3-22-2018

Radiological Decontamination in the Urban Environment Utilizing an Irreversible Wash-Aid Recovery System

Keith A. Sanders

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THESIS

Keith A. Sanders, Major, USAF

AFIT-ENV-MS-18-M-233

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENV-MS-18-M-233

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THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Industrial Hygiene

Keith A. Sanders, MA

Major, USAF

March 2018

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AFIT-ENV-MS-18-M-233

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Keith A. Sanders, MA

Major, USAF

Committee Membership:

Dr. Jeremy Slagley
Chair

Dr. Michael Kaminski
Member

Dr. Matthew Magnuson
Member

Lt Col (Dr.) Robert Eninger
Member

AFIT-ENV-MS-18-M-233

Abstract

The radioactive fallout from the Fukushima Daiichi nuclear reactors accident and the ongoing threat of nuclear or radioactive terrorism have forced the need for urban radiological decontamination into the forefront. Many of the established decontamination techniques are not ideally suited for the urban milieu. One of the keys to maximize the effectiveness of long-term remediation and recovery in the urban environment is immediate mitigation within a few days of the incident and before a rain event.

The Integrated Wash-Aid, Treatment, and Emergency Reuse System (IWATERS) provides a potentially safe and effective method for early responders and remediation teams to perform decontamination operations in urban areas. The system is set up with water barriers to catch wash water coming off of the building, pumps are then used to move the water through a series of absorbent beds, ion exchange filter, and finally into a holding bladder for eventual reuse. The goal of this research was to characterize: filter bed sizes for the decontamination of a modeled city block, exposure rates pre and post decontamination, and equivalent dose to early responders.

The research found that the expected cesium activity from an entire city block can be contained safely in a filter bed of approximately one cubic meter. Shielding of the filter bed brings exposure rates down to a negligible level and enables the filter beds to be deployed in multiple configurations. The highest estimated exposure rate at the working locations of 0.66 milliroentgen per hour is kept below the Nuclear Regulatory Commission public exposure rate limit of 2 milliroentgen per hour. In addition, the

worst-case expected equivalent dose of 46 millirem for a person who was exposed at the middle of the street for the entire decontamination process is below the 5,000 millirem guideline of the Environmental Protection Agency protective action guide for emergency responders and the 5,000 millirem per year limit for occupational radiation workers set by the Nuclear Regulatory Commission.

Acknowledgments

I must thank my family, they have been wonderful through this entire process. My children have been amazingly understanding each time I have had to work late or on the weekends, even bringing me snacks to keep me going. I cannot wait for them to have all of my nights and weekends again.

Of course, the person who makes everything possible is my amazing Wife. For 10 years she has made sacrifices and met every challenge the Air Force has asked of us. This thesis process has been the largest. From finding another new job, having our second kid, and dealing with a sometimes MIA spouse she has done it all. I will never be able to thank her enough, but thank you. I love you.

For my thesis committee members, thank you so much for the wonderful opportunity to research in an area I am passionate about. I wanted to do something outside of the normal industrial hygiene realm and my committee not only allowed but encouraged my pursuit. Thank you for all of your time and guidance.

Have a Wonderful Day

Keith Sanders

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Radiological Decontamination in the Urban Environment Utilizing an Irreversible Wash-aid Recovery System

I. Introduction

Background of the Problem

The nuclear age brought a new technology into the world that forever altered the state of warfare and energy. In doing so, the nuclear age created a need to develop and implement decontamination and recovery procedures following intentional acts and accidents. The potential malicious use of radiological dispersal devices was recognized in the first United Nations document defining weapons of mass destruction [1]. During the testing of nuclear weapons, agencies began research into how to clean the environment. For clear safety reasons, nuclear tests have been conducted in remote locations with no predicted future to house any kind of permanent population. Many of the decontamination techniques developed by the nuclear remediation community have been intended for use in remote environmental cleanup or local controlled cleanup at a reactor site.

A series of world events brought urban decontamination into the public consciousness. In 1979, a stuck valve at the Three Mile Island reactor led to the release of nuclear material near Middletown, Pennsylvania. Epidemiological studies have found that there have been no extra cancers caused by the release, the cleanup process still took 14 years and cost $1 billion dollars [2]. Urban contamination following the Chernobyl disaster in 1986 has led to an exclusion zone that is still not populated 31 years later. The city of Pripyat once held over 49,000 people and now sits empty [3]. The remediation of cities and the environment from the Fukushima Daichi release are still on-going and have produced significant interest and research into urban decontamination [4]. The cost of decontamination alone, not including disposal of waste, reached $13 billion as of 2016. All these incidents involved long term clean up that denied access to urban areas, used specialized personnel and equipment in the reactor areas, and generated large volumes of contaminated waste. On top of the risk presented from nuclear reactor accidents the threat of terrorism attack using radiological dispersal devices (RDD) or improvised nuclear devices (IND) continue to persist. The economic impact from an RDD is predicted to significantly outpace the effects of a similar conventional attack. Research has shown that an RDD attack in the business district of a medium sized city would result in approximately 18,000 lost jobs over the short term [5]. In order to reduce the negative consequences the contamination must be cleaned quickly and effectively.

The Integrated Wash-Aid Treatment, Emergency Reuse System (IWATERS) is designed to help early responders mitigate negative outcomes following a release of radioactive material in an urban environment. The system quickly and efficiently removes the contamination before it can bind with building or road materials, enabling a faster return to normal operations and reduced radiation exposure for both emergency responders and the public. The system is set up with water barriers to catch wash water coming off of the building. Pumps are then used to move the water through a series of absorbent beds that are filled with material that has a high affinity for radioactive ions such as clay, the ions adsorb to the filter material and are removed from the wash water. The effluent is then sent through an ion exchange filter to remove any remaining radioactive ions and finally sent into a holding bladder for eventual reuse. See Figure 1 for a conceptual rendering of the IWATERS. The goal of the IWATERS is to reduce waste and exposure by integrating the wash and recovery to quickly remove the contamination from the urban area.

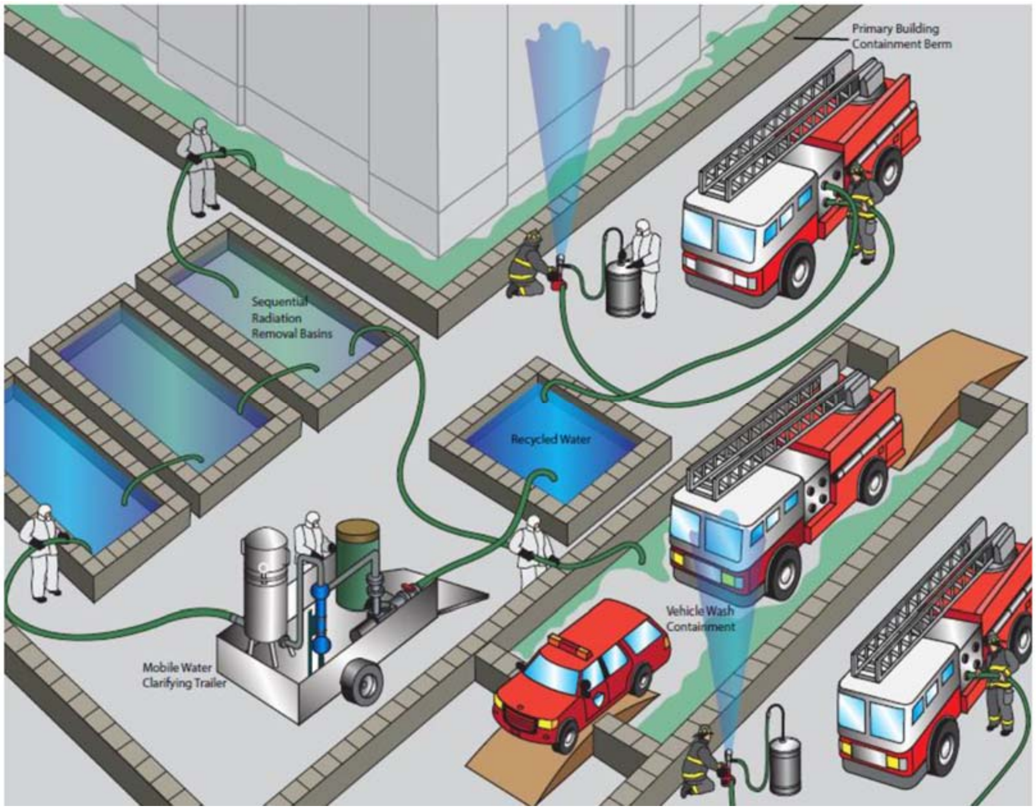


Figure 1: Conceptual Depiction of the IWATERS

Statement of the Problem

The IWATERS concept has been developed and tested both at the bench and pilot scale. The removal of the radioactive ions and transport from the surface of interest into the filter beds is fairly well characterized [6]. However, the dose to responders who are using the system and the expected external exposure rate reduction to the public from decontamination operations has not been characterized. The dose to the early responders will come initially from radioactive material that is deposited on the surface of the street and buildings. As the material is washed into the filter bed the source of exposure will change from the surface of the buildings and become the filter beds themselves.

Purpose of the Study

This research models the expected external exposure rate to cleanup personnel operating in an urban environment following an isotropic release of radioactive Cs-137 in the form of cesium chloride salt. For this hypothetical situation, an RDD detonation is described. The exposure rate modeling allows for the comparison of three different street decontamination methods, two different vertical decontamination filter bed options, estimates the percent reduction in exposure rate, and provides an estimate of early responder total exposure during the course of the mitigation operation.

In addition, the principle of As Low As Reasonably Achievable (ALARA) still applies during emergency response situations. Leadership and guidance agencies are under an obligation to ensure that workers are protected to the maximum extent possible. Therefore, it is prudent to estimate exposure prior to fielding of IWATERS because there are multiple options for setting up and deploying the IWATERS. Exposure modeling allows rough bounds of acceptable operation to be established so that it may be turned into technical guidance.

Significance of the Study

This is the first modeling to estimate exposure to cleanup personnel during use of the IWATERS. It is a needed step in for the implementation of a new technology. In addition, the ionic wash mechanism of the IWATERS is an emerging form of radioactive material decontamination and potentially offers health and economic improvements over traditional remediation methods.

Significance to Leadership

Radioactive dispersal devices present a unique challenge for local emergency responders. The type of response changes instantly as soon as radioactive contamination is detected. The initial wave of response to secure the scene and rescue victims in the hot zone may occur before radioactive material is identified. However, due to the recognized threat of terrorism, the National Incident Response Framework has made an all-hazards approach to response the national standard [7]. If there is a potential that an emergency originated as a terrorist act, the response procedure is to monitor for potential chemical, biological, radiological, and nuclear threats as soon as possible. Once an incident commander has identified the radioactivity, they may need to make mitigation decisions in real time while also executing other emergency operations. Because radiation expertise is not always readily available for the first responders, it is critical that clear and simple guidance is made available about what materials are required for specific mitigation options, how to set them up, and how to operate them. The National Incident Management System specifically addresses the need to resource and stockpile necessary supplies [7]. As IWATERS is proven to be effective, guidance can be written for incident commanders or local emergency operations centers to ensure proper mitigation measures are enacted in an expedient manner.

Nature of the Study

Exposure estimations will be performed with commercial modeling code. Modeling also allows for multiple runs with various configurations of filter bed layout and radionuclide concentrations. MicroShield version 10.04 was selected for use. This version was chosen because it includes ICRP Publication 116 protocols for fluence to dose conversion coefficients and implements the ICRP 2007 recommendations [8]. The official ICRP phantoms, in addition to Monte Carlo simulations using five different modeling codes, were used to create the conversion coefficients [8]. Reference gamma dose conversion factors from ANSI/ANS-6.1.1-1977 are also new to version 10.04. The software allows for custom designed shielding material, and enables custom built source geometry and activity concentration.

Assumptions and Limitations

This study focused on cesium-137 because it is highlighted in the Department of Homeland Security national planning scenario [9]. Even though cesium-137 presents an internal dose health risk via ingestion or inhalation, those routes of exposure will not be considered during this study. The IWATERS is a wet process that utilizes low pressure washing to decrease resuspension. Also, emergency responders have access to respiratory protection to mitigate the risk of inhaling or ingesting beta particles. In absence of internal dose, external dose is a function of time and dose rate. MicroShield will produce an estimated dose rate. The time workers spend performing the task has is based on recommended wash rates developed during field testing of the system.

Research Goals

In order to estimate the dose and provide operational guidance design, several research goals were established:

- Determine the best filter bed configuration to keep exposures ALARA
  - Are there more than one acceptable alternative?
- Determine the percent reduction of the exposure rate following decontamination
- Estimate dose equivalent for early responders

In addition to answering the above questions, it is the goal of this research to find an option that maintains exposure rates below 2 mR per hour and total estimated dose below 5 rem.

II. Literature Review

Introduction

The stochastic nature of long-term health effects caused by ionizing radiation drives the ALARA exposure guideline. ALARA principles are codified in 10 CFR Part 20 *Standards for Protection Against Radiation* [10]. The US Environmental Protection Agency (EPA) also requires the use of ALARA for exposure to personnel [11]. The principle of ALARA applies even during emergency response [12]. The exposure rates and dose that are considered reasonable may increase during emergencies based on the nature of the operation, but leaders are still obligated to protect the health of their workers to the greatest extent possible. The EPA Protection Action Guide for 2017 provides recommendations for responder total dose based on the importance of the mission. For mitigation operations, the goal of 5 rem was selected because it is the occupational limit. During the mitigation phase of the response, it is assumed that all lifesaving and critical infrastructure task have been completed. The EPA Protective Action Guidelines do not contain an exposure rate guidance level or limit. The Department of Energy, in a report on emergency action guidelines for RDD events, used 1 mR per hour as a notional exposure rate to calculate stay times within the contaminated area [13]. The Nuclear Regulatory Commission in 10 CFR 20.1301 defines the maximum allowable exposure rate to the public from a licensed source as 2 mR per hour [10]. The level of 2 mR per hour was selected because it is a well-recognized guidance value within the radiation and emergency response community.

The IWATERS Field Decontamination System is designed:

> “To reduce the external dose from contamination on vehicles and urban surfaces while simultaneously decreasing the spread of contamination and treating wash-down water to ensure an adequate water supply for public consumption and continued mitigation and decontamination operations across a wide area.” [14]

To date, no research has been conducted on worker exposure rates and expected total exposure during RDD mitigation using the IWATERS. Following an RDD incident, radioactive material is spread through the urban environment on the vertical facades of buildings and on the horizontal surfaces of streets and sidewalks. The dispersion of the radioactive material dictates the starting source geometries which, in turn, affects radiation exposure rates. At the beginning of the decontamination process, there are essentially three large unshielded sources of exposure with planar geometry; the street and each building. During the decontamination process, each of those sources will effectively be converted into either point sources or line sources that are shielded using sand filled berms. The change in source geometry will have an effect on the exposure rate at a fixed distance from the source [15]. Therefore, it is possible for real-time monitoring to show the area at an acceptable level prior to mitigation; but then have the change in particle dispersion geometry significantly increase the dose rate. It is expected that the change from planar to point sources will increase the exposure rate at the same distance from the source. In order to achieve acceptable exposure levels, filter beds can be shielded using the same earth berms that are utilized to set up the IWATERS.

Problem Statement

The IWATERS concept has been developed and tested both at the bench and pilot scale. The removal of the radioactive particles and transport from the surface of interest into the filter beds is fairly well characterized [6]. However, the dose to responders who are using the system and the expected external exposure rate reduction to the public from before decontamination to after has not been characterized.

