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Re-Aerosolization of Dense Metal Oxide Simulating Radiological Contamination from Military Clothing

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THESIS

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Abstract

Radiological contamination from nuclear accidents or the terrorist use of a Radiological Dispersal Device (RDD) are mass casualty events that first responders and medical personnel must be prepared for. During a radiological attack, large numbers of victims will need to be quickly decontaminated. It is currently assumed that removal of the victims' clothing will remove 80-90% of contamination. What is often not considered is the threat of re-aerosolization of radiological contamination from the victims' clothing during removal and disposal. Many of the radioisotopes ideally suited for use in an RDD would produce dense aerosols that would then contaminate victims. In order to better understand the re-aerosolization of contamination, a series of experiments were conducted. In these experiments, clothing was contaminated with a dense aerosol selected to simulate a commonly available radioisotope of Strontium 90. The contaminated clothing was shaken for several minutes next to an Institute of Occupational Medicine inhalable sampler (IOM) to simulate the clothing removal process while the IOM captured any inhalable re-aerosolized particles. When compared to background trials, there was a statistically significant amount of re-aerosolization from the clothing. This result demonstrates the inhalation hazard from the re-aerosolization of dense radioactive particles on clothing during the decontamination process. Precautions to protect the health of victims, first responders, and medical personnel should be taken to mitigate the re-aerosolization threat.

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Joseph M. Chapman

Table of Contents

List of Figures

List of Tables

List of Acronyms

ABU	Airman Battle Uniform
ALARA	As Low As Reasonably Achievable
ALI	Annual Limit on Intake
ARS	Acute Radiation Syndrome
CBRN	Chemical, Biological, Radiological, and Nuclear
CMD	Count Median Diameter
DNA	Deoxyribonucleic Acid
EDS	Energy Dispersive X-Ray Spectroscopy
HAZMAT	Hazardous Material
HEPA	High Efficiency Particulate Air
HVAC	Heating, Ventilation, and Air Conditioning
ICRP	International Commission for Radiological Protection
IOM	Institute of Occupational Medicine
JSLIST	Joint Service Lightweight Integrated Suit Technology
MMD	Mass Median Diameter
OPC	Optical Particle Counter
PAPR	Powered Air Purifying Respirator
SCBA	Self-Contained Breathing Apparatus
RBG	Rotating Brush Generator
RDD	Radiological Dispersal Device
RTG	Radioisotope Thermoelectric Generators

RE-AEROSOLIZATION OF DENSE METAL OXIDE SIMULATING RADIOLOGICAL CONTAMINATION FROM MILITARY CLOTHING

I. Introduction

Radiation is a threat to human health. Getting radioactive particles on or inside of the body is especially hazardous following the accidental or intentional release of radioactive contamination. Real world events such as the nuclear accidents at Chernobyl and Fukushima released radioactive particles that then contaminated large areas. This radioactive contamination covered the bodies and clothes of people who were within these areas, and it was inhaled it into their lungs. When inhaled into the body, radioactive particles can cause long term negative health effects such as cancer.

Terrorists have sought to exploit the damaging effects of radioactive contamination by attempting to build devices that intentionally spread radioactive particles in order to cause casualties and make contaminated areas unlivable. A Radiological Dispersal Device (RDD) is a weapon designed for this purpose. One iteration of an RDD is known as a "dirty bomb" uses an explosion to disperse radioactive material and cause contamination. The general public's lack of understanding of radiation compounds the terror effect that would be produced by the use of an RDD. There has yet to be a successful attack using an RDD, but such an attack is high on the list of priorities for terrorist organizations and only second to acquiring nuclear weapons capable of producing a nuclear explosion (Mowatt-Larssen 2010).

Mitigating radiological contamination and its health effects on humans is critical to responding to an RDD attack. The US militaries' Multi-Service Tactics, Technique, and Procedures manual on Chemical, Biological, Radiological, and Nuclear (CBRN)

Consequence Management Operations states that “Emergency decontamination is a process that removes contamination from personnel in order to save lives, minimize casualties, and limit the spread of the contamination”. It also advises that the first step in the decontamination process should be victim clothing removal regardless of the suspected CBRN agent used (2015). Clothing removal is a vital step in the decontamination process; the US Army Edgewood Chemical Biological Center Special Report on mass casualty decontamination (ECBC-SP-024) estimates that removing clothing can eliminate 80-90% of contamination (2009).

A major concern is the transport of removable radiological contamination on the victims’ clothing during and after its removal. The materials that are likely to be used in an RDD would produce a dense aerosol that would contaminate victims and their clothing. During the clothing removal process, the re-aerosolization of radioactive particles from the clothing poses an inhalation hazard for anyone involved in the decontamination process including the victims, the first responders, and the medical personnel working the decontamination line.

The body of research on the re-aerosolization of particles from clothing is somewhat limited and what is available focuses on low density particles such as silicon. The re-aerosolization of dense particles from clothing has not been well investigated.

This research is to investigate the inhalation hazard of dense radioactive particles re-aerosolized from contaminated clothing. The objective of this research is to determine if a significant number of particles can be re-aerosolized from clothing contaminated with a dense aerosol and if the re-aerosolized particles constitute an inhalation hazard.

To answer these questions, an aerosol test chamber was used. A mannequin dressed in clothing was placed inside the aerosol test chamber and contaminated with particles selected to simulate the radioactive contamination that would be produced by an RDD. Copper oxide was selected as a simulant because it is a relatively dense and can be acquired cheaply in the required particle size range.

For the treatment trials, the mannequin's clothing was contaminated with the copper oxide aerosol inside the test chamber. After contamination, the chamber was cleaned to remove any contamination not on the clothing. The contaminated clothing was then removed from the mannequin and shaken from outside the aerosol test chamber using a series of pulleys and string. The clothing was shaken to simulate the forces that would be experienced during the clothing removal step of decontamination. The number and size of particles re-aerosolized from the clothing was then measured using an Optical Particle Counter (OPC) and an Institute of Occupational Medicine inhalable sampler (IOM). The IOM is designed to capture the inhalable range of particles and can be used to effectively measure the number of particles that an average person would inhale.

For the background trials, a clean uniform was shaken inside a clean test chamber. The OPC and IOM were used to record any aerosols produced in the chamber. This would give a background count for particles such as lint produced from the uniform. Also, any copper oxide particles missed during the cleaning process would be observed and could be subtracted out. A statistically significant difference between the treatment trials and the background trials would show that particles are being re-aerosolized from the clothing.

The implication of this research is that it will establish what kind of threat is posed by the re-aerosolization of radioactive particles from contaminated clothing. Improved decontamination procedures can be designed that better protect victims and first responders.

II. Literature Review

Radiological contamination presents unique challenges for remediation. It can come from a variety of sources, either from an accidental release or an intentional attack. In this work, the focus will be on intentional contamination using a Radiological Dispersal Device (RDD), colloquially known as a "dirty bomb".

An RDD is a device that is designed to spread radioactive contamination over an area ("NRC: Backgrounder on Dirty Bombs" 2007). It does not necessarily have to use explosive force to disperse the radioactive material and could be constructed without the use of any explosives. A sprayer system mounted on an airplane and used to disperse radioactive material would also meet the definition of an RDD. Also, powdered radioactive material could be placed in the Heating, Ventilation, and Air Conditioning (HVAC) system of a building for dispersal. However, the most likely scenario for the use of an RDD involves the use of explosives. The usual design of an RDD is to place a suitable radioactive material on top of an explosive device and detonate it ("Radiological Attack Fact Sheet" 2015) so that the force of the explosion would then scatter the radioactive materials over a wide area.

An RDD is not a nuclear bomb. A nuclear bomb uses nuclear fission and/or fusion to produce an explosive yield. Although a nuclear bomb does produce nuclear contamination in the form of nuclear fallout, that is not the main goal. An RDD is the "poor man's nuke" and does not produce a nuclear yield or blast. The goal of the RDD is to spread contamination.

The threats from an RDD are the blast from the explosion, the radiological hazard, and the fear and panic caused by the attack (Ford 1998). An RDD is not generally considered a weapon of mass destruction but rather a weapon of mass disruption (Rickert 2005). Attacking the urban core of a major city with an RDD would cause major economic disruption and the displacement of a large population, but the number of people killed by the RDD would likely be low. The real effects are the fear generated and the residents' reluctance to return to the contaminated area. A backpack containing explosives and 185 Tera-Becquerels (TBq) (or 4.47 grams) of ground cobalt-60 (Co-60) metal would expose a victim to 0.12 Sieverts (Sv) at the point of detonation (Ford 1998). Although this level of exposure would be above the recommended yearly dose of 0.05 Sv for a radiation worker, it would not be fatal ("NRC: Information for Radiation Workers" 2019). In effect, an RDD is an area denial weapon.

A becquerel is the number of nucleus decays in a given amount of material per second. One becquerel is equivalent to one decay per second. The sievert is a measurement of the health effects of ionizing radian on the human body. The sievert converts the different types of ionizing radian, measured in grays, to an equivalent impact on the human body. This is done by multiplying the dose by a quality factor based on the different types of radiation. For example, the same dose in grays of alpha radian would have a much greater human health impact than an equivalent dose of gamma radiation. A gray is a measurement of absorbed radiation (dose) and is defined as one joule of radiation energy absorbed per kilogram of matter.

Because RDD's are designed to spread radioactive contamination, their effectiveness is directly dependent on what radioactive material is used and how much is dispersed. There are several threat isotopes that are of interest in building an RDD. These isotopes are listed in Table 1 as well as the commonly available chemical forms and uses. In addition, the densities of the chemical forms are listed in the table. The density of a material is one of the factors that determines how long a particle will remain suspended as an aerosol and how likely it is to re-aerosolized from a surface. Denser aerosols will deposit faster than lighter particles and are less likely to aerosolize.

Table 1 - This table shows some of the most common radionucleotides that could be used in an RDD (Andersson et al. 2008).

Radionuclide	Chemical Form/Common Sources	Available Strong Sources	Density of Chemical Form
Co 60	Elemental Metal	Sterilisation irradiator (up to 400,000 TBq). Teletherapy source (up to 1000 TBq)	8.90 g/cm^3
Sr 90	Ceramic ($SrTiO_3$) - insoluble, brittle, soft (Mohs hardness: 5.5)	Radioisotope thermoelectric generator (1000-10.000 TBq)	5.11 g/cm^3
Cs 137	Salt (CsCl), soluble	Sterilisation irradiator (up to 400,000 TBq). Teletherapy source (up to 1000 TBq)	3.98 g/cm^3
Ir 192	Metal – soft - Mohs hardness 6.5	Industrial radiography source (up to 50 TBq)	22.56 g/cm^3
Ra 226	Salt ($RaSO_4$) very low solubility	Old therapy source (up to 5 TBq)	-
Pu 238	Ceramic (PuO_2) - insoluble	Radioisotope thermoelectric generator (up to 5,000 TBq)	11.5 gg/cm^3
Am 241	Pressed ceramic powder (AmO_2)	Well logging source (up to 1 TBq)	11.68 g/g/cm^3
Cf 252	Ceramic (Cf_2O_3) - insoluble	Well logging source (up to 0.1 TBq)	-

Radiation is electromagnetic energy and particles that are released when radioactive isotopes decay. Each type of isotope decays in a specific way. Ionizing radiation is of great concern because it has high enough energy to decouple electrons from atoms and cause a negative impact on the human body. Ionizing radiation can disrupt the structure of DNA inside cells and lead to cancer. There are four main types of ionizing radiation: alpha, beta, gamma, and neutron. Alpha particles can only travel a

few inches in air and are stopped by the human skin. Beta particles can travel several feet in air and can be stopped by something as thin as aluminum foil. Gama radiation will only be stopped by thick, dense materials like several inches of lead. Neutron radiation is even more penetrating and requires the use of very thick shielding or low atomic number materials such as water (Colella et al. 2005).

