A Poor Man's Nuclear Deterrent: Assessing the Value of Radiological Weapons for State Actors

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Abstract of Thesis

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The threat of weapons of mass destruction is an issue which remains at the forefront on national security. Nuclear, chemical, and biological weapons are all considered very dangerous by both state and non-state actors. Radiological weapons exist in that same category yet are not held in the same regard; the reason that is given is that these types of weapons are not the weapons of mass destruction that the other three are. Instead, radiological weapons are better considered weapons of mass disruption. Accordingly, in the academic and policy literature there has been very little perceived value associated with such weapons for use by state actors. However the historical focus on the military efficacy of radiological weapons has obscured the obvious truth that they may pose significant value for state actors.

What this research shows is that the explosion of a radiological weapon could disrupt a target area in ways which could cripple the economy of an adversary state and promote widespread fear concerning exposure to radiation. Any such attack would not only necessitate large scale evacuation, but cleanup, decontamination, demolition, territory exclusion, and relocation. Moreover, the effects of such an attack would be unlikely to remain an isolated event as evacuated and displaced citizens spread across the nation carrying both fear and residual radiation. All of these factors would only be compounded by a state actor's ability to not only develop such weapons, but to manufacture them in such a composition that contemporary examples of such weapons grossly underestimate their impact.

Accordingly, radiological weapons could hold great value for any state actor wishing to pursue their development and to threaten their use. Moreover, “while RDDs may not be well suited as "military weapons" in the classic sense, the use of RDDs could be powerfully coercive.”[1] In that sense, state actors could even acquire radiological weapons for their deterrent value.

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[1] James L. Ford, “Radiological Dispersal Devices: Assessing the Transnational Threat,” *Strategic Forum*, No. 136, (March 1998), March 29, 2012, http://www.au.af.mil/au/awc/awcgate/ndu/forum136.htm.

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Chapter 1: Introduction

With the attack on the World Trade Center on September 11, 2001, and with the growing threat of terrorism across the globe, the threat posed by terrorists acquiring and utilizing radiological weapons has come to the forefront of national security in the United States, as well as numerous other countries. At the same time, the threat posed by radiological weapons is not a new threat. The dangers of radiological weapons have been discussed since the Manhattan Project. Radiological weapons have the potential of causing mass disruption, including large area denial, and incalculable economic and psychological damage. In fact, as early as 1948, there have been attempts to ban their usage.[2]

Given the inherent dangers with which radiological weapons are attributed, there is currently a dearth of contemporary analysis which evaluates the significance of state actors possessing radiological weapons. The preponderance of research that does exist, overwhelming focuses on the use of radiological weapons or "dirty bombs" by non-state actors such as terrorists. Yet, as the International Atomic Energy Agency noted in June 2011, "almost every nation in the world has the radioactive materials needed to build a dirty bomb."[3] And as is noted by the Federation of American Scientists, "the nearly unchecked growth in radiological source distribution has provided every state and non-

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[2] In 1948, it was proposed by the UN Commission on Conventional Armaments that "radioactive material weapons" be included in the definition of a weapon of mass destruction (WMD).

[3] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.

state actor with at least the capability to easily develop a wide range of radiological weapons."[4]

With this understanding, the purpose of this research piece is to address the dearth of analysis on states possessing radiological weapons. Analyzing the available research on radiological weapons, this thesis seeks to garner a better understanding of the potential radiological weapon that a state could build, along with the subsequent effects from its usage. The overall question that this research seeks to evaluate is, "What is the value of a radiological weapon, or more specifically an explosive radiological dispersal device (ERDD), for a state actor?"[5]

The conclusion of this research posits that there is indeed a value for states possessing radiological weapons and, owing to their demonstrable effects and the ability to threaten those effects, such radiological weapons could function as a deterrent to a state's adversaries, even those possessing nuclear weapons. This conclusion is arrived at by a number of steps. This report first develops a base line of understanding regarding the dynamics of radioisotopes and radiation. Second, the report will give a review of the history of radiological weapons. Third, the report will examine the current literature on radiological weapons, highlighting their findings as they relate to non-state actors. Fourth, this report will examine relevant examples of radiological incidents which have

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[4] Bill Richardson, Charles Streeper and Margarita Sevci, "Sweeping Up Dirty Bombs: A Shift From Normative to Pro-Active Measures," *Federation of American Scientists*, (Fall 2011), accessed February 9, 2012, http://www.fas.org/pubs/pir/2011fall/2011fall-dirtybombs.pdf.