Key Terms

- RDD – Radiological Dispersal Device
- IND – Improvised Nuclear Device
- IWATERS – Integrated Wash-Aid, Treatment, and Emergency Reuse System
- WMD – Weapon of Mass Destruction

Scope of Literature Review

The foundation of this literature review was the extensive meta-analysis into wide-area decontamination in an urban environment published by The Nuclear Engineering Division at Argonne National Lab [16]. A conference hosted by Argonne National Lab in March, 2017, comprised more than 40 radiation professionals from the United States and United Kingdom with the purpose to discuss current trends in urban decontamination and potential future areas of research. Extensive sources were provided to all attendees, including this researcher. The AFIT Library provides the Ebsco Discovery Service for all students. The main key-words searched were: urban decontamination, MicroShield, urban dose modeling, and RDD decontamination techniques. Expert recommendations were provided by Dr. Matthew Magnuson, U.S. Environmental Protection Agency (EPA) and Dr. Michael Kaminski, Argonne National

Laboratory; both are thesis committee members. All research sources were stored and managed using the Mendeley System.

IWATERS

Following the 2011 reactor meltdown at Fukushima Daiichi, multiple agencies began research into wide area urban decontamination. In anticipation of such a need, the IWATERS was developed, starting in 2010, as a joint effort between the U.S. EPA, Department of Defense Combating Terrorism Technical Support Office, and Argonne National Laboratory. In 2012, the IWATERS was field tested in a pilot study in Denver, Colorado. The pilot test showed the viability of the technology [17]. In 2015, live field testing was accomplished in Columbus, Ohio, and was open to local, state, and federal emergency responders to showcase emerging capabilities and to compile user feedback, i.e., the pros and cons of each system. This feedback can help to guide future research into operational systems [18].

History of Nuclear Decontamination Operations

Decontamination techniques for radionuclides have been extensively studied since the 1940s [19]. The National Homeland Security Research Center of the Office of Research and Development within U.S. Environmental Protection Agency has collaborated with the Nuclear Decontamination and Separations Branch, of the Nuclear Engineering Division at Argonne National Laboratory, to review existing wide-area radiation decontamination strategies in an urban environment and to develop new methods [16]. One of the identified gaps in this field is an estimate of exposure and effective dose in emergency responders.

Threat of Radioactive Material Dispersal Devices

In the modern era of international terrorism, Radiological Dispersion Devices (RDD) have captured the attention of both the American public and leaders in Congress. The need for federal RDD response planning was highlighted in a report to the U.S. Government Accountability Office in 2009 [20]. The 2006 polonium-210 incident in the United Kingdom demonstrated the importance of proper government planning for RDD incidents. Failing to establish national decontamination standards for urban RDD release may lead to the improper selection of decontamination techniques and the generation of waste that is more difficult to dispose of than the original contamination and impede recovery operations [21].

In 2011, Jonathan Medalia from Lawrence Livermore National Laboratory presented a special brief to Congress on the threats and hazards posed by RDDs [22]. However, going back to 1948, radioactive material weapons were included in the original United Nations definition for Weapons of Mass Destruction [1], [22], [23]. The RDD differs from other WMDs because they are not predicted to cause high-volume casualties. The primary concern is economic disruption via access denial to important areas and psychological terror by leveraging the public's general lack of radioactive material knowledge [22]. IWATERS is specifically designed to combat this issue by providing mitigation during the intermediate phase [12] of the emergency response to reduce dose and ensure that radioactive material does not adhere to surface materials [14].

The U.S. Department of Homeland Security has produced national planning scenarios for the use of emergency response agencies at all levels of government to build realistic exercises around. Scenario 11 is for an RDD attack in a heavily populated urban area [9]. The scenario provides a realistic jumping off point for contamination levels and incident scale. This research used the values provided in the scenario as a standard starting point. The planning scenario addresses decontamination in general terms and states it will be costly and time consuming. The methods discussed in the scenario mirror standard recommendations made for cleaning up nuclear contamination. These methods are discussed at great length in the U.K. Recovery Handbooks [24]; however, these Handbooks are not specifically aimed at wide area, urban RDD contamination (i.e., DHS planning Scenario 11). The IWATERS provides an alternative method that can be used during the intermediate response phase to aid decontamination, decrease waste, and allow access to critical facilities more quickly.

Dirty bomb research in Europe predicts that the plume of a dirty bomb could be fine, evenly-dispersed particles. These particles are capable of traveling outside the immediate blast area and contaminating large inhabited urban areas [25]. Dirty bombs present an issue for modeling because the nuclide and deposition nature are unpredictable. The dose contributions following an RDD may come from different sources than what is standard in current modeling libraries [25], [26]. Following an RDD detonation the radioactive material can take three forms; inert particles, soluble salts, or oxides. Modeling particle distribution from a blast is outside the scope of this project. Contamination levels based on the national planning factors were used.

Urban Radionuclide Decontamination

The International Atomic Energy Agency (IAEA) commissioned a team of 180 experts from 42 countries to review the entire response, decontamination, and final remediation of the Fukushima Daichi incident [4]. Five technical volumes were produced. The fifth dealt with post-accident recovery. The report found that due to a lack of pre-accident preparedness, the Japanese government was forced to enact protection criteria, legislative basis, and guidance documents to guide workers in real-time. Multiple factors led to a delay in the commencement of remediation activities. First, the devastation of the earthquake and tsunami created extreme resource demands within the first year. On top of the external resource demands, the lack of preparedness meant that the government instituted large scale pilot testing to determine the best methods for decontamination. The remediation techniques focused on external exposure pathways. The external pathways were found to be most relevant to long-term post-accident population dose. The combination of these two factors meant that remediation of the contaminated areas did not start until after a year of data-gathering [4], [27]–[30]. The IAEA recommends that dose reduction techniques be based on the scale of a mediation efforts, site-specific factors, and resource constraints. The resource constraints and acceptable dose to the public drove significantly different decisions and remediation efforts for the Fukushima Daiichi clean-up compared with Chernobyl. Following the Chernobyl disaster, cost was a significant driver of remediation techniques. Societal and ethical drivers played a large role in the selection of conservative decontamination practices in Japan, which greatly increased the cost of remediation [31].

The fallout from Chernobyl provided a unique environment to test and verify the validity of environmental radioactive material modeling. There were towns such as Pripyat, Ukraine, that were evacuated and left mostly uninhabited for decades after the accident. In Pripyat, simple decontamination measures were undertaken on living quarters so that workers could be staged immediately after the accident with no other work done. In 2008, the Urban Remediation Working Group, a subset of the International Atomic Energy Agency's Environmental Modeling for Radiation Safety program, set out to test the dose-prediction capabilities of a variety of models [3], [26], [32]. The modelers were provided basic guidelines for radioisotope densities and a detailed history of the area. For calibration purposes, they also received real-world external dose-measurement data. The requirement for the models was to produce external dose rates, breakdowns of component contributions to dose rate, radionuclide concentrations, and estimated annual and cumulative doses to the public. The modelers were also asked to predict the effect different remediation actions would have on cumulative dose. Two models found that washing of roofs or roads provided little reduction, while another found a 20% reduction. The difference between the models was in the major dose component each model selected [3]. Low efficacy of washing for cesium decontamination is a phenomenon found throughout decontamination literature; the cause of this will be discussed in the radiochemistry section of the literature review. The information learned from Chernobyl studies has enabled researchers to develop more effective decontamination strategies.

In an effort to stay current with ICRP recommendations and the evolving threat of global terrorism, experts from across Europe have updated the European Decision handbook for radioactive emergency response (EURANOS). The handbook includes 59 countermeasures and guidance for when and how to employ them. The guidance is supported by modeling efforts using ARGOS and RODOS code [25]. It is noted that following Chernobyl, a lack of understanding of the behavior and deposition of radioactive particles in the urban inhabited environment led to arguably poor decontamination decisions. This point is highlighted by showing the expected percent remaining of cesium on roofs against the actual value measured. There is an approximately 25% difference between simple extrapolation and the measured data points at 15 years. The most common cesium found in radioactive material is soluble and causes the cesium to adhere strongly to common porous construction material [25].

Radiochemistry

The difficulty of cesium decontamination has been studied and verified since before the Chernobyl disaster. Even though the studies used a limit sample size, Warming showed that once radio-cesium becomes wet the standard decontamination techniques no longer reduced external exposure [33], [34]. Argonne National Laboratory has conducted bench-scale testing to quantify the difference in removal efficiency between tap water and various ionic solutions and the difference between wet and dry cesium. The results show that washing mobile radioactive particles, such as Cs-137, with a 0.5 M KCl solution improves the removal for Cs-137, Sr-90, and Eu-152 across brick, concrete and asphalt [35]. Research conducted by the Argonne National Laboratory found that multiple washings does not significantly improve cesium removal [6]. The data matches results found by researchers studying urban decontamination following the Chernobyl disaster [26]. It clearly demonstrates that if cesium is applied in solution or becomes wet, it becomes very difficult to remove. Using an ammonium chloride rinse, wet cesium was removed with 20% efficiency, while dry cesium was removed at nearly 80%. For removal from asphalt, the findings were more extreme; wet cesium was removed at lower than 20%, dry cesium achieved over 90%. Based on the findings in this study that dry cesium can be removed with at least 80% efficiency but that wet cesium proves much more difficult, the exposure rate calculations will be performed using removal efficiencies of 80, 50 and 30%. A new source for the material left on the buildings will be created so that a percent exposure reduction can be found.

In 2000, French researchers used the ASTRAL and ABRICOT modeling codes to evaluate different remediation techniques in three zones following a BORAX-type accident in a nuclear reactor. The study looked at Cs-137, Cs-134, and I-131. The population was broken up into different milieu: adult farm worker, adult in urban private house, child in urban private house, infant, and adult in urban apartment block. The urban adult apartment block scenario most closely resembled the IWATERS scenario of this study [36]. In the French study, the urban milieu was broken up into compartments of roads/pavements, façades, roofs, soil in parks, and trees and bushes. The study-selected washings as the countermeasure for the first three with roof replacement also an option. The soil could be stripped and the trees and bushes pruned. Each of the countermeasures was evaluated for effect on external dose at the end of the first year if enacted individually or in combination with the others. (IWATERS deals specifically with washing the outside of the façade [36].) The results confirm the difficult nature of cesium contamination. Earlier washing provided better dose reduction than delayed washing. However, immediate washing followed by successive washing during the first month only marginally improved the dose reduction.

The findings of Kaminski et al. [6] are in agreement with this study and point out that after the first wash the cesium behaves effectively as if it was applied with a wet technique. To achieve the best dose reduction, it is imperative that washing occur as soon as possible and ideally before a rain event.

Site Selection

The financial district of Chicago was selected as the modeling site. The most appropriate decontamination technique for use in a given scenario is driven by the radionuclide of interest, the building material, the location, and structure of buildings [25], [32]. The desired location traits were brick or concrete building façades because they are the most susceptible to radiocesium binding [6]. In addition, the area needed to be an urban canyon similar to the site used in the National Planning Scenario so that the deposition concentrations could be used. The urban canyon also allows the modelled source pre-decontamination to be infinite plane sources with all contamination on the surface. An area with historic or important architecture was also desired because IWATERS is non-abrasive, and one of the benefits of the system is that it does not destroy the building material.

Research from the Sandia National Laboratory studied the effect of rain storms on contaminated asphalt surfaces. The study found that asphalt will hold up to 3 mm of rain; therefore, no radioactive material runoff is expected until at least 3 mm of rain has fallen [37]. It should be noted that this value may vary depending on the age and condition of the asphalt and any prior contaminates. The level of water that a material will hold will also vary passed on the type of material, so concrete or brick will be different than asphalt. The important thing to note is that there is some low level of moisture that the porous material will hold before runoff starts. The intensity and frequency of rain will vary by location. Warming cites that there is only a 3% probability of intense rain in the country of Denmark [33]. However, an analysis of the average number of days with rain per month and the average number of inches of rain per month in Chicago finds that the lowest average number of millimeters expected per rain event is 4 [38]. This means that any rain event occurring in the Chicago area post contamination, on average, will lead to radioactive material runoff if mitigation is not accomplished promptly.

Barrier Structure and Fill Material

The IWATERS can be set up and used with any non-permeable barrier that is capable of withstanding the combined force of the fill material and wash solution. HESCO is a private company that specializes in rapidly deployable barriers. Their products were selected for use in IWATERS design and testing for three principle reasons: ease of use, modularity, and current world-wide availability [17].

The fill material for both the filter beds and earth berms may vary significantly. The type of sand that is available at any given location will have a unique composition and density. The buildup factor is used to correct for underestimation of exposure at the point of the receiver due to scattering as the radiation is traveling through material [13]. The buildup factor will change based on the density of the material used for the filter beds and berm fill material, furthering underscoring the role of dose characterization and modelling during all decontamination operations. The density values used for this experiment are explained in the methodology section.

MicroShield

The MicroShield software program has been recognized as an appropriate and useful tool to model worker dose for more than 25 years [39]. The Department of Energy study led by Travis laid out basic criteria for estimating dose: the identity and concentration of the radionuclide, the distance to and duration of worker exposure, and the type of shielding available. MicroShield is able to account for each of those parameters. The user is also able to build custom source material and shield composition. Travis identified myriad tasks and workers involved with nuclear site decontamination and decommissioning; of these the most appropriate proxy for urban RDD mitigation is the building decontamination workers. The methodology used in the Travis study for the building decontamination workers helped to inform the modeling methodology for this research.

A few significant differences exist between the DOE work and RDD mitigation. For instance, DOE sites are by and large restricted access sites with no public exposure and do not have a firm timeline for reopening. Following an RDD event in a city area, there will be a need to quickly reopen assets, which makes IWATERS preferable to many of the decontamination techniques used in the DOE study [39]. Also, the DOE sites are performed by radiation-trained workers. In the event of rapid, wide-area decontamination, there may not be time to wait for specially-trained workers; therefore, local emergency responders with just-in-time training may be required. This necessitates a review of the exposure time frame, and it may be longer for workers not used to performing the operation.

The IWATERS system consists of a two-part filtration system. The radioactive material is washed off of the side of the building or vehicle and routed through a series of vermiculite filter beds. The radioactive particles adhere to the filter material, and then the water is passed through a particle removal unit to ensure that the reused water is free of radionuclides [14]. This process concentrates the contamination from a large surface area planar source into a de facto point source or line source. One of the reasons that MicroShield was selected for this research is its ability to create a source made of customizable material, geometry, and activity concentration. The code accounts for build-up and self-shielding of the source. Research into the external dose presented by concentrated sludge as a result of uranium mining showed that the MicroShield code was in agreement with field measurements [40].

Numerous radiation dose-modeling software programs exist for emergency responders. Each one operates on different assumptions and requires a different level of user knowledge to produce results. MicroShield is a platform that is kept up-to-date with recommendations from the ICRP [8]. A review of software that is available to emergency responders found that MicroShield is useful for “determining doses from a number of fixed geometries, source configurations and shielding materials." [41]. For their analysis Waller et. al broke end-users into seven categories: First-on-the-scene, CBRNe responders, Incident Commanders, Health Physics Reach-back, Hospital Emergency Services, Radiation Biodosimetry, and Forensic Criminal Investigation. They then defined the software application categories as: medical triage, medical treatment, hazard prediction, dosimetry, and training. There is a review of 11 software codes, all of which fall short for this research because they do not also contain shielding code. MicroShield is included in the section for shielding code. The research states that shielding code is most applicable for RDD events involving a gamma exposure. Four shielding codes are reviewed: MicroShield, MCNP, MCNPX, and GEANT). The last three require expert users and perform three-dimensional Monte Carlo analysis. It is noted that the point kernel analysis of MicroShield is more user friendly and includes are required properties for RDD scenarios.

