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Analysis Of Non-Conventional Radiological Terrorism

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ANALYSIS OF NON-CONVENTIONAL RADIOLOGICAL TERRORISM

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LIST OF ABBREVIATIONS

ALARA: As Low as Reasonably Attainable

ARS: Acute Radiation Sickness

CDC: Center for Disease Control

GI: Gastrointestinal

IAEA: International Atomic Energy Agency

ICRP: International Commission on Radiological Protection

KGB: Komitet Gosudarstvennoy Bezopasnosti

MCNP: Monte Carlo N-Particle Transport Code

PET: Positron Emission Tomography

RDD: Radiological Dispersal Device

RTG: Radioisotope Thermoelectric Generator

Vised: Visual Editor

ABSTRACT

Nuclear terrorism has been a risk since the dawn of the first atomic bomb. Though state sponsored nuclear weapons development is of concern for countries, non-state sponsored terrorism with radiological material can be of even greater concern. This stems from the fact that the material is under less stringent or no safeguards and can readily change hands between different terrorist groups or innocent civilians may accidently come into contact with the material.

Within this paper an analysis of previous accidents using orphan radiological sources, malicious use of orphan radiological sources, and how these sources could be used by terrorists is analyzed. Literature pertaining to doses received during theoretical dirty bomb attacks is reviewed and compared to potential consequences to the human body.

With this review of literature complete, a methodology is created to generate realistic scenarios in which a non-conventional nuclear terrorist attack using radiological material could be carried out. These scenarios are re-created in MCNP models to quantify dose estimates civilians would receive. These scenarios include a source placed under a metro seat, a particulate source distributed in a children's sandbox, a source placed in a government building waiting room, and a source placed in a bush next to a line at a theme park. These scenarios are designed to analyze changing different aspects of the situation to show how different sources, shielding, time, and placement could affect the dose and effectiveness of a terrorist attack. The scenarios showed that the individuals in the subway model and waiting room models received the highest dose with the sandbox model receiving the third highest dose and the theme park line receiving the lowest dose.

These results are later discussed and the potential impact an attack of this type could have to those exposed. This ranges from medical impacts, such as acute radiation sickness, birth defects, increased cancer rates, economic impacts to society, and civil turmoil from a distrustful public. Lastly, a means of countering such an attack is analyzed from detection to prevention. This in total provides a comprehensive review of how an attack could occur, motives for such an attack, the impact of said attack, and how to prevent or mitigate the consequences of the attack.

1. INTRODUCTION

1.1 MOTIVATION

Nuclear terrorism has been a risk since the dawn of the first atomic bomb. Though state sponsored nuclear weapons development is of concern for countries, non-state sponsored terrorism with radiological material can be of even greater concern. This stems from the fact that the material is under less stringent or no safeguards and can readily change hands between different terrorist groups or innocent civilians may accidently come into contact with the material.

By definition, nuclear terrorism is the employment of nuclear or radiological weapons by a terrorist group [1]. This can either be by stealing nuclear weapons or acquiring the materials to make a crude nuclear weapon or dirty bomb [1]. A dirty bomb, or radiological dispersal device (RDD) is a device that combines a conventional explosive with radioactive material with an aim to create anxiety and contaminate locations [2]. However, there is an even simpler method that has been used before. Rather than require explosive devices and means of detonation, a terrorist group can instead simply use the radioactive material as is and leave it in an area they desire to target [3]. In this way they do not need to rely on an explosive detonating, and instead rely on the danger from the passive radiation being emitted from the material [3].

A terrorist organization may choose this method for several reasons. First it is less expensive and far simpler than building a nuclear weapon, stealing a nuclear weapon, or building a dirty bomb [4]. Next, the ability to get larger groups of individuals sick before authorities are alerted to and able to locate the irradiation device makes it of prime interest to groups more interested in causing mass panic and building anxiety [4]. And finally, it’s an extremely easy task to take an orphan medical source and place it in a location where large groups of people would be exposed to it and potentially become sick [4].

These scenarios present a clear and present danger to the public. Furthermore, the problem is exasperated by the loss of orphan source on a daily basis [5] [6] [7]. With relatively easy access to high activity radiological material, and only needing a low skill set to hide the material, the use of this non-conventional radiological terrorism approach is extremely tempting to most terrorist groups [4].

1.2 OBJECTIVE

The primary objective of this study is to analyze the potential damage caused by a non-conventional radiological attack and how to prevent or mitigate one. This will involve manipulating the source, its surroundings, and time of exposure. By varying these factors, the dose can be determined for each situation and then compared to known medical literature for acute radiation sickness (ARS). Once a clear danger is shown, this study will discuss the impacts on public trust and subsequent panic that would arise upon the discovery of this attack. After having determined potential doses, and consequences, means of mitigation and/or prevention of an attack will be reviewed. This will clearly warrant analysis due to the dangerous and non-conventional nature of this type of attack.

1.3 BACKGROUND

1.3.1 CONVENTIONAL NUCLEAR TERRORISM

Conventional nuclear terrorism, for the sake of this thesis, encompasses any method that employs explosive force as a means of distribution or destruction. Essentially, either classic nuclear weapons (hydrogen bombs, thermonuclear weapons, fission weapons, etc.) or dirty bombs (RDDs). Both classic nuclear weapons and dirty bombs are appealing to terrorist for the amount of damage and contamination they produce and the sheer psychological and economic damage they do [4]

A dirty bomb is a RDD that uses a conventional explosive (C4, dynamite, TNT, etc.) to detonate a device that contains a readily dispersed radionuclide. The intent being to contaminate a large area, and cause physical damage from the explosive. The actual chance of dying from the resulting radiation is relatively low due to the overt nature of the explosion and civilians quickly dispersing from the area [4]. This of course depends on the radionuclide used and the type of radiation released by said radionuclide.

1.3.2 NON-CONVENTIONAL RADIOLOGICAL TERRORISM

For the purposes of this study, non-conventional radiological terrorism is any terrorism that does not involve the creation of a nuclear weapon or a dirty bomb. This type of terrorism would instead rely on fixed radioactive material to passively expose a large amount of people to induce acute radiation sickness or increase the likelihood of cancer [3]. The means of where this material is located could greatly vary [4] and its form when used could equally vary.

1.4 LAYOUT OF THESIS

This thesis consists of five chapters. The first is an introduction and general background on the topic of non-conventional radiological terrorism and relevant subjects, such as orphan sources and previous radiological accidents. The second chapter is a literature review of relevant material. Since the topic of non-conventional radiological terrorism isn't well studied, the majority is spent on adjacent subjects, dirty bombs and radiological accidents, that lend insight into potential doses and modeling techniques. The third chapter is a discussion on the methodology consisting of a model-based approach in

Monte Carlo N-Particle Transport Code (MCNP) and results reported as doses to extremities, torso, and whole body. The fourth chapter is the results and discussion section. Here results from the MCNP models will be reported and then discussed with relevant context such as appropriate medical literature regarding ARS, potential economic impact, and mental strain. This will help illustrate the potential damage and long-lasting effects of a non-conventional nuclear attack well beyond the actual radiation doses received. This chapter will end with discussing how to mitigate or even stop non-conventional radiological attacks from occurring. Finally, the fifth chapter concludes the study discussing the potential threat presented by a non-conventional radiological attack, and reasserting the clear and present danger. The chapter is concluded with a discussion on future works and how this study can be expanded and additional details added for an even more comprehensive review.

2. LITERATURE REVIEW

2.1 NUCLEAR SOURCES

2.1.1 INDUSTRIES AND NUCLEAR SOURCES

Radioisotopes are attractive for use in a variety of nuclear and non-nuclear industries thanks to several key properties [7]. Most notably radionuclides generally have a distinct type and energy level of radiation they produce when they decay. As such, they are often easily distinguished from background radiation even in low concentrations [8]. Some radionuclides, like ^{238}Pu, give off large amounts of thermal heat during decay, and thus can be used as radioisotope thermoelectric generator (RTG), as shown in Fig. 1 [8].

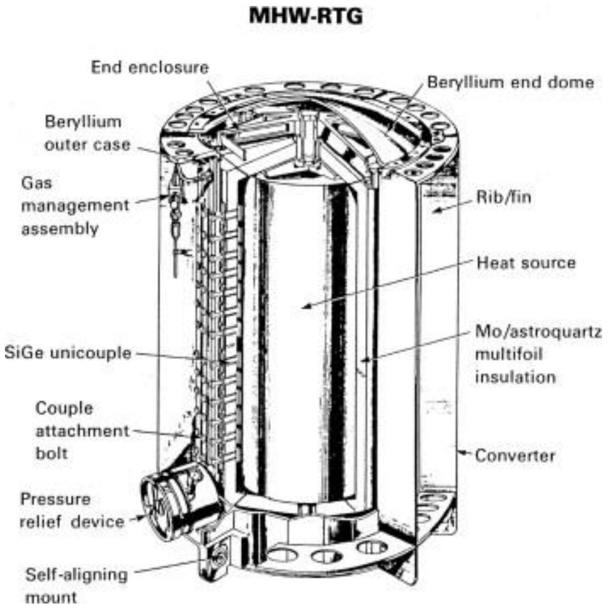


Fig. 1 Radioisotope thermoelectric generator simplified diagram [9]

Other isotopes, such as ^{144}Ce, ^{137}Cs, and ^{90}Sr share this same property and can also be used as RTGs [8]. However, some radionuclides such as ^{60}Co have an extremely high gamma ray emission (1.173 MeV and 1.333 MeV) whilst having a relatively long half-life of 5.27 years compared to most isotopes that decay with a high energy gamma ray emission [8]. Because of this, it is easy to see that these radionuclides have a wide variety of uses in industry [8].

Within the medical industry, radioisotopes have been in use since the 1950s, with ^{60}Co being used for cancer treatment and before then radium being used prior to higher voltage x-ray machines [10]. ^{131}I, ^{103}Pd, and ^{192}Ir, to name a few are used in brachytherapy (sealed sources) to be placed, either permanently or temporarily, within the body [7]. Medical radionuclides also have practical uses in diagnostic imaging such as in positron emission tomography (PET) scans using ^{18}F tracers [7]. Within the agricultural industry, radioisotopes can be used to deliver high doses to help kill pathogens and extend the shelf life, determine the strength of fertilizers, and help mutate plants for bioengineering purposes [7]. Within more standard industry radionuclides are used for non-destructive testing purposes to find leaks in pipes, defective welds, or measure the fill heights within containers that do not allow for direct measurement (nucleonic gauges) [7].

This is an extremely small list of the former, current, and future potential uses of radionuclides. However, they all possess two common facts. First, they all possess a half-life and thus with time will lose activity. In some applications, such as diagnostic imaging or cancer treatment, this requires the sources be replaced. But even at a lower level of activity, the radiation doses for exposed periods can still be well above safe limits [11]. Thus, even a "used" source is still potentially deadly. This leads to the second fact, that for those that require disposal, they are generating nuclear waste, in non-nuclear industries [7]. Though the dangers of radiation are blatantly obvious to any worker in the nuclear industry, the same cannot be said for those outside of it. It would be assumed that training and proper licensing from nuclear regulatory bodies would be enough to ensure these sources are not mishandled or lost. However, time and time again, this has and continues to be proven false [12] [11] [13] [10].

2.1.2 ORPHAN SOURCES

An orphan source refers to a sealed radioactive source that is not in the control of a specific licensed entity or unable to be safely controlled by the entity that possesses it [14]. However, these sources don't start orphaned. Typically, a licensed entity will no longer need a source and put it into long term storage with no plans for disposal. As a result of change over in ownership, documentation being lost, or theft, these sources become orphaned. An example of a potential orphan source is shown in Fig. 2. As discussed in section 2.3.3 A similar Gammacell was lost in Mayapuri India causing the death of one person. One would expect those who have a license to posses' radioisotope sources would follow proper guidelines and would believe this to be a somewhat isolated issue. However, expensive and limited disposal options lead to sources becoming orphan far more frequently than one may anticipate.