The radiation hazard from the gamma rays produced from the material used in an RDD is more dangerous to the perpetrators before detonation than to victims after the attack (Luckey 2003). Radioactive sources can give off significant amounts of gamma radiation and thus the RDD will need to be shielded in order to protect the perpetrators from receiving high doses of radiation. Alternatively, the perpetrators of the attack could forgo the use of shielding if they are unconcerned with surviving the attack. The hazard to the victims of the attack is higher from the alpha and beta radiation given off by the material. Once dispersed, the effects of gamma radiation are much reduced and the threat becomes contamination with radioactive particles inside the body(Luckey 2003).

Radiological contamination poses the greatest risk to humans when it is absorbed into the body where it can kill cells and damage DNA. Radiation exposure can cause Acute Radiation Syndrome (ARS) if high enough doses are received. Typically, a whole body dose of 0.7 Sv received in a relatively short time will cause ARS ("CDC Radiation Emergencies | Acute Radiation Syndrome: A Fact Sheet for Physicians" 2019). Symptoms can include weakness, vomiting, and death. If a lower dose of radiation is received, it may not cause ARS but will still damage the DNA of cells and could manifest later in life as cancer.

There is a distinct difference between radiation and radioactive contamination. Radioactive materials give off radiation which has a negative effect on the human body. A person standing near a radioactive source will receive a dose of radiation. However, as they move away, the dose received will begin to reduce. When dealing with radiation, the principles of time, distance, and shielding reduce the risks of radiation exposure.

- Time: We want to reduce the amount of time exposed to radiation and keep the amount of radiation received to As Low As Reasonably Achievable (ALARA).
- Distance: We want to increase the distance from the radiation source.
- Shielding: If unable to use distance, then we want to shield ourselves from the radiation source using materials such as lead that will stop the radiation.

Radioactive contamination is what happens when radioactive material is spread around the environment in the form of small particles. The danger of radioactive contamination is that it is easily spread from environmental sources to tools and people. Alpha and beta emitting isotopes are relatively benign when outside the body. However, if small radioactive particles are inhaled or ingested, then that same alpha and beta radiation is extremely harmful. Once inside, it takes the body a long time to remove these isotopes, thus extending the exposure time.

The danger posed by radioactive particles differs based on their size and what part of the body they are infiltrating. These areas can be divided into gastrointestinal, dermal and pulmonary. Particles of any size can be ingested. Particles greater than 10 μm cannot penetrate the skin but smaller particles can work their way into the hair follicles, and

particles under 3 μm can diffuse through the stratum corneum and make their way into the blood (Shekunov et al. 2007). One of the most damaging areas for a particle to reach is the alveolar region deep in the lung, although only particles less than 10 μm can reach this area (Hinds 1999). Small particles under 10 μm are the most concerning to human health.

The International Commission for Radiological Protection (ICRP) is an international organization that has developed models for how radiation is absorbed by the body. The ICRP model divides the respiratory system into three main areas: Head Airways, Tracheal Bronchial, and Alveolar. The head airways include the nose and mouth areas, the tracheal bronchial area includes the airway from the head areas down to the lungs and the major airway branches in the upper lung, and the alveolar region is deeper within the lung and includes the area where the gas exchange occurs. When engaged in light exercise while nose breathing at 30 L/min, the average adult will have 80% of inhaled 5 micron particles and 95% of 10 micron particles trapped in the nose (Hinds 1999). Figure 11.3 in the Hinds text shows that the vast majority of particles deposited in the tracheal bronchial region and alveolar region are under 10 microns. It also shows that particles over 10 microns represent a relatively small percentage of respirable particles and that most large particles are trapped in the head and nose region. It should be noted that the head airways capture the vast majority of particles over 10 microns while smaller particles are able to penetrate into the alveolar region.

Radioactive material deposited in the respiratory system is cleared by the body in several different ways. Particles caught in the head airways and nose can be cleared by

sneezing or nose blowing. Particles caught in the throat and tracheal bronchial regions are cleared by the mucus conveyor. The upper respiratory system is coated in mucus and inhaled particles are captured by this mucus. Tiny cilia hairs in the respiratory system are continually moving mucus to the back of the throat where it is swallowed. Radioactive particle that are swallowed then go on to impact the gastro intestinal tract. Particles that make their way to the alveolar region are absorbed by the blood and can be transported to the lymph nodes (*Individual Monitoring for Internal Exposure of Workers: Replacement of ICRP Publ. 54 ; Adopted by the Commission in May 1997* 1998). The effects of radionucleotides in the body differ, depending on the radionucleotide. For example, Sr 90 follows a similar biological course to that of calcium. Strontium is treated by the body as if it were calcium and is absorbed into the bones where it can cause bone cancer. Some radionucleotides are more easily excreted in urine or solid waste.

The ICPR recommends that radiation workers limit their internal exposure to 20 mSv per year or 100 mSv in a 5-year period; their internal body dose from inhaled and ingested radioactive material should not exceed these limits. The Annual Limit on Intake (ALI) for any one radionucleotide can be determined using the following equation:

Where e(50) is the does coefficient in Sv Bq^{-1}.

Equation 1.

$$ALI = \frac{0.02}{e(50)}$$

The e(50) for inhaled Sr 90 is 3.0×10^{-8} Sv Bq^{-1}. So, Sr 90 has an Annual Limit on Intake of 6.6×10^{5} Bq.

Equation 2.

$$\lambda(s^{-1}) = \frac{\ln(2)}{half\ life}$$

Equation 3.

$$\mathrm{N(atoms)} \times \lambda(s^{-1}) = Activity\ in\ Bq$$

The half-life of Sr 90 is 28.8 years. Using Equation 2, the decay constant is found to be 7.63×10^{-10} s^{-1}. Strontium has 6.022×10^{23} atoms/mol. We can then calculate that strontium has 4.59×10^{14} Bq/mol using Equation 3. Strontium has 87.62 g/mol so we can calculate that Sr 90 has 5.243×10^{12} Bq/g. This means that the Annual Limit on Intake for Sr 90 is 1.26×10^{-7} g or 0.126 micrograms. The density of Sr 90 is 2.63 g/cm^3. From this we can calculate the number of particles needing to be inhaled in order to reach the maximum annual dose. In order to reach the ALI for Sr 90, a person would only need to inhale 11,438 particles that were 1 micron in diameter or 12 particles that were 10 microns in diameter. This is a conservative calculation because it is unlikely that someone would be inhaling pure Sr 90. A person is much more likely to be exposed to a compound of Sr 90. This would increase the amount that could be inhaled before

reaching the Annual Limit on Intake. In order to make that calculation, the activity level of that compound of Strontium would need to be known.

Mitigating radiological contamination and its health effects on humans is critical to responding to an RDD attack. The goal of decontamination is to remove the damaging agent from the victim's skin and hair, protect first responders and medical personnel from secondary exposure, and to prevent the victims from spreading contamination to other areas. The US militaries' Multi-Service Tactics, Techniques and Procedures manual on Chemical, Biological, Radiological and Nuclear (CBRN) Consequence Management Operations advises that the first step in the decontamination process should be victim clothing removal regardless of the suspected CBRN agent used (Combs et al. 2015). The US Army Edgewood Chemical Biological Center Special report on mass casualty decontamination (ECBC-SP-024) estimates that removing clothing can removes 80-90% of contamination ("U.S. ARMY EDGEWOOD CHEMICAL BIOLOGICAL CENTER SPECIAL REPORT ECBC-SP-024" 2009). Clothing removal is a vital step in the decontamination process that removes the vast majority of contamination.

A decontamination line for a mass casualty CBRN event is designed to quickly decontaminate a large number of people. In a CBRN attack, the area of greatest contamination is designated as the hot zone. Immediately outside of the hot zone is the warm zone, and areas free from contamination are designated as the cold zone. The decontamination line should be set up within the warm zone just outside of the area of contamination. In the United States in the aftermath of a CBRN attack, the immediate decontamination of victims would most likely be conducted by Hazardous Material (HAZMAT) teams from the local fire department. In the early stages of a CBRN attack,

it is unlikely that first responders will know exactly what kind of agent was used. For this reason, decontamination procedures are the same for all CBRN agents. Victims leaving the hot zone would be directed to the decontamination line where the first step is to remove clothing. The best advice is to remove all clothing. When removing clothing, shirts should be unbuttoned rather than pulled over the head so that contamination from the clothing does not get on the face or inhaled. If a garment must come off over the head, then it should be cut off or the victim should place their arms and hands inside the garment and push it away from the face as it comes off over the head. If people refuse to remove all clothing, they should at least remove all outer clothing because this will contain the majority of contamination. Leaving on underwear is a decent compromise between decontamination and modesty. If time and resources allow, victims should be provided with plastic bags and markers so that they can place their clothing and personal items inside the bags and label them for later identification and retrieval. The next step of the process is to wash the victims with high volumes of low-pressure water at 60 psi. The easiest method is to use the hoses from fire trucks. Two fire trucks can be parked parallel to each other about 20 feet apart to create a decontamination corridor. The hoses from the trucks are then directed into this corridor so that the victims can walk through it. It is recommended that the victims be deluged with water for 30 seconds to 3 minutes, depending on the scale of the attack and the number of victims. Each side of the victim should be directly sprayed to get off the most contamination. Soap and water are not necessary unless the agent is oily and cannot be removed with water alone. In the case of an oily agent, victims who still have some of the agent left on their skin after the initial water deluge should be taken for secondary decontamination using soap and water. The

area selected for the decontamination line should be up hill from the hot zone so that the contaminated water from washing victims will flow into the hot zone and not contaminate new areas. After the victims have been through the water deluge, they should be directed to a holding area where they can be monitored for further symptoms. Victims that are physically injured or experiencing symptoms from the agent should be taken to a hospital where additional decontamination and treatment can occur. In cold weather where decontamination is occurring outdoors, it could be hazardous to the victims' health to wet them. In this case, the victims should remove clothing, and any contamination should be blotted away with an absorbent material. Victims should then be moved into a warm area ("U.S. ARMY EDGEWOOD CHEMICAL BIOLOGICAL CENTER SPECIAL REPORT ECBC-SP-024" 2009).

The first responders running the decontamination line should be in protective gear. For a fire department HAZMAT team, this should take the form of their Self-Contained Breathing Apparatus (SCBA) and firefighting gear. An SCBA is a mask connected to a back-worn compressed air tank. However, other types of respiratory protection could be used such as a Powered Air Purifying Respirator (PAPR) that runs air through a filter before blowing it into a mask system. In a military context, the Joint Service Lightweight Integrated Suit Technology (JSLIST) system can be used. The JSLIST consists of an activated carbon impregnated suit with rubber gloves and boots and an M50 gas mask. The M50 gas mask uses a High Efficiency Particulate Air (HEPA) filter to remove 99.9% of 0.3 micron particles in conjunction with activated carbon to filter out CBRN agents (Barrett, n.d.).

During the 1986 Chernobyl disasters, massive amounts of radiological contamination were released into the atmosphere when a Soviet nuclear reactor in the Ukraine suffered a catastrophic explosion and subsequently released significant amounts of Cs 137. The Chernobyl accident released $0.089x10^{18}$ becquerels of cesium and $1.8x10^{18}$ becquerels of radioactive iodine. During the cleanup of Chernobyl, 600,000 people worked within the exclusion zone around the reactor. The workers in this area received an average dose of 0.11 Sv; 1.4% of workers received up to 0.25 Sv. It should be noted that the occupational limit for radiation workers in the United States is 0.05 Sv per year ("Radiation, How Much Is Considered Safe for Humans?" 1994). Immediately following the reactor explosion, 134 plant workers and fire fighters received doses over 0.7 Sv; of these, 28 people died (Ingram 2005). The clothing worn by the fire fighters was so highly contaminated that it was dumped in the basement of the hospital where they were treated. The hospital and the surrounding town were later abandoned due to contamination. Scientists entering the hospital's basement 27 years later in 2013 recorded radiation levels as high as 16 mSv per hour (Bevelacqua 2016).