Before an environmental site can be officially declared clean or safe for use, the governing agency generally demonstrate adherence with a dose or risk-based standards. The Multi-Agency Radiation Survey and Site Investigation Manual provides detailed guidance on how to show all requirements have been met—including the use of modelling [42]. MicroShield is one of the accepted technologies that have been used to estimate external dose from low level environmental exposures [43]. Chapter 6 in the book "Environmental Remediation and Restoration of Contaminated Nuclear and NORM Sites" details modelling of contaminated sites. The author reviewed 19 different modeling software and broke them up into three tiers based on the complexity and sophistication of the model [44]. MicroShield is placed in the third tier as being appropriate for the most detailed work. The other tier 3 codes reviewed were CHAIN, CHAIN 2D, PC-CREAM, SATURN, MILDOS AREA, MULTIMED DP. MicroShield was the only code that included shielding analysis as a core function.

In 2009, Sandia National Lab performed a modeling exercise to determine the dose to first responders following a loss of lead shielding during transportation of a spent nuclear fuel cask. In the event of a vehicle crash, the lead shielding for the cask may deform or, if a fire is involved, melt and flow away. Ten different shield-loss scenarios were run. These are reasonable approximations of RDD events because of the asymmetrical nature and potential to occur in urban areas. MicroShield was used by the researchers to model the effects of the different level of shielding on responder dose. [45].

Conclusion

The asymmetrical nature of RDD events makes planning difficult. One of the fundamental issues with RDDs is that even with low casualty numbers they may still deny access to important assets. Immediate time-scale mitigation efforts may serve to reduce cost, contaminated waste generation, and down time. Cs-137 is a common isotope with potential for use in an RDD. The radiochemistry of cesium makes it mobile and adhere to porous construction materials. IWATERS uses an ion exchange wash to quickly and efficiently remove the contamination before it has a chance to adsorb to the building material. An estimate of dose for the responders may facilitate widespread implementation of the system.

III. Methodology

In order to meet the research objectives, the modeling was broken down into three phases. The first was to determine the pre-decontamination conditions. This included: finding total activity, the amount of filter material required, the exposure rate prior to decontamination, and the acceptability of different filter bed options and locations.

The second phase dealt with the exposure rates throughout the process of decontamination. This meant: finding the activity concentrations for 80%, 50%, and 30% wash efficiency, determining the main source of exposure, and the exposure rate for each phase of the decontamination.

The final phase was the expected total exposure to emergency crews. In order to convert exposure rate to exposure, the estimated time and shift breakdown was required.

Site Selection

46 N. Canal Street was selected as the location of the decontamination. The buildings at this location form an urban canyon which can be seen in Figures 1 and 2. The images shown of the area were taken from Google Maps on 8 January 2018. It should be noted that while the buildings are this location do contain porous building material there are also other materials such as glass that are easier to remove radioactive material from. This may improve the overall removal efficiency in a real-world scenario. Figures 3 and 4 show the dimensions of the city block and form the foundation for the area source sizes used through the research. The range of distances for the length were

between 394 and 402 feet based on 10 measurements. The range of width was between 88 and 91 feet based on 10 measurements. For ease, the assumed length and width of the street were set at 400 feet and 90 feet, respectively.

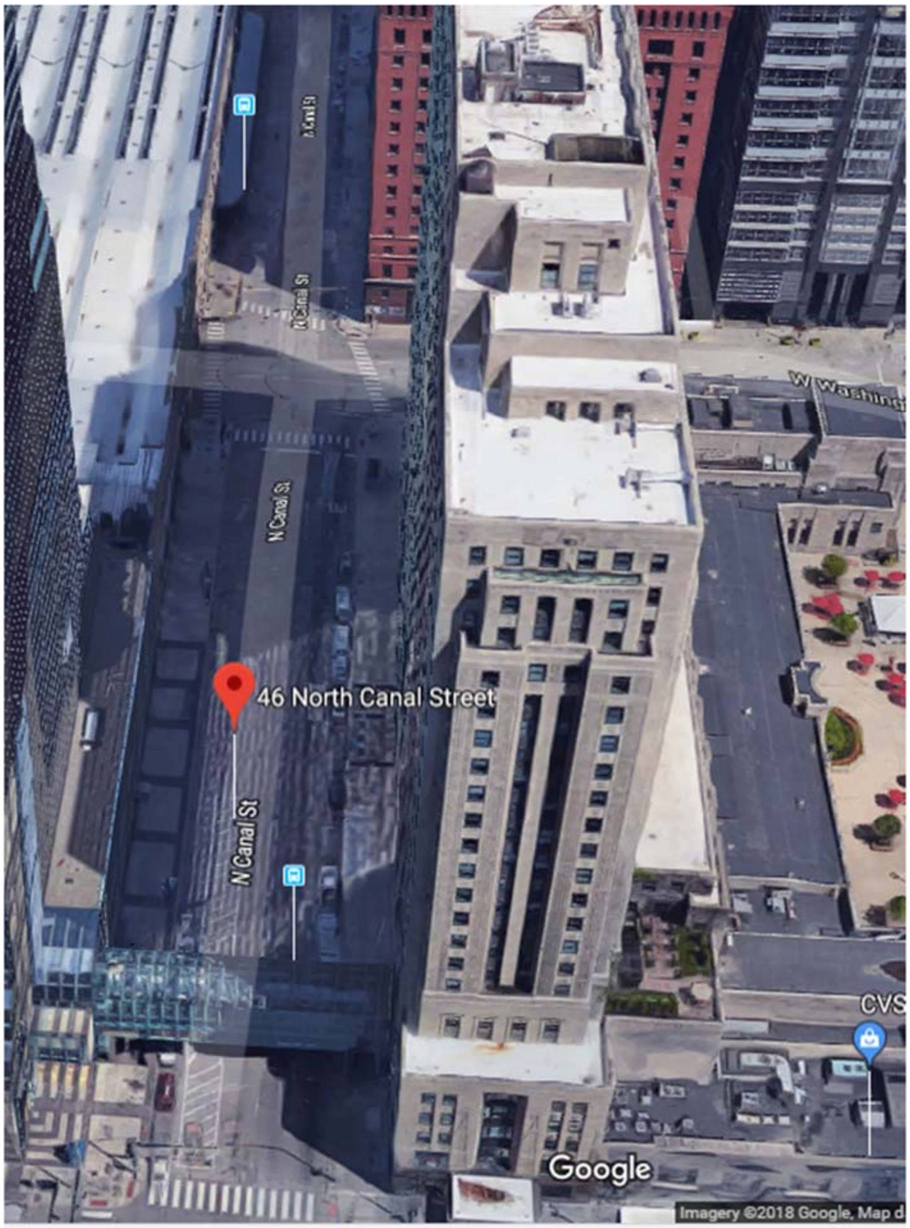


Figure 2: 46 N. Canal Street

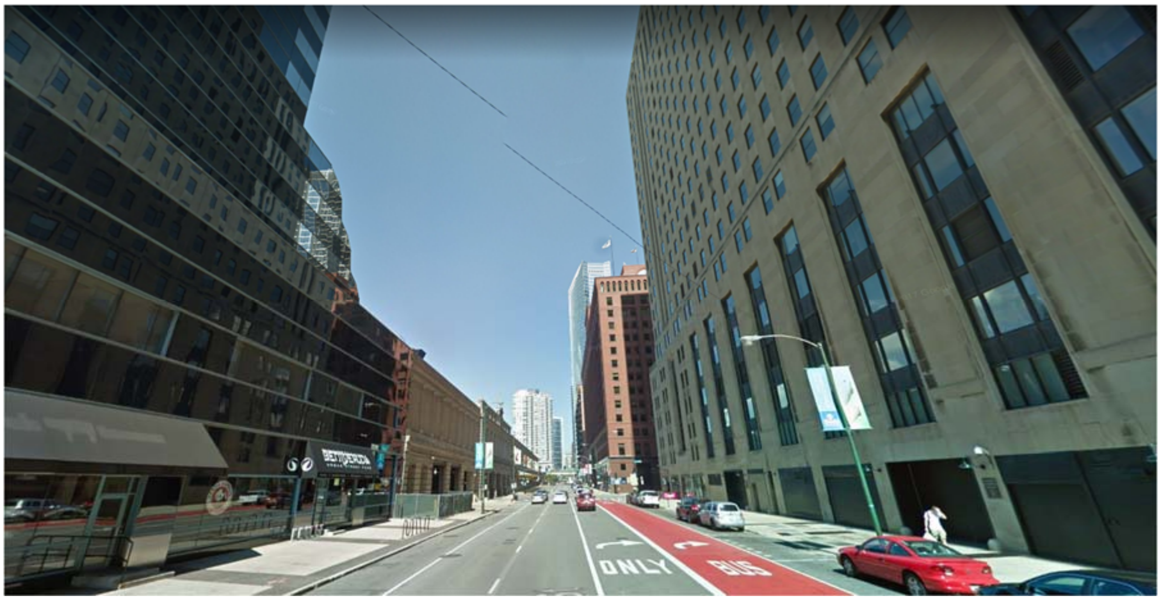


Figure 3: Street View 46 N. Canal Street

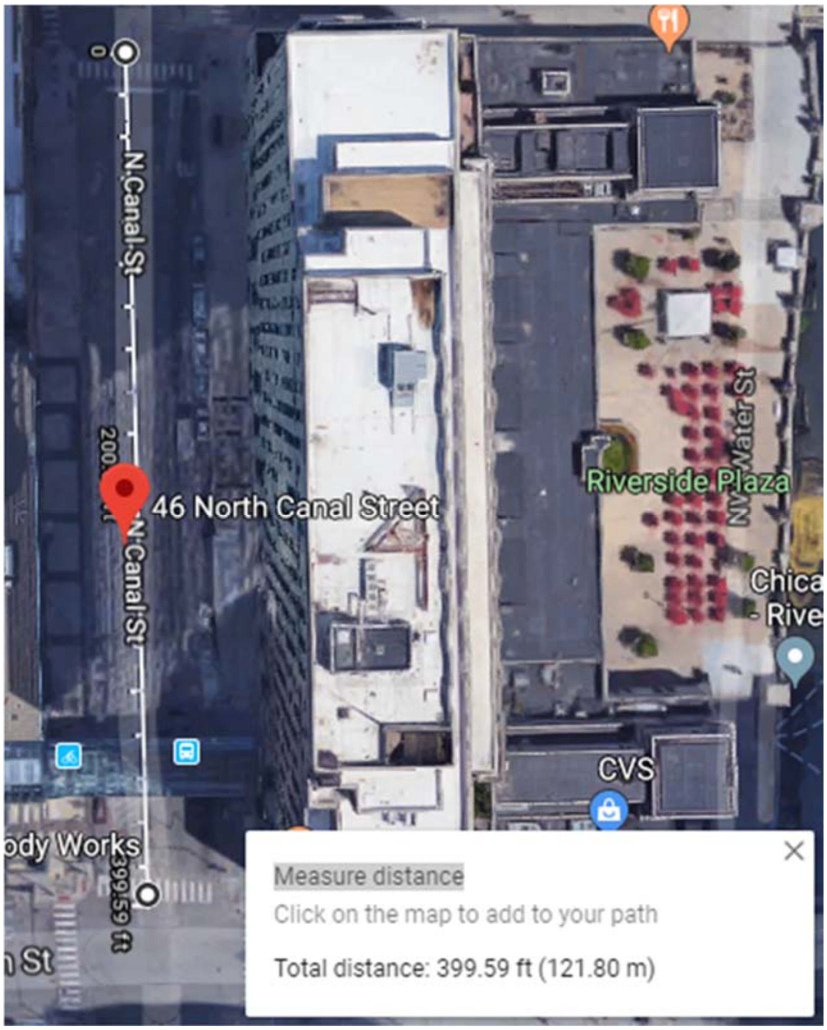


Figure 4: Length Measurement of Modeling Site

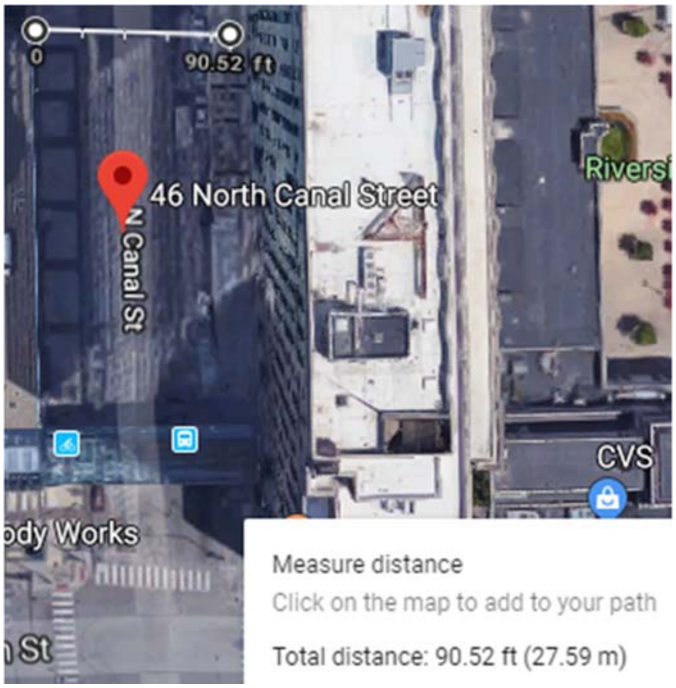


Figure 5: Width Measurement of Modeling Site

MicroShield Inputs

The MicroShield software allows for significant user input. Each input required an initial assumption with results driving further analysis.

Source strength.

The 2006 National Planning Scenario 11 provided the realistic basis for the total Cs-137 involved in the incident. The total activity is 2,300 Curies. The modeling used in the planning scenario predicts that, "Radioactivity concentrations in this zone are on the order of 5 to 50 microcuries per meter squared, with hot spots measuring 100 to 500 microcuries per meter squared" [9]. The scenario does not provide a geometric mean or geometric standard deviation of the concentrations; this means that a distribution profile cannot be generated. It is known that most natural distributions are adequately described by the lognormal profile [46], [47]. For all calculations, a concentration of 50 microcuries per meter squared was used.

Source geometry

The side of the buildings and the street were represented as vertical and horizontal rectangular area sources in relation to a person standing on the street. Figures 6 and 7 show the modeled plane sources with exposure points down the middle of the street. The units in the embedded table are in feet and depict the coordinates of individual dose points from the origin of the source. The point source approximation for a radiation source is only valid if the receiver is more than three times the longest dimension from the source [15]. This is not the case when the activity is spread out over the surface of the buildings or street. Once the Cs-137 particles are washed into the filtration basins, the activity density will increase and the point source approximation becomes more valid. A limitation of MicroShield is that the dose point must be outside of the source. If the street is modeled as a single rectangular plane, with the dose point hovering over the top of the source the software returns as error message and will not compile. To account for the exposure from the street, the source was broken into two 44 foot by 100 foot sources and then added together.

Two geometries were considered for the filter beds. The first is a rectangular volume source the size of a single Jackbox HESCO cell, 27 cubic feet (3’ x 3’ x 3’) [48]–[50]. The second was a line source along the building. The line source was considered for operational reasons. It can be set up along the edge of the building and reduce the number of times the water has to be moved. The wash water falls directly into the line filter bed and then is pumped straight into the ion exchange system. As opposed to having the wash water fall into a trough then be pumped to the filter bed and then pumped a second time to the ion exchange system. In addition, the line source is predicted to lower exposure rates because it spreads the activity over a larger volume, decreasing the activity concentration at any single point. Figures 8-10 depict the line and point sources with shielding as modeled in MircoShield. The units in the embedded table for these figures are in feet and depict the coordinates of each dose point from the origin of the source.