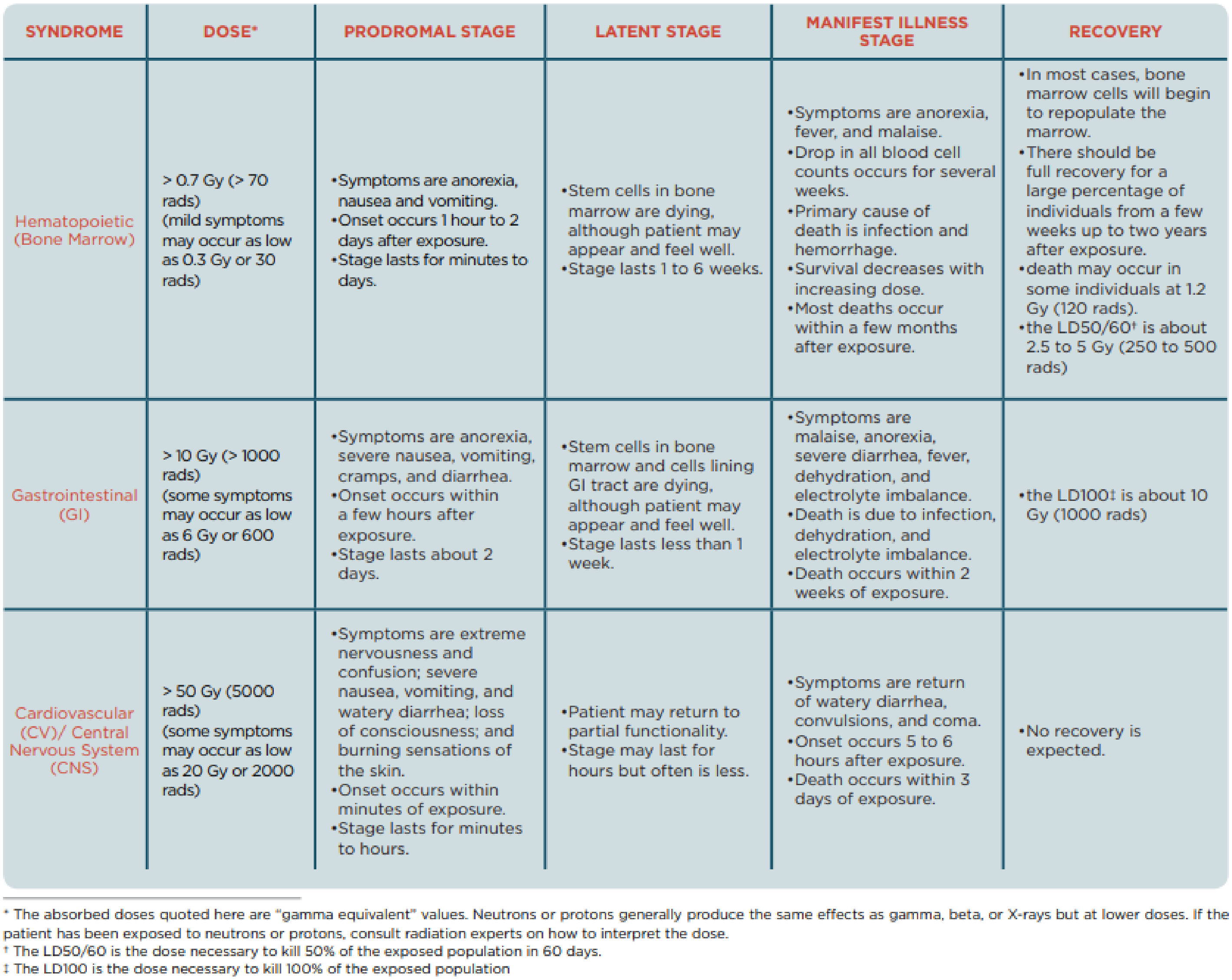
Fig. 2 Sandia Lab Gammacell 220 from AECL [15]

Within the United States alone there is an estimated 2,000,000 radioactive sources, of which 500,000 are no longer used or wanted [16]. Of this, approximately 375 sources are reported lost, stolen, or abandoned per year, though it is likely this number is higher for the total number of orphaned sources as this is only based on the reported number [16]. Again, this is only in the United States. Nations like Russia and former soviet bloc countries contain a large number of orphan sources resulting from industrial activity by the former Soviet Union [17]. Nations that deal with large amounts of scrap metal, such as India or Thailand, are also at high risk, as the scrappers may inadvertently take scrap metal and begin processing it without the realization that it is in fact radioactive [18] [11]. One source of radioactivity in material commonly targeted by metal scrappers are old RTGs. These were widely used in the Soviet Union to power remote unmonitored locations including lighthouses, radio stations, environmental monitoring stations, and other remote structures that required power. In particular Rosatom reports there are 651 RTGs in Russia alone subject to decommissioning, 200 of which are located in lighthouses [19]. However, this is only in the Russian Federation. Many of the former soviet states still have radioactive sources, including ^{90}Sr RTGs. In Georgia alone around 300 radioactive sources have been recovered since the mid-1990s [19]. Many of these sources were discovered by accident with metal looters who find RTGs and try to take the metal surrounding it for money. The radioactive cores may be discarded in random locations, with the looters not realizing the danger they present. These have been found at bus stops, in forests, and some sources were found in piles of dirt and workbench drawers [19].

2.2 Health Effects of Radiation Exposure.

The effects of radiation on the human body are subject to dose, type, if external or internal exposure occurred, amount of time exposed, and what part of the body was exposed to name a few of the factors [10] [20]. However, there are general dose levels where one can begin to expect specific effects.

Table 1 CDC Acute Radiation Syndrome table [21]



SYNDROME	DOSE*	PRODROMAL STAGE	LATENT STAGE	MANIFEST ILLNESS STAGE	RECOVERY
Hematopoietic (Bone Marrow)	> 0.7 Gy (> 70 rads) (mild symptoms may occur as low as 0.3 Gy or 30 rads)	•Symptoms are anorexia, nausea and vomiting. •Onset occurs 1 hour to 2 days after exposure. •Stage lasts for minutes to days.	•Stem cells in bone marrow are dying, although patient may appear and feel well. •Stage lasts 1 to 6 weeks.	•Symptoms are anorexia, fever, and malaise. •Drop in all blood cell counts occurs for several weeks. •Primary cause of death is infection and hemorrhage. •Survival decreases with increasing dose. •Most deaths occur within a few months after exposure.	•In most cases, bone marrow cells will begin to repopulate the marrow. •There should be full recovery for a large percentage of individuals from a few weeks up to two years after exposure. •death may occur in some individuals at 1.2 Gy (120 rads). •the LD50/60† is about 2.5 to 5 Gy (250 to 500 rads)
Gastrointestinal (GI)	> 10 Gy (> 1000 rads) (some symptoms may occur as low as 6 Gy or 600 rads)	•Symptoms are anorexia, severe nausea, vomiting, cramps, and diarrhea. •Onset occurs within a few hours after exposure. •Stage lasts about 2 days.	•Stem cells in bone marrow and cells lining GI tract are dying, although patient may appear and feel well. •Stage lasts less than 1 week.	•Symptoms are malaise, anorexia, severe diarrhea, fever, dehydration, and electrolyte imbalance. •Death is due to infection, dehydration, and electrolyte imbalance. •Death occurs within 2 weeks of exposure.	•the LD100‡ is about 10 Gy (1000 rads)
Cardiovascular (CV)/ Central Nervous System (CNS)	> 50 Gy (5000 rads) (some symptoms may occur as low as 20 Gy or 2000 rads)	•Symptoms are extreme nervousness and confusion; severe nausea, vomiting, and watery diarrhea; loss of consciousness; and burning sensations of the skin. •Onset occurs within minutes of exposure. •Stage lasts for minutes to hours.	•Patient may return to partial functionality. •Stage may last for hours but often is less.	•Symptoms are return of watery diarrhea, convulsions, and coma. •Onset occurs 5 to 6 hours after exposure. •Death occurs within 3 days of exposure.	•No recovery is expected.

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* The absorbed doses quoted here are "gamma equivalent" values. Neutrons or protons generally produce the same effects as gamma, beta, or X-rays but at lower doses. If the patient has been exposed to neutrons or protons, consult radiation experts on how to interpret the dose.

† The LD50/60 is the dose necessary to kill 50% of the exposed population in 60 days.

‡ The LD100 is the dose necessary to kill 100% of the exposed population

Before explaining some of the nuances of Table 1 it's important to explain the units of measurement for radiation. First is the gray. The gray is an SI unit, and used throughout the world [20]. One Gray (Gy) is equal to an absorbed dose per unit mass, imparted by ionizing radiation, of one joule per kilogram [20]. The non-SI equivalent is the Rad. One Gray is equal to 1000 Rad. It is only used in the United States nuclear industry [10]. A Rad is defined as the amount of energy required to release 100 ergs per gram of matter [10]. One erg is defined as 10^{-7} Joules, or 100 nJ [10]. And lastly the Rem. A Rem, Röntgen equivalent man, like the Rad, is defined as the energy required to release 100 ergs per gram of matter. However, there is an important distinction, and that is that a Rem is multiplied by a weight factor [10]. The weight factor is a multiplication factor designed to account for the effectiveness of different types of radiation to penetrate organic matter [20]. That is why the Rem is used for determining the Equivalent Dose received, rather than just the Absorbed Dose. However, the SI unit for the Equivalent Dose is the Sievert (Sv) which is also defined as joule/kilogram, like the Gray. However, the Sievert is determined using weight factors based on known interactions of biological mass with radiation [20]. Lastly, the notation for quantities of radioactive material should be discussed. The SI unit for quantities of radioactive material is the becquerel (Bq) which is defined as 1 disintegration, or decay, per second [20]. The non-SI equivalent is the Curie (Ci) which is equal to 37 billion Bq [20]. Now, with an understanding of some of the basic units of measurement for radiation, Table 1 can be discussed and better appreciated.

Table 1 illustrates these effects and the associated doses. For the purpose of this study, radiation effects at doses above 50 Gy will not be examined. A passive irradiation device, though potentially a significant source of radiation, would not be designed to impart radiation at levels this high. This is in part to retain covertness, but also in part to ensure the terrorist in question has time to transport the device without succumbing to ARS before they are able to drop the device off. An important fact should be taken from the prodromal stages, and that is the initial symptoms at doses up to 50 Gy are extremely similar to food poisoning [21]. In fact, in Goiania [12], Lia [13], and Mayapuri [11] the initial diagnosis had been food poisoning. As noted, these effects typically take between a few hours to a few days to onset [21]. Thus, unless a person knows they had been exposed prior, would be very unlikely to know where they were exposed, or even for how long. This logic has been proven true again and again with accidental exposure to orphan sources, including the incidents discussed above [5] [11]. As noted in the latent stages stem cells in the bone marrow begin to die. This results in a drop in the white blood cell count and the beginning of the failure of the immune system [21]. Ultimately this failure in the immune system leads to infections that will later kill the victim.

2.3 ACCIDENTS WITH ORPHAN SOURCES

2.3.1 Goiania Brazil

According to an International Atomic energy Agency (IAEA) Report [12], in 1985 a dispute over an abandoned radiotherapy site "Instituto Goiano de Radioterapia" led to a ^{137}Cs radiotherapy unit being stored in an unsafe condition. During the storage in this unguarded and unkept location, two local scrap metal dealers broke into the site and ransacked the location. During this theft they noted the radiotherapy unit and because the source capsule was shiny in appearance, being made of stainless steel, they took it with them. A similar source capsule is shown below in Fig. 3. The two men began to attempt to disassemble the machine and through the disassembly began to show signs of acute radiation poisoning (dizziness, nausea, vomiting, swelling of hands) but continued to work on the machine. When one of the men sought medical attention, the local hospital diagnosed an allergic reaction to food since radiation poisoning was not a common illness. Eventually the men removed the source wheel from the shutter designed to shield the source when not in use. The shutter window was punctured during this time which leaked through it a blue glow from the ^{137}Cs salt used as the source.

