ARGOS includes a module for simulating the transfer of radioactive material in food chains, and for assessing doses via all relevant pathways (i.e., internal exposure via inhalation and ingestion, external exposure from the plume and from deposited radioactive material) to the population. The food dose model estimates doses to the public (individual as well as collective doses).
- Countermeasure modules:
    - The Agricultural Countermeasure Program (AGRICP), which extends the food dose model to cover agricultural countermeasures, instead of just calculating doses.
    - The STRATEGY food-chain countermeasure model, developed under the European Commission's Fifth Frame-work Program.

5.2. ERMIN

Summary: The European Model for Inhabited Areas (ERMIN) was developed under EURANOS, an integrated project of the European Commission Sixth Framework Program. ERMIN is both a model and a software tool. As a model, it simulates the behavior of radionuclides in the inhabited environment and calculates the exposure of the population as well as other relevant endpoints. ERMIN brings together a number of models and datasets and embeds an actual transfer model that also takes into account the weathering of material on building surfaces and movement of radionuclides around inhabited environments. As a tool it allows a user to explore different recovery options following the contamination of an urban environment with radioactive material. ERMIN was designed to be implemented within both the RODOS and ARGOS Nuclear Emergency Decision Support System, and also as a standalone application.

Model type: Decision support system

Affiliated organization: Health Protection Agency, Centre for Radiation, Chemical and Environmental Hazards, UK (Now Public Health England); Risø National Laboratory for

Sustainable Energy, Technical University of Denmark, Denmark; Helmholtz-Zentrum Muenchen, Germany-Forschungszentrum Karlsruhe, IKET, Germany; Danish Emergency Management Agency, Denmark; and Prolog Development Center, Denmark-Bundesamt für Strahlenschutz, Germany.

Model algorithm:

- Ratios to distribute deposition on the reference surface onto all urban surfaces.
- Databases for estimating indoor and outdoor dose rates.
- Convection–diffusion equation for estimating migration.
- Empirical functions for estimating long-term retention and resuspension.

5.3. RODOS

Summary: The Real-time On-line DecisiOn Support (RODOS) tool was designed as a comprehensive system, incorporating models and databases, for assessing, presenting, and evaluating accident consequences over all distances, taking into account the mitigating effects of countermeasures. The flexible coding used to develop RODOS enables it to cope with differences in site and source term characteristics, in the availability and quality of monitoring data, in national regulations and emergency plans, etc. RODOS provides decision support on four levels:

1. Acquisition and checking of radiological data and their presentation, directly or with minimal analysis, to decision-makers, along with geographic and demographic information.
2. Analysis and prediction of the current and future radiological situation (i.e., the distribution over space and time in the absence of countermeasures) based upon information on the source term, monitoring data, meteorological data, and models.
3. Simulation of potential countermeasures (e.g., sheltering, evacuation, issue of iodine tablets, relocation, decontamination, food bans), in particular the determination of their feasibility and quantification of their benefits and disadvantages.
4. Evaluation and ranking of alternative countermeasure strategies by balancing their respective benefits and disadvantages (e.g., costs, averted dose, stress reduction, social, and political acceptability) while taking account societal preferences as perceived by decision-makers.

Affiliated organization: European Commission

Model type: Decision support system

Model algorithm: RODOS consists of three primary modules, each with numerous sub-modules performing a different function (i.e., modular). The primary modules include:

- DIsPersion over COmplex Terrain (DIPCOT), an atmospheric dispersion model using a Lagrangian puff/particle methodology based on a Langevin equation.
- A hydrological module.

- A terrestrial food chain module and a terrestrial dose module.
- An aquatic food chain module and an aquatic dose module.
- A forest food chain and dose module.
- A tritium food chain and dose module.
- A dose combination module.
- A countermeasure subsystem (i.e., early and late countermeasure models).

5.4. CONDO

Summary: The CONsequences of Decontamination Options (CONDO) tool was developed for estimating the consequences of decontamination options, including dose, required resources, timescales, and waste management. CONDO incorporates the EXPURT external dose model for inhabited areas.

Affiliated organization: UK Environment Agency (EA) and Food Standards Agency (FSA) for version 2.1; EA for version 3; research contractor: National Radiological Protection Board

Model type: Decision support system

Model algorithm: CONDO consists of a factor-based deposition, radionuclide distribution, and decontamination model. The dose model (i.e., EXPURT) calculates external whole-body dose and effective dose from resuspension. External dose to the public is calculated by summing calculated exposures from different surfaces for varying exposure times and shielding factors. Doses in various time periods are supplied by a database; external doses are calculated at run time, and are subsequently integrated from time since deposition to time of interest, accounting for decontamination.