In the former Soviet Union, Radioisotope Thermoelectric Generators (RTG's) containing 1000 - 10,000 TBq of strontium-90 were used to power equipment such as light houses and beacons in remote places (Andersson et al. 2008). An RTG uses the decay of radioactive material to produce electricity. Many of these RTG's are unaccounted for and could easily be used in an RDD attack. It is estimated by Lawrence Livermore National Labs that the Soviets produced and installed approximately 1000 RTG's. Since 2003, a joint effort between the U.S. and Russia has replaced many of the old RTG's with solar and wind powered generators and removed the RTG's to secure

locations for disposal. However, at least 20 of the Soviet RTG's remain in the field and several are unaccounted for (Porter 2014). The type of chemical composition of the strontium in these RTG is in the form of a ceramic, strontium titanate ($SrTiO_3$).

In 2001, wood cutters in the country of Georgia discovered two canisters containing strontium-90 from an old Soviet era RTG. The wood cutters retrieved the canisters and used them as a heat source during the night. They soon became sick from the radiation exposure. When removed from their protective containers, the strontium sources could emit enough radiation to deliver a fatal dose in two minutes (Schmid and Spencer-Smith 2012).

It is difficult to determine the exact size range of particles from an RDD incident but it appears to be dependent on the form of the material. It has been shown that in an attack using solid cobalt-60 metal, very little of the material would be aerosolized by the explosion. However, milling cobalt-60 into a fine powder would greatly increase the amount that is aerosolized in an explosion. In ceramic and salt forms of radiological materials, explosive dispersal can produce larger particles in the range of 30-100 μm and smaller particles in the 1-10 μm range (Harper, Musolino, and Wente 2007).

Metals tend to break apart into larger pieces when distributed explosively. More brittle materials like ceramics tend to shatter along grain lines and produce smaller particles in the 1-50 μm range (Green et al. 2016). In an RDD, the larger particles settle faster and are not likely to spread beyond the immediate vicinity of the blast (Andersson et al. 2008). Particles that are less than 10 μm are the most likely to stay aerosolized and impact a much wider area.

In 1961, the Canadian Department of National Defense conducted a series of experiments in which glass microspheres were released from a tower to show the potential for drift. The microspheres ranged in size from 50-100 μm and were released 15 meters above a flat prairie. The experiments were conducted on days with an average wind speed of 5 m/s. It was found that all of the particles fell out of suspension within 300 meters of the tower (Hage 1961). Particles smaller than the ones used in this experiment are likely to stay airborne much longer.

In 1968, a B-52 carrying nuclear weapons crashed in Greenland. The conventional explosives in the nuclear weapons exploded but due to the extremely safe nature of nuclear weapons design, there was no nuclear yield. Essentially, the nuclear warheads detonated in a manner similar to an RDD. It was found that 98.7% of the contamination was under 18 μm in size. Plutonium spontaneously oxidizes to plutonium oxide PuO_2 in the atmosphere. Plutonium oxide is a ceramic with a density of 11.5 g/cm^3. When the bomb detonated the plutonium in the nuclear bomb would have quickly oxidized into a ceramic material and could account for the relatively small particle sizes observed (McMahon et al. 2000).

It is clear that smaller particles are the greatest threat from an RDD, but it should be noted that the heat and force of an explosion can also fuse particles together (Harper, Musolino, and Wente 2007). The Canadian Ministry of Defense conducted several full scale RDD tests using radioactive material in a device that used 200 grams of explosives and 12 grams of lanthanμm-140. Based on their small-scale testing, the powdered form of lanthanum oxide (La_2O_2) was chosen. The median diameter of the particles used in this

experiment was 25 μm before the explosion and 45 μm afterward. It was assumed that the increase in particle size was due to particles fusing together under the force of the explotion (Green et al. 2016). It is important to note that in a particle distribution, there is a wide range of particle sizes that are above and below the mass mean diameter. As we have seen, large particles will be deposited close to the explosive site while the smaller end of the distribution is more likely to contaminate a large area.

In order for a particle that has been deposited on a surface to be re-aerosolized, the lift force on the particle must exceed the forces of attraction. As diameter increases, the amount of surface area for air currents to act on increases. At the same time, increasing mass causes the gravitational force keeping a particle on a surface to increase as well (Hinds 1999). There is a point where increasing surface area counteracts the increasing mass of a particle and makes it more likely to re-aerosolize. The number of particles that are re-suspended from clothing is dependent on their size. In a study by McDonagh (2014), silica particles ranging in size from 3-10 μm were deposited on clothing and a test subject performed various physical activities. The number of particles that aerosolized from the clothing was measured, and it was found that particles in the 10 μm size range were more likely to re-aerosolize than larger particles. In studies of the re-aerosolization of household dust, it has been found that in the size range of 0.3-25, the potential for re-aerosolization increases with particle size. However, the trend reverses for particles above 25 μm (Thatcher and Layton 1995). Particles under 10 μm are the most likely to re-aerosolize from clothing and they are also the size range of particles that would be most widely distributed over an area by a well-designed RDD.

There have been two examples of viable RDD's that were deployed by a terrorist group but not detonated. In the 1990's, Chechnyan rebels fighting for independence from Russia placed an RDD containing 13 kg of cesiμm-137 in a park in Moscow (Ford 1998). Later, another RDD was found on a railroad line where an unidentified radioactive material had been placed on top of a landmine (Colella et al. 2005). It is unknown how effective these devices would have been if they had functioned as designed.

In 1987, there was an accidental release of cesiμm-137 in Goiania, Brazil. Although this release was accidental, the circumstances of the release illustrate the hazards of an intentional RDD attack. Several metal scavengers removed a sealed container of cesium chloride salt from a radiotherapy unit in an abandoned hospital (Lage et al. 2020). Eventually they were able to open the sealed container and brought it home to show their families. Large areas of the town were contaminated with cesium; 249 people were identified as being contaminated, 20 required hospitalization/treatment, and 4 people died (Stone 2007). The most heavily contaminated buildings were demolished and the topsoil removed in an effort to decontaminate them. This radiological accident shows the dangers of readily available medical sources. An intentional attack could be much worse.

The current body of knowledge does a good job of describing the threats posed by RDD's. The threat isotopes that are most likely to be used in an RDD are well cataloged. Also, much research has been conducted by the Canadian Ministry of Defense and The Lance Livermore National Laboratory to describe the partial ranges that an RDD is likely

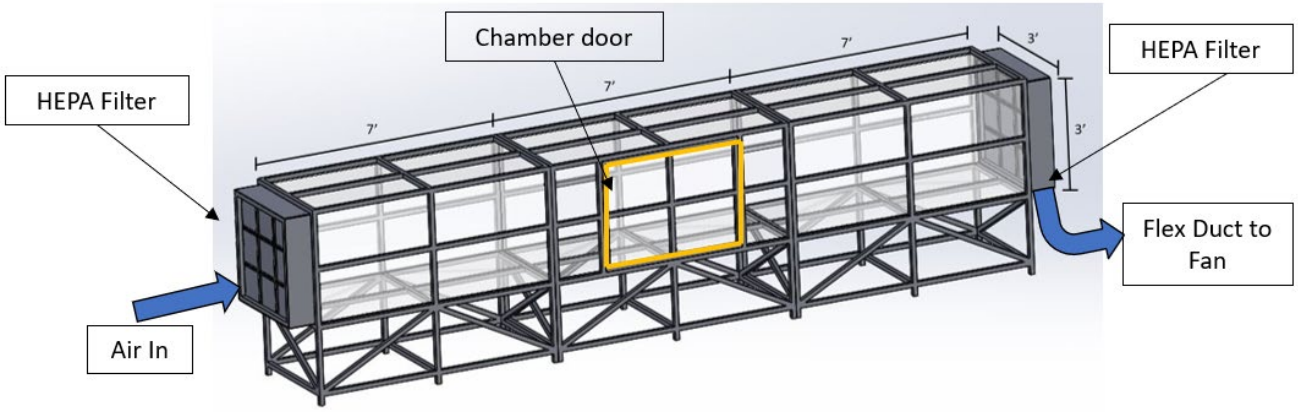
to produce. Research in the area of re-aerosolization has been conducted and there have even been studies examining the re-aerosolization from clothing. However, this research has focused on unit weight particles (the density of water) and has not explored the re-aerosolization of dense particles from clothing and the inhalation risk those particles pose.

III. Methodology

This research examined the potential for the re-aerosolization of radioactive contamination from clothing. This contamination was simulated with non-radioactive dense particles used as a simulant. The procedure was to first contaminate clothing with a dense aerosol (copper oxide). The clothing was then shaken to simulate removal and disposal of the clothing in a medical decontamination setting. The number of particles that were re-aerosolized from the clothing were measured using various instruments.

An aerosol test chamber was used for the testing. The chamber was 0.914 m × 0.914 m × 6.401 m (3 ft × 3 ft × 21 ft) and made of plexiglass. A 93 cm × 118 cm access door was located in the center of the chamber's side. A High Efficiency Particulate Air (HEPA) filter was positioned at each end of the chamber for the air supply entering the chamber and at the exhaust for the removal of particles. The HEPA filter removes 99.97% of particles that are 0.3 microns and higher percentages of particles that are larger and smaller than 0.3 microns (US EPA 2019). HEPA filtered air was then drawn through the chamber by a fan. The air flow through the chamber was 0.762 m/s and was measured using a Lab Safety Supply model 193996-00 vaneometer. A rotating brush generator (RBG) was used to aerosolize the copper oxide powder.

Figure 1- Aerosol Test Chamber.



The copper oxide used for this experiment was Black Copper Oxide (CuO) made by Alpha Chemicals. 99.9% of the copper oxide passes through a 325 mesh (44 µm size holes). The d50 is 625 mesh (20 µm size) (Hinds 1999). Copper oxide has a density of 6.315 g/cm^3 at 25° C. The copper oxide was selected because of its density and safety characteristics. As discussed in the literature review, the radionucleotide strontium 90 has a commonly available oxide in the chemical form of strontium titanate ($SrTiO_3$). The density of strontium titanate is 5.11 g/ cm^3, similar to the density of the copper oxide, although the copper oxide is a little denser than strontium titanate. Using a slightly denser material than strontium titanate for aerosol testing will produce slightly more conservative results because denser particles will settle out faster and are less likely to re-aerosolize (Hinds 1999). The size range of the copper oxide is consistent with the particle size ideal for an RDD. The sources in the literature review identified the particle size range created by an RDD to be in the 1-50 µm with the most widely dispersed particles be in the 1-10 µm range. The particle size distribution of the chosen copper

oxide meets the size range of particles expected from an RDD. Finally, the copper oxide was chosen due to availability and affordable price.

The copper oxide aerosol from the RBG was injected into the chamber using a small diameter copper tube. The tube extended into the center of the chamber and had a 90-degree bend at the end in order to inject the copper oxide aerosol into the air stream as it flowed through the chamber. The tube injected the aerosol into the wind in order to create a more uniform distribution of aerosol in the chamber.

A Simulaids Rescue Randy® adult mannequin was laid in the chamber "wearing" an Airman Battle Uniform (ABU). To facilitate the removal of the uniform, the mannequin was not fully inside the uniform. The uniform was placed on top of the mannequin so that the legs of the pants were laying directly on top of the mannequin's legs (see figure 1). The uniform blouse was draped over the torso and the sleeves were laid on top of the mannequin's arms. The uniform was covering the mannequin in an anatomically correct way as it lay in the chamber. Fifteen-pound test polyethylene braided fishing line was attached to the uniform and run through a pulley located 15.24 cm from the top of the chamber. The fishing line was tied through the top button hole on the uniform pants fly and the top button hole on the uniform blouse. The other end of the line went through a small hole in the side of the chamber so that it could be pulled from outside the chamber. The pulley system allowed the uniform to be lifted off of the mannequin and shaken (see figure 3).