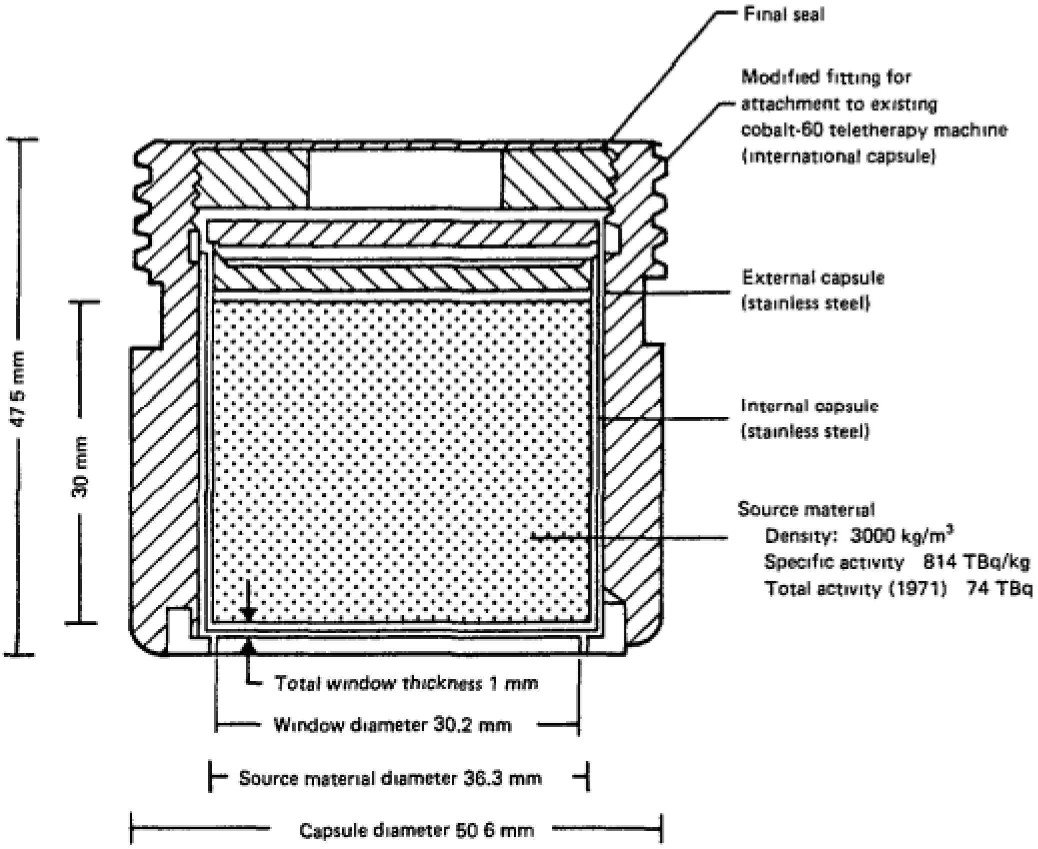

Fig. 3 Cross-section of international standard capsule which is what was stolen in Goiania Brazil [12]

The men sold it to a new scrapyard dealer who, noting the blue glow, thought it to be ghostly or spiritual. The new scrapyard dealer, Devair Alves Ferreria, decided to bring it home to show to friends and family and gave out the blue powder inside. One recipient, Devair's brother Ivo, brought the powder home to his seven-year-old daughter who played with it and put the glowing substance on her skin. Eventually the capsule changed hands again to a new scrapyard. During this time multiple people began showing similar illness and Devair's wife, Gabriella, decided to bag up the unit and take it with her to the hospital. One of the doctors recognized the radiation poisoning symptoms and that the unit was part of an x-ray unit of some kind. A medical physicist later arrived, and determined there was mass levels of contamination all over the city. By the end of the event several houses and the hospital that Gabriella was treated at had to be demolished, 3 buses, 14 cars, 5 pigs, and 3500 M^2 of waste and soil had to be disposed of. Even worse was the loss of 4 lives, including Gabriella, Ivo's seven-year-old daughter, and two of the scrapyard workers at Devair's scrapyard.

2.3.2 LIA GEORGIA 2001

According to an IAEA Report [13], three men in the winter of 2001 were searching for firewood outside of their village Lia, in the country of Georgia. As night approached, they sought a site to setup camp. During this search they encountered two cylinders that appeared to be melting all snow within three feet and creating steam from the water. Unbeknownst to them, these were source containers for Beta-M RTGs containing ^{90}Sr. The container diagram for Beta-M RTGs is shown in Fig. 4.

Fig. 4 Initial location of the radioactive sources under a large stone [13]

They had been previously used by the Soviet Union to power small isolated radio relays and after the fall of the Soviet Union were abandoned and sat unused and disassembled from their shielding/housing. With the winter being cold and hard, the men took the units with them, using wiring to carry them, and kept them nearby to keep warm during the night. They began to feel sick after they settled in, but had been drinking vodka. The next morning, they left the devices behind and returned to Lira feeling exhausted and ill. One of the men reported to the doctor who stated they were simply intoxicated. However, after the other two men also reported feeling ill, along with arrythmia and burns on their backs and hands. They were later diagnosed with acute radiation poisoning and taken to the capital of Tbilisi. Georgia requested IAEA assistance in locating the lost sources, and with some searching where the men reported to be. The source, shown in Fig. 5, was located and quickly recovered after a few hours of operational planning. As for the men, one who did not handle the sources, was released fairly quickly having only received a dose of 1.3 Gy. One who received a total dose of 4.4 Gy was eventually released from the hospital in 2003. The final one received an estimated dose of 3.1 Gy and eventually passed away in 2004. The man had complicating factors that made treatment more difficult and the majority of his dose was to his vital organs. However, it is believed that two more of these Beta-M sources are still located somewhere in Georgia and have yet to be located.

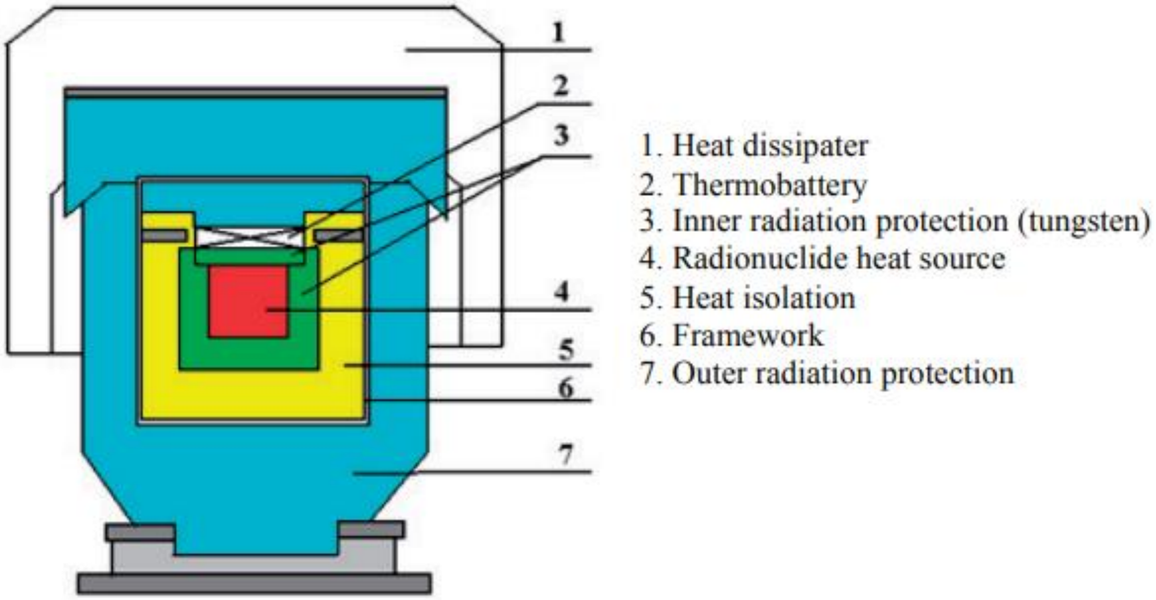

Fig. 5 Beta M RTG [13]

2.3.3 MAYAPURI INDIA 2010

According to an IAEA Report/Presentation [11], Delhi university had a Gammacell irradiator unit containing ^{60}Co for chemistry and physics studies. It had been purchased in 1968 and eventually put into storage in 1985. In 2010, the university sold off the unit to a scrap metal dealer who was unaware of what the device was or what it contained. At the time it was estimated that 18.6 Ci of ^{60}Co remained inside the unit in the forms of 16 cobalt pencils, each containing 7 slugs. The unit was progressively disassembled, eventually removing the source cage within the machine and thus exposing the cobalt pencils. During this disassembly process the unit changed ownership four different times, with cobalt pencils, and even slugs in the pencils being left at the shops during each transfer. One worker had even kept a cobalt slug in his wallet. This occurred over a time period of two weeks. One worker finally reported to the hospital for odd pigmentation of his hand and other symptoms including nausea, dizziness, and lesions. The hospital suspected radiation poisoning and treated him for it, whilst reporting his condition to the Indian Atomic Energy Regulatory Board and the Delhi Police. The two agencies searched the scrap yards and immediately found elevated radiation levels.

Fig. 6 Cobalt pencil recovered by at scrapyard in Mayapuri [11]

They identified the source as ^{60}Co and began the eventual cleanup process. One of the many Cobalt pencils they recovered is shown above in Fig. 6. This resulted in 400 kg of soil and 100 kg of scrap metal had to be removed, with the road in front of the shops having to have concrete poured to fix some contamination that could not be removed. In the end, two of seven victims received radiation burns, but one who had about two weeks of exposure for 12-15 hours per day and touched one of the pencils succumbed to his exposure, estimated to be 3.1 Gy.

2.4 LESSER-KNOWN ACCIDENTS WITH ORPHAN SOURCES

The discussion in section 2.3 primarily involved well known and highly publicized accidents with orphan sources. However, there have been many other accidents involving orphan sources and below are several listed as bullet points, with brief descriptions to help illustrate the number of incidents

- 1962 Mexico City, Mexico: Four individuals died as a result of exposure to a 5 Ci ^{60}Co capsule which had been stolen by a 10-year-old boy. The boy kept the capsule in his pocket and placed it in his family's kitchen cabinet. He passed away 38 days later. His mother, younger sister, and grandmother passed within 8 months as a result of the exposure [22].
- 1977 Sasolburg, Transvaal, South Africa: A radiographer lost a small 6.7 Ci ^{192}Ir source. It was later found by a construction supervisor who picked it up and placed it in his shirt pocket. He began experiencing nausea and vomiting and placed the source in a cupboard. The source was later stated as lost and the supervisor recognized the replica being shown to locate it. He received an estimated whole-body dose of 116 Rad. The resulting dose required the removal of two fingers on his left hand and a rib removed along with several skin grafts on his chest. His wife and child received 17 and 10 Rad respectively [23].
- 1980-1989 Kramatorsk Ukrainian SSR: A small ^{137}Cs source was lost in a mine after being used for radiography purposes. The source was written off as a loss. However, the source became entrapped in the ore that was dug up and later used in concrete to build an apartment complex. The source ended up in the wall of apartment 85. Over nine years two families lived in the apartment, with a child's bed being located

next to it. In 1981, one year after moving in, an 18-year-old woman living in the apartment died unexpectedly. The following year her 16-year-old brother passed, and then their mother that same year. All of their deaths were found to be from leukemia. A new family moved in, and their son a year later also passed from leukemia. The father managed to start an investigation and the source as finally located. It was determined the wall was emitting 1800 Rad a year [24].

- 1983 Ciudad Juarez, Mexico: A scrap yard obtained a disused medical teletherapy unit with 6,000 1 mm pellets of ^{60}Co totaling to 400 Ci. Many of the pellets ended up in scrap steel that was later melted and eventually transported to the United States. The contamination was only discovered when a truck carrying the contaminated steel took a wrong turn at the Los Alamos Scientific Laboratory in New Mexico and triggered radiation alarms. Additional trucks were found later. It was estimated 931 tons of contaminated steel was transported to the United States. It was believed that 4 individuals received doses from 100 to 450 Rem whole body with one later dying from bone cancer. 109 new houses in Sinaloa Mexico had to be demolished after having been found to have been built with contaminated rebar [25].
- 1984 Casablanca Morocco: a 16.3 Ci ^{192}Ir industrial radiography source was lost and taken home by one of the workers at a soon to be built fossil fuel plant. The source was placed on a table in the family's bedroom. Between May and June of 1984 eight people including the laborer, his entire family, and several relatives, died of lung hemorrhages, later determined to be ARS. The source was recovered [26].
- 1992 Xinzhou, Shanxi, China: A 10 Ci ^{60}Co source used at an industrial irradiation facility, undergoing decommissioning, was removed from a 6-meter-deep water

well. The source was taken home by the worker who removed the source and kept in his jacket pocket. That afternoon he was taken to hospital. His father, brother, and his pregnant wife provided care at the hospital. He died 15 days later due to his exposure. His father and brother died within a week. The wife required medical care due to her exposure. It is estimated 37 individuals at the hospital received substantial doses with 14 exceeding 25 Rad. The worker, brother, and father received doses greater than 800 Rad. The wife received a dose of 230 Rad and her unborn child 180 Rad. The child was born with severe mental disabilities. The source was secured 76 days after having been taken [27]

- 1994 Tammiku Estonia: An unguarded nuclear waste storage facility in Estonia was raided by three brothers looking for scrap metal to sell. They took several pieces of metal in their pockets and returned home. One piece was a small metal cylinder that was actually a ^{137}Cs source. It resulted in one of the brothers receiving a 4,000 Rad whole-body dose and dying 12 days later. It was not until the family dog died and the stepson of one of the brothers showed a radiation burn was the matter formally investigated. The break-in was later discovered and the storage facility secured, later being decommissioned in 2008 [28].
- 1999 Henan, China: A 577 Ci ^{60}Co source had been sold as scrap metal, with the scrap dealer taking it home and placing it in his bedroom shared by himself, his wife, and his 8-year-old son. The wife and son began vomiting that night, with the worker soon to follow. They went for medical treatment that morning, initially being diagnosed as having food poisoning. A separate doctor recognized ARS and ran bloodwork. It was determined they had ARS and the source was later recovered that

same day. The wife received a dose of 610 Rad with severe ARS. The man and his son received a dose of 340 and 240 Rad respectively. A separate individual sustained a 90 Rad dose, with three others receiving a smaller dose [29].