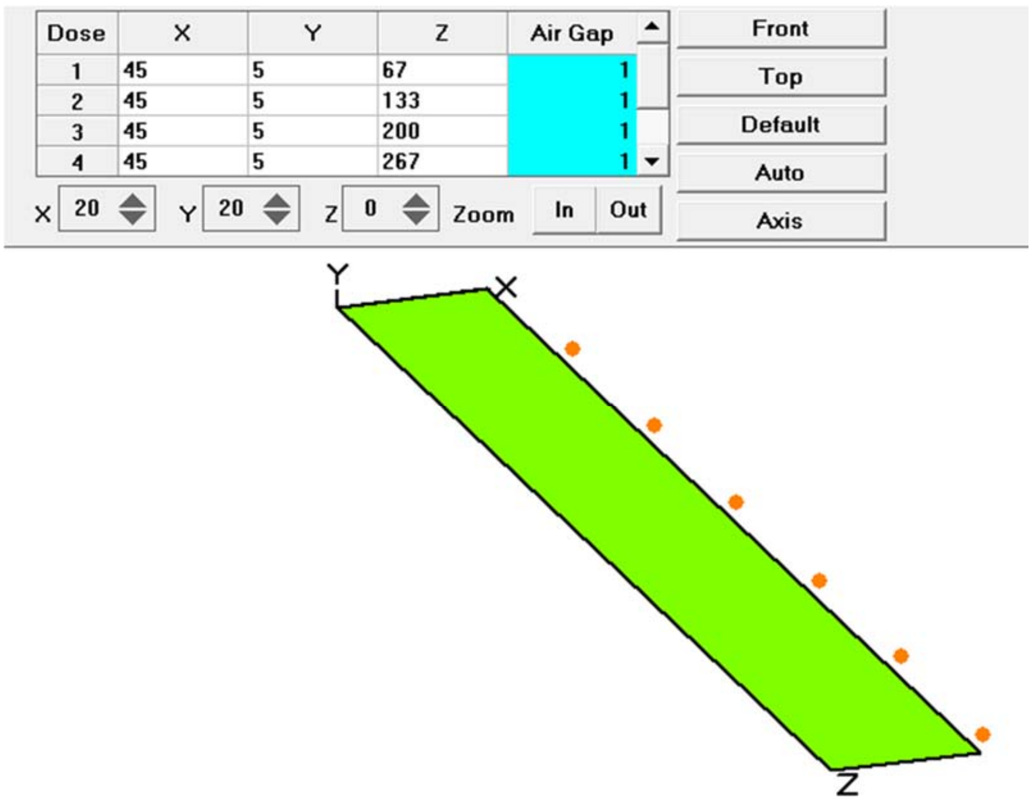


Figure 6: Horizontal Plane Source

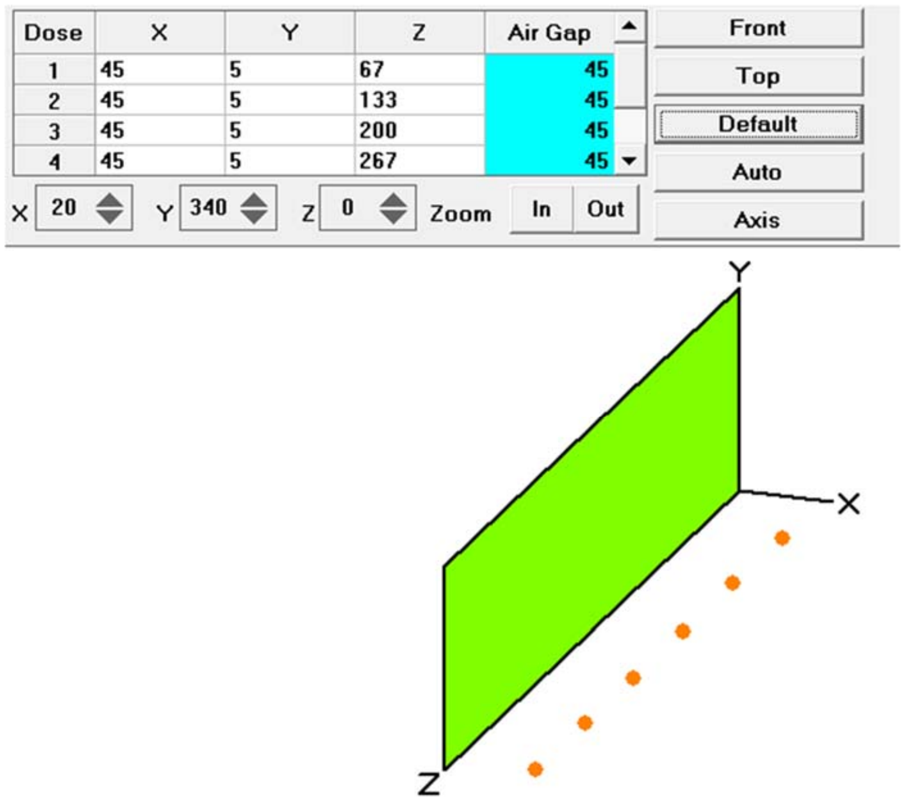
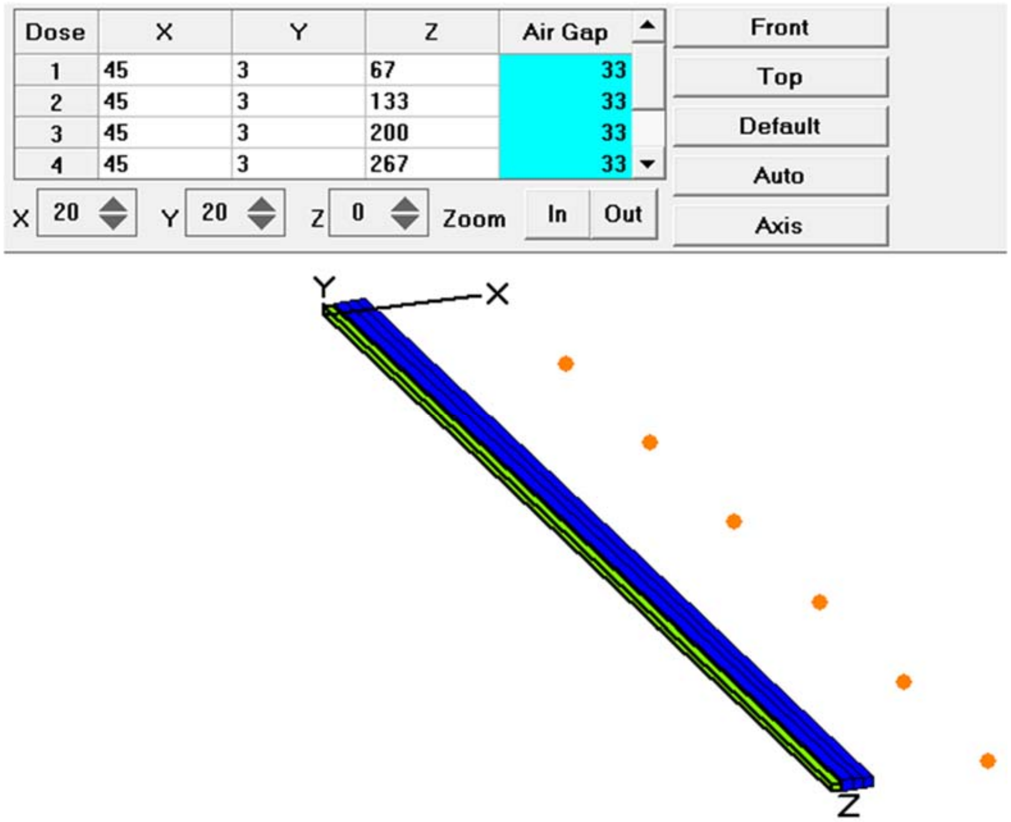
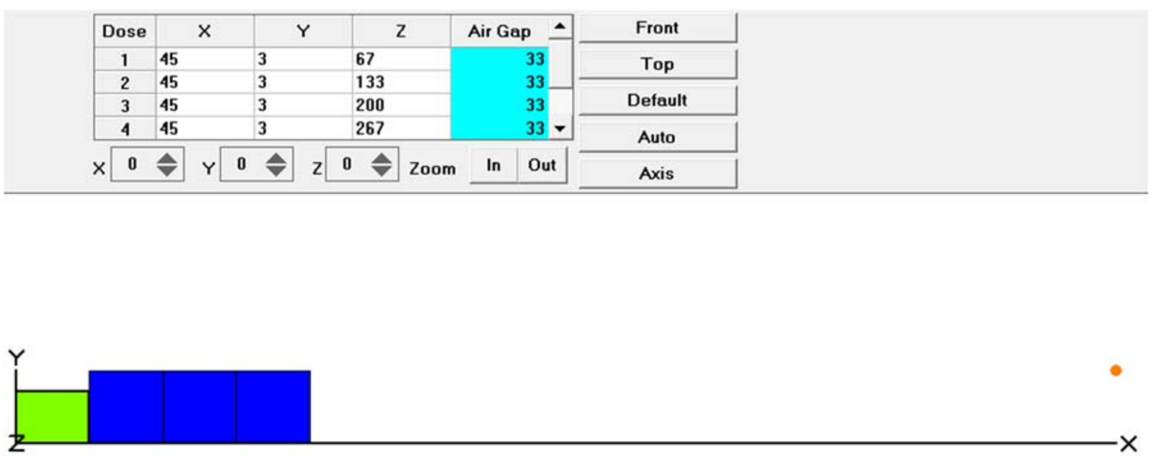


Figure 7: Vertical Plane Source



Dose	X	Y	Z	Air Gap
1	45	3	67	33
2	45	3	133	33
3	45	3	200	33
4	45	3	267	33

Figure 8: Line Source in Front of Building 1 with Shielding Coordinates in Feet



Dose	X	Y	Z	Air Gap
1	45	3	67	33
2	45	3	133	33
3	45	3	200	33
4	45	3	267	33

Figure 9: End View of Line Source

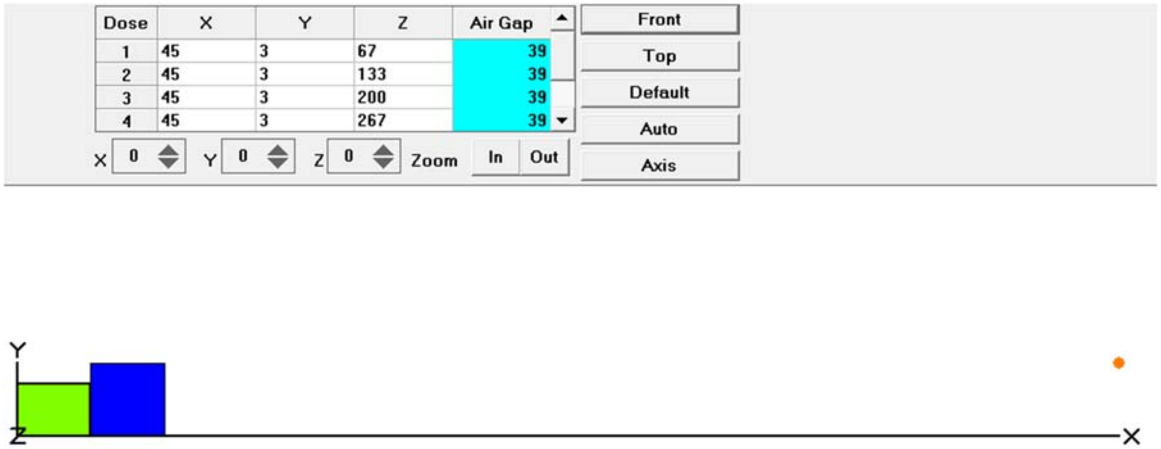


Figure 10: End View of Point Source

Source composition

The filter beds are filled with a vermiculite and clay mixture. As the radiocesium ions adhere to the adsorption sites, they will change the molecular composition of the source. MicroShield always assumes a homogeneous distribution of the activity within the source. In environmental transport modeling, there are two common models used for mass balance systems; plug flow reactors and continuously stirred tank reactors (CSTR) [51]. The IWATERS geometry more closely resembles a plug flow reactor with contaminant coming in the top and slowly working its way down the column. However, due to the homogeneous limitation of MicroShield, the source is modeled as if it is a CSTR with instantaneous and complete mixing. This means that to meet the restraints of the modeling code, the filter bed can only be modeled at the completion of a mitigation phase. Using sensitivity analysis, the software will allow for increasing or decreasing source strength over time; but each time the activity level is changed, the particles are modelled as being uniformly distributed throughout the volume of the source.

MicroShield has the capability to custom build the source material to match the exact density of the source. It is able to account not only for the vermiculite, sand, and water molecules, but also for the Cs-137 molecules. It was decided not to use this option because it did not add to the achievement of the research. The objective is to establish initial feasibility and to compare different techniques. During the course of this research, Grove Inc. released a new MircoShield version along with six new custom build material files with buildup factors that have been tested and verified by the company. These files included two different sands and a clay. The sand used is Florida Fine Sand with a density range of 1.70-2.30 grams per cubic centimeter. The default density of 2.0 was used for all shield material because the sand density in any given situation is unknown. The clay is Kansas Summit Clay with a density range of 1.64 to 2.6 grams per cubic centimeter. During the Denver pilot study of IWATERS, it was noted that the VCX vermiculite used has a particularly low density [17]. The filter material for this modeling exercise was a 70:30 sand to clay ratio. The given density of the VCX vermiculite is a range of 0.640-1.041 grams per cubic centimeter [52]; a default of 0.67 was selected. The formula below shows the combination of the sand and clay densities in a ratio of 70:30 to yield a density of 1.6 grams per cubic centimeter. This value was used as the source density for all models.

$$0.3 * 0.67 g/cc + 0.7 * 2 g/cc = 1.6\ g/cc$$

Filter bed volume

The first step in determining the filter bed volume was to determine the maximum activity load of the source material. Soluble radioactive transport modeling was performed by the Argonne National Laboratory using the GoldSim software[53]. Table 1 shows the volume of filter material required to hold 100, 500, and 1000 Curies of activity before breakthrough; defined as effluent from the filter bed with a concentration of more than 10 percent the activity concentration as the incoming wash water. The standard bed volume activity loads were calculated using the 70:30 sand to clay ratio, tap water, and a water concentration of 15 millicuries per liter.