5.5. MOIRA

Summary: The MOdel based computerized system for management support to Identify optimal remedial strategies for Restoring radionuclide contaminated Aquatic ecosystems (MOIRA) software system is a decision support tool that allows users to evaluate optimal intervention strategies for radiological contamination of aquatic ecosystems. The software uses various mathematical models to assess the transport and radiation dose of ^{137}Cs and ^{90}Sr and the effects of various countermeasures. The software uses Multi-Attribute value Analysis (MAA), which allows evaluation of various countermeasure alternatives by accounting for impacts on the economy, society, and the environment.

Affiliated organization: European Commission

Model type: Decision support system

Model algorithm: The dose models are based on dose rate factors. The concentration models are composed of differential equations.

5.6. RESRAD

Summary: RESidual RADioactive (RESRAD) is a computer code developed at Argonne National Laboratory to calculate site-specific residual radioactive material guidelines in addition to radiation dose and excess lifetime cancer risk to an onsite resident (i.e., a maximally exposed individual or a member of a critical population group). Major pathways include:

- External radiation exposure.
- Internal radiation dose from inhalation (dust and radon).
- Internal radiation dose from ingestion:
    - Drinking water (surface and/or groundwater)
    - Produce, meat, and milk
    - Fish
    - Soil

Affiliated organization: Argonne National Laboratory

Model type: Risk assessment

Model algorithm: Mass balance is maintained between the contaminated source and each transport pathway. RESRAD tracks losses from radioactive decay, leaching (sorption-desorption ion exchange), erosion, resuspension, and volatilization.

5.7. MOGRA

Summary: Migration Of Ground Additions (MOGRA) is a code to predict the migration of toxic substances in terrestrial environments, including radionuclides. The computational code consists of a dynamic compartment model, a graphical user interface for model formation, computation parameter settings, and results displays. MOGRA also includes various databases for radionuclide decay data; solid and liquid distribution coefficients; soil and plant transfer factors; feed, beef, and milk transfer coefficients; concentration factors; and age-dependent dose conversion factors for many radionuclides. Additional code MOGRA-MAP can import GIS files and calculate target land areas.

Affiliated organization: Japan Atomic Energy Research Institute (JAERI)

Model type: Dynamic compartment model

Model algorithm: Simultaneous solution using six-step fifth-order Runge-Kutta method, or Fehlberg

5.8. PARATI

Summary: Program for the Assessment of RAdiological consequences in a Town and of Intervention after a radioactive contamination (PARATI) is a dynamic model developed to assess the long-term consequences of accidental radiological contamination of urban environments. The model is based on empirical data from the Chernobyl and Goiania accidents.

Affiliated organization: Instituto de Radioproteção e Dosimetria, Brazil

Model type: Dynamic compartment model

Model algorithm: Surface activities and contributions to exposure fields

6. DISCUSSION

6.1. Source Characterization

Regardless of the source and explosive yield, high-magnitude radiological events such as NW detonations or NPP accidents will likely generate a large amount of radioactive materials. The physiochemical properties of these materials will depend on a number of variables present at the time of release. Deposition, resuspension, and concentration values resulting from NPP accidents and NW detonations are within one order of magnitude. Furthermore, NPP accidents and NW detonations are very similar in scope, in that the area of contamination following initial deposition is substantial in size and remains largely unaltered over time. Any sizeable disturbances of deposited material will quickly be diluted or will pale in comparison to the extent of initial deposition. Furthermore, the nature and magnitude of contamination for NPP accidents and NW detonations are comparable. To the contrary, even under the most pristine conditions, RDDs are limited in terms of magnitude. Like NPP accidents and NW detonations, RDDs are susceptible to particle transport; however, given the minimal distribution of contamination resulting from RDDs, the effects of transport mechanisms are more apparent. For instance, the Bravo shot of Operation Castle, a 15-megaton nuclear weapon test conducted in 1954, contaminated over 11,000 square kilometers [4]. In contrast, the majority of highly radioactive material released by an RDD will likely be limited in lateral spreading (i.e., a few city blocks) [107]. It is for this purpose that this paper highlights the extent of contamination as the most significant disparity, in terms of particle transport, between large-scale (i.e., NW and NPP) incidents and small-scale radiological sources (i.e., RDDs).