2.5 RADIOACTIVE SOURCES USED FOR MURDER

In November of 1995 a Chechen terrorist group planted a device containing ^{137}Cs at Izmilovsky Park in Moscow [4]. Though the device did not cause a release of material and did not result in any deaths, it still caused significant psychological fear in Moscow and helped make the Chechen terrorist a larger threat in the eyes of the Russian Federation [4]. In 1998 the Russian-backed Chechen Security Service found a container of radioactive material attached to an explosive mine near a railway line [30]. The device was diffused. In 1999 thieves attempted to steal a container of 200 g of radioactive material from a chemical factory in Grozny, Chechnya. It was later revealed to be nine 12 cm rods of ^{60}Co each containing 27,000 Ci of material. One thief died half an hour after exposure, two died later in hospital, with the last three receiving extreme ARS [31] [30]. Though these examples are more akin to terroristic use of radioactive sources, there are examples of them having been used to commit murder [32]. These homicides have ranged from more famous examples, such as tea laced with ^{210}Po used to kill former Komitet Gosudarstvennoy Bezopasnosti (KGB) agent Alexander Litvinenko, to lesser-known examples such as ^{60}Co being placed in an office chair to kill a manager of a packing plant [32]. A lesser known, but far more devastating example occurred in 2002 in China when a disgruntled employee hid ^{192}Ir pellets in the ceiling panels of a hospital. It resulted in acute radiation sickness of 74 hospital staff, a near miscarriage, and severe symptoms for the targeted business man [32]

Using radioactive material to kill people in a covert fashion is nothing new. Typically, it requires either extremely radioactive source, or a large amount of time to induce enough exposure. In the example of Litvinenko, it took approximately 3 weeks to die from time of exposure [32]. This can be tied to ^{210}Po having a high specific alpha emission rate such that 1 μg was enough to kill an average adult [33]. As for the packing manager, it took well over a month and a half with weeks of sitting and exposure [32]. Thus, it is clear that a terrorist organization could take a sufficiently powerful source, conceal it in a location, or disperse it, and expose a large quantity of people to doses that could be sufficient enough to induce acuate radiation sickness.

2.6 NUCLEAR TERRORISM

A primary question when discussing non-conventional radiological terrorism is what would drive a terrorist group to choose a method that is more discrete than typical explosion-based terrorist attacks. Typically, terrorist attacks can be recalled as attention grabbing, grandiose, and resulting in scores of people dead. Infamous examples include 9/11 [34], the Lockerbie Bombing (Pan Am Flight 103) [35], Tokyo subway Sarin Attack [36], and many others. Thus, a group who seeks to use a more discreet method, as that described above, wouldn't be seeking an attack that calls a lot of attention to itself initially. Instead, the attack would be centered on causing a large amount of sickness, and when found out, mass hysteria and panic. It could also be used to target a specific population to affect the political landscape. An instance similar to this was in 1984 when the Rajneeshee cult committed a bioterror attack in The Dalles Oregon by leaving salmonella at local restaurants and several high traffic surfaces [37]. The four restaurants involved are shown below in Fig. 7. The hope of this attack was to make enough people ill that the cult could elect one of their own into office with little interference.

Fig. 7 The four restaurants attacked in 1984 Rajneeshee bioterror attack [38]

Though the cult was unable to successfully elect one of their own, they managed to poison 751 people, and hospitalize 45 [37]. It wouldn't be hard to imagine a terrorist group pulling a similar attack, with sources hidden in key public areas with high foot traffic, but long enough stay times to make people sick. Waiting rooms in public buildings, public transportation, in busy restaurants, movie theatres, malls, etc. All of these locations would be vulnerable to such an attack, and potentially difficult to trace. The most likely diagnosis would be food poisoning as was done initially in Brazil [12] and Samut Prakarn [18].

This said, what if the terrorist group was not interested in political revolution, and instead causing damage to an economy and inducing fear. Generally killing a large number of people would be enough to induce that fear. However, as denoted by the examples, and even the instances of Goiania, Samut Prakarn, and Mayapuri [12] [18] [11] the death rates were not particularly high. They are far lower than what a terrorist group would get with either a well-placed conventional explosive or a shooting at a crowded location. A terrorist group would instead be relying on the fear of radiation itself. The fear of radiation can be traced back to the atomic bombs, the radium girls, and the awful radiation poisoning that followed [39].

However, in this instance it comes down to a much simpler principal; the fear of the unknown. Radiation cannot be seen, heard, felt, tasted, or smelled. It is effectively an invisible killer like any bacterial or viral infection. Thus, people would never realize they are being continually exposed until they've received a dose large enough to induce ARS, and by then it may already be too late. The constant fear of using anything with high foot traffic, and the worry of bringing the contamination home would weigh heavily on the day-to-day citizens life. All of this could be caused by a simple low skill attack using a stolen orphan source that is placed in a high traffic area. Thus, this makes the attack of particular interest to terrorist groups, because of the high likelihood of success, the readily available material in the form of a high activity orphaned medical source, and the likely long delay until it is discovered, leading to a large number of people developing acute radiation syndrome.

2.6.1 Dirty Bombs and Associated doses

Due to the ever-present threat of dirty bombs, modeling of potential attacks is commonplace in nuclear security. First is the actual dose and dispersion of the nuclide in question. As proposed by Shin et al. [40] there is a relatively small list of nuclides that would be of interest to terrorist, consisting of 9 specific isotopes. These include ^{241}Am, ^{252}Cf, ^{137}Cs, ^{60}Co, ^{192}Ir, ^{238}Pu, ^{210}Po, ^{226}Ra, and ^{90}Sr, which are common in various industries, are relatively radioactive, tend to have low security measures, and have multiple forms they can be used in. Next decisions regarding the actual method of dispersion, exposure, and ingestion would be made based on several assumptions involving weather, initial location, etc. This framework would be devised and implemented using a similar method to Andersson et al. [41]. This uses the ARGOS decision support system to help estimate doses based a theoretical dirty bomb attack. The ARGOS system runs a variety of simulations where the dose is calculated based on contamination, ingestion, specific radionuclide, etc. The supporting argument, combined with the attained data, relies, in part, on data obtained from nuclear incidents such as Chernobyl, the nuclear bombings of Hiroshima and Nagasaki, and even accidental exposure to orphan sources. This in turn creates a framework for determining the radionuclide most at risk, the likely dispersion method, and potential associated doses for a variety of levels of exposure. A similar thought process is seen used by Dr. Reshetin [42], though without the use of the ARGOS system. Instead, a specific dirty bomb containing ^{90}Sr is placed in an urban setting with a specific release height and varying weather conditions. This was used to determine potential doses received by people at various points from the epicenter of the explosion.

With the data from these models, the next step is counteracting the effects of a dirty bomb. Dr. Moore [43] suggests that medical professionals with extensive nuclear knowledge, such as radiologists, be prepared to provide information, guidance, and direct support for their local medical community. Williams et al. [44] discusses how to ensure the safety of a surgical team who are operating on victims of a dirty bomb. This involves the use of radiation measurement devices, identifying contaminated patients, using the principals of ALARA (As Low As Reasonable Attainable), and triage in the worst of circumstances.

3.0 METHODOLOGY

3.1 MODELS

In order to properly demonstrate how these attacks could take place, and the potential damage they could cause, a computer model will be created of theoretical attacks. These models are chosen are designed to simulate the most realistic scenarios in which one could place a non-conventional radiological device. These are all locations where one could anticipate large amounts of traffic, sufficiently long, but not excessive exposure time, and ease of placement. This will allow a terrorist to place the devices unnoticed by the intended victims, and leave without question. However, each of them also represents a unique perspective in the way they target their victims. The metro seat would be a general attack on a populace of any city or country. The waiting room could be a specific business or government with the intent of causing chaos or profit loss. The theme park would be a general attack but instead aimed at presumably families and other park goers. Whereas finally a sandbox is primarily aimed at children of a specific town. Thus, a would-be terrorist could tailor their attack to suit the specific intent of their organization.

3.1.1 MODELING PEOPLE

People will be modeled as several cylinders composed of water. This is routinely used for modeling people in radiation transport simulations since it serves as a rough approximation for the composition of a human [45]. The individuals modeled will have their mass be the approximate average for a North American male at the appropriate age. Their geometry will be based on average dimensions and are shown in the Tables 2 and 3 [46]

Table 2 Dimensions of average North American human male in their early 20's

Body Part	Radius (cm)	Height (cm)	Volume(cm^3)
Torso	15.24	62	45238.8
Leg L	6	93	10518.1
Leg R	6	93	10518.1
Arm L	5	71	5576.3
Arm R	5	71	5576.3
Head	9	20	5089.4
		Total Weight (kg)	82.1
		Total Volume (cm^3)	37278.1

Table 3 Average dimensions for North American male human child between 8-12

Body Part (Child)	Radius (cm)	Height (cm)	Volume (cm^3)
Torso	7.62	31	5654.9
Leg L	3	46.5	1314.8
Leg R	3	46.5	1314.8
Arm L	2.5	35.5	697.0
Arm R	2.5	35.5	697.0
Head	4.5	10	636.2
		Total Weight (kg)	82.1
		Total Volume (cm^3)	4659.8

The weight will be distributed amongst the limbs in an anatomically correct fashion, citing literature for the average North American male of the appropriate age. The water itself will be modeled as 1.0 g/cm^3 [47].

3.2 TOOLS FOR MODELING

The models will be created and ran in MCNP 6.2 [48] [49]. The models use SDEF with F4 tallies with International Commission of Radiological Protection (ICRP) ICRP - 21photon flux to dose conversion factors to determine the dose received in each instance within the person being modeled. Their dose will be multiplied by the strength of the source and the time spent exposed to the source. The sandbox, waiting room, and metro models are run for 15 minutes before the simulation ends. The theme park line model is run for 8 minutes at each position until the simulation ends. Visual Editor (Vised) [50] [48]was used to help identify any potential geometry errors in the models and to create 3D images of the models. The sources will be modeled based on the most appropriate approximation based on the geometry of the model. The sandbox is modeled as a distributed volumetric source spread throughout the top layer of sand. The theme park line is modeled as a point source [49]. And finally, the waiting room and metro models use sources modeled as small pucks. The complete MCNP input decks for each modeled scenario can be found in Appendix A.

3.2.1 Results Reporting

The results are reported as a calculation of the dose received as either whole body, torso, or extremities (arms and legs) using the F4 tally results from MCNP [48] [49]. Microsoft Excel is used to generate tables that show the doses as mentioned above. The source geometry, time spent near the source, and distance are reported with the results. A Vised compilation of each scenario has been created as well and included with the results to help the reader visualize the scenario.

3.3 SOURCES USED

As noted above in section 2.1, nuclear sources exist in many areas of industry and a single radioisotope can find use in several industries [7]. However, the most common found in medical, science, and food sterilization is ^{60}Co [7] [11]. This was present in Mayapuri India and several of the lesser-known accidents listed in section 2.4 [11] . As such, the doses, quantity of radionuclides present, and geometry can be used as a starting point to generate an approximate idea of what a terrorist may use when stealing an orphan source.

The sources geometry and consistency will be varied according to each model being created.