Table 1: Standard Bed Volume Activity Loads

Height (cm)	Radius (cm)	Area (cm^2)	Volume (cm^3)	Max Cs-137 (Ci)
19.6	1,380	5.95×10^6	1.67×10^8	100
64.2	1,380	5.95×10^6	3.82×10^8	500
111.0	1,380	5.95×10^6	6.61×10^8	1000

The total amount of activity required to be decontaminated was found by multiplying the surface area of each building in the street by the concentration of 50 microcuries per meter squared. The concentration is the high end of the expected concentrations from the National Planning Scenario number 11 [9]. The total activity to be decontaminated is 0.5388 Ci. There is 0.186 Ci on each building and 0.167 Ci on the street. For the purpose of calculating the surface area of the sources the length of the buildings and street are both 400 feet. The building height was set at 100 feet, as explained in the height of building decontamination section on page 40. The width of the street is set at 90 feet based on measurements taken using Google Maps, these are shown in the Location section of the methodology.

$$(400\ ft * 100\ ft) = 40{,}000\ ft^2$$

$$40{,}000\ ft^2 * 0.093\ m^2/ft^2 = 3{,}716\ m^2$$

$$3{,}716\ m^2 * 50\frac{mCi}{m^2} = 0.186\ Ci\text{: for 2 buildings } 0.186 * 2 = 0.372 \text{ Ci}$$

$$(400\ ft * 90\ ft) = 36{,}000\ ft^2$$

$$36{,}000\ ft^2 * 0.093\ m^2/ft^2 = 3{,}345\ m^2$$

$$3{,}345\ m^2 * 50\ mCi/m^2 = 0.167\ Ci$$

In order to scale down the size of the filter beds from the standard bed volume, the height was kept the same while the surface area footprint was reduced at the ratio required to hold the amount of curies necessary. The height must be kept the same because the GoldSim model assumes there is a head of water sitting on top of the bed that produces the downward flow rate due to gravity. The model predicted bed volume for activity load before breakthrough not just total activity load because of this the height must be maintained and only the footprint area scaled. For example, 500 Ci are held in a bed with a height of 64.2 cm and foot print area of 5.95 x 10^6 cm^2. The total curie required for the block is roughly 1000 times less than the 500 Ci standard. The footprint can therefore be reduced by a factor of 1000 to 5,950 cm^2. In order to hold the required activity the filter bed needs to be at least 65 cm in height with a foot print area of 5,950 cm^2. For a circular filter bed this means a bed with a radius of approximately 44 cm. These constraints led to the selection of four filter beds for testing. Table 2 shows the activity load of the filter bed options. The four options explored were a standard 55-gallon drum and three different HESCO barrier products. The base unit for each HESCO product is a wired cage that can be filled with a liner and then barrier material. The dimensions of the base units for all are approximately 27 cubic feet. The difference between the products are in how many base units form a single deployable unit. The Jackbox is the most modular and can be deployed in any combination of singular base units. The Floodline recoverable comes in deployable units of 5. The CART is the fastest to set up, it can be deployed from a sled behind a moving vehicle to lay 280 linear feet of barrier is under a minute. The CART is also the least modular [48]–[50]. It was found that at least three 55-gallon drum volumes are required to hold the necessary activity. However, any of the three HESCO products will hold enough activity to decontaminate the entire site.

To obtain realistic drum thickness values the Uline-10758 drum was used as the model. The top, bottom, and side thickness of the drum are all 1 mm [54]. The dimensions for the HESCO barriers are all pulled from the latest HESCO product catalog [48]–[50].

Table 2: Filter Bed Activity Capacities

55 Gallon (200 L) Drum					Notes
Height (cm) all filled to 64.2	Radius (cm)	Area (cm^2)	Volume (cm^3)	Max Cs-137 (Ci)	
88.1	28.6	2,570	2.27×10^5	0.216	
HESCO Options					
Height (cm) all filled to 64.17	Radius (cm)	Area (cm^2)	Volume (cm^3)	Max Cs-137 (Ci)	
100	N/A	1.17×10^6	1.17×10^6	0.980	CART(SL3942)
100	N/A	9,150	9.15×10^5	0.769	Jackbox (3939)
91	N/A	8,320	7.57×10^5	0.699	Floodline (3636) Recoverable

Shielding material

MicroShield enables the user to build custom shielding material based on the molecular composition of the shield. It will also assign buildup factors to custom materials based on the composition. The software also comes preloaded with a variety of shielding materials that have been verified by the manufacturer. For this research, the initial runs contained no shielding material. There will be negligible shielding of high energy gamma-rays while the radionuclides are on the building. The filter beds were tested both without shielding and with shielding for exposure rate at 1 m. The shielding consisted of 1 row of HESCO barriers filled with sand at an assumed density of 2 grams per cubic centimeter. The 55 gallon drums also included the steel walls (1mm) as shielding.

Exposure Locations

The MicroShield software allows for the simultaneous calculation of six dose points on each run. For the pre-decontamination and post-decontamination comparison, the dose points are six evenly spaced locations down the centerline of the street. Prior to decontamination there are three modeled sources for each of the six points. Figure 11 shows a conceptual model of the modeled exposure points and each of the area sources. For all future references building one is grey in color and building two is brown. Figure 11 is to scale. The length of the street and buildings is 400 feet. Each building is 100 feet tall and the street is 90 feet wide.

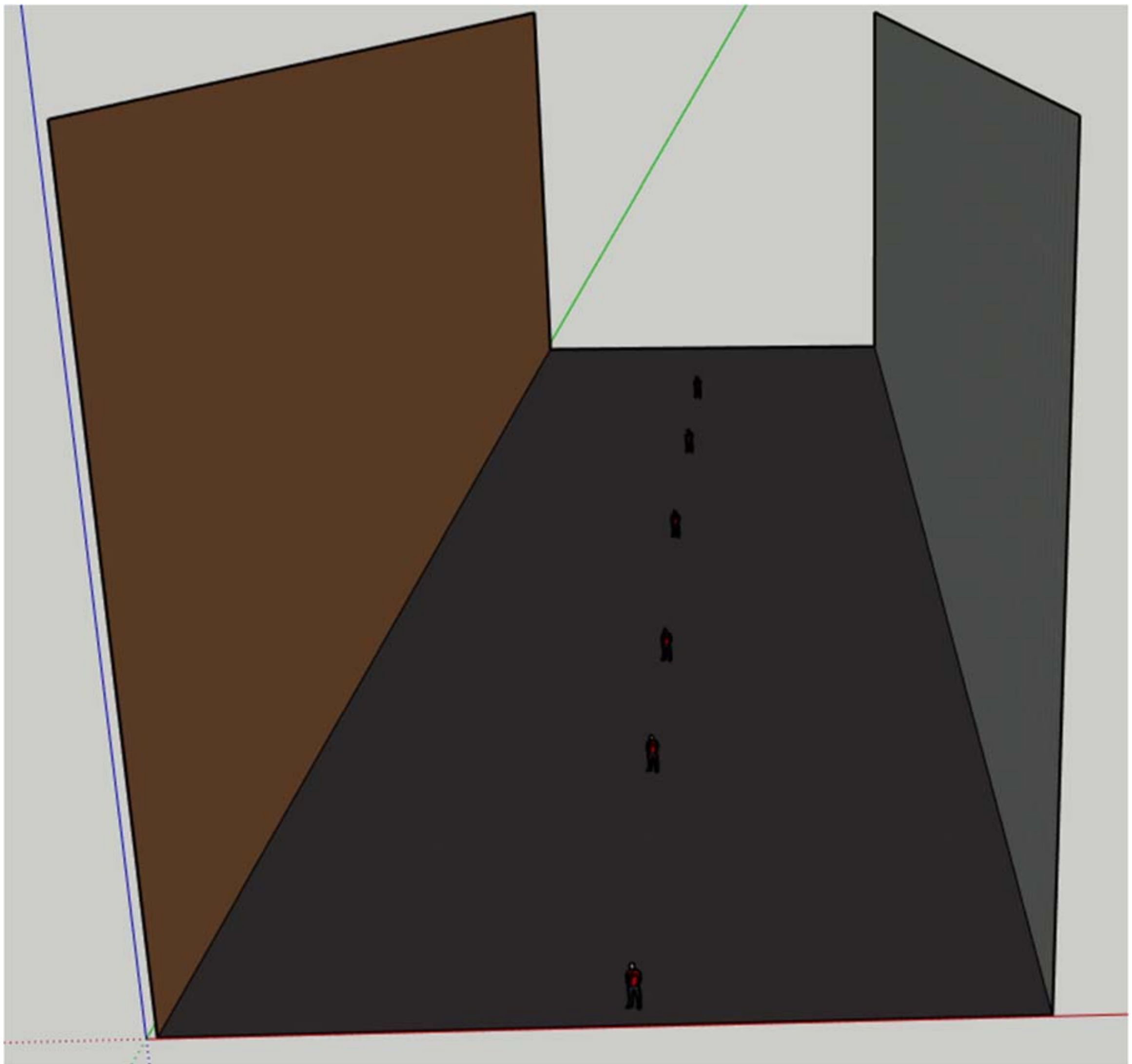


Figure 11: Conceptual Model of Worker Exposure Points

Individual Run Variables

Height of Building Decontamination

There are practical restrictions on how high emergency responders are able to decontaminate a building. It is important to have clear guidance on how high up the building responders need to decontaminate to achieve successful mitigation. MicroShield has the built-in capability to vary one user-defined input. By running the exposure calculation in predefined vertical segments, the percent each vertical segment contributes to the overall exposure rate at each of the six exposure locations was determined. Each vertical segment was defined as 10 feet because this is the standard height of an American building floor. The sensitivity analysis of the vertical area sources found that 90 percent of the exposure rate at ground level comes from the activity in the first nine stories of the building. The vertical height of the source was set at 100 ft or 10 stories. The Chicago Fire Department has multiple ladder companies within the vicinity of 46 N. Canal Street. The closest is Company 3, and their ladder trucks are capable of reaching the required height [55].

Number of Filter Beds

The number of filter beds required will be based on the dose rate to workers when the bed is at Cs-137 saturation. It is desired to keep total exposure rate below 2 mR/hour. During contingency response, federal guidance allows workers to be exposed to rates higher, but the goal is to engineer the system to keep exposure ALARA. The four filter beds were tested without shielding. Table 3 shows that all four options are over the desired dose rate at 1 meter. The 55-gallon drum is the tallest with the three HESCO options virtually the same. The options were tested again utilizing the shielding described in the shielding material section above. Table 4 shows that with shielding all four options have an acceptably low exposure rate for use. In the final analysis, the 55-gallon drum was dropped from consideration because it clearly has the highest exposure rate, does not hold as much radioactive material, and is made of steel. Cesium-137 decays via beta emission to form Ba-137m [56]. The half-life of BA-137m is approximately two and a half minutes and decays with the emission of a 661.7 kiloelectron volt gamma [57]. The

MicroShield software is not capable of modeling beta interactions with high Z materials (like steel) that produce Bremsstrahlung x-rays. Through self-shielding the filter bed material will block most of the beta particles from interacting with the steel walls and only the particles on the outer most edge of the filter material will interact to create Bremsstrahlung x-rays. Even though the production of Bremsstrahlung x-rays is predicted to be a minor addition to the overall exposure rate, the 55-gallon drum is already the filter bed with the highest exposure rate so any addition to the exposure rate widens the exposure rate gap between the drum and the other options. Due to these draw backs, it is not recommended at this time to use a 55-gallon drum, especially a steel one.

Table 3: Exposure Rates Without Shielding at 1 meter for Different Filter Bed Options

Filter Bed	1m Exposure Rate w/buildup (mR/hr)
55 gal Drum	7.0
Floodline	4.3
CART	4.3
Jackbox	4.2

Table 4: Exposure Rates at 1 meter for Filter Bed Options with 1 m^3 Sand Shielding

Filter Bed	1m Exposure Rate w/buildup (mR/hr)
55 gal Drum	6.1×10^{-5}
HESCO	2.2×10^{-5}

Location of Filter Beds

If the first stage of decontamination operations is to remove contamination from the street, worker exposure can be reduced. Based on modeling and real-world sampling from Chernobyl and Fukushima Daiichi, it is expected that the horizontal surfaces will contribute the most to personal dose[25], [30], [32]; it is also desired to have the shortest linear feet required for particle washing. This helps to ensure that particles are not resuspended during long wash times. Three filter bed locations were tested for this phase. The first option was to have the filter bed at the end of the street and wash all particles toward that location. The second option was to have a filter bed in the middle of the street and then wash contamination towards the filter bed from each side. The final configuration was to have the filter set-up as a long line along the front of building one and wash all contamination across the street toward the building.

Receiver Exposure Time

The external dose to the workers is a function of exposure rate and time. The time required to decontaminate depends on the size and type of building. An estimate of time to use the system was established by pilot-scale testing. The range of wash rates selected came from the IWATERS technical guidance published by the U.S. EPA. It is recommended that washing occurs between 40 and 80 square meters per hour [14]. These wash rates were used to determine the total amount of time required for the operation and the total number of crew shifts required. The decontamination time was found by multiplying the wash rate by the total combine surface area of both buildings and the street.

Table 5 shows the time requirements using three different flow rates. To meet the principle of ALARA it was decided that working shifts would last 8 hours.

Table 5: Time Require to Perform Decontamination Based on Wash Rate

Wash rate m^2/hr			Decontamination Time			Number 8 hour shifts		
40	60	80	92.9	61.9	46.5	12.0	8.0	6.0
Wash rate m^2/hr			Decontamination Time			Number 8 hour shifts		
40	60	80	83.6	55.7	41.8	11.0	7.0	6.0

Exposure Rate Modeling

The list below outlines the steps used to generate all model trials for this research. MicroShield exports all data into Microsoft Excel format. The trial data can be found in Appendix A. The trial parameters found in Appendix A combined with the steps below will recreate all model trials. Figure 6 provides an example of the data that is exported from MicroShield. The key input parameters to recreate a modeling event are all shown in their own box at the top of the MicroShield export. The following steps were used to generate all model trials:

1. Open MicroShield version 10.04.
2. Select new.
3. Select source geometry from 16 menu options.
4. A new screen opens. The default units are centimeters. The units were changed to feet.
5. Enter length of the source.
6. Enter width of the source.
7. Enter the thickness of up to 10 shields.
8. Enter the XYZ coordinates of up to 6 dose points.
9. Select materials tab.
10. Select custom material button. Add sand and clay.
11. Enter the density of each material.
12. Select source tab.
13. Select nuclides button. Choose Cs-137 click okay.
14. Center the total activity or the activity concentration.
15. Select group photons. Click yes to include Ba-137m daughter products and yes to use 5 groupings.
16. Select buildup tab to ensure values have populated.
17. Select integration tab. Leave default settings of 20.
18. Select title tab to label the trial.
19. Selected sensitivity tab to perform single variable sensitivity analysis, if desired.
20. Click on the red run case button. If button is not red there has been an error in data entry.

	A	B	C	D	E	F	G	H
1	MicroShield 10.04							
2	Environmental Protection Agency							
3	Date				By	Checked		
4								
5	File Name				Run Date	Run Time	Duration	
6	Case1				27-Jan-18	3:33:42 PM	0:00:00	
7	Project Info							
8	Case Title				Pre-decon Vertical Area			
9	Description				Center Line			
10	Geometry				4 - Rectangular Area - Vertical			
11	Source Dimensions							
12	Width	1.2e+4 cm (400 ft)						
13	Height	3.0e+3 cm (100 ft)						
14	Dose Points							
15	A	X	Y	Z				
16	#1	1.4e+3 cm (45 ft)	152.4 cm (5 ft .0 in)	2.0e+3 cm (67 ft .0 in)				
17	#2	1.4e+3 cm (45 ft)	152.4 cm (5 ft .0 in)	4.1e+3 cm (133 ft .0 in)				
18	#3	1.4e+3 cm (45 ft)	152.4 cm (5 ft .0 in)	6.1e+3 cm (200 ft)				
19	#4	1.4e+3 cm (45 ft)	152.4 cm (5 ft .0 in)	8.1e+3 cm (267 ft)				
20	#5	1.4e+3 cm (45 ft)	152.4 cm (5 ft .0 in)	1.0e+4 cm (333 ft .0 in)				
21	#6	1.4e+3 cm (45 ft)	152.4 cm (5 ft .0 in)	1.2e+4 cm (400 ft)				
22	Shield							
23	Shield N	Dimension	Material	Density (g/cm^3)				
24	Air Gap		Air	0.00122				
25	Source Input: Grouping Method - Actual Photon Energies							
26	Library: Grove							
27	Nuclide				Ci	Bq	$\mu Ci/cm^2$	Bq/cm^2
28	Ba-137m				1.76E-01	6.51E+09	4.73E-03	1.75E+02
29	Cs-137				1.86E-01	6.88E+09	5.01E-03	1.85E+02
30	Buildup: The material reference is Air Gap.							
31	Integration Parameters							
32	Z Direction				20			
33	Y Direction				20			

Figure 12: Example of MicroShield Input Data

Following the completion of a modeling run MicroShield exports the data as a formatted text file. The user has the option to save the file as a Microsoft Excel document. Figure 12 is the top half of the modeling results file. It contains all of the relevant data that was input to generate the model. All model runs are exported in the same format. The first nine lines contain descriptive information about the modeler, date, and titles. In this example, starting with line 10, there is the source geometry (rectangular area – vertical). Working down the image are the source dimensions, coordinates of all dose points, all shields with their thickness and density, the radio nuclides with activity and concentration, and finally the buildup and integration parameters.