6.2. Surface Migration

Surface migration plays an important role not only in the dose received by local inhabitants, but in the overall fate of radionuclides. Once deposited, radioactive particles may migrate by means of weathering. The rate of migration is largely dependent on the physiochemical properties of the contaminant and on the surface in which it resides. The physiochemical properties will vary depending on a number of factors contributed to the source of contamination. Furthermore, the residing surface, in particular its physiochemical properties, orientation, and condition, are important components of surface migration. These characteristics may vary greatly across urban and rural areas. Urban areas, for instance, boast an extensive surface area that is oriented vertically or horizontally, a majority of which is less permeable than rural surfaces. During precipitation events, these less-permeable surfaces give rise to fluvial transport. Particles then collect in low-lying areas or are transported into sewer or drainage systems, where they are either captured or dispensed into natural aquifers [25]. This phenomenon has been noted in Fukushima studies where the mobilization of ^{137}Cs in urban areas is significant in comparison to undisturbed flat fields [35]. In contrast, rural areas consist largely of permeable surfaces that tend to act as sinks for radioactive contaminants. This phenomenon is particularly noticeable in soil where migration rates of radionuclides are reduced and may remain for many decades. This migration process by runoff is best indicated by a runoff coefficient—a dimensionless factor for estimating the amount of runoff resulting from rainfall. This factor varies depending on the type, orientation, and level of saturation of a particular surface [108]. Runoff coefficients vary greatly by environment. Water movement on urban surface is easier than rural surface. In terms of mobility, this phenomenon might increase the area of distribution of radionuclides—especially water soluble ones. For instance, the runoff coefficient for an urban area is between 0.30 and 0.50, whereas values for forest values are much less (i.e., 0.05–0.20) [108].

Literature has shown that rural or natural environments are somewhat efficient in managing pollutants and are of less concern, as they are not likely to impact a large number of people. This is where the distinction between urban and rural environments in terms of surface migration is most evident. While rural areas are efficient in capturing contaminants, urban environments are designed to reroute runoff to outlying areas away from populated areas. In regard to a radiological incident, this design is rather adverse and is prone for spreading contaminants to otherwise clean areas. Therefore, it may be advantageous in the long term to contain contaminants originating from small-scale events such as RDDs before they infiltrate sewage and drainage systems. These countermeasures would be most favorable in urban areas within days of initial deposition or before a major rain/water washdown event.

6.3. Resuspension

Resuspension is a viable cause for concern arising from radiological incidents, and is the primary mechanism responsible for increased respirable dose and for the lateral expanse of contamination following the initial plume. This is especially evident within the first few weeks of initial deposition. Resuspension may be initiated by either natural or human-derived mechanisms, the latter being more efficient. Accordingly, human activities are closely associated with urban areas where resuspension is most prominent. Resuspension is a primary concern for two reasons: 1) as mentioned above, the deposition area associated with RDDs is very limited, so the effects of resuspension have a greater chance of increasing the expanse of contamination; and 2) RDDs are likely to target populated areas with no warning, resulting in mass panic and uncontrolled evacuations. These actions will likely result in an abundance of human-aided resuspension, with pedestrian and vehicle traffic being the largest contributors. Containment options should be available for responders during evacuation and remediation. In spite of adverse effects associated with resuspension, very little is understood in terms of potential, especially within urban areas.

6.4. Modeling and Simulation

Radiological models are a product of event-driven research, in that resources tend to fluctuate and are contingent on the prevalence of large-scale events (e.g., Chernobyl). Resources for research quickly surge immediately after an incident, then slowly dwindle as public awareness wanes. Following Chernobyl, advancements in computer code enabled more sophisticated modeling capabilities. A majority of these models are geared toward large-scale incidents, though, or are strictly based on post-Chernobyl data. As highlighted by this paper, the radiological threats to urban areas have evolved from large- (e.g., NWs) to small-scale threats (e.g., RDDs). These smaller-scale threats present unique challenges that require advances in current modeling practices and capabilities. Radiological models must account for the increased spatial scales to include particle transport while also taking urban geometry into consideration. Based on a literature review of radiological transport models, the following observations were made:

- Developers are starting to leverage existing software platforms in order to conserve resources that would otherwise be spent on developing pre-existing technologies (e.g., urban planning software). This type of practice encourages developers and researchers alike to address specific gaps without having to start from scratch.
- Smaller event-driven models (i.e., multi-compartment models) that address specific phases of a radiological emergency that would otherwise be too complex or resource-intensive to develop are becoming more prevalent. These compartment models can then be incorporated into larger platforms for addressing a range of radiological incidents.
- Different phases of a radiological incident may require stringent computer codes that are not necessarily all-inclusive, which lends itself to the above observation [9]. Furthermore, as highlighted by this paper, there are a significant number of gaps in the literature regarding particle transport. These incompatibilities and research gaps result in increasingly complex models that require a large number of inputs in order to mitigate these uncertainties.