Figure 2 - Clothed mannequin in the aerosol test chamber.

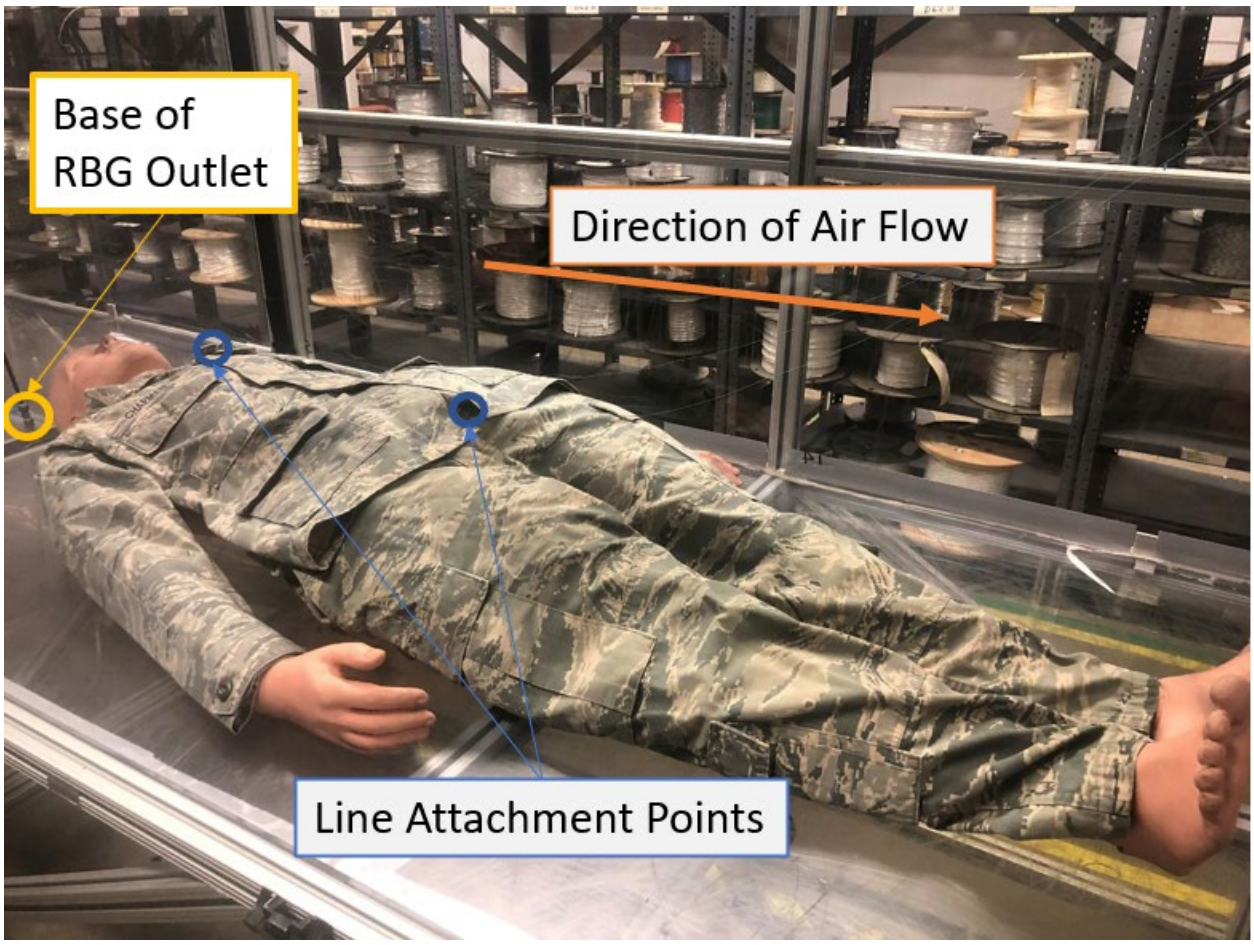


Figure 3 - RBG and RBG Outlet.

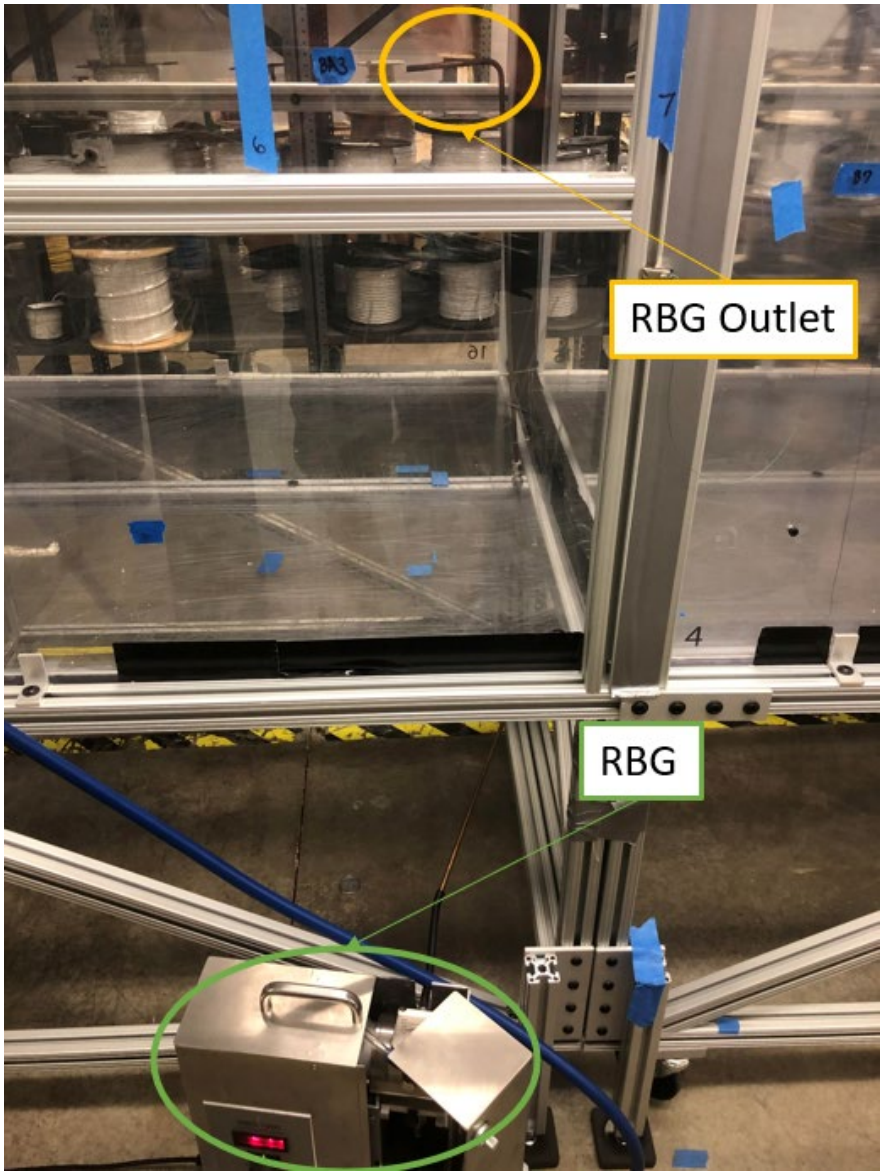
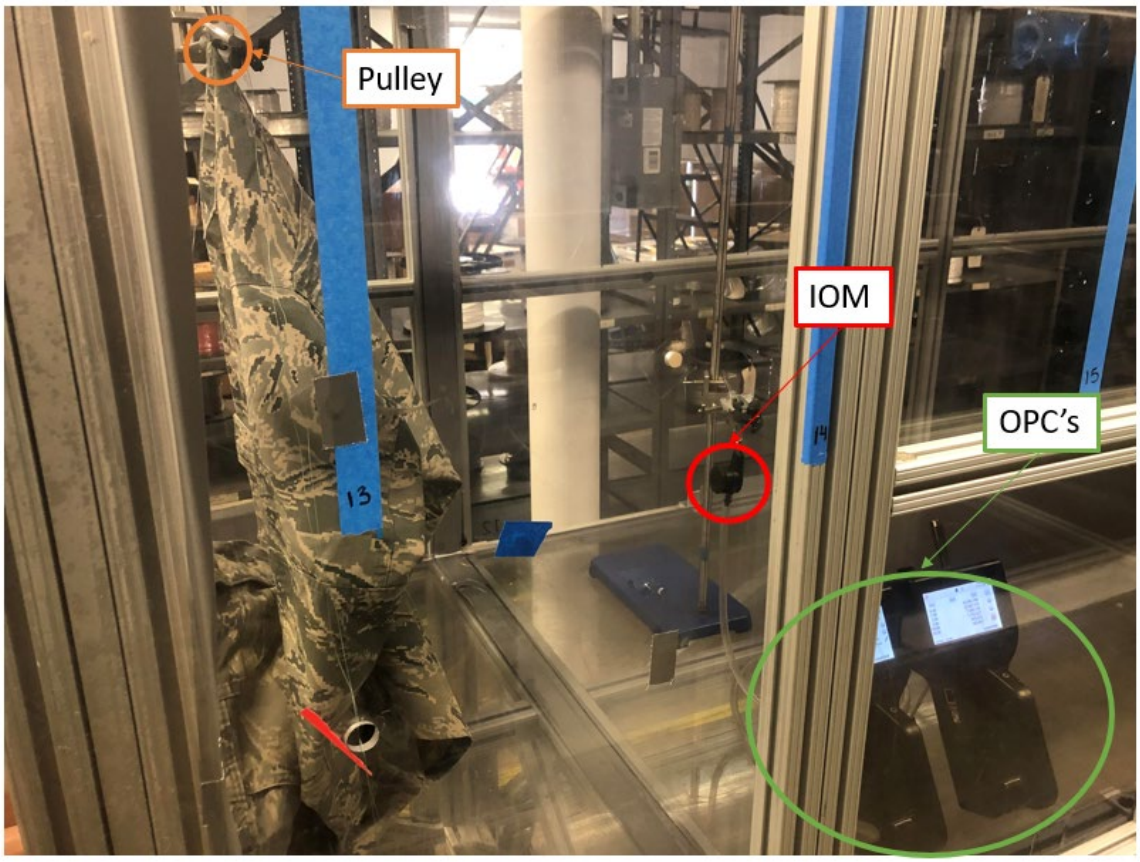


Figure 4 - Pulley system inside the chamber used for clothing removal from the mannequin.

Figure 5 - ABU uniform suspended from the pulley. The uniform was pulled to the top of the pulley as shown and dropped from this height onto the chamber floor. This process was repeated for 5 minutes.



ABU's were selected for use in this research for several reasons. The research was commissioned by the Air Force Institute of Technology (AFIT) to study Chemical Biological Radiological and Nuclear (CBRN) decontamination. Due to the military connection and because this research is focused on decontamination of military personnel, a military uniform was selected. ABU's were also a convenient choice because the Air Force was at the time transitioning from the ABU to a new uniform, the

Operational Camouflage Pattern (OCP). This left a large supply of old uniforms that could be recycled for research purposes. The ABU uniform is similar in construction to the OCP, and both are a 50/50 nylon-cotton blend (Wharton 2017). The ABU uniform is also a close approximation to what a typically dressed civilian might wear. Civilian work pants and a long-sleeved shirt are of similar construction.

For each trial, the mannequin was placed in the chamber wearing a clean uniform. After the chamber was closed, the chamber fan was started; finally, the RBG was turned on. Each trial used 4.01 cubic centimeters of copper oxide dust loaded into the RBG. The RBG used was a Palas RBG 1000 solid particle dispenser.