Estimate of Dose Equivalent

The EPA protective action guides and the NRC limits are given in millirem. Rem is the traditional unit for dose equivalent that enables comparison of biological effects across radiation types through the use of a quality factor. The quality factor helps to equate health risk (dose equivalent) with absorbed dose in tissue. MicroShield does not calculate the dose equivalent nor the absorbed dose in tissue. The absorbed dose value that is produced from MicroShield is for air [8]. Exposure has units of coulombs per kilogram of air and is a measure of the ability of photons to produce charge in a set mass of air and does not account for the amount of energy absorbed by the material nor the ionization potential of the radiation. F-Factors are derived values that enable conversion from exposure to absorbed dose. The f-factor for water is 0.96 and can be used as a reasonable facsimile for soft tissue [58]. For the purpose of this research the f-factor was rounded up to 1. The quality factor for gamma rays is also one [13]. This means for the purpose of this research equivalent dose from external gamma radiation will be assumed to be the same as the exposure.

IV. Results and Discussion

The results of the modeling trials are presented below. The results are organized by decontamination phase.

Pre-Decontamination

Before modeling was accomplished, the total area, total activity, wash rate, decontamination time, and required number of shifts, were calculated. The activities remaining on the wall and transitioning into the filter bed after each shift based on a steady work rate are shown below in Tables 6 and 7. Each table contains the activity partition between the original source and filter bed for 80%, 50%, and 30% removal efficiency. The final activity breakdown was used to calculate the source strength of the buildings and streets post decontamination in the exposure models. The 80%, 50%, and 30% removal efficiencies were not utilized for the street decontamination. For the sake of the of this study, we simplify our scenario by assuming 100% of the horizontal contamination is removed. All street activity is contained within the filter bed.

Table 6: Activity Partition on Building 1 Following Decontamination with Removal Percentages of 80, 50, and 30 Percent

Percent Removal	Activity on Building 1 (Ci)	Activity in Filter Bed (Ci)
80%	0.037	0.149
50%	0.093	0.093
30%	0.130	0.056

Table 7: Activity Partition on Building 1 Following Decontamination with Removal Percentages of 80, 50, and 30 Percent

Percent Removal	Activity on Building 2 (Ci)	Activity in Filter Bed (Ci)
80%	0.037	0.149
50%	0.093	0.093
30%	0.130	0.056

Table 8 shows the exposure rates in milliroentgens per hour at six points down the center line of the street prior to any mitigation operations. Figure 11 illustrates the pre-decontamination conditions with all three surfaces covered with contamination at a concentration of 50 microcuries per meter squared. The range of exposure rates is between 0.25 and 0.62 milliroentgens per hour. As noted in the literature review, it is desired to maintain exposure rates below two milliroentgens per hour. The exposure rates prior to decontamination might not prohibit non-radiation workers from being trained in the operation of IWATERS and being able to implement mitigation techniques.

Even though the total surface area of the horizontal sources makes up less than a third of the total contaminated surface area, it is the single largest contributor to the overall exposure rate. At each point, the total exposure rate from the street is roughly four times greater than the exposure contribution from the vertical surfaces. Using point one as an example, the total rate from the street is 0.5 milliroentgen per hour and from the two buildings it is 0.12 milliroentgen per hour. At point one the street exposure rate is 4.17 times greater than the combined building exposure rate. This finding is consistent with research from Chernobyl and Fukushima Daiichi. It was expected that the horizontal area source would have the most significant impact on exposure.

Table 8: Pre-Decontamination Exposure Rates at Street Centerline (mR/hr)

Point	Street 1	Street 2	Bldg 1	Bldg 2	Total
1	0.25	0.25	0.06	0.06	0.62
2	0.26	0.26	0.06	0.06	0.65
3	0.27	0.27	0.06	0.06	0.66
4	0.26	0.26	0.06	0.06	0.65
5	0.25	0.25	0.06	0.06	0.62
6	0.14	0.14	0.04	0.04	0.34

Street Decontamination

Based on preliminary modeling of filter bed activity concentration, three filter bed options were selected for further analysis. Table 9 shows the results of 100% removal of all street activity into a single HESCO berm located at the end of the block.

The filter bed was shielded by a single layer of Jackbox HESCO berms. Figure 13 shows the filter bed in light blue with HESCO berms surrounding it.

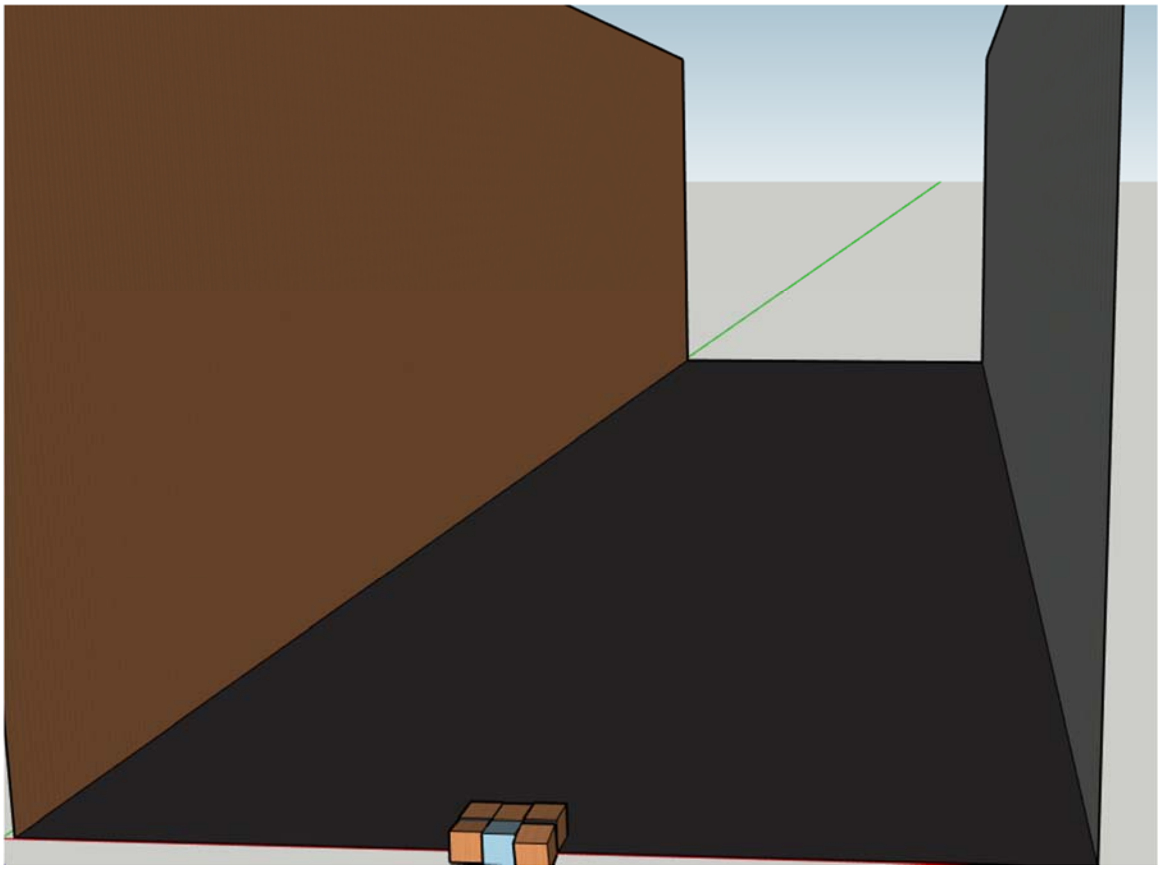


Figure 13: Filter Bed at the end of the Street with HESCO Berm Shielding

The exposure rate contribution from the activity originally on the street following decontamination drops to negligible values between the ranges of 4.4×10^{-5} and 1.1×10^{-8} milliroentgen per hour. The single act of decontaminating the street produces a reduction in exposure rate between 79% and 82%.

There is minimal difference between the three filter bed placement options. Each of the three options are within 0.1% of each other across all six exposure points.

Depending on the amount of available berm material, access points into the mitigation area, location of fire hydrants, or any other variable unique to a particular response, the incident commander can choose any of the three set-ups; single HESCO filter bed at the end of the street, single HESCO filter bed in the middle of the street or a line source along the front of building one and expect similar amounts of exposure. Figures 14 and 15 show the center of the street and line source configurations, respectively. It should be noted that in tables 9-11 the exposure rates from each building are contained and they match each other. This is because they are identical in area and contamination concentration and the six exposure points are the same distance from all points on each of the two sources. As the phases of the decontamination progress the exposure rate contribution from the different sources will change.

Figure 14: Single HESCO Filter Bed with HESCO Berm Shielding in the Center of the Street

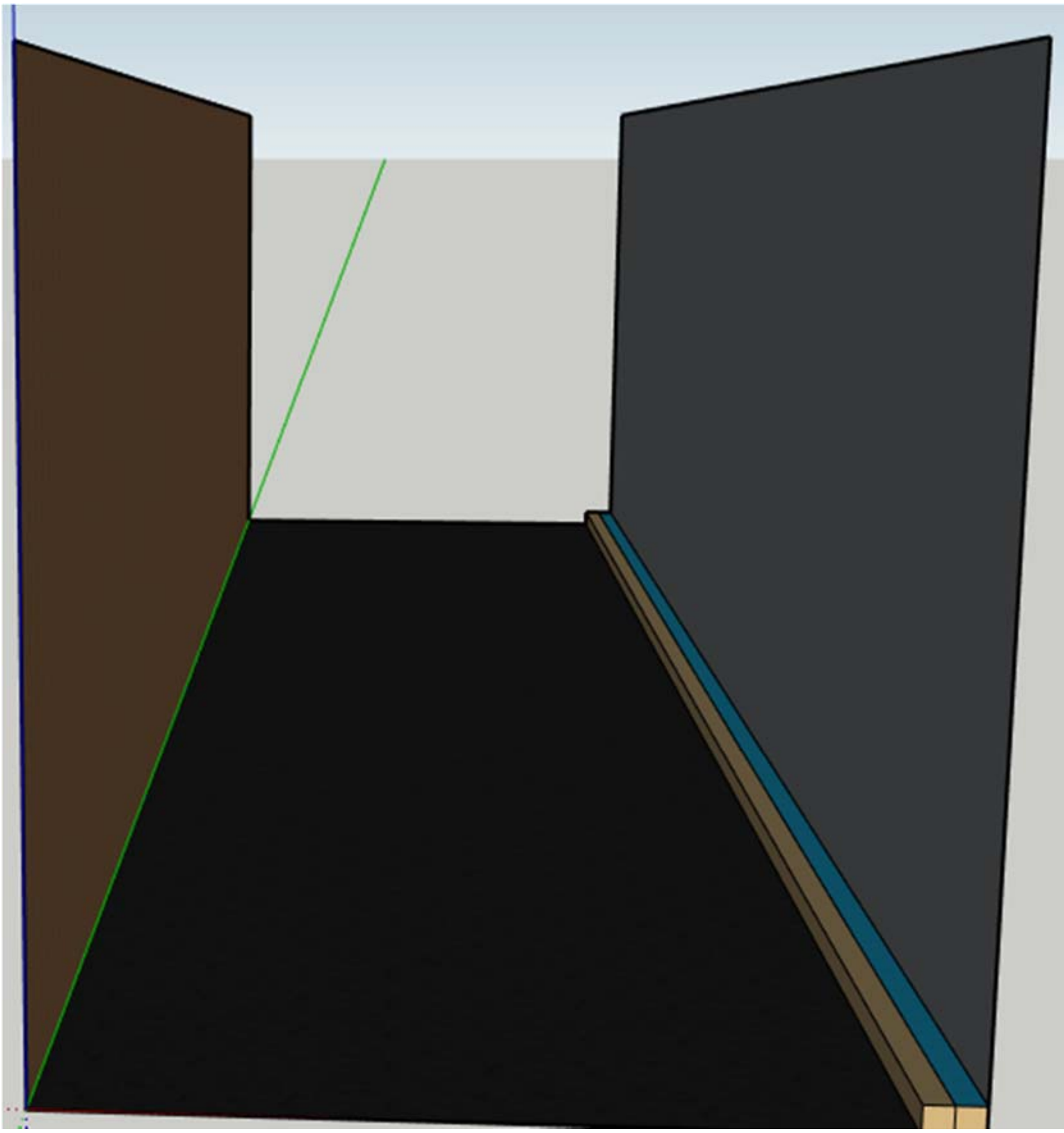


Figure 15: HESCO Line Source with HESCO Berm Shielding along the Front of Building 1

Table 9: Exposure Rates Post-Street Decontamination with Single HESCO Filter Bed Located at the End of the Block. (mR/hr)

Point	Street	Bldg 1	Bldg 2	Total	% reduction
1	4.4×10^{-5}	0.06	0.06	0.11	81.87%
2	4.5×10^{-7}	0.06	0.06	0.13	80.80%
3	1.0×10^{-7}	0.06	0.06	0.13	80.55%
4	3.9×10^{-8}	0.06	0.06	0.13	80.80%
5	1.8×10^{-8}	0.06	0.06	0.11	81.88%
6	1.0×10^{-8}	0.04	0.04	0.07	79.25%

Table 10 shows the results of the street decontamination with the same single HESCO filter bed shielded by one layer of HESCO Jackbox berms placed in the center of the street. The average exposure rate contribution from the middle of the street configuration has two dose points (3 and 4) on the scale of 10^{-5} and then rates dropping down into the range of times 10^{-7}. This is slightly higher than the end of street option that has only point 1 at 10^{-5} and then steadily decreases into the range of times 10^{-8} However, the exposure rate contribution from the street after the activity in in the filter bed is still at a low enough level that it does not change the exposure rate at two significant figures The percent reduction in overall exposure rate is virtually the same when utilizing either street decontamination filter bed placement.

Table 10: Exposure Rates Post-Street Decontamination with a Single HESCO Filter Bed Located at the Center of the Street. (mR/hr)

Point	Street	Bldg 1	Bldg 2	Total	% reduction
1	1.0×10^{-7}	0.06	0.06	0.11	81.88%
2	4.4×10^{-7}	0.06	0.06	0.13	80.80%
3	4.3×10^{-5}	0.06	0.06	0.13	80.55%
4	4.3×10^{-5}	0.06	0.06	0.13	80.80%
5	4.4×10^{-7}	0.06	0.06	0.11	81.88%
6	1.0×10^{-7}	0.04	0.04	0.07	79.25%

Table 11 shows the results of the final filter bed option for use in decontaminating the street. The filter material is placed in a line along the front of building 1. This allows the decontamination crew to wash radioactive material only 90 linear feet as opposed to 400 or 200 linear feet in the first two options. The linear filter bed also has the advantage of spreading out the concentration of radioactive material over a longer surface area. This means that as the decontamination crews work on sections of the vertical buildings, their exposure rate contribution from the line source will be lower than if the radioactive material was concentrated in a point source.