3.3 METRO SEAT

In the metro seat model, a source was placed directly against the bottom of a seat on a train/bus that would commonly be found in a public transportation system. This seat was modeled as a quarter inch thick polyethylene sheet for both the bottom and back rest. Six, one inch thick, sheets of aluminum formed a box that represent the walls, floor, ceiling, and ends of the metro. The metro is 51 feet long and 8.6 feet tall. An image of this is shown below in Fig. 8. This allows the radiation to be reflected and doses calculated from reflection in addition to extremity doses on the legs and radiation that penetrates the seats. It is assumed that individuals will only spend fifteen minutes per ride since this is a regional metro route. The source is modeled as a 0.5 Ci ^{60}Co puck placed beneath the seat of the metro. This puck is modeled as emitting radiation in all directions with ICRP-21 photon flux to dose conversion factors. All material data was pulled from the Pacific Northwest National Labs *Compendium of Material Composition Data for Radiation Transport Modeling* [51]

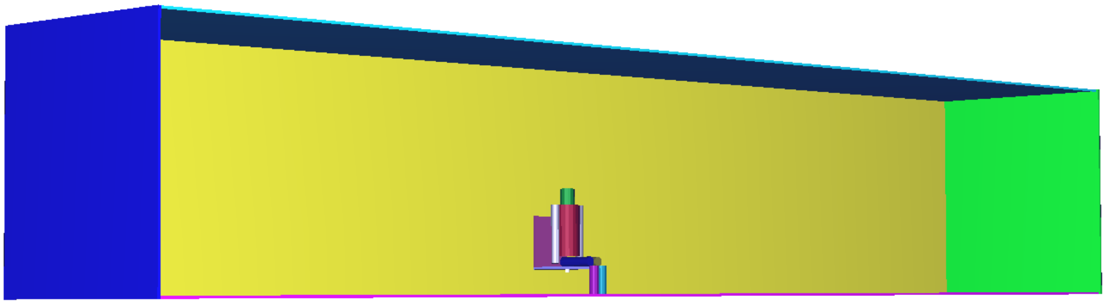

Fig. 8 Metro seat with human in center and front wall removed

3.4 SANDBOX

In the sandbox model, a typical park sandbox is constructed with sand three feet deep. The source is assumed to be ground up and evenly dispersed in the sand. The individual is modeled as child (i.e., their model will be of a lower weight and size) and spends 15 minutes in the center of the sandbox. The child is assumed to be 40.5 kg and is in a sitting position in the sand. Their arms are to their sides and they are located at approximately the center of the sandbox, as shown in Fig. 9.

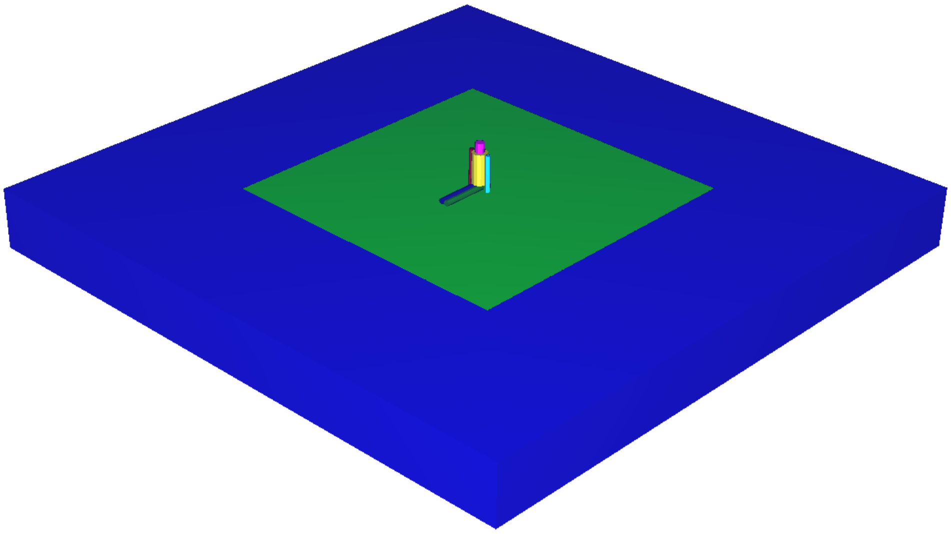

Fig. 9 Sandbox with child sitting in the center of the sand (colored green) surrounded by dirt (colored blue).

3.5 WAITING ROOM

The waiting room model is representative of a typical government or medical facility. The chair is modeled as a plastic back and plastic seat with four metal poles extending from the four corners of the seat bottom to the floor. The floor is modeled as an 8-inch-thick tile floor. The space beneath the floor is not modeled. The walls are modeled as quarter inch thick plasterboard. The ceiling is also made of the same plasterboard. The individual in the model is placed in a sitting position on the chair. The source is taped to the bottom of the seat in the form of a small puck placed approximately in the center of the bottom of the seat. The chair is placed in the center of the back wall. This model, shown in Fig. 10, is different from the metro example in that the chair has metal legs, the materials of the walls are less reflective, and the walls are spaced further apart from the individual.

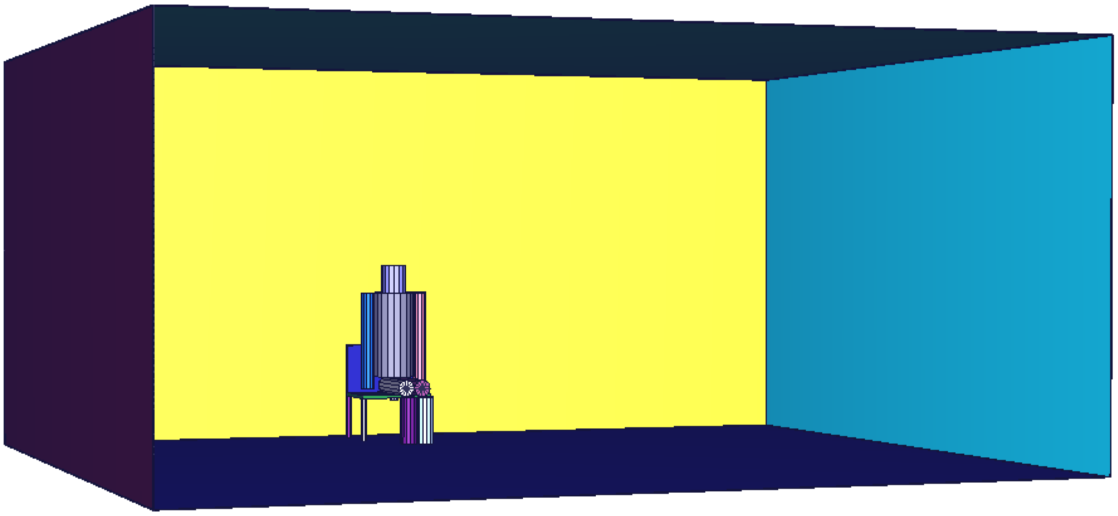

Fig. 10 Waiting room with human seat in center of back wall and front wall removed

3.6 THEME PARK LINE

The theme park line is modeled as having a source hidden in bushes next to an outdoor theme park line. The floor for the line itself is modeled as concrete with a depth of 2 inches. The individual is modeled as standing, as shown in Fig. 11. The source itself is modeled as a puck of ^{60}Co. This source will move from three positions. Position A is the furthest left side of the sidewalk. Position B is the middle of the sidewalk, and closest to the person. Position C is the furthest right of the sidewalk. This simulates the person moving 8 feet every 6 minutes allowing. Thus, their dose is a collective received on a sixteen-foot track over eighteen minutes. Photon attenuation from the bushes is considered negligible and thus the bushes are not modeled. The surrounding area is modeled as dirt, with the air modeled as a mixture of carbon, nitrogen, oxygen, and argon.

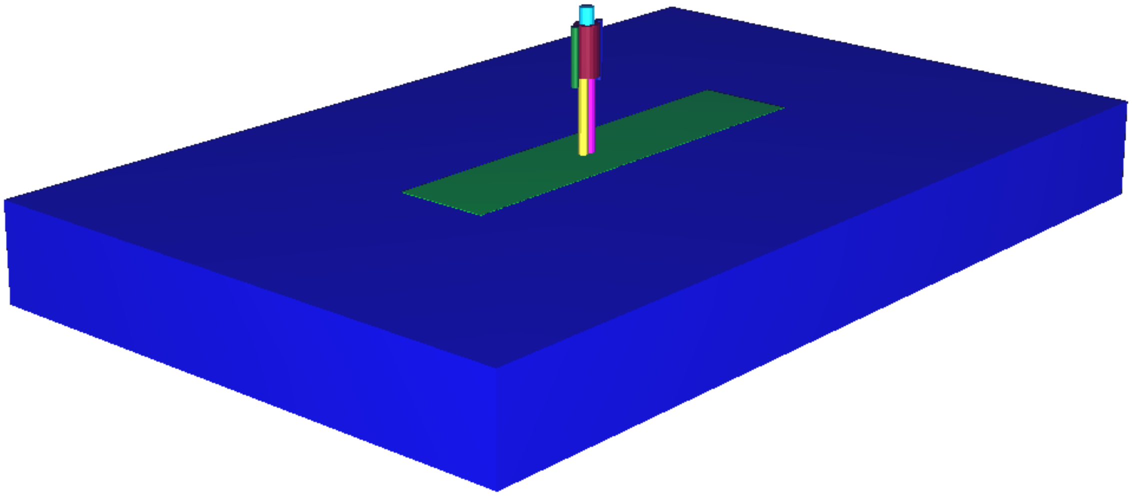

Fig. 11 Theme Park line with human model in center. The blue is modeled as dirt and the green is concrete

4.0 RESULTS

4.1 Numerical Data

4.1.1 Metro Seat Data

Below in Table 4 is the data compiled from the metro seat model for sections of the human body. The time was for 15 minutes of exposure, for a 0.5 Ci ^{60}Co source.

Table 4 Dose for human after 15 minutes of exposure in metro seat model

Metro Line 15 Minutes	Dose Per Photon	Dose Per Second	Total Dose
Body Part	Rad/Photon	Rad/s	Rad
Human Torso	4.601E-11	8.513E-01	766.1
Human Head	1.035E-12	1.914E-02	17.2
Human Left Leg Top Section	2.177E-10	4.027E+00	3624.4
Human Right Leg Top Section	2.195E-10	4.060E+00	3654.4
Human Left Leg Bottom Section	4.742E-11	8.772E-01	789.5
Human Right Leg Bottom Section	4.736E-11	8.762E-01	788.6
Human Left Arm	4.584E-11	8.480E-01	763.2
Human Right Arm	4.601E-11	8.511E-01	766.0

4.1.2 Sand Box Data

Below in Table 5 is the data compiled from the sand box model for section of the human body. The time was for 15 minutes of exposure, for a 0.5 Ci ^{60}Co source.

Table 5 Dose for child after 15 minutes of exposure in sandbox model

Sandbox 15 Minutes	Dose Per Photon	Dose Per Second	Total Dose
Body Part	Rad/Photon	Rad/S	Rad
Child Torso	1.711E-11	3.166E-01	284.9
Child Head	1.277E-11	2.362E-01	212.6
Child Left Arm	2.053E-11	3.798E-01	341.9
Child Right Arm	2.045E-11	3.783E-01	340.5
Child Left Leg	2.444E-11	4.521E-01	406.9
Child Right Leg	2.439E-11	4.512E-01	406.1

4.1.3 Waiting Room Data

Below in Table 6 is the data compiled from the waiting room model for section of the human body. The time was for 15 minutes of exposure, for a 0.5 Ci ^{60}Co source.

Table 6 Dose for human after 15 minutes of exposure in waiting room model

Waiting Room 15 Minutes	Dose Per Photon	Dose Per Second	Total Dose
Body Part	Rad/Photon	Rad/s	Rad
Human Torso	2.917E-11	5.396E-01	485.6
Human Head	2.408E-13	4.454E-03	4.0
Human Left Leg Top Section	1.466E-10	2.711E+00	2440.1
Human Right Leg Top Section	1.468E-10	2.716E+00	2444.4
Human Left Leg Bottom Section	2.677E-11	4.952E-01	445.7
Human Right Leg Bottom Section	2.673E-11	4.945E-01	445.0
Human left arm	2.699E-11	4.993E-01	449.4
Human right arm	2.717E-11	5.026E-01	452.3

4.1.4 Theme Park Line Data

Below in Table 7 is the data compiled from the theme park model for section of the human body. The time was for 8 minutes of exposure at position A, B, and C, for a 0.5 Ci ^{60}Co source. Column D shows the total dose positions A, B, and C and then a total dose for all three combined. Column C shows the dose per second, and Column B shows the dose per photon. As explained above in section 3.6, position A is the furthest left side of the sidewalk (around 8 feet away from the individual). Position B is the middle of the sidewalk (approximately next to the individual). Position C is the furthest right of the sidewalk (approximately 8 feet from the individual).