During contamination, the particulate levels inside the chamber were monitored using two optical particle counters (OPC) and an Institute of Occupational Medicine inhalable sampler (IOM). The OPC's used were a Particles Plus Model 8306 and a Particles Plus Model 8506 (Particles Plus, Stoughton, MA). The bin sizes were set to 0.3-0.5, 0.5-1, 1-2.5, 2.5-5, 5-10 and 10-25 μm for the Model 8306. The bins for the Model 8506 were set to 0.5-1, 1-2.5, 2.5-5, 5-10, 10-15 and 15-30 μm. The data was recorded as total particle counts for a 5 minute period.

It should be noted that the OPC's used the index of refraction of particles to measure their size. Every material has a different index of refraction and an OPC would need to be calibrated to that index of refraction in order to have an accurate measurement. In this case, the OPC's were unable to have their index of refraction adjusted to that of copper oxide. The factory default index of refraction for these OPC's is that of water, so that the measurements taken from the OPC's are not the exact size of the particles present. However, the measurements are internally consistent with themselves. The

OPC data should be seen as a relative measure and not an absolute measure and was primarily used to get a real time measurement of relative number of particles in the chamber and to ensure that the RBG was properly dispensing particles.

The IOM was selected because it is designed to capture the amount of particles that a typical human would breathe in. This research is concerned with the danger that re-aerosolized radioactive particles from a victim's clothing would pose to a medical professional providing care. Radioactive particles that are inhaled also present a hazard to the contaminated individual by significantly increasing the chances of lung and bone cancer (Todorov and Ilieva 2004). Radioactive particles that decay through the release of alpha and beta particles pose little threat outside of the body. Alpha particles can only travel a few inches in air while beta particles can travel several feet in air (Hodnett 1961). However, if radioactive particles enter the body through inhalation or ingestion, they can cause great harm. The IOM is designed so that when it is operation at a flow rate of 2 L/min, it will capture the inhalable fraction of particles (Hinds 1999). An IOM is typically worn on the lapel in the breathing zone of a worker exposed to an aerosol hazard (Zhou and Cheng 2009). After exposure, the IOM filter is then weighed or examined using microscopy to determine the worker's aerosol exposure. In this experiment, the IOM was placed in close proximity to the contaminated ABU's while they were being shaken. The IOM captured the inhalable fraction of the re-aerosolized contamination that a medical worker would be exposed to while working closely with a contaminated patient.

The RBG brush was set to spin at 1200 rpm, the piston was set to rise at a rate of 120 mm per minute while it was fed with 2.4 psi air. It took approximately 25 minutes

for the RBG to dispense the copper oxide powder before shutting off. To account for variability, the IOM was allowed to collect a sample for 30 minutes at 2 lpm sampling flow rate. The OPCs were placed next to each other on the floor of the chamber using the included wire stand and even with the IOM. The IOM was suspended in the center of the chamber 1 meter downwind from the mannequin's feet and 0.66 meter from the pulley.

The RBG dispensed dust into the chamber for 25 minutes. The chamber fans were allowed to run for 30 minutes to allow any dust remaining in the air to settle. After the RBG stopped dispensing dust, the OPC counts in the chamber would typically fall to background levels within a minute. Waiting 5 minutes between the RBG shut off and turning off the chamber fans ensured that any remaining dust contamination in the chamber could settle out.

The fan and RBG were shut off 30 minutes after the start of the contamination. The chamber was then carefully cleaned: the chamber floor that was reachable through the open door was HEPA vacuumed, then the chamber floor, walls, and ceiling were wiped down with a long-handled disposable dust mop (Swiffer™ brand Swiffer mop and Swiffer brand mop pads). All of the equipment inside the chamber was wiped down with a paper towel wetted with ethyl alcohol. The mannequin’s exposed face, hands, and feet were also wiped down with paper towels and ethyl alcohol. All visual contamination was removed from the chamber, while great care was taken to not disturb the mannequin or the uniform. After cleaning, the chamber was allowed to dry for 5 min. The IOM was replaced with a new one and a 30-minute background sample taken. During the background sampling, the chamber fan was left off.

After taking the background sample, the chamber was opened and the IOM was again replaced. The chamber was then resealed and the uniform was shaken for five minutes continuously. The chamber fans were again left off. The uniform was hoisted to the top of the chamber by the pulley system and allowed to fall to the chamber floor. After the uniform hit the floor it was again pulled back to the top of the chamber and released. This was done to simulate expedient clothing removal during the decontamination process. The uniform was pulled upwards at a rate of 61 cm/s. It took approximately 1 second for the uniform to be pulled from the chamber floor to the top of the pulley. After five minutes of shaking, the uniform was left on the bottom of the chamber until the full 30-minute IOM sample had been taken. The IOM collected a full 30 minutes in order to maintain a consistent volume of air being pulled through the filters. Also, this allowed any residual cloud of particles to be collected by the IOM.

After collection, the IOM filters were sputter coated with 10 nm of gold using a Quorum Q150R Plus: Rotary Pumped Coater for Noble Metals Sputtering, then observed under a JEOL scanning electron microscope. Six sites per filter were selected and observed at 1500 times magnification. The microscope used was a JEOL JSM-IT500 controlled using the JEOL Version 1.020 software package. This magnification level was selected because it allowed the microscope to more efficiently perform Energy Dispersive X-Ray Spectroscopy (EDS). The six sites were selected using a pattern determined during pilot runs. Four equally spaced sites around the edges of the filter were selected. Because the IOM filter holder covered the outer 2 mm of the filter during sample collection, the four sites used were 7 mm from the edge to avoid the area that was covered by the filter holder. Two sites 2 mm on either side of the filter's center were also

used, for a total of 6 sites. The microscope provided a low magnification view of the filter; each site was selected before zooming in. Once zoomed in to 1500 times magnification, the microscope operator did not move the field of view. The field of view for each site was 85.33 μm by 64.00 μm for a total area of 5461.12 square μm.

An energy dispersion spectroscopy (EDS) was used on each site in order to confirm that the particles on the filters were in fact copper oxide and no other dust or clothing lint. The EDS works by bombarding a target with X-rays. When excited by the X-rays, each element will give off unique wave lengths of electromagnetic radiation. The peaks of these emissions can be analyzed to determine what elements are present (Nasrazadani and Hassani 2016). The Oxford Instruments X-ManN controlled with Aztec Version 3.3 software was used to perform the energy dispersion spectroscopy. The number of particles per site were counted using the FIJI Image-J image processing software. The average number of particles per site was calculated and recorded for each filter in a spreadsheet.

The ABU uniforms used in the trials were cleaned between trials and reused. The uniforms were first HEPA vacuumed, then washed using a residential washer and dryer. Five pairs of ABU pants and six ABU blouses were used in a continuous rotation so that no one set was used more than the others and the same pants were not paired with the same blouse. Washing the uniforms after every use removed loose uniform fibers and helped to ensured that the particles collected during the trials were the copper oxide contaminate and not uniform particles.

Seven background trials were conducted to ascertain the efficiency of the chamber cleaning methods. In these trials, the mannequin was placed in the chamber in a

clean uniform and contaminated as it was in the normal trials. However, when the chamber was cleaned, the contaminated uniform was removed from the mannequin and replaced with a clean one. The trial then continued as normal. The goal was to ensure that the contamination collected on the IOM was coming off the uniform and was not residual contamination left in the chamber that was being stirred up by the action of shaking the uniform. Shaking a clean uniform in a completely clean chamber should produce an IOM filter with zero copper oxide particles on it. It was noted in these background trials there were a few particles of copper oxide found on the filters. This indicated that the chamber cleaning method used was not 100 percent effective. However, this could then be used as a point of comparison for the normal trial runs.

A total of 18 trials were conducted. The number of trials was determined by conducting a statistical power analysis (Faul et al. 2009) using the software G*Power Version 3.1.9.2. The program was set to calculate the required sample size needed for an independent t-test given an alpha of 0.5, a power of 0.8, and a 2.035 effect size (Hunt 2019). The effect size was calculated using the G*Power software with data from six pilot trials. The mean and standard deviation of the pilot studies were fed into the software to calculate the effect size. The data from the pilot trials is shown in Appendix A and the output from the G*Power software can be seen in Appendix B.

Pilot trials were conducted in order to determine the number of trials needed and used different methods than the final trials protocol. A full uniform was not used during the pilot trials; only a blouse was placed in the chamber and connected to the pulley system so that it could be shaken. The chamber containing the blouse was contaminated with the copper oxide before the blouse was shaken in front of the IOM for 5 minutes.

The chamber was not cleaned between the time that the uniform was contaminated and when the shaking began. Also, the chamber fan was kept running during the shaking process. The protocol to clean the chamber after uniform contamination was not implemented until after the pilot trials that were used for the power analysis. The data for the background pilot trials was also collected differently than the final protocol. For the background trials, the chamber was contaminated with a uniform inside. After the chamber and uniform were contaminated, the IOM samples were then collected while the chamber fans were running. The uniform was not shaken during the background samples and the chamber was not cleaned between trials.

Additional pilot trials were also conducted to determine the viability of gravimetric analysis of the IOM filters instead of using microscopy. These trials were conducted in the same way as the already discussed pilot trials. However, instead of preforming microscopy to visually analyze the filters, the filters were weighed before and after each trial to determine if there was any change in weight. The filters were weighed immediately before a trial and then again immediately afterward. This was done to reduce the likelihood that any weight change observed in the filter was not due to moisture absorbance. The filters were weighed using a XPR2 (Mettler Toledo, Columbus, OH), which is accurate down to the 0.001 mg. It was discovered that there was not a detectable weight difference for the filters before and after the trial because the scale available was not sensitive enough to detect the weight of the copper oxide particles that were deposited on the filter.

The G*Power software showed that 5 trials each would be needed for the background and treatment groups for a total of 10 trials. It was decided to increase the

number of trials to 10 each. This was done to ensure that there would be enough trials in case there were problems or if any trials were invalidated. Due to time constraints, 10 normal treatment trials were conducted and 7 background trials.

IV. Results

The results from this research are broken down into two groups. The data from the IOM and the data from the OPC's were analyzed separately. The results of the study were analyzed using the software PASW statistics 18 release 18.0.0 (30 Jul 2009).

The number of particles counted per site for each of the IOM filters can be seen in Table 2. The number of particles per site for each filter was averaged. The average number of particles per site was what was used in the analysis.

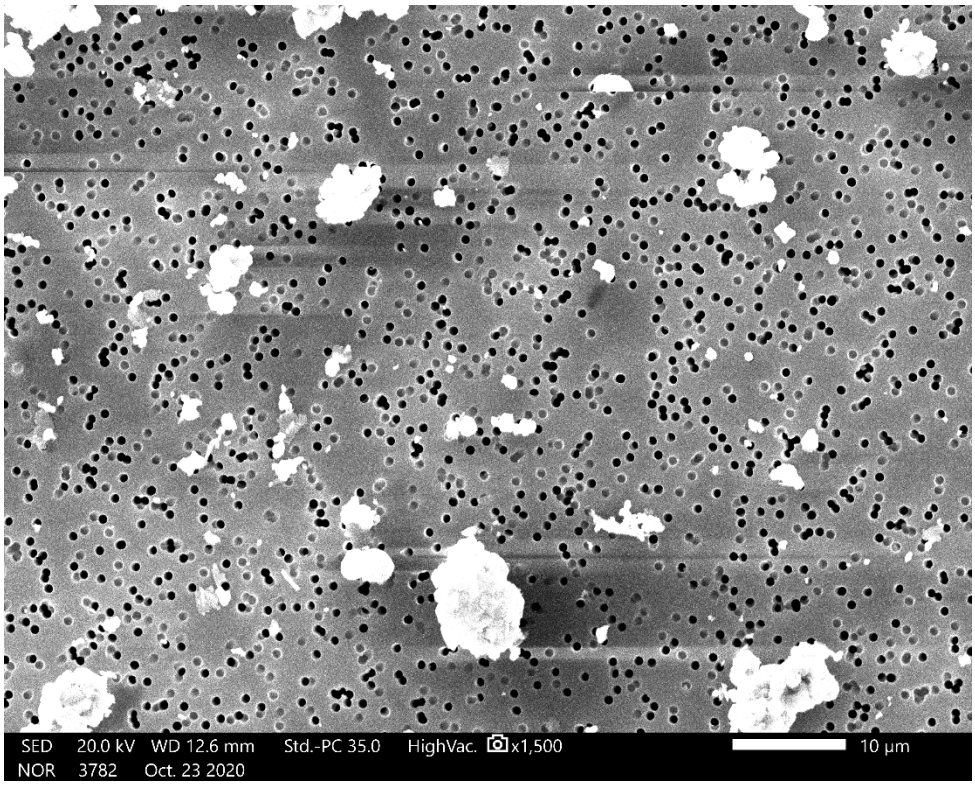
Table 2 - <u>IOM Filters Particle Counts</u>

Number of particles counted on the IOM filters for each of the six sites observed.