All three filter bed options are acceptable in that each configuration presents a similar reduction in exposure rate. The linear source configuration was selected for use as the post street decontamination exposure rate contribution when calculating the pre- and post- exposure rate values of the vertical sources because it has the lowest expected exposure rate and presents the operational advantage of shortening the wash distance.

Table 11: Exposure Rates Post-Street Decontamination with Line HESCO Filter Bed Located along Building 1 (mR/hr)

Point	Street	Bldg 1	Bldg 2	Total	
1	1.9×10^{-7}	0.06	0.06	0.11	81.88%
2	1.9×10^{-7}	0.06	0.06	0.13	80.80%
3	1.9×10^{-7}	0.06	0.06	0.13	80.55%
4	1.9×10^{-7}	0.06	0.06	0.13	80.80%
5	1.9×10^{-7}	0.06	0.06	0.11	81.88%
6	9.5×10^{-8}	0.04	0.04	0.07	79.25%

Vertical Area Source Decontamination

Each tested removal efficiency-- 80%, 50%, and 30% --was tested using two different filter bed options. For Tables 12-23 the exposure rate component for the street is modeled as having 100% of the street activity confined to a line source (Figure 15). For

Tables 12-17 the building 2 (brown building in diagrams) component is constant because that building still contains 100% of the radioactivity on the surface. In Tables 12-17 the only components that change are building one and the two filter bed options to contain the activity from building one. In Tables 18-23 the results of 100% street decontamination and decontamination of both buildings at 80, 50, and 30%.

The first option is a single HESCO Jackbox filter bed with a single line of Jackbox berms as shielding, depicted in Figure 14. The second filter option is a linear source along the front of the building. For the linear source, it was assumed that the two linear filter beds would be set up prior to decontamination. This was modeled with the filter bed for the building on the inside separated from the filter bed for the street by a single HESCO berm shield and then another single HESCO berm shield outside of the street filter bed. This set up in shown in Figure 16.

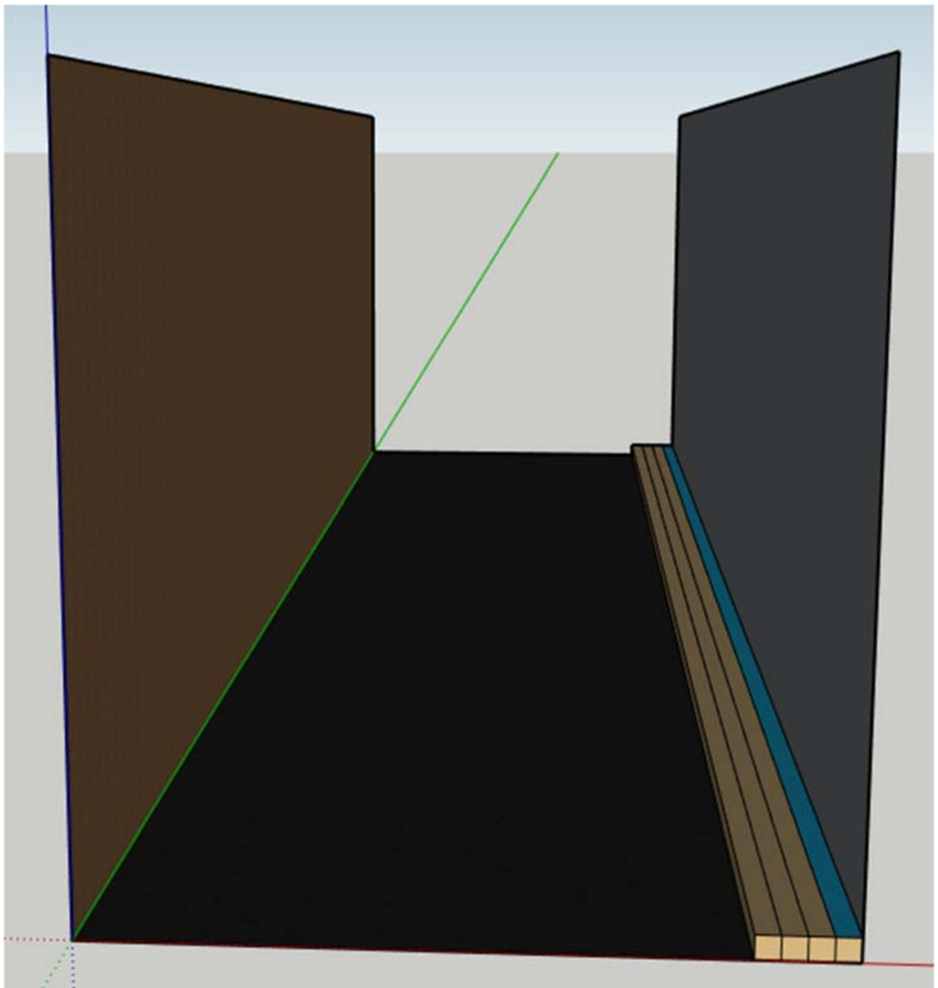


Figure 16: Line Source in Front of Building 1 with Three Layers of HESCO Berm Shielding

Tables 12 and 13 show the percent reduction in exposure rate following the decontamination of the street with 100% removal efficiency and building 1, the grey building in the diagrams, with 80% removal efficiency. Decontaminating building 1 with an 80% removal efficiency provides a roughly 5% increase in the exposure rate reduction over decontamination of just the street (Tables 10 and 11). Both filter bed configurations, when shielded, reduce the exposure rate component from the filter bed (column 3) low enough, on the order of times 10^{-7} for the single filter bed and times 10^{-18} for the line source, that there is no difference in the exposure rate percent reduction at 0.1% between the two options, shown in the right-hand columns of Tables 12 and 13.

Table 12: Exposure Rates Post-Decontamination of Building 1 Utilizing the Jackbox Filter Bed with 80% Removal Efficiency (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	4.1×10^{-8}	0.01	0.06	0.07	89.14%
2	1.9×10^{-7}	1.2×10^{-7}	0.01	0.06	0.08	88.49%
3	1.9×10^{-7}	6.7×10^{-7}	0.01	0.06	0.08	88.34%
4	1.9×10^{-7}	6.7×10^{-7}	0.01	0.06	0.08	88.49%
5	1.9×10^{-7}	1.2×10^{-7}	0.01	0.06	0.07	89.14%
6	9.5×10^{-8}	4.1×10^{-8}	0.01	0.04	0.04	87.56%

Table 13: Exposure rates Post-Decontamination of Building 1 Utilizing Line Source Filter Bed with 80% Removal Efficiency (mR/hr)

Point	Street 1	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	4.800E-18	0.01	0.06	0.07	89.14%
2	1.9×10^{-7}	4.800E-18	0.01	0.06	0.08	88.49%
3	1.9×10^{-7}	4.800E-18	0.01	0.06	0.08	88.34%
4	1.9×10^{-7}	4.800E-18	0.01	0.06	0.08	88.49%
5	1.9×10^{-7}	4.800E-18	0.01	0.06	0.07	89.14%
6	9.5×10^{-8}	4.800E-18	0.01	0.04	0.04	87.56%

Tables 14 and 15 show the results of decontaminating the street with 100% removal efficiency and building 1 (grey building) with 50% removal efficiency. The overall percent reduction in exposure rate only drops roughly 3% with a reduction in removal efficiency from 80 to 50%. The two filter bed options are the same center of street single HESCO bed and line source shown in Figures 14 and 16. A comparison of exposure rate contribution from the filter beds (third column) shows that the line source does provide a greater reduction in exposure rate over the single HESCO filter but they are both so low that the filter bed contributions do not affect the total exposure rate at two significant figures.

Table 14: Exposure Rates Post-Decontamination of Building 1 Utilizing the Jackbox Filter Bed with 50% Removal Efficiency (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	2.6×10^{-8}	0.02	0.06	0.08	86.42%
2	1.9×10^{-7}	7.3×10^{-8}	0.03	0.06	0.09	85.61%
3	1.9×10^{-7}	4.2×10^{-7}	0.03	0.06	0.10	85.42%
4	1.9×10^{-7}	4.2×10^{-7}	0.03	0.06	0.09	85.61%
5	1.9×10^{-7}	7.3×10^{-8}	0.02	0.06	0.08	86.42%
6	9.5×10^{-8}	2.6×10^{-8}	0.02	0.04	0.06	84.44%

Table 15: Exposure Rates Post-Decontamination of Building 1 Utilizing a Line Source Filter Bed with 50% Removal Efficiency (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	2.2×10^{-18}	0.03	0.06	0.08	86.42%
2	1.9×10^{-7}	2.1×10^{-18}	0.03	0.06	0.09	85.61%
3	1.9×10^{-7}	2.1×10^{-18}	0.03	0.06	0.10	85.42%
4	1.9×10^{-7}	2.1×10^{-18}	0.03	0.06	0.09	85.61%
5	1.9×10^{-7}	2.1×10^{-18}	0.03	0.06	0.08	86.42%
6	9.5×10^{-8}	1.1×10^{-18}	0.02	0.04	0.05	84.44%

A reduction in removal efficiency to 30% decreases the overall percent reduction by 1% from the 50% removal and 4% from the 80% removal. Tables 16 and 17 show the data for decontamination of the street at 100% removal efficiency and building 1 at 30% removal efficiency. Both filter bed configurations provide the same total percent reduction in exposure rate.

Table 16: Exposure Rates Post-Decontamination of Building 1 Utilizing the Jackbox Filter Bed with 30% Removal Efficiency (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	1.6×10^{-8}	0.03	0.06	0.09	85.63%
2	1.9×10^{-7}	4.4×10^{-8}	0.04	0.06	0.11	83.69%
3	1.9×10^{-7}	2.5×10^{-7}	0.04	0.06	0.11	83.48%
4	1.9×10^{-7}	2.5×10^{-7}	0.04	0.06	0.11	83.69%
5	1.9×10^{-7}	4.4×10^{-8}	0.04	0.05	0.10	84.61%
6	9.5×10^{-8}	1.6×10^{-8}	0.02	0.03	0.06	82.37%

Table 17: Exposure rates Post-decontamination of building 1 utilizing a line source filter bed with 30% removal efficiency (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	1.3×10^{-18}	0.03	0.06	0.09	85.63%
2	1.9×10^{-7}	1.3×10^{-18}	0.04	0.06	0.11	83.69%
3	1.9×10^{-7}	1.3×10^{-18}	0.04	0.06	0.11	83.48%
4	1.9×10^{-7}	1.3×10^{-18}	0.04	0.06	0.11	83.69%
5	1.9×10^{-7}	1.3×10^{-18}	0.04	0.06	0.10	84.61%
6	9.5×10^{-8}	1.6×10^{-18}	0.02	0.04	0.06	82.37%

Exposure Rate Following Decontamination

Tables 18 through 23 show the results of full decontamination of the street and both buildings, i.e., the results of combining the two steps. The percent reduction in exposure rate utilizing two filter bed configurations and three different removal efficiencies are displayed. The maximum expected reduction in exposure rate is 96.40 %. The minimum expected reduction is 80.72%. However, that minimum percent reduction is based on location 6 that had the lowest exposure rate at the start. The lowest expected reduction for the other five locations is 86.41%.

Decontaminating the street provides the greatest reduction in exposure rate per unit of time. The street has the lowest surface area and does not require the use of ladders or special equipment to decontaminate. Decontaminating the street, with 100% efficiency, offers a roughly 80% reduction in exposure rate with an expected range of decontamination time between 40 and 84 hours based on the wash rates between 40 and 80 meters squared per hour. Decontaminating the vertical surfaces of the building only adds approximately 5 to 16% reduction in exposure rate while increasing the total operation time an estimated 80 to 160 hours. Figure 17 shows the average percent reduction for each option presented in tables 9-23. The first three bars are following the 100% decontamination of the street. The middle six bars show the exposure rate percent reduction following 100% decontamination of the street and the decontamination of building 1 at the labeled removal efficiencies. The final six bars show the average total percent reduction in exposure rate post-decontamination, this includes the 100% decontamination of the street and the decontamination of buildings 1 and 2 at the labeled removal efficiencies. The information in parenthesis indicates which filter bed option was used for that model. The abbreviations are End of Street (EOB), Line Source (Line), and the single HESCO filter (Jackbox).

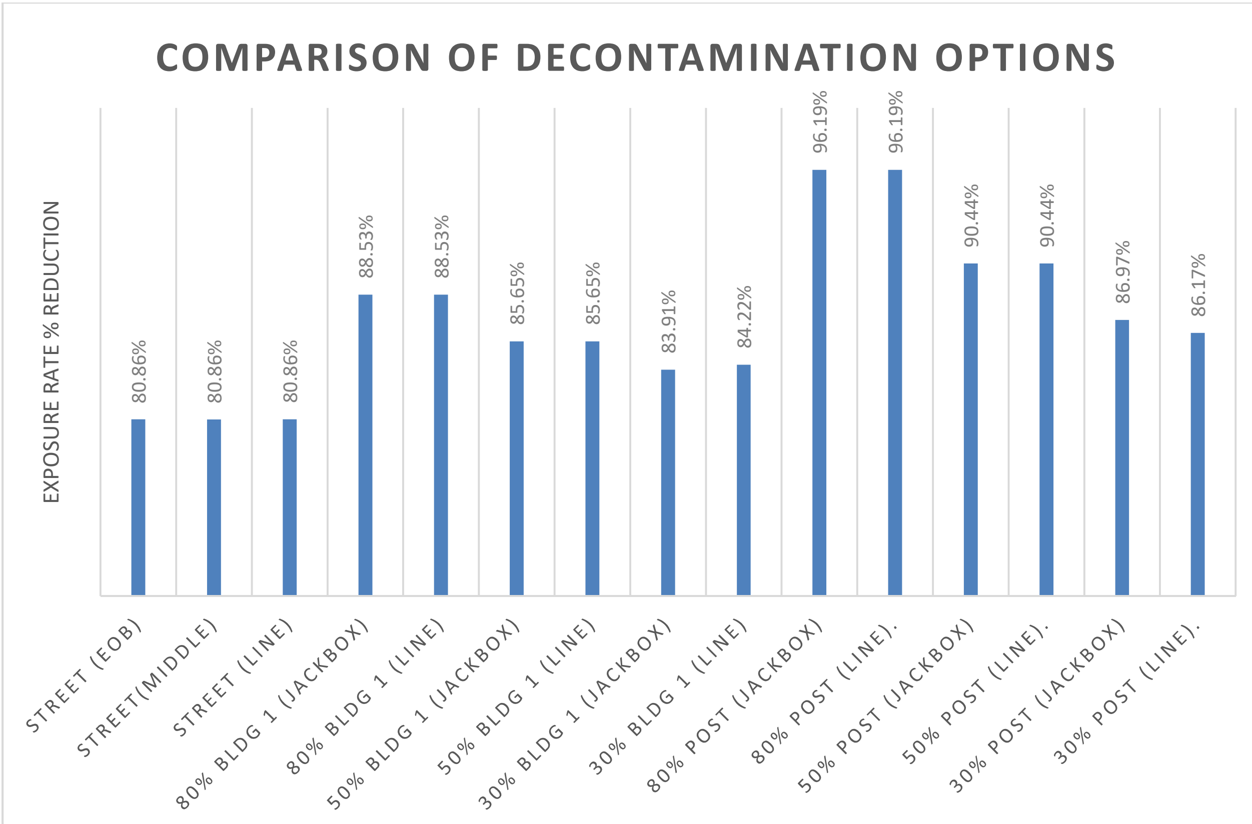


Figure 17: Comparison of Decontamination Options

Table 18: Exposure Rates After Completion of Decontamination with 80% Removal Efficiency Using the Jackbox Filter Bed (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	8.3×10^{-8}	0.01	0.01	0.02	96.40%
2	1.9×10^{-7}	2.3×10^{-7}	0.01	0.01	0.02	96.18%
3	1.9×10^{-7}	1.3×10^{-6}	0.01	0.01	0.03	96.13%
4	1.9×10^{-7}	1.3×10^{-6}	0.01	0.01	0.02	96.18%
5	1.9×10^{-7}	2.3×10^{-7}	0.01	0.01	0.02	96.40%
6	9.5×10^{-8}	8.3×10^{-8}	0.01	0.01	0.01	95.87%