Table 7 Dose for theme park model at each position

Sandbox 15 Minutes	Dose Per Photon Position A	Dose Per Second Position A	Total Dose Position A
Body Part	Rad/Photon	Rad/s	Rad
Human Left Leg	1.792E-12	3.315E-02	15.9
Human Right Leg	1.525E-12	2.821E-02	13.5
Human Head	1.166E-12	2.157E-02	10.4
Human Torso	1.185E-12	2.193E-02	10.5
Human Left Arm	1.778E-12	3.290E-02	15.8
Human Right Arm	8.804E-13	1.629E-02	7.8

Sandbox 15 Minutes	Dose Per Photon Position B	Dose Per Second Position B	Total Dose Position B
Body Part	Rad/Photon	Rad/s	Rad
Human Left Leg	4.709E-12	8.712E-02	41.8
Human Right Leg	4.727E-12	8.745E-02	42.0
Human Head	2.004E-12	3.707E-02	17.8
Human Torso	2.723E-12	5.037E-02	24.2
Human Left Arm	3.650E-12	6.753E-02	32.4
Human Right Arm	3.656E-12	6.763E-02	32.5

Sandbox 15 Minutes	Dose Per Photon Position C	Dose Per Second Position C	Total Dose Position C
Body Part	Rad/Photon	Rad/s	Rad
Human Left Leg	1.071E-12	1.981E-02	9.5
Human Right Leg	1.309E-12	2.423E-02	11.6
Human Head	9.294E-13	1.719E-02	8.3
Human Torso	8.942E-13	1.654E-02	7.9
Human Left Arm	5.428E-13	1.004E-02	4.8
Human Right Arm	1.351E-12	2.500E-02	12.0

Body Parts	Total Dose All Positions (Rad)
Human Left Leg	67.2
Human Right Leg	67.1
Human Head	36.4
Human Torso	42.6
Human Left Arm	53.0
Human Right Arm	52.3

4.2 Health Consequences of Above Doses

4.2.1 Waiting Room and Metro Seat Examples

These examples showed similar patterns in their dosage in that the highest dose was to the top sections of the leg resting on the seat, and in closest proximity to the source. The remainder of their bodies received approximately the same dose, with their heads receiving the lowest dose. The individual in the metro received a dose of 7.6 Gy to their torso, 7.8 Gy's to their legs, and 7.6 Gy's to their arms. As shown by the examples given above, this would be more than sufficient for a lethal dose with or without treatment. This person would likely begin to experience symptoms within hours, possibly less, of leaving the metro. The symptoms this would include are bouts of nausea, diarrhea, weight loss, cramping [21]. All of these symptoms, would likely be dismissed as a stomach bug or food poisoning. They may even begin to feel well after the initial stage ends. However, their prognosis at such a high dose, without treatment, would be grim and likely lead to their passing within two weeks [21]. However, there is a key component that would likely immediately make apparent their symptoms are not a result of food poisoning. Having received a 32 Gy dose to their thighs and legs would result in extreme radiation burns. They would likely have burns appear in under an hour, and necrosis begin soon after [13] [28] [52]. This model does not show the likely extreme damage to the persons gastrointestinal tract, and thus the individual would have a slim chance of survival, even if they have their legs amputated and Gastro Intestinal (GI) tract somehow kept functioning.

The individual in the waiting room has a slightly better prognosis. Having a whole-body dose of around 4 Gy, they too will begin to experience similar symptoms including bouts of nausea, diarrhea, weight loss, cramping, etc. [21]. However, at a dose of 4 Gy their likelihood of survival is significantly higher, especially if treatment is immediately sought. That said, like the individual in the metro seat, their legs would suffer extreme trauma. At a dose of 24 Gy, they too would receive extreme radiation burns and a rapid onset of necrosis. This would require immediate amputation of their legs, and quick surgery to repair damage to their GI system. However, their prognosis is still survivable assuming their body can survive the trauma and resist infection.

4.2.2 Sandbox

The child in the sandbox received the highest doses to their extremities with their legs receiving 4 Gy, their arms 3Gy, and their head and torso 2 Gy. These are survivable for most adults. The initial onset of symptoms may be hours after, and like those in the metro and waiting room examples would include bouts of nausea, diarrhea, weight loss, cramping, and other ailments similar to any childhood stomach bug or food poisoning [52]

[21]. However, these symptoms only last for two days, and they will likely move to the latent and manifest stages soon after, with the assumption being they recovered. However, if they do not receive treatment, it is likely they will have a fatal infection and die. The primary issue is that it is potentially less likely the parent will seek treatment for the initial sickness, since the symptoms will be very similar to a stomach bug or food poisoning. It is not until the manifest stage that they would likely seek treatment, and at that point, recovery is unlikely. There are two additional factors this model does not account for. First, is that the child will likely bring some of the source home. The model assumes 15 minutes of exposure, and nothing after. However, if the sand clings to the child's clothes, under their nails, on their skin, etc. then some of the source may be brought home and continue to irradiate them. This would then result in their family members, schoolmates, or anyone else who interacts with the child to receive a dose. Second, assuming this child survives, the likelihood of issues developing later on for the child, or cancer, are extremely high [20]. This alone makes it clear that the effects on this child will be lifelong and extreme.

4.2.3 Theme Park Line

The parkgoer in this example has the lowest dose by far. This is reasonable to expect since the source was a fair distance away from them, and they were not in a confined space for the radiation to reflect off of. Their whole-body dose is around 0.4 Gy. This dose is low enough, that they may not even experience noticeable symptoms of ARS [21]. And even if they do in latent stages, they will likely be mild. However, their chances of cancer will likely increase over their lifetime with a dose that is equivalent to 10 years in the United States nuclear industry receiving the max dose of 5 Rem per year [20]. However, quantifying the actual increase in cancer is difficult since factors such as age, weight, sex, radiation type and energy, environmental conditions, etc. play a role in the development of cancer. As such, though the individual has the lowest dose by far, they may still suffer from cancer caused by their exposure [21].

4.3 The consequence to the greater public

Regardless of how effective the passive irradiation device is at maiming or killing people, the effect on the public will likely be the same; panic and fear. However, unlike other terrorist attacks involving guns or explosives, the effects of radiation cannot be detected without special detection equipment. The fear of radiation can be traced back to the atomic bombs, the radium girls, and the awful radiation poisoning that followed [39]. However, in this instance it boils down to a much simpler principal; the fear of the unknown. Radiation cannot be seen, heard, felt, tasted, or smelled. It is effectively an invisible killer like any bacterial or viral infection. Thus, people would never realize they are being continually exposed until they've received a dose large enough to induce acute radiation sickness, and by then it may already be too late.

People have seen pictures of children born after Chernobyl, the radium girls, mushroom clouds from atomic bombs, and heard the click of a Geiger counter. This all culminates to the same terrifying image in the person's head. And knowing that terrorists may have already planted a device would permeate the minds every day citizens, wondering if the chair they sit on, or the utensils at a restaurant they touched, or even pen they used at a local courthouse had a source stored in it or wiped onto it. Without proper equipment there is no way to detect the radiation, and even with the proper equipment, there is a certain amount of knowledge required to understand the readings it provides. Thus, a mass hysteria would likely ensue, where movie theaters are empty, trains and busses are empty, restaurants struggle to attract customers, until people are assured there is no contamination.

All of this has an economic impact. In Goiania Brazil it was estimated that 30% of sales decreased resulting in a loss of $7 million USD and around $12 million USD was lost in crops (note this is in 1988 monies) [53]. Some sellers were willing to drop their prices by 50% to drop “tainted” goods even if they weren’t contaminated [53]. 9/11 is believed to have dropped the real GDP growth in 2001 by 0.5% and result in the loss of 598,000 jobs [54]. Depending on the scale and effectiveness of a non-conventional radiological attack, an equally devastating economic impact could be seen. Businesses could easily go under and governments having to cut budgets to either pay for new monitoring equipment, or make up for lost revenue.

4.4 Mitigation of Non-Conventional Radiological Terrorism

Countering non-conventional radiological terrorism begins with detection. Since the primary focus of a non-conventional attack is exposure to radiation without shielding, detection is made significantly easier than for something like a nuclear weapon or even dirty bomb. The key would be proper placement of the detection equipment at areas most likely to result in detection. Consider the public transit example. Placing a detector on each and every vehicle would likely cost a large amount of money, require months of downtime, and depending on power requirements, a complete redo of the onboard electrical systems. The far easier and equally effective method would be to instead place portal monitors at all entrances to depots where trains and busses return at the end of every run. An example of a rail detector is the TM850 by Rapiscan systems AS&E, shown in Fig. 12 [55].

Fig. 12 TM850 Radiation Portal Monitor [55]

As shown above, this system resides on both sides of the track and allows a train to pass between to detect any radiological material on board. It is capable of both detecting gamma and neutron radiation [55]. A similar model called the GCS-1500, created by the same company, can be used for bus lines and trams. The benefit to this method of countering non-conventional attacks is that the concept of installing radiation detection on public transit is nothing new. For example, in Washington D.C., Metro Transit Police received personal radiation detection devices along with specialized equipment for when material is detected [56]. The move was funded by a Department of Homeland Security grant, used to help protect vulnerable assets [56]. Using a similar system in other public transportation systems would increase the chance of detection exponentially. In public buildings, such as court houses, tax offices, town halls, etc. radiation detectors could be installed at the entrance to these buildings, either in the form of a portal monitor, or a wall mounted unit. By installing one at each egress, the building is protected before an attack even begins, by ensuring the material is detected before it has a chance to be brought in and installed.

The next phase to countering this threat is education. Recognizing symptoms of radiation sickness and tracing it back to the locations that are most probable will help end an attack before it claims more lives or makes more people fall ill. The Center for Disease Control and Prevention (CDC) provides an easy-to-understand website with information on, what to do in a radiation emergency, what to expect, treatments, where to go, contamination versus exposure, and much more. Figure 13 is one of the figures shown on the website [57].

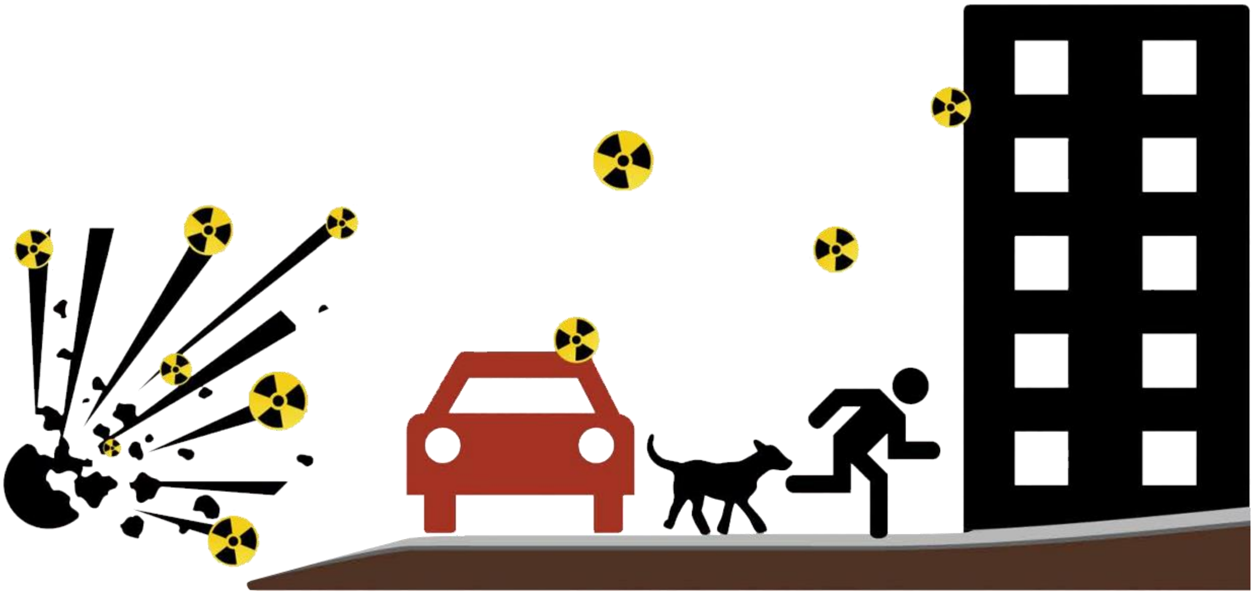

Fig. 13 CDC Diagram used to explain danger of RDDs and actions to take when they are detonated [52]

An easy way to help disseminate this information is making it a mandatory part of education at the middle school and high school levels. For adults, mailing out pamphlets with a summary of the information will help to catch people's interest, since it's a rare site to see a trefoil on one's mail, and spread to those who take the time to read it. Combining these tactics along with smart billboard placement, television ads, etc. (similar to anti-smoking campaign), will help to keep people safe in the midst of a radiation emergency. Similar to the United Kingdom's protect and survive campaign used in the 1970s to help educate its citizens what to do in the case of a nuclear war [58].