Trial	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Avg	Background Trial (Y/N)
2	19	7	23	22	16	19	17.7	N
3	4	8	8	6	8	7	6.8	Y
4	24	22	26	22	20	29	23.8	N
5	5	7	5	2	2	3	4.0	Y
6	12	15	22	17	10	12	14.7	N
7	80	64	83	74	70	84	75.8	N
8	2	4	5	3	5	3	3.7	Y
9	13	14	12	7	11	10	11.2	N
10	3	5	5	7	5	8	6.1	N
11	10	9	21	3	14	5	10.3	N
12	9	10	7	6	6	9	7.8	N
13	12	5	8	6	5	12	8.0	N
14	1	0	1	0	0	0	0.3	N
15	4	3	3	8	3	4	4.2	N
16	1	0	0	3	1	5	1.7	Y
17	5	7	4	1	4	5	4.3	Y
18	0	0	1	0	0	0	0.2	Y
19	0	2	2	5	4	2	2.5	Y

First, the IOM filter results were analyzed for normality, skewness, and kurtosis. Within the PASW software, the explore function under descriptive statistics was used to conduct a Shapiro-Wilk test. This was to determine if the data was normally distributed. It was determined that the background trial data was normally distributed but the treatment trial data was not normally distributed.

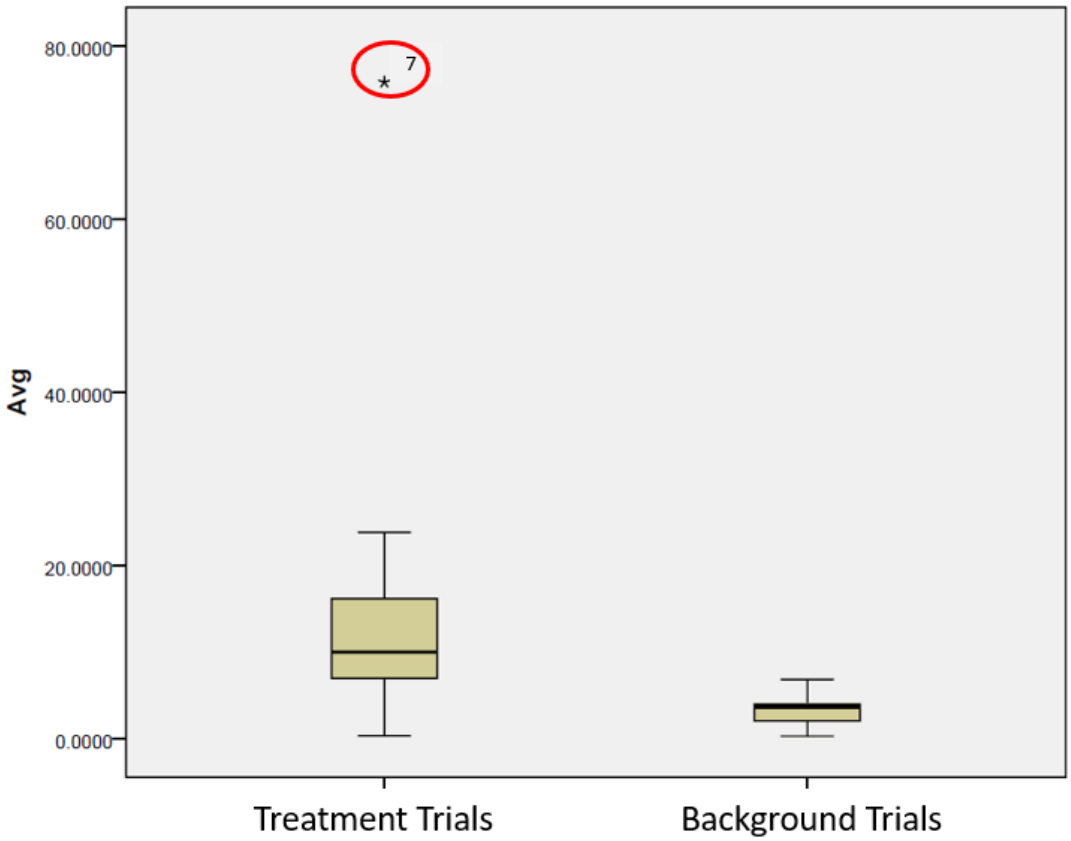
Figure 6 - Electron microscope image of IOM filter at 1500 times magnification. Particles of copper can be seen as irregular white areas on the filter. The small black circles are 0.8 micron holes in the filter.



Using the PASW software, a box plot of the treatment data was constructed, which can be seen in Figure 6. The software noted an outlier in the treatment data. Because the data for trial 7 was three standard deviations above the mean, trial 7 was eliminated from the data as an outlier. The Shapiro-Wilk test was rerun on the new data

with an alpha value of 0.05. The Shapiro-Wilk test showed that the data was now normally distributed. The skewness and kurtosis of the data set was less than one.

Figure 7 - Boxplot of IOM data. Note the start indicating that trial 7 is an outlier.



The IOM filter data was found to be normally distributed after removing the outlier, so an independent t-test was performed. The background trials had a mean of 3.269 (95% confidence interval ± 1.929) and a standard deviation of 2.086. The treatment trials had a mean of 10.364 (95% confidence interval ± 4.902) and a standard

deviation of 6.853. The t-test showed that there was a statistically significant difference between the background group and the treatment group with a p-value of 0.010.

The results of the Energy Dispersive X-Ray Spectroscopy (EDS) analysis can be seen in Table 3. Over 80% of the particles found on the treatment group IOM filters were identified as copper. However, on the background trials' IOM filters, the EDS only identified 41% of the particles as being copper. It is to be expected that not all of the particles found on the IOM filter are copper. Clothing particles and other dust are also present. Finding such a huge difference between the background trials and the treatment trials further strengthens the findings from the t-test. The background trials contained less particles than the treatment trials and a lower percentage of the particles were copper. This further supports the finding that there is re-aerosolization of copper particles from the clothing.

Table 3 - IOM Filters EDS Elemental Analysis Results

Results from the Energy Dispersive X-Ray Spectroscopy analysis of the IOM filters. One site for each IOM filter was analyzed.

Trials	# Cu Particles	# Other Particles	Percent Cu	Background Trial (Y/N)
2	22	3	88.0	N
3	4	2	66.7	Y
4	27	3	90.0	N
5	2	2	50.0	Y
6	10	2	83.3	N
7	41	29	58.6	N
8	1	1	50.0	Y
9	13	2	86.7	N
11	8	3	72.7	N
12	8	3	72.7	N
13	8	3	72.7	N
15	1	0	100.0	N
16	0	1	0.0	Y
17	3	2	60.0	Y
18	0	1	0.0	Y
19	2	1	66.7	Y
Total Avg			63.6	
Treatment Avg			80.5	
Background Avg			41.9	

The data collected from the IOM filters is in terms of particles per observed site. This is not a particularly meaningful or useful number. The IOM filter data can be converted to an air concentration because the flow rate through the filter is known as well as how long the sample was taken. The IOM pump was pulling 2 liters per minute and the samples were taken for 30 minutes. Using the average values, it was determined that

there were 31,617,445,993 particles per cubic meter of air during the treatment trials. During the background trials, the concentration of particles in the air was 9,975,670,436 particles per cubic meter of air.

Table 4 - Change in OPC Bucket Counts

This table shows the change in OPC bucket counts from before shaking the uniform subtracted from the OPC count after shaking.

Trial	0.3 – 0.5 um	0.5 – 1 um	1 – 2.5 um	2.5 -5 um	5 – 10 um	10 – 15 um	15 – 30 um	Background
2	6.00E+07	5.55E+07	3.28E+07	1.38E+07	3.43E+06	8.15E+05	2.28E+05	N
3	5.09E+06	5.19E+06	4.08E+06	2.41E+06	1.05E+06	5.62E+05	2.69E+05	Y
4	3.87E+07	3.52E+07	2.00E+07	6.66E+06	1.20E+06	3.30E+05	1.37E+05	N
5	-1.79E+07	2.88E+06	2.09E+06	1.13E+06	4.40E+05	2.10E+05	2.57E+05	Y
6	8.13E+06	9.75E+06	6.90E+06	2.84E+06	8.32E+05	3.19E+05	2.34E+05	N
7	4.56E+06	6.16E+06	3.95E+06	1.61E+06	3.19E+05	1.76E+05	6.97E+04	N
8	-5.35E+05	2.27E+06	1.94E+06	-8.90E+03	5.32E+06	5.35E+05	1.44E+05	Y
9	1.87E+07	2.03E+07	1.08E+07	3.72E+06	7.80E+05	3.37E+05	1.32E+05	N
10	8.81E+06	9.58E+06	6.28E+06	2.19E+06	5.40E+05	1.74E+05	5.92E+04	N
11	1.04E+07	1.23E+07	7.04E+06	2.58E+06	7.01E+05	2.82E+05	1.42E+05	N
12	1.34E+07	1.84E+07	1.04E+07	3.48E+06	7.83E+05	2.92E+05	1.54E+05	N
13	1.33E+07	1.44E+07	7.06E+06	2.17E+06	4.52E+05	1.12E+05	5.63E+04	N
14	1.13E+07	1.12E+07	6.01E+06	1.83E+06	3.17E+05	9.79E+04	3.41E+04	N
15	1.67E+07	1.60E+07	8.79E+06	2.90E+06	5.80E+05	1.56E+05	6.07E+04	N
16	1.27E+07	2.44E+06	1.71E+06	9.42E+05	3.66E+05	1.67E+05	9.10E+04	Y
17	-1.84E+06	1.22E+06	1.08E+06	5.57E+05	1.90E+05	6.73E+04	2.63E+04	Y
18	-1.05E+07	-6.19E+05	8.70E+05	5.87E+05	2.08E+05	8.53E+04	1.80E+04	Y
19	-7.53E+04	5.94E+05	7.14E+05	4.04E+05	1.44E+05	6.07E+04	3.43E+04	Y

The OPC data that was collected was also analyzed. The raw data can be seen in Appendix B. The OPC readings from before the shaking and 3 minutes into shaking the

uniform was used in the analysis. The readings from before shaking were subtracted from the readings taken 3 minutes in; the change for each bucket can be seen in Table 4. This data was then analyzed using the PASW statistics software. Trials 2 and 4 were discarded because they contained outliers. After removing trials 2 and 4, a Shapiro-Wilk test was conducted on the data. It was found that the data for the 0.3-0.5, 0.5-1, 1-2.5 and 2.5-5 micron buckets were normally distributed. However, the data for the 5-10, 10-15 and 15-30 micron buckets were not normal. Due to this, the 0.3-0.5 through the 2.5-5 micron buckets were analyzed using an independent t-test. It was found that there was a statistically significant difference between the treatment group and the background group. The result of the t-test can be seen in table 5.