Table 19: Exposure Rates After Completion of Decontamination with 80% Removal Efficiency Using a Line Source Filter Bed (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	8.3×10^{-8}	0.01	0.01	0.02	96.40%
2	1.9×10^{-7}	2.3×10^{-7}	0.01	0.01	0.02	96.18%
3	1.9×10^{-7}	1.3×10^{-6}	0.01	0.01	0.03	96.13%
4	1.9×10^{-7}	1.3×10^{-6}	0.01	0.01	0.02	96.18%
5	1.9×10^{-7}	2.3×10^{-7}	0.01	0.01	0.02	96.40%
6	9.5×10^{-8}	8.3×10^{-8}	0.01	0.01	0.01	95.87%

Table 20: Exposure Rates After Completion of Decontamination with 50% Removal Efficiency Using the Jackbox Filter Bed (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	5.2×10^{-8}	0.03	0.03	0.06	90.95%
2	1.9×10^{-7}	1.5×10^{-8}	0.03	0.03	0.06	90.41%
3	1.9×10^{-7}	8.3×10^{-7}	0.03	0.03	0.06	90.29%
4	1.9×10^{-7}	8.3×10^{-7}	0.03	0.03	0.06	90.41%
5	1.9×10^{-7}	1.5×10^{-8}	0.03	0.03	0.06	90.95%
6	9.5×10^{-8}	5.2×10^{-8}	0.02	0.02	0.04	89.64%

Table 21: Exposure Rates After Completion of Decontamination with 50% Removal Efficiency Using a Line Source Filter Bed (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	5.2×10^{-8}	0.03	0.03	0.06	90.95%
2	1.9×10^{-7}	1.5×10^{-8}	0.03	0.03	0.06	90.41%
3	1.9×10^{-7}	8.3×10^{-7}	0.03	0.03	0.06	90.29%
4	1.9×10^{-7}	8.3×10^{-7}	0.03	0.03	0.06	90.41%
5	1.9×10^{-7}	1.5×10^{-8}	0.03	0.03	0.06	90.95%
6	9.5×10^{-8}	5.2×10^{-8}	0.02	0.02	0.04	89.64%

Table 22: Exposure rates after completion of decontamination with 30% removal efficiency using the Jackbox filter bed (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	3.1×10^{-8}	0.03	0.03	0.07	89.39%
2	1.9×10^{-7}	8.8×10^{-8}	0.04	0.04	0.09	86.58%
3	1.9×10^{-7}	5.0×10^{-7}	0.04	0.04	0.09	86.41%
4	1.9×10^{-7}	5.0×10^{-7}	0.04	0.04	0.09	86.58%
5	1.9×10^{-7}	8.8×10^{-8}	0.04	0.04	0.08	87.33%
6	9.5×10^{-8}	3.1×10^{-8}	0.02	0.02	0.05	85.50%

Table 23: Exposure rates after completion of decontamination with 30% removal efficiency using a line source filter bed (mR/hr)

Point	Street	Filter bed	Bldg 1	Bldg 2	Total	% reduction
1	1.9×10^{-7}	2.6×10^{-18}	0.03	0.03	0.07	89.39%
2	1.9×10^{-7}	2.6×10^{-18}	0.04	0.04	0.09	86.58%
3	1.9×10^{-7}	2.5×10^{-18}	0.04	0.04	0.09	86.41%
4	1.9×10^{-7}	2.6×10^{-18}	0.04	0.04	0.09	86.58%
5	1.9×10^{-7}	2.6×10^{-18}	0.04	0.04	0.08	87.33%
6	9.5×10^{-8}	2.6×10^{-18}	0.03	0.03	0.07	80.72%

Estimated Total Exposure to Emergency Responders Utilizing the IWATERS

The average total exposure rate at each of the six dose points was found by averaging the pre- and post- exposure rates of each phase and then summing each phase. Table 24 shows the pre- and post- exposure rates in milliroentgen per hour for each of the three sources, the street, building 1 and building 2. The exposure contribution from the filter beds was assumed to be zero because once the radioactive material was contained in any of the filter bed alternatives, the exposure rates were below 10^{-5} and did not contribute to the final total after rounding to the hundredths place.

Table 24: Pre- and Post- Exposure Rates at Centerline of Street with 100% Removal from the Street and 80% Removal Efficiency from Buildings 1 and 2 (mR/hr)

	Street Exposure		**Bldg 1 Exposure**		**Bldg 2 Exposure**	
	Pre	Post	Pre	Post	Pre	Post
1	0.51	0.00	0.06	0.01	0.06	0.01
2	0.53	0.00	0.06	0.01	0.06	0.01
3	0.53	0.00	0.06	0.01	0.06	0.01
4	0.53	0.00	0.06	0.01	0.06	0.01
5	0.51	0.00	0.06	0.01	0.06	0.01
6	0.27	0.00	0.04	0.01	0.04	0.01

Total Expected Exposure by Decontamination Phase

Table 25 shows the average exposure rates by decontamination process. The street exposure values are comprised of the pre- and post- average exposure rates for the street plus the pre- exposure rates from buildings 1 and 2. This is because during the decontamination of the street each building still has 100% of the deposited contamination. The building 1 exposure rates include the post- street rate in addition to the average of the building 1 exposure rates and the pre- building two exposure rate. Finally, building two average exposure rate was found by adding the post- exposure rates from the street and building 1 to the average rate for building two.

Table 25: Average Exposure Rate during Decontamination (mR/hr)

Point	**Street**	**Bldg 1**	**Bldg 2**
1	0.37	0.09	0.04
2	0.39	0.10	0.05
3	0.39	0.10	0.05
4	0.39	0.10	0.05
5	0.37	0.09	0.04
6	0.21	0.06	0.03

As noted in the literature review, the recommended wash rate for the IWATERS system is between 40 and 80 m^2/hr. Table 26 shows the exposure to personnel during each phase of the decontamination at the various wash rates.

Table 26: Total Exposure by Decontamination Phase and Wash Rate (mR)

	Total Exposure by Decontamination Phase and Wash Rate (mR)								
	Wash rate 40 m^2/h			Wash rate 60 m^2/h			Wash rate 80 m^2/h		
Point	Street	Bldg 1	Bldg 2	Street	Bldg 1	Bldg 2	Street	Bldg 1	Bldg 2
1	30.64	7.52	3.75	20.42	5.01	2.50	15.32	3.76	1.88
2	32.56	8.39	4.19	21.71	5.59	2.79	16.28	4.19	2.09
3	33.00	8.59	4.29	22.00	5.73	2.86	16.50	4.30	2.14
4	32.56	8.39	4.19	21.71	5.59	2.79	16.28	4.19	2.09
5	30.64	7.52	3.75	20.42	5.01	2.50	15.32	3.76	1.88
6	17.24	4.74	2.37	11.49	3.16	1.58	8.62	2.37	1.18

Table 27 combines all three sources and provides the total expected dose equivalent during decontamination of 46 North Canal Street utilizing line filter bed configurations and 80% removal efficiency of dry cesium. Table 28 is a breakdown of the expected dose equivalent per person based on how many eight-person crews are used during the decontamination process. The goal is to keep total dose equivalent below 5 rem or 5,000 mrem per worker. The highest estimated dose equivalent at a single exposure point in the center of the street over the totality of the operation is approximately 46 mrem. The highest estimate dose equivalent for a single person is approximately 14 mrem.

Table 27: Total Dose Equivalent (mrem) at Various Wash Rates for the Entire Decontamination Operation at Fix Exposure Points

Point	40 m^2/h	60 m^2/h	80 m^2/h
1	42	28	21
2	45	30	23
3	46	31	23
4	45	30	23
5	42	28	21
6	24	16	12

Table 28: Exposure (mrem) Per Person Based on Number of 8-Person Crews Required

Wash rate	Total shifts	3 crews	4 crews	5 crews	6 crews	7 crews	8 crews
40 m^2/h	35	14	10	8	7	6	5
60 m^2/h	23	9	7	5	5	4	3
80 m^2/h	18	7	5	4	3	3	3

Uncertainty Analysis

Uncertainty and variability are part of every risk characterization. The variability is the range of true values that can occur for a given situation. Uncertainty is a product of imperfect knowledge and introduced as a byproduct of assumptions [59]. The assumptions are required to complete the analysis, but each time a simplifying assumption is made it introduces uncertainty and bias. Table 29 is a summary of major assumptions discussed throughout the analysis and the potential direction of bias on the final exposure rate and dose equivalent estimate.

The primary goal of this research was to test filter bed options and establish initial exposure rate and dose estimates because of that some simplifying assumptions were made to leave out potential exposure pathways or routes that are predicted to be minor contributors to the overall exposure rate and dose. It is possible that real-world exposure rates will be higher than the rates found in this research. There is currently a safety factor of 108 between the highest estimated dose equivalent and the occupational limit.

Selecting the high end of the expected activity concentration and using it as a uniform distribution will have mostly likely proved a high bias. The lack of activity hotspots will bias the results low. It is unknown which of these two assumptions will result in a greater magnitude of exposure rate and dose equivalent bias, or if they may even cancel each other out.

The density of the source and shielding material was fixed for all experiments in this analysis, but there is no way to predict future densities even if responders use the same ratio of sand to clay or even the same type of sand and vermiculite. Based on the output files from MicroShield, the difference between the exposure rates with and without buildup for the densities used is approximately 20 percent higher when buildup is included. Due to the fact that buildup factors are a correction to account for scattering, the uncertainty in exposure rate caused by a difference in the densities of shielding is predicted to be less than the difference between the exposure rates with and without buildup.

There will be some particles and ions are that resuspended in the air as a result of wind currents, decontamination operations, and general movement that will contribute to the exposure. The degree of resuspension is a product of multiple variables and will be unique to each situation. If the concentration of resuspended particles is known the derived air concentrations for Cs-137 from the Nuclear Regulatory Commission can be used to estimate exposure rate and dose equivalent.

Table 29: Potential Bias of Assumptions

Potential Uncertainty	Direction of Bias
External Gamma Only	Low. Internal dose and charged particles were not included.
Uniform high activity concentration	High.
Density of source and shield material	Possibly high or low depending on the density of the real-world shielding compared to the model.
Lack of hot spots	Low.
No back scatter	Low. Direct beam buildup increases the exposure rate 20%. Back scatter is expected to be well below this value.
No Resuspension	Low.

V. Conclusion

The Global War on Terror has been underway since 2001. The threat of terrorist attack using radiological dispersal devices has been recognized by the U.S. Congress. Recent events in Japan highlight the difficulties in decontaminating within the urban landscape. There is a clear and pressing need for the development of modern radiological decontamination strategies for the urban environment. One of the keys to effective long-term remediation and recovery is immediate mitigation within a few days of the incident and before a rain event.

The IWATERS system provides a potentially safe and effective method for emergency responders to perform decontamination operations in urban areas. This research found that the total expected activity for a city block can be contained in filter beds small enough to fill onto a standard forklift pallet making movement and replacement easy.

The modular nature of the IWATERS means that the filter beds can be deployed in a variety of configurations. This research explored three options for horizontal area decontamination and two options for vertical area combinations and found that all options and combinations thereof provide sufficient reduction in exposure rate, so all can be used with similar confidence. The exposure rates for the different bed geometries are within 0.1% of each other.

The stochastic nature of radiation health effects require that exposures are maintained ALARA. To help ensure low excess risk due to radiation exposure, federal laws provide exposure rate and dose equivalent limits of 2 mR per hour and 5 rem per year. Using the IWATERS under the configuration of this research maintains exposure rates and dose equivalents below federal standards and provides potentially over 80 percent reduction of exposure rate post decontamination.

Future Research

This analysis does not account for exposure from charged particles nor resuspension of radioactive material. To provide a more accurate estimate of exposure and dose to emergency responses, research needs to be accomplished in these areas. Another avenue of research to refine the accuracy would be the inclusion of particle deposition distribution. To study these effects, a more advanced software than MicroShield is required.

If an estimated geometric mean and standard deviation of RDD dispersed particles is obtained, then a Monte Carlo simulation of activity concentration can be accomplished. Using the MicroShield software will always present the limitation of the uniform source concentration; however, if the probability of certain area concentration is known, then the software can generate exposure rates at a fixed point from the high end of the distribution to the low end using the sensitivity analysis. Once that is complete, the exposure rates can be given a probability of occurring in order to generate a post hoc exposure rate distribution.

Appendix A: MicroShield Excel Output Files

Pre-Decontamination

Vertical Area Pre-Decontaminatio	Horizontal Area Pre-Decontaminatio

Decontamination of Street

Line Source 100%_ Street Removal.xls	Single HESCO in Middle of Street 10(	Single HESCO at End of Street 100%_

Decontamination of Building 1

HESCO point filter 30_ removal from bl(	Hesco line filter bed after 30_ remov	HESCO point filter in street center afte	HESCO point filter center of street afte	HESCO point filter_center of stree
HESCO Line filter after 80_ removal frc				

Post Decontamination

Vertical Area source after 30_ activity rer	HESCO point 80_ removal.msd.xls	Hesco line 50_ removal_3 Shields.xl	Hesco line 50_ removal_0_1858Ci.xl:	Hesco line 30_ removal.xls
vertical area source after 80_ activity rer	Vertical area source after 50_ activity rer			

Filter Bed Testing

- Floodline no shielding.xls
- Filter Bed with R_47cm.xls
- CART_shielding.xls
- CART no shielding.xls
- 55G_Barrel_0_186Ci_200m.xls
- 55G_Barrel_0_186Ci.xls
- Width Sensitivity.xls
- waterline x sensitivity.xls
- Water line.xls
- Jackox no shielding.xls
- HESCO CART w_shielding 1_20m.›

Notebook

The file is the master spreadsheet for this research. This notebook contains all information that went into the final analysis. It also contains information from other runs and aborted analysis.

- Sanders Thesis.xlsx

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1. REPORT DATE *(DD-MM-YYYY)* 22-03-2018	**2. REPORT TYPE** Master's Thesis		**3. DATES COVERED** *(From – To)* August 2016 – March 2018
TITLE AND SUBTITLE Radiological Decontamination in the Urban Environment Utilizing an Irreversible Wash-Aid Recovery System			**5a. CONTRACT NUMBER: N/A**
			5b. GRANT NUMBER N/A
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Sanders, Keith A., Major, USAF			**5d. PROJECT NUMBER**
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/ENV) 2950 Hobson Way, Building 640 WPAFB OH 45433-8865			**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT-ENV-MS-18-M-233
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) United States Environmental Protection Agency 26 W. Martin Luther King Dr. MS NG-16 Cincinnati, OH 45268 513-569-7321 and Magnuson.Matthew@epa.gov ATTN: Matthew Magnuson			**10. SPONSOR/MONITOR'S ACRONYM(S)**
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **DISTRUBTION STATEMENT A.** APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.			
13. SUPPLEMENTARY NOTES This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.			
14. ABSTRACT The Integrated Wash-Aid, Treatment, and Emergency Reuse System (IWATERS)			