Finally, to reduce the chance of a non-conventional radiological attack, countries need to implement policies and more stringent rules on radiation sources and the management of these sources [59] [60]. This requires greater oversight by governing bodies, more accountability of the private sector that uses these sources, and a rapid notification of authorities in the event of the loss of control over a now orphan source [59] [60]. Governing bodies can also offer easier means of source reclamation that are at the end of their service life. As noted above, many sources are abandoned in indefinite storage at the end of their service life, without any proper means of disposal readily available [6]. If governing bodies were to instead offer easier ways out and reclamation programs for these end of service life sources, as shown in Fig. 14, commercial entities and public institutions would be far less likely to simply store them away and eventually lose track of these sources.

Fig. 14 Used smoke detectors that contained radioisotopes being prepped for proper disposal [61]

This may be the most difficult to implement means of reducing the chances of an attack, but it is the primary means of stopping one from occurring. The other methods listed above act more as countermeasures once an attack has begun. An attack will have begun the moment civilians become exposed to the radiation from the source, including transportation to the intended concealment location. By securing these sources, terrorist groups are cut off from the material they would need to carry out this attack, and thus unable to use the material to perpetuate an attack [6] [11].

5.0 Conclusion

In modern society, terrorism is a constant threat, and using radiation as a tool to cause suffering and death has been a concern since the dawn of the atomic era. However, the typical thought process focuses on either nuclear weapons', capable of delivering a nuclear explosion, or dirty bombs that use conventional explosives combined with radioisotopes. However, a separate but equally destructive, if not more so, avenue is possible in light of previous incidents. Orphan sources have and continue to present issues to local populations around the world, and elude authorities who have been attempting to regain control. Combined with misdiagnosis of food poisoning and populations that don't recognize the symptoms of ARS or the warning symbols for nuclear material is a situation for a guaranteed disaster. As shown above, this has, and continues to occur into present day. However, these have all been accidents, and it's only a small jump in logic to see how it could be repeated with malintent. As such, this paper performs an analysis on a relatively weak source in common situations a terrorist may target to try and cause the most damage and sickness. As shown above, of the four models, only one was likely non-fatal. The other three were likely to either kill or severely injury the person with life altering damage. Thus, mitigation is absolutely necessary to combat this problem before it can present a risk. This would include education, detection, and prevention. The key component being the prevention of access to sources and radioisotopes through stricter regulation of sources and easy access to means of proper disposal. If these steps for mitigation are taken, then this possibility can hopefully remain just that, and never reach a reality.

5.1 Future Works

Though the data from this study is fairly general, it still holds merit in showing likely outcomes in the various scenarios shown. However, this study could be expanded to include more detailed information with additional data, models, and identifying factors of current risks. Additional models could be added for other at-risk situations, such as airports, train stations, schools, pools, etc. This would take advantage of seeing how different materials and geometries could affect potential doses. This would also allow for different types of sources in different form factors to be analyzed and determine the risk presented to the population. Water soluble sources could be placed in pools. Solid rod sources could be placed in sidewalk cracks in stations. Sand could be mixed at beaches. A variety of form factors and sources could be used, with each source being tailored to the current at-risk isotopes in that region or country. Lastly additional people, obstacles, and even weather could be modeled to all determine the risks of each situation and likely effects on each victim. This could be used to identify patterns that might indicate this type of attack, and potentially mitigate losses. Overall, there is a lot of potential research that could be done on this subject, and it is something that would benefit both the realms of nuclear and national security.

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APPENDIX A: MCNP Deck Inputs

Waiting Room Example:

```
Title Cs Input Waiting Room Rum
c cell block
1   4   -2.32 (1 -2) (5 -7) (9 -11) imp:p=1 $ceiling
2   4   -2.32 (3 -4) (5 -7) (9 -11) imp:p=1 $floor
3   4   -2.32 (5 -7) (10 -9) (3 -2) imp:p=1 $Back wall of room
4   4   -2.32 (5 -7) (11 -12) (3 -2) imp:p=1 $ Front wall of room
5   4   -2.32 (6 -5) (10 -12) (3 -2) imp:p=1 $Left of wall room
6   4   -2.32 (7 -8) (10 -12) (3 -2) imp:p=1 $Right wall of room
7   5   -0.9 (13 -14) (15 -16) (17 -18) imp:p=1 $Seat of chair
8   5   -0.9 (14 -19) (15 -16) (17 -20) imp:p=1 $Back of seat of chair
9   1   -2.6989 (22 -21) (4 -13) imp:p=1 $Bottom left metal leg of chair
10   1   -2.6989 (24 -23) (4 -13) imp:p=1 $Bottom right metal leg of chair
11   1   -2.6989 (26 -25) (4 -13) imp:p=1 $Top left metal leg of chair
12   1   -2.6989 (28 -27) (4 -13) imp:p=1 $Top right metal leg of chair
13   3   -1.0 -29 (31 -32) vol=45238 imp:p=1 $Human torso
14   3   -1.0 -30 (32 -33) vol=5089 imp:p=1 $Human head
15   3   -1.0 -34 (36 -37) vol=5202 imp:p=1 $Human left leg top section
16   3   -1.0 -35 (36 -37) vol=5202 imp:p=1 $Human right leg top section
17   3   -1.0 -38 (4 -14) vol=3789 imp:p=1 $Human left leg bottom section
18   3   -1.0 -39 (4 -14) vol=3789 imp:p=1 $Human right leg bottom section
19   3   -1.0 -40 (42 -32) vol=5576 imp:p=1 $Human left arm
20   3   -1.0 -41 (42 -32) vol=5576 imp:p=1 $Human right arm
```

```
21   6   -3.36 -43 (44 -13) imp:p=1 $Cobalt 60 source
22   2   -0.001225 (5 -7) (9 -11) (4 -1) #21 #20 #19 #18 #17 #16 #15 #14 &
#13 #12 #11 #10 #9 #8 #7 imp:p=1 $Air in the room
23   0   -3:2:-6:8:-10:12 imp:p=0 $void

c surface cards
1 PZ 274.3 $ height of waiting room ~9 feet
2 PZ 274.9 $Thickness of ceiling
3 PZ -0.3175 $ lowest plane tile floor is 1/8th inch thick
4 PZ 0 $ top of floor
5 PX 0 $ Far left of room
6 PX -0.6 $To Represent thickness of left wall
7 PX 609.6 $ Far right of room ~20 feet
8 PX 610.2 $ To Represent thickness of right wall
9 PY 0 $ Back wall of room
10 PY -.6 $To Represent Thickness of back wall
11 PY 457.2 $ Front of room ~ 15 feet from back
12 PY 457.8 $To Represent Thickness of front wall
13 PZ 31 $bottom of chair
14 PZ 33.5 $top of chair
15 PX 302.8 $Left side of chair
16 PX 356.44 $Right side of chair
17 PY 15.24 $Back of bottom section of chair
18 PY 53 $Front of bottom section of chair
19 PZ 68.56 $Top of back section of chair
20 PY 17.7 $Front of back section of chair
21 C/Z 304.8 15.24 2 $Bottom left metal leg 2 cm radius outer cylinder .1cm thick Al leg
22 C/Z 304.8 15.24 1.9 $Bottom left metal leg 2 cm radius inner cylinder .1cm thick Al leg
23 C/Z 354.44 15.24 2 $Bottom right metal leg 2 cm radius outer cylinder .1cm thick Al leg
```

```
24 C/Z 354.44 15.24 1.9 $Bottom right metal leg 2 cm radius inner cylinder .1cm thick Al leg

25 C/Z 304.8 50.79 2 $Top left metal leg 2 cm radius outer cylinder .1cm thick Al leg

26 C/Z 304.8 50.79 1.9 $Top left metal leg 2 cm radius inner cylinder .1cm thick Al leg

27 C/Z 354.44 50.79 2 $Top Right metal leg 2 cm radius outer cylinder .1cm thick Al leg

28 C/Z 354.44 50.79 1.9 $Top Right metal leg 2 cm radius inner cylinder .1cm thick Al leg

29 C/Z 325.11 33.02 15.24 $Human Torso

30 C/Z 325.11 33.02 9 $Human Head

31 PZ 46 $Bottom of human torso

32 PZ 108 $Top of human torso and arms/Bottom of human head

33 PZ 128 $Top of human head

34 C/Y 319 39.5 6 $Human Left Leg Top Section

35 C/Y 331.2 39.5 6 $Human Right Leg Top Section

36 PY 33.02 $Back of human legs top section

37 PY 79.02 $Front of human legs top section

38 C/Z 319 85 6 $Human Left Leg Bottom Section

39 C/Z 331.2 85 6 $ Human Right Leg Bottom Section

40 C/Z 304.87 33.02 5 $Human Left Arm

41 C/Z 345.35 33.02 5 $Human Right Arm

42 PZ 37 $Bottom of human arms

43 C/Z 325.11 33.02 3 $Source 3cm in radius under seat centered approximately

44 PZ 28 $Bottom of source


c data cards

MODE P

SDEF CEL=21 POS 325.11 33.02 28 RAD=D1 ERG=.662 EXT=D3 AXS 0 0 1

SI1 0 3 $geometry of source

SP1 -21 1

SI2 L 1.173 1.333

SP2 D 0.5 0.5
```

```
SI3 0 3
SP3 -21 0
c NPS 100000
CTME 15.0
c ------------------------ ICRP-21 (REM/h per unit flux) for photon
f4:p 13 14 15 16 17 18 19 20 T
de4   log 0.01    0.015   0.02    0.03    0.04    0.05    0.06
         0.08    0.1     0.15    0.2     0.3     0.4     0.5
         0.6     0.8     1.0     1.5     2.0     3.0     4.0
         5.0     6.0     8.0     10.0
C FLUX TO DOSE CONVERSION FACTOR VALUES ICRP-21 (REM/h per unit flux)
df4   log 2.78e-6 1.11e-6 5.88e-7 2.56e-7 1.56e-7 1.20e-7 1.11e-7
         1.20e-7 1.47e-7 2.38e-7 3.45e-7 5.56e-7 7.69e-7 9.09e-7
         1.14e-6 1.47e-6 1.79e-6 2.44e-6 3.03e-6 4.00e-6 4.76e-6
         5.56e-6 6.25e-6 7.69e-6 9.09e-6
M1 13000.84p -1.0 $Al for metal chair support
M2 & $ Air (C:-0.000124, N:-0.755268, O:-0.231781, Ar:-0.012827)
6000.84p -0.000124 &
7014.84p -0.752290 &
7015.84p -0.002977 &
8016.84p -0.231153 &
8017.84p -0.000094 &
8018.84p -0.000535 &
18000.84p -0.012827
M3 1000.84p -0.11190 8000.84p -0.88810 $ water for human
M4 1000.84p -0.023416 8000.84p -.557572 16000.84p -.186215 20000.84p -.232797
$Gypsum for ceiling and walls
M5 1000.84p -.143711 6000.84p -.856289 $Polypropylene for chair
M6 27060.84p -.589332 17000.84p -.35453 $Cobalt 60 chloride isotope
```