Table 5 - <u>OPC Buckets Background vs Treatment with t-test Significance</u>

Difference in OPC buckets for background and treatment group means. The table also shows the result of a t-test to determine if there was a difference in means between the background group and the treatment group. The counts for each bucket are total counts for a 5 minute period.

Bucket	Background Mean	Treatment Mean	Significance
0.3 – 0.5 um	1.17E+07	-1.86E+06	.010
0.5 – 1 um	1.31E+07	2.00E+06	.000
1 – 2.5 um	7.47E+06	1.78E+06	.000
2.5 -5 um	2.59E+06	8.60E+05	.001
5 – 10 um	5.89E+05	1.10E+06	.499
10 – 15 um	2.16E+05	2.41E+05	.785
15 – 30 um	1.17E+07	-1.86E+06	.749

The 5, 10 and 15 micron buckets were found to not be normally distributed. A log transform was used on the data but the data was not able to be made into a normal distribution. This leaves non-parametric analysis. The Mann–Whitney and Kolmogorov-Smirnov non-parametric test is used to determine if there is a statistical difference in the median of two independent non-parametric data sets (Hart 2001). The Mann–Whitney and Kolmogorov-Smirnov tests were not able to show a statistically significant difference between the treatment group and the background group. The result of this test can be

seen in Table 6. For the larger particle bucket sizes, there does not appear to be a statistically significant difference between the treatment group and the background group.

Table 6 - <u>OPC Buckets Background vs Treatment</u>

This table shows the mean for the OPC buckets that did not show significance using parametric testing. The background and treatment means for each bucket and the resulting significant levels for the Mann–Whitney and Kolmogorov-Smirnov tests is shown.

Bucket	Background Mean	Treatment Mean	Mann-Whitney Significance	Kolmogorov-Smirnov Significance
5 – 10 um	7.01E+05	3.66E+05	.189	.177
10 – 15 um	2.82E+05	1.67E+05	.342	.412
15 – 30 um	1.32E+05	9.10E+04	.821	.714

V. Discussion

The results of this research indicate that there is a significant inhalation hazard created by the re-aerosolization of dense particles from clothing. The findings from the IOM samples show that the movement of contaminated clothing produces an aerosol that can be inhaled. The re-aerosolization of particles from the victims' clothing presents a nontrivial hazard and the victims' own movements continue to expose them to an inhalation hazard even after they have left the area of initial contamination. Medical personnel treating the victims of an RDD attack would also be exposed to an inhalation hazard from victims' clothing. Victim decontamination should focus on removing clothing as soon as possible, and procedures should emphasize limiting the amount of movement that the clothing is subjected to and respiratory protection for personnel. Vigorous movement of contaminated clothing should be discouraged during removal and disposal in order to limit the exposure of the victim and the people working the decontamination line.

The data from the IOM shows that there was a significant number of particles re-aerosolized from the clothing during the 5 minutes of shaking. These results are significant because they correspond to the amount of material that a typical person would inhale. Although this research does not closely examine the health effects of inhaled radioactive particles and uses a dense aerosol as a surrogate, any amount of radioactive particles inhaled into the body is a health concern.

There is a statistically significant difference between the number of particles of copper found on the IOM filter between the treatment group and the background group.

This confirms with a reasonable level of statistical significance that an aerosol is generated during clothing removal when contaminated with a dense aerosol. There was some copper found on the background IOM filter. In a perfect experiment, there would be no copper oxide on the IOM filter when a clean uniform is shaken in front of it. The fact that there was a small number of copper particles found on the background IOM is a reflection of the chamber cleaning procedures. The parts of the chamber that could be reached by the researcher were thoroughly cleaned during each trial. However, due to the design of the chamber, a low level of copper particles remained inside. The chamber was cleaned each time using the same procedures so any level of residual copper particles would remain consistent between trials. The EDS analysis preformed on the IOM filters showed that the vast majority of the particles (80%) found on the treatment filters were copper particles. The remaining particles were either too small for the EDS system to identify definitively as copper or they were dust and lint from the uniform. There were less particles found on the background IOM filters and a much lower percentage (41%) of these were copper. This indicates that over half of the particles on the background IOM were lint/dust. In the results section for the IOM filter, no distinction was made for the difference between copper particles and dust/lint. The fact that there was a lower percentage of copper on the background filters provides additional evidence that there was a significant difference between the background trials and the treatment trials.

The OPC data confirms the IOM data. There was a statistically significant difference found between the background trials and the treatment trials. However, the OPC data should be considered a relative measure and not an exact measure of particle size. An OPC uses the index of refraction of a particle to determine its size. Different

materials have different indexes of refraction. The OPC's used were not able to be calibrated for copper oxide and so they were left at their factory default settings. This means that the measurements given by the OPC's are not the actual particle sizes. However, they are accurate relative to themselves. The OPC data should be seen as a relative measure and not an absolute measure. The OPC data for the treatment trials show significantly more particles than the background trials for the 0.3 – 0.5 μm particle buckets. The OPC data for the 5 – 30 μm particle buckets did not show a significant difference between the background and treatment trials. This is consistent with the IOM data because the IOM captures respirable particles. While larger particles up to 100 microns are respirable, the vast majority of those particles are less than 10 microns. If the aerosol being produced by shaking the uniform is a respiratory hazard, it would have many more smaller particles than larger ones. Although the OPC data does not show the exact size range, it does show that there is a significant increase in smaller particles when shaking the uniform.

In the larger size ranges for the OPC, there is no statistically significant difference between the background and treatment groups. This is not necessarily cause for concern. Several factors likely contributed to this outcome. The copper oxide particles that were used each have a Mass Median Diameter (MMD) of 20 μm. Particles over 20 μm contribute 50% of the mass but they do not represent 50% of the particles present. Larger particles have more mass and so less are needed to reach the same mass as smaller particles. This means that the Count Median Diameter (CMD) is much lower than 20 μm. The CMD is the median based on the number of particles, not weight. The geometric standard deviation (σ_g) of the copper particles used was not obtained. However, if we

assume a relatively average geometric standard deviation (σ_g) of 2, then the CMD can be calculated. Using equation 4.47 form Hinds, it is found that the CMD is 8 μm (Hinds 1999).

$$MMD = CMD \exp\left(b\ ln^2 \sigma_g\right)$$

$$20 = CMD \exp(3\ ln^2(2))$$

$$20 = CMD \exp(1.44\ 1)$$

$$20^{\left(\frac{1}{1.441}\right)} = CMD$$

$$CMD = 7.996$$

Larger particles are less likely to re-aerosolize in the first place. The lift force on the particle must exceed the force of gravity holding it down. Also, larger particles will settle out more quickly and would be less likely to be collected by the OPC.

This research has identified that re-aerosolization of dense aerosols from clothing is a hazard. The OPC and IOM data shows that the particles that are re-aerosolized are small and within the respirable range; they are the ideal size to be deeply inhaled into the lungs. Because radioactive particles deep in the lung are the most damaging, the decontamination process should seek to minimize the number of particles that are re-aerosolized. This means that clothing should be removed with a minimum of shaking and clothing should not be dropped or tossed into disposal containers. In order to mitigate the inhalation threat from re-aerosolization, the victim can put on a disposable N95 mask before the clothing removal step. This would be a quick and cheap way to minimize the

re-aerosolization threat. Also, if decontamination activities are occurring indoors or in a tent, the air should be HEPA filtered to remove any re-aerosolized contamination.

In this research, the contaminated clothing was shaken vigorously for 5 minutes. This amount of shaking was selected to simulate a worst-case scenario and designed to simulate an expedient decontamination process seen during a mass casualty event or the removal of clothing from a critically injured patient. However, a real-world decontamination line situation may not allow for the gentle removal of a victim's clothing.

ABU uniforms were used in this experiment, as opposed to CBRN personal protective equipment, because in a real world RDD attack the victims would likely be caught unprepared and wearing everyday clothing. The open weave of uniforms and civilian cloths would act to trap small particles within the fabric and reduce the amount of small particles that are aerosolized. Also, some fabrics are more prone to becoming electrically charged. The static electricity produced by certain fabrics would keep particles stuck to the clothing. Specially designed protective suits made of plastic or rubber material do not have fibers to trap particles and could have more particles re-aerosolize from their surface.

Further research should investigate techniques for expedient clothing removal that minimizes re-aerosolization. Wetting the victim's clothing before removal would likely reduce the amount of re-aerosolization from the clothing by making the particles of contamination stick to each other as well as the clothing. This is similar to the practice of spraying dirt roads with water to keep down dust. The use of different clothing types should be tested to see what materials would minimize the re-aerosolization hazard from

protective gear. This experiment could be rerun using Tyvek suits or JSLIST's to determine the re-aerosolization risk from these materials.

The methods developed during the course of this research can be applied to future aerosol investigations using the same test chamber. The setup used in this research can easily be adapted to investigating the re-aerosolization properties of different types of particles. Other RDD threat materials like plutonium and uranium oxides are much denser the copper oxide used in this experiment. Tungsten and Bismuth powders are cheap available and non-toxic. Their densities are 19.3 g/cm^3 and 9.78 g/cm^3 respectively.

The particle sizes used in for this experiment were selected based on the threat of a well-designed RDD using ideally sized particles. In the RDD test conducted by the Canadian Ministry of Defense, the median particle diameter was under 25 microns which would represent a well-designed RDD. In a real-world RDD, an attacker is likely to use whatever radioactive material that is available so it is unlikely to be a sophisticated RDD design. The actual threat from a real-world RDD could be significantly less than a well-designed RDD using finely ground particles. Radioactive material that is in large pieces would be less effectively dispersed by an explosion than a finely ground particulate.

During the course of this research operational limits on the test chamber were observed. During the early pre-trial phase of this research, it was found that facing the RBG outlet downwind while the chamber fan was running did not produce any significant readings on the OPC or IOM. However, when the RBG outlet was faced into the wind, the OPC and IOM were able to detect copper particles. It was discovered that when the outlet faced down wind, the force of the airstream would carry the particles

through the chamber in a thin jet without dispersing them. When facing the RBG outlet into the airstream complete aerosol mixing was achieved within the chamber and ensured that the mannequin and clothing were thoroughly exposed to the copper oxide.

VI. Conclusion

The most significant finding of this research is that dense particles in the inhalable range can be re-aerosolized from clothing. This data was obtained using an IOM, which is designed to capture particles that the average person would inhale. A statistically significant difference was found between the uniforms that were contaminated and shaken next to the IOM and the clean uniforms shaken next to the IOM.

The filters from the IOM were examined under an electron microscope to determine the number of particles that were present. Also, Energy Dispersive X-Ray Spectroscopy (EDS) was used to confirm that the particles that were present were the copper oxide used to contaminate the uniform. This allowed for the differentiation between the simulated radioactive contamination and lint/dust from the clothing.

The copper oxide used for this research most closely simulates strontium 90 because they are of a similar density. Also, the copper oxide is in the ideal particle size range for use in an RDD. Strontium 90 is a prime candidate for use in the construction of an RDD and there are significant unsecured sources from which terrorists could source material.

Future research should look into using different techniques for minimizing the re-aerosolization threat. Future work can study the effects of wetting clothing before removal and the use of different clothing materials.

When conducting decontamination operations for victims that have been exposed to radioactive contamination, there is a significant threat of re-aerosolizing the

contamination that is on the victims' clothing. Measures need to be taken to protect the victims, first responders, and medical personnel from this hazard.