6.5. Conclusion

An extensive survey of the literature was conducted for the purpose of: 1) determining whether empirical evidence exists for further characterizing RDDs according to NW detonation and NPP accident literature, 2) providing an overview and analysis of the current state of literature related to radiological sources with reference to particle transport, 3) contrasting the behaviors of radionuclides in urban and rural environments, and 4) exploring the current state of radiological models, taking the above findings into consideration. Firstly, while the radiological sources investigated by this paper (i.e., RDDs, NPP accidents, and NW detonations) differ in magnitude and overall impact on the environment, these disparities were more evident when NPP accidents and NW detonations were compared to RDDs. The differences were largely a function of the impacted area, in that particle transport appears to be a localized problem. Therefore, factoring in the magnitude of NPP accidents and NW detonations, RDDs offer the greatest potential for the dispersion of contamination. Second, explosive RDDs can be made of an array of materials, which in turn influence the physiochemical properties of the dispersed contaminants. Accordingly, greater uncertainty exists about RDDs' particle characteristics and transport. Third, the environment in which the contaminant is deposited, and the spreading mechanisms that environment hosts, greatly influence the behavior of the particle and the availability of exposure pathways. Urban environments host an array of spreading mechanisms not present in rural areas. The effects are augmented by the presence of less permeable surfaces that make up urban environments, further encouraging the spreading of contaminants. Lastly, taking the above points into consideration, more advanced models are needed to account for these physiochemical and spatial variations. Current radiological models are adequate for large-scale incidents; however, they lack spatial resolution to account for the inconsistencies afforded by RDDs, especially in urban environments.

The findings of this literature review support a need for research in the transport of radionuclides following a radiological incident in addition to more stringent computer codes capable of site specific modeling. Site specific modeling is key to understanding the interaction of radiological contaminants with the environment and how those interactions might affect potential radiation exposure, remediation, and waste management strategies [35]. Site specific modeling results would likely help determine potential contaminated hot spots, monitoring and sampling locations, gross mitigation methods, and waste storage locations and techniques [35]. Based on these findings, this report recommends future work as described in the subsections below.

6.5.1. Spreading Mechanisms

The migration of radionuclides in urban areas is poorly understood. Particularly, the interaction and transport of radioactive contaminants within urban areas while accounting for infrastructure, biomass, wastewater collection/treatment systems, and eventual disposal processes are of great concern. Further research is needed to better understand the underlying processes and the overall impacts of the following areas:

- The interaction (e.g., removal, and sorption) of radionuclides with surfaces and geometries commonly found in urban areas. This research might provide a better understanding of the dynamics that may lead to the migration of deposited particles, produced by an RDD, in urban areas.
- The magnitude and effects of anthropological resuspension in urban areas. Much is known in terms to resuspension in rural arid environments; although, very little data exists for sub-tropical urban environments. Literature suggests that contaminants residing in urban areas are more prone to resuspension. However, the impact of resuspension in urban areas is largely unknown. Such research might lend to improved modeling capabilities and, to a much greater extent, a better understanding of the implications of resuspension in urban areas.
- Although this report (for brevity's sake) does not discuss this subject in great detail, the literature lends itself to the need for near-term countermeasures that could reduce the spread of contamination, by means of human and natural activities, immediately following a radiological incident [25]. This paper would recommend that future research focus on fast-acting technologies capable of affixing contaminants (i.e., retarding their

movement) until more permanent options become available. This would potentially restrict the expanse of the contamination while emergency response and evacuation operations take place, which (the authors conclude) is of great importance immediately following initial deposition.

6.5.2. Modeling

Following previous radiological incidents, numerous prediction models have been developed to estimate radiation exposure and to predict fate of radioactive materials in urban and rural areas. Based on a high-level review assessing the current state of radiological models, this paper recommends the following:

- Very little is known in terms of the movement and magnitude of water-soluble contaminants. It is suspected that these contaminants will follow the topography of the land and, depending on the extent of urbanization, eventually enter storm drain systems. Therefore, it may be advantageous to explore the use of commercial software applications for modeling urban runoff to better predict the migration of water-soluble radioactive contaminants in urban environments introduced via water applications (i.e., decontamination activities, etc.) and precipitation (i.e., rain, snow, fog, etc.).
- Studies have shown that surface waters play an important role in particle transport, particularly in river banks and flood zones within close proximity to large rivers [35]. Therefore, leveraging flood and surface runoff models might be a viable option for predicting the impact of surface water aided particle transport for rural areas.

In order to achieve the above recommendations, this report recommends the following actions:

- A more thorough technical review evaluating available models relevant to radiological incidents.
- Leveraging of existing software platforms by integrating radiological capabilities into pre-existing computer codes.
- The modularization of smaller event-based models that address specific gaps.
- The incorporation of Fukushima-derived measurements into radiological models.
- The development of an operational tool capable of supporting multi-compartment models for predicting the transport of radioactive materials within urban areas to support monitoring, remediation, and waste management decisions.

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