Theme Park Line (Position A, other positions were single line change):

```
Title Theme Park Line Cobalt Run
c cell block
1   1   -1.52 (5 -8) (9 -12) (3 -1) #2 vol=102393716 imp:p=1 $dirt
2   4   -2.3 (6 -7) (10 -11) (2 -1) vol=906139 imp:p=1 $sidewalk
3   3   -1.0 -14 (1 -21) vol=10518 imp:p=1 $Human left leg
4   3   -1.0 -15 (1 -21) vol=10518 imp:p=1 $Human right leg
5   3   -1.0 -16 (20 -19) vol=5089 imp:p=1 $Human head
6   3   -1.0 -13 (21 -20) vol=45238 imp:p=1 $Human torso
7   3   -1.0 -17 (22 -20) vol=5576 imp:p=1 $Human left arm
8   3   -1.0 -18 (22 -20) vol=5576 imp:p=1 $Human right arm
9   2   -0.001225 (5 -8) (9 -12) (1 -4) #3 #4 #5 #6 #7 #8 vol=232387398 imp:p=1 $Air
10   0   -5:8:-9:12:-3:4 imp:p=0 $void

c surface block
1 PZ 0 $ground level
2 PZ -15.24 $concrete thickness
3 PZ -121.92 $dirt thickness
4 PZ 274.32 $Skybox height
5 PX 0 $Leftmost side of simulated square section
6 PX 304.8 $Leftmost point of sidewalk
7 PX 853.44 $Rightmost point of sidewalk
8 PX 1158.24 $Rightmost side of simulated square section
9 PY 0 $Bottom most side of simulated square
```

```
10 PY 304.8 $Bottom side of sidewalk
11 PY 426.72 $Upper side of sidewalk
12 PY 731.52 $Upper most side of simulated square
13 C/Z 548.64 365.75 15.24 $human Torso
14 C/Z 542.68 365.75 6 $human left leg
15 C/Z 554.68 365.75 6 $human right leg
16 C/Z 548.64 365.75 9 $human head
17 C/Z 527.64 365.75 5 $human left arm
18 C/Z 569.88 365.75 5 $human right arm
19 PZ 175 $top of human head
20 PZ 155 $top of human torso, arms, bottom of head
21 PZ 93 $top of human legs, bottom of torso
22 PZ 84 $Bottom of human arm

c data block
MODE P
SDEF POS=304.8 548.64 0.01 ERG=d1
SI1 L 1.173 1.333 $Energy of cobalt 60
SP1 0.5 0.5 $ frequency of occurrence
c NPS 1000000
CTME 8.0
c CTME 15.0
F6:p 3 4 5 6 7 8 T
c ------------------------ ICRP-21 (REM/h per unit flux) for photon
f4:p 3 4 5 6 7 8 T
de4   log 0.01   0.015   0.02   0.03   0.04   0.05   0.06
      0.08   0.1    0.15   0.2    0.3    0.4    0.5
      0.6    0.8    1.0    1.5    2.0    3.0    4.0
      5.0    6.0    8.0    10.0
```

```
C FLUX TO DOSE CONVERSION FACTOR VALUES ICRP-21 (REM/h per unit flux)
df4   log 2.78e-6 1.11e-6 5.88e-7 2.56e-7 1.56e-7 1.20e-7 1.11e-7
      1.20e-7 1.47e-7 2.38e-7 3.45e-7 5.56e-7 7.69e-7 9.09e-7
      1.14e-6 1.47e-6 1.79e-6 2.44e-6 3.03e-6 4.00e-6 4.76e-6
      5.56e-6 6.25e-6 7.69e-6 9.09e-6
M1 & $ Earth, U.S. Average PNNL cite
8000.84p -0.513713 &
11000.84p -0.006140 &
12000.84p -0.013303 &
13000.84p -0.068563 &
14000.84p -0.271183 &
19000.84p -.014327 &
20000.84p -0.051167 &
22000.84p -0.004605 &
25000.84p -0.000716 &
26000.84p -.056283
M2 & $ Air (C:-0.000124, N:-0.755268, O:-0.231781, Ar:-0.012827)
6000.84p -0.000124 &
7014.84p -0.752290 &
7015.84p -0.002977 &
8016.84p -0.231153 &
8017.84p -0.000094 &
8018.84p -0.000535 &
18000.84p -0.012827
M3 1000.84p -0.11190 8000.84p -0.88810 $ water for human
M4 1000.84p -0.01 8000.84p -0.532 11000.84p -0.029 13000.84p -0.034 & $Concrete, regular PNNL Cite
14000.84p -0.337 20000.84p -0.044 26000.84p -0.014
```

Sandbox Example:

```
Title Sandbox Cobalt Run
c cell
1   1   -1.45   (2 -3) (6 -7) (9 -10) imp:p=1 $Sandbox
2   4   -1.52   (1 -4) (5 -8) (9 -10) #1 imp:p=1 $dirt around sandbox
3   3   -1.00   -12 (18 -19) vol=5654 imp:p=1 $child torso
4   3   -1.00   -13 (19 -20) vol=631 imp:p=1 $child head
5   3   -1.00   -14 (10 -19) vol=697 imp:p=1 $child left arm
6   3   -1.00   -15 (10 -19) vol=697 imp:p=1 $child right arm
7   3   -1.00   -16 (22 -21) vol=1314 imp:p=1 $child left leg
8   3   -1.00   -17 (22 -21) vol=1314 imp:p=1 $child right leg
9   2   -0.001225 (1 -4) (5 -8) (10 -11) #3 #4 #5 #6 #7 #8 imp:p=1 $Air
10   0   -1:4:-5:8:-9:11 imp:p=0 $void

c surface cards
1 PX 0 $Furthest left of total simulated box
2 PX 152.4 $Furthest left of sand box
3 PX 457.2 $Furthest right of sand box
4 PX 609.6 $Furthest right of total simulated box
5 PY 0 $Bottom of total simulated box
6 PY 152.4 $Bottom of sand box
7 PY 457.2 $Top right of sand box
8 PY 609.6 $Top right of total simulated box
9 PZ -60.96 $Depth of sand and dirt
10 PZ 0 $ground level
11 PZ 274.32 $Height of skybox
12 C/Z 304.8 304.8 7.62 $Torso of child
```

```
13 C/Z 304.8 304.8 4.5 $Head of child
14 C/Z 304.8 294.6 2.5 $Left Arm of Child
15 C/Z 304.8 314.92 2.5 $Right Arm of child
16 C/X 301.8 3 3 $Left leg of child
17 C/X 307.8 3 3 $Right leg of child
18 PZ 6 $Bottom of child torso top of legs
19 PZ 37 $Bottom of child head top of torso
20 PZ 47 $Top of child head
21 PX 304.8 $Top of child legs
22 PX 258.3 $Bottom of child legs

c data cards
MODE P
SDEF CEL=1 POS 304.8 304.8 0 AXS 0 0 -1 EXT=D3 RAD=D1 ERG=D2
SI1 0 431.05 $ 304.8*2^0.5 needed to sample in the corners
SP1 -21 1
SI2 L 1.173 1.333
SP2 D 0.5 0.5
SI3 0 2.54
SP3 -21 0
CTME 15.0
F6:p 3 4 5 6 7 8
M1 14028.84p -.491986 8016.84p -.508014 27060.84p -.00000017 $ Cobalt Contaminated sand
M2 & $ Air (C:-0.000124, N:-0.755268, O:-0.231781, Ar:-0.012827)
6000.84p -0.000124 &
7014.84p -0.752290 &
7015.84p -0.002977 &
8016.84p -0.231153 &
8017.84p -0.000094 &
```

```
8018.84p -0.000535 &
18000.84p -0.012827
M3 1000.84p -0.11190 8000.84p -0.88810 $ water
M4 & $ Earth, U.S. Average PNNL cite
8000.84p -0.513713 &
11000.84p -0.006140 &
12000.84p -0.013303 &
13000.84p -0.068563 &
14000.84p -0.271183 &
19000.84p -.014327 &
20000.84p -0.051167 &
22000.84p -0.004605 &
25000.84p -0.000716 &
26000.84p -.056283
```

Metro Line Example:

```
Title Metro Line Cobalt Run
c cell
1   1   -2.6989 (2 -1) (6 -8) (10 -12) imp:p=1 $Left most wall of train
2   1   -2.6989 (3 -4) (6 -8) (10 -12) imp:p=1 $Right most wall of train
3   1   -2.6989 (6 -5) (1 -3) (10 -12) imp:p=1 $Bottom most wall of train
4   1   -2.6989 (7 -8) (1 -3) (10 -12) imp:p=1 $Top most wall of train
5   1   -2.6989 (10 -9) (1 -3) (5 -7) imp:p=1 $Floor of train
6   1   -2.6989 (11 -12) (1 -3) (5 -7) imp:p=1 $Ceiling of train
7   3   -1.0 -21 (23 -24) vol=45238 imp:p=1 $Human Torso
8   3   -1.0 -22 (24 -25) vol=5089 imp:p=1 $Human Head
9   3   -1.0 -26 (28 -29) vol=5259 imp:p=1 $Human Right Leg Top Section
10   3   -1.0 -27 (28 -29) vol=5259 imp:p=1 $Human Left Leg Top Section
```

```
11   3   -1.0 -30 (9 -32) vol=3845 imp:p=1 $Human Right Leg Bottom Section
12   3   -1.0 -31 (9 -32) vol=3845 imp:p=1 $Human Left Leg Bottom Section
13   3   -1.0 -33 (35 -24) vol=5576 imp:p=1 $Human Right Arm
14   3   -1.0 -34 (35 -24) vol=5576 imp:p=1 $Human Left Arm
15   4   -0.9 (13 -14) (15 -16) (17 -18) imp:p=1 $Bottom Metro Seat
16   4   -0.9 (14 -19) (15 -16) (17 -20) imp:p=1 $Back Metro Seat
17   5   -3.36 -36 (37 -13) imp:p=1 $Source
18   2   -0.001225 (1 -3) (5 -7) (9 -11) #7 #8 #9 #10 #11 #12 #13 #14 &
#15 #16 #17 imp:p=1 $Air in metro
19   0   -2:4:-6:8:-10:12 imp:p=0 $void

c surface cards
1 PX 0 $ Far Left Wall
2 PX -3 $Thickness of train wall far left wall
3 PX 1554.5 $Far right wall (51 feet away) of train
4 PX 1557.5 $Thickness of train wall far right wall
5 PY 0 $Bottom most wall of train
6 PY -3 $Thickness of Bottom most wall of train
7 PY 262.1 $Top most wall (8.6 feet away) of train
8 PY 265.1 $Thickness of train top most
9 PZ 0 $Floor of train
10 PZ -3 $Thickness of floor of train
11 PZ 274.32 $Ceiling of train 9 feet
12 PZ 277.32 $Thickness of ceiling of train
13 PZ 30.48 $Bottom of metro seat
14 PZ 33.48 $Top of metro seat
15 PX 762 $Left side of metro seat (25 feet from right most side)
16 PX 816.86 $Right side of metro seat (1.8 feet width)
17 PY 1 $back of seat 1 cm away from back
```

```
18 PY 62 $Front of seat (2 foot length)
19 PZ 95.48 $Top of back of metro seat (2 foot height)
20 PY 3 $From of back of seat 3 cm thicknes)
21 C/Z 789.43 31.5 15.24 $Torso of human
22 C/Z 789.43 31.5 9 $Human Head
23 PZ 46.48 $Bottom of human Torso
24 PZ 108.48 $top of human Torso and Arms/Bottom of human head
25 PZ 128.48 $Top of Human Head
26 C/Y 796 39.5 6 $Human Right Leg Top Section
27 C/Y 783 39.5 6 $Human Left Leg Top Section
28 PY 31.5 $Top of Human Leg Top Section
29 PY 78 $Bottom of Human Leg Top Section
30 C/Z 796 84.01 6 $Human Right Leg Bottom Section
31 C/Z 783 84.01 6 $Human Left Leg Bottom Section
32 PZ 34 $Top of Human Legs Bottom Section
33 C/Z 810 31.5 5 $Human Right Arm
34 C/Z 769 31.5 5 $Human Left Arm
35 PZ 37.5 $Bottom of Human Arms
36 C/Z 789.43 31.5 3 $source under seat
37 PZ 27 $Bottom of source

c data
MODE P
SDEF CEL=17 POS 789.43 31.5 27 AXS 0 0 1 EXT=D3 RAD=D1 ERG=D2
SI1 0 3
SP1 -21 1
SI2 L 1.173 1.333
SP2 D 0.5 0.5
SI3 0 2.54
```

```
SP3 -21 0
CTME 15.0
F6:p 7 8 9 10 11 12 13 14
c ----------------------- ICRP-21 (REM/h per unit flux) for photon
f4:p 7 8 9 10 11 12 13 14 T
de4   log 0.01    0.015   0.02    0.03    0.04    0.05    0.06
         0.08    0.1     0.15    0.2     0.3     0.4     0.5
         0.6     0.8     1.0     1.5     2.0     3.0     4.0
         5.0     6.0     8.0     10.0
C FLUX TO DOSE CONVERSION FACTOR VALUES ICRP-21 (REM/h per unit flux)
df4   log 2.78e-6 1.11e-6 5.88e-7 2.56e-7 1.56e-7 1.20e-7 1.11e-7
         1.20e-7 1.47e-7 2.38e-7 3.45e-7 5.56e-7 7.69e-7 9.09e-7
         1.14e-6 1.47e-6 1.79e-6 2.44e-6 3.03e-6 4.00e-6 4.76e-6
         5.56e-6 6.25e-6 7.69e-6 9.09e-6
M1 13000.84p -1.0 $Al for train shell
M2 & $ Air (C:-0.000124, N:-0.755268, O:-0.231781, Ar:-0.012827)
6000.84p -0.000124 &
7014.84p -0.752290 &
7015.84p -0.002977 &
8016.84p -0.231153 &
8017.84p -0.000094 &
8018.84p -0.000535 &
18000.84p -0.012827
M3 1000.84p -0.11190 8000.84p -0.88810 $ water for human
M4 1000.84p -.143711 6000.84p -.856289 $Polypropylene for chair
M5 27060.84p -.589332 17000.84p -.35453 $Cobalt 60 chloride isotope
```