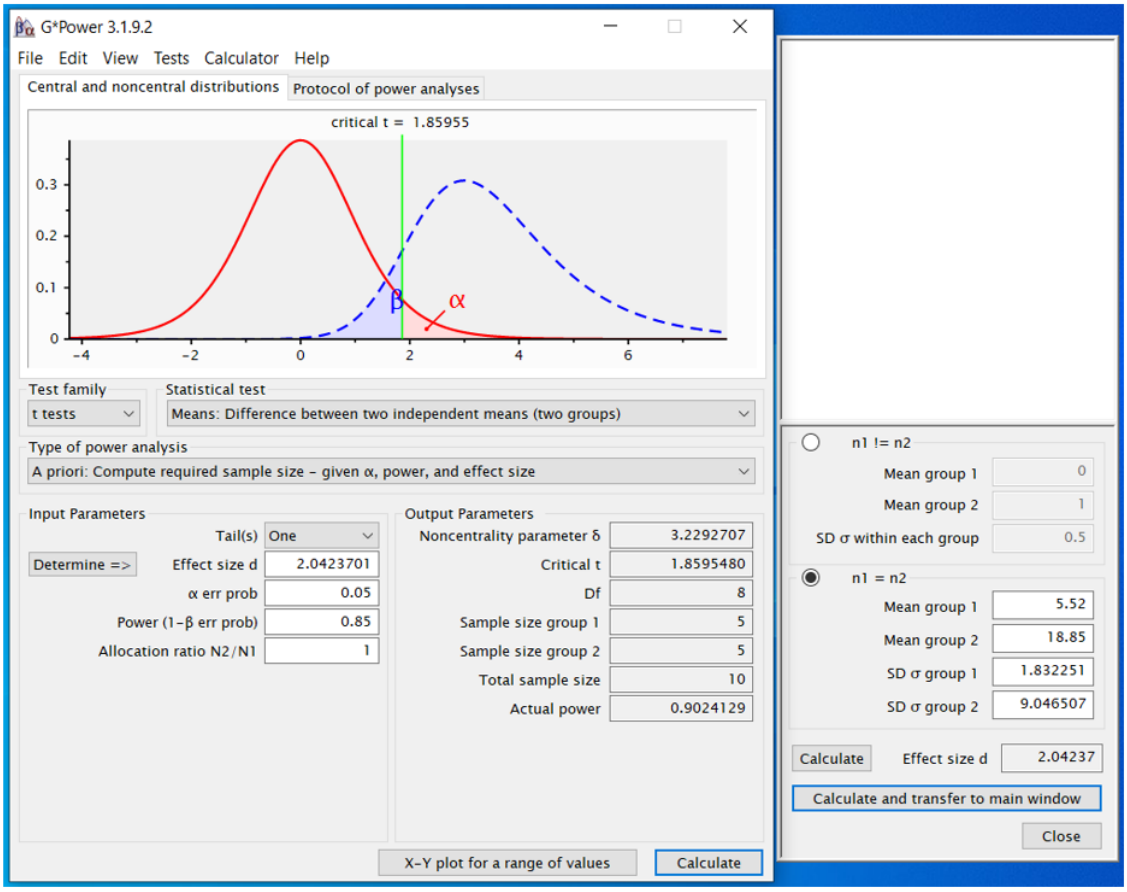
Appendix A

This table shows the results of the pilot trials conducted. The data was then used to conduct a statistical power analysis to determine the number of trials needed for the experiment.

Background Trial	Number of Particles per site		
1	6		
1	4		
1	3		
1	7		
2	8		
2	3		
2	5		
2	6		
3	3		
3	5		
3	4		
3	7		
		mean	5.0833
		SD	1.7298
Treatment Trial	Number of Particles		
1	5		
1	20		
1	26		
1	16		
2	12		
2	16		
2	21		
2	35		
3	29		
3	12		
3	28		
3	6		
		mean	18.833
		SD	9.3985

Appendix B

This print out shows the output of the G*Power statistical power analysis software.



Appendix C

0.3 – 0.5 Micron OPC Bucket

Trial	Before Shaking	After 3 min of Shaking	Change
3	26,494,836.00	31,581,924.00	5,087,088.00
5	17,934,312.00	20,506.00	-17,913,806.00
6	33,567,960.00	41,697,648.00	8,129,688.00
7	65,565,036.00	70,127,536.00	4,562,500.00
8	39,140,844.00	38,606,004.00	-534,840.00
9	28,236,624.00	46,965,248.00	18,728,624.00
10	26,366,804.00	35,178,560.00	8,811,756.00
11	26,643,372.00	37,011,256.00	10,367,884.00
12	37,866,048.00	51,235,240.00	13,369,192.00
13	15,992,950.00	29,269,472.00	13,276,522.00
14	14,234,544.00	25,538,152.00	11,303,608.00
15	9,874,932.00	26,562,688.00	16,687,756.00
16	102,890.00	12,839,770.00	12,736,880.00
17	52,477,600.00	50,638,908.00	-1,838,692.00
18	57,895,256.00	47,398,432.00	-10,496,824.00
19	21,603,072.00	21,527,760.00	-75,312.00

0.5 – 1 Micron OPC Bucket

Trial	Before Shaking	After 3 min of Shaking	Change
3	9,009,760.00	14,202,456.00	5,192,696.00
5	3,515,101.00	6,393,141.00	2,878,040.00
6	14,743,488.00	24,492,476.00	9,748,988.00
7	3,887,133.00	10,049,846.00	6,162,713.00
8	3,458,432.00	5,726,264.00	2,267,832.00
9	2,644,123.00	22,909,066.00	20,264,943.00
10	1,954,701.00	11,535,790.00	9,581,089.00
11	2,601,900.00	14,852,036.00	12,250,136.00
12	4,282,181.00	22,634,936.00	18,352,755.00
13	2,968,207.00	17,408,628.00	14,440,421.00
14	1,327,005.00	12,518,014.00	11,191,009.00
15	1,320,593.00	17,297,460.00	15,976,867.00
16	1,779,506.00	4,221,521.00	2,442,015.00
17	5,135,886.00	6,352,403.00	1,216,517.00
18	6,243,422.00	5,624,697.00	-618,725.00
19	6,466,496.00	7,060,791.00	594,295.00

1 – 2.5 Micron OPC Bucket

Trial	Before Shaking	After 3 min of Shaking	Change
3	1,574,132.00	5,657,653.00	4,083,521.00
5	527,681.00	2,621,835.00	2,094,154.00
6	3,799,427.00	10,697,860.00	6,898,433.00
7	645,006.00	4,590,350.00	3,945,344.00
8	649,735.00	2,588,680.00	1,938,945.00
9	612,398.00	11,422,193.00	10,809,795.00
10	209,022.00	6,489,625.00	6,280,603.00
11	401,503.00	7,442,067.00	7,040,564.00
12	708,888.00	11,063,640.00	10,354,752.00
13	503,952.00	7,566,350.00	7,062,398.00
14	230,185.00	6,242,416.00	6,012,231.00
15	268,671.00	9,061,098.00	8,792,427.00
16	251,222.00	1,960,073.00	1,708,851.00
17	796,836.00	1,875,980.00	1,079,144.00
18	1,121,789.00	1,991,775.00	869,986.00
19	1,206,133.00	1,919,859.00	713,726.00

2.5 – 5 Micron OPC Bucket

Trial	Before Shaking	After 3 min of Shaking	Change
3	328,968.00	2,739,839.00	2,410,871.00
5	108,688.00	1,234,633.00	1,125,945.00
6	1,027,953.00	3,863,981.00	2,836,028.00
7	178,021.00	1,786,409.00	1,608,388.00
8	142,607.00	133,709.00	-8,898.00
9	129,906.00	3,850,763.00	3,720,857.00
10	53,610.00	2,247,610.00	2,194,000.00
11	103,629.00	2,680,739.00	2,577,110.00
12	156,524.00	3,638,561.00	3,482,037.00
13	100,148.00	2,275,037.00	2,174,889.00
14	66,066.00	1,895,295.00	1,829,229.00
15	61,964.00	2,962,853.00	2,900,889.00
16	44,034.00	985,600.00	941,566.00
17	136,824.00	694,095.00	557,271.00
18	270,336.00	857,096.00	586,760.00
19	205,768.00	609,447.00	403,679.00

5 – 10 Micron OPC Bucket

Trial	Before Shaking	After 3 min of Shaking	Change
3	23,570.00	1,077,591.00	1,054,021.00
5	15,526.00	455,474.00	439,948.00
6	109,930.00	941,789.00	831,859.00
7	144,835.00	463,774.00	318,939.00
8	15,994.00	5,339,709.00	5,323,715.00
9	129,906.00	909,637.00	779,731.00
10	4,517.00	544,045.00	539,528.00
11	10,790.00	711,686.00	700,896.00
12	20,582.00	803,289.00	782,707.00
13	9,835.00	462,002.00	452,167.00
14	12,164.00	329,138.00	316,974.00
15	8,771.00	589,018.00	580,247.00
16	2,164.00	368,044.00	365,880.00
17	7,874.00	197,437.00	189,563.00
18	25,486.00	233,753.00	208,267.00
19	13,145.00	157,426.00	144,281.00

10 – 15 Micron OPC Bucket

Trial	Before Shaking	After 3 min of Shaking	Change
3	2,562.00	564,230.00	561,668.00
5	2,866.00	213,295.00	210,429.00
6	13,632.00	333,010.00	319,378.00
7	1,290.00	177,180.00	175,890.00
8	3,604.00	538,215.00	534,611.00
9	11,663.00	348,344.00	336,681.00
10	1,204.00	175,275.00	174,071.00
11	2,226.00	284,026.00	281,800.00
12	3,279.00	295,634.00	292,355.00
13	1,490.00	113,702.00	112,212.00
14	3,146.00	101,027.00	97,881.00
15	2,146.00	158,330.00	156,184.00
16	721.00	167,850.00	167,129.00
17	984.00	68,312.00	67,328.00
18	2,378.00	87,657.00	85,279.00
19	1,278.00	61,986.00	60,708.00

15 – 30 Micron OPC Bucket

Trial	Before Shaking	After 3 min of Shaking	Change
3	0.00	269,006.00	269,006.00
5	1,306.00	257,827.00	256,521.00
6	1,390.00	235,204.00	233,814.00
7	0.00	69,731.00	69,731.00
8	2,223.00	146,123.00	143,900.00
9	548.00	133,025.00	132,477.00
10	283.00	59,440.00	59,157.00
11	329.00	142,524.00	142,195.00
12	553.00	154,605.00	154,052.00
13	147.00	56,495.00	56,348.00
14	991.00	35,064.00	34,073.00
15	282.00	60,995.00	60,713.00
16	0.00	90,961.00	90,961.00
17	0.00	26,330.00	26,330.00
18	688.00	18,648.00	17,960.00
19	185.00	34,525.00	34,340.00

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14. ABSTRACT
Radiological contamination from nuclear accidents or the terrorist use of a Radiological Dispersal Device (RDD) are events that first responders must be prepared for. It is currently assumed that removal of the victims' clothing will remove 80-90% of contamination. Many RDD radioisotopes produce dense aerosols that would then contaminate victim clothing and re-aerosolize during clothing removal. A series of experiments were conducted during which clothing was contaminated with a dense aerosol simulating the radioisotope of Strontium 90. Compared to background, there was statistically significant re-aerosolization from the clothing. This demonstrates inhalation hazards from re-aerosolization of RDD contamination.

15. SUBJECT TERMS
AIRMEN BATTLE UNIFORM, CBRN, CHAMBER, CLOTHING, DECONTAMINATION, COPPER OXIDE, DENSE AEROSOL, ENERGY DISPERSIVE X-RAY, METAL, MICROSCOPY, MILITARY, OPTICAL PARTICLE COUNTER, UNIFORM, RADIOLOGICAL, RE-AEROSOLIZATION, RADIOLOGICAL DISPERSAL DEVICE

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