[5] It should be noted that by definition there are a number of different mechanisms that can comprise a radiological weapon. For the purpose of this thesis, the research and analysis will focus on the development and usage of a radiological dispersal device (RDD). An RDD can take a number of forms including "explosive or non-explosive and passive or active means, to spread radioactive material." Accordingly, for the purpose of this research piece, we will use the term ERDD to denote a device that utilizes an explosion to disperse radioisotopes.

resulted in the dispersal of large amounts of radioisotopes. Fifth, this report will draw conclusions from these findings and posit what could be expected by a state possessing radiological weapons. The resulting conclusions present a definitive example of the significance of radiological weapons possessed by states actors, in turn, highlighting a significant area of national security which is currently unexplored and which demands further investigation and research.

Chapter 2: Radiation and its Effects

Background Primer on Radiation

Before analyzing the value of radiological weapons, it is important to begin with a general understanding of how radiation works and how that radiation affects human tissue. To begin, there are roughly 100 elements that comprise all the substances on Earth and make up what is commonly known as the Periodic Table of Elements. Each of these elements has unique chemical properties, which are the direct result of "the number of protons (positively charged particles) inside the nucleus, or core, of each atom."[6] In addition, the neutrons inside the nucleus of each atom also help define the nuclear properties of the element. Each of these elements may take various nuclear forms, distinguished as isotopes. These isotopes differ in their nuclear properties, specifically in that the number of neutrons in any given element may vary from one to another.

These varying isotopes are divided into two categories: stable or unstable. Any single element can have several different stable isotopes. For example, the element helium has two stable isotopes; these are designated as helium-3 and helium-4. In their nuclear composition, each of these isotopes of helium has the same number of electrons and the same basic structure. Nevertheless, the properties of these two isotopes of helium

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[6] Charles D. Ferguson and Michelle M. Smith, "Assessing radiological weapons: Attack methods and estimated effects," *Defence Against Terrorism Review*, Vol. 2, No. 2 (Fall 2009): 15-34, January 7, 2012, http://www.tmmm.tsk.tr/publications/datr4/02-CharlesFerguson.pdf.

are quite different, the significance of which plays "a key role in understanding why some isotopes are radioactive or fissile and others are not."[7]

Though each element has a range of isotopes for which it is stable, outside of this range, the isotope is unstable and is a radioisotope. In fact, all elements with "atomic numbers greater than 83 are radioisotopes,"[8] meaning they are unstable and radioactive. These radioactive isotopes, or radioisotopes, go through a process called radioactive decay, whereby the unstable isotope will emit ionizing radiation through "transmutation" and decay to another form. This new form will either be another unstable isotope or a new stable isotope. Consequently, radioisotopes are constantly changing to try and stabilize and "the radioactive decay and transmutation process will continue until a new element is formed that has a stable nucleus and is not radioactive."[9] The time in which this process occurs is measured by what is called half-life: "the average time interval required for one-half of any quantity of radioactive atoms to undergo radioactive decay."[10] A short half-life denotes a period of rapid decay while a long half-life denotes a longer period of decay.

Before delving further, it is important to also recognize that there are two major divisions in terms of radiation: non-ionizing radiation and ionizing radiation. The distinction lies in how energy reacts with an atom. As the EPA denotes, non-ionizing

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[7] Allan Krass, "Nuclear Proliferation: The Basic Science and Technology," (paper presented at Brookhaven National Laboratory for the summer course on Nuclear Nonproliferation, Safeguards and Security in the 21st Century, Upton, New York, June 7, 2011).
[8] "Radioactivity and Radioisotopes," *Nondestructive Testing Resource Center*, accessed January 20, 2012, http://www.ndt-ed.org/EducationResources/HighSchool/Radiography/radioactivity.htm.
[9] "Radioactivity and Radioisotopes," *Nondestructive Testing Resource Center*, accessed January 20, 2012, http://www.ndt-ed.org/EducationResources/HighSchool/Radiography/radioactivity.htm.
[10] Sybil P. Parker, ed., *Dictionary of Scientific and Technical Terms* (New York: McGraw-Hill, 1994): 895.

radiation has “enough energy to move around atoms in a molecule or cause them to vibrate, but not enough to remove electrons.”[11] Conversely, ionizing radiation “has enough energy to remove tightly bound electrons from atoms through scattering or absorption, thus creating ions.”[12] The significance between these distinctions is that while non-ionizing radiation can create what we commonly accept as essentially harmless radio waves and microwaves, ionizing radiation instead creates what are known as alpha (α), beta (β), and gamma (γ) radiation. Though alpha, beta and gamma particles have different characteristics, each of these three types of ionizing radiation has the ability to strip electrons from atoms and break chemical bonds, expelling energy. For human cells, exposure to ionizing radiation can result in the death or mutation of cells, which in turn can damage or kill the entire organism. Ionizing radiation and the effect on human cells is the underlying reason why radioisotopes are incorporated into an ERDD.

These three forms of ionizing radiation vary both in the amount of radiation they discharge as well as in their ability to penetrate materials. Alpha radiation is the most ionizing of the three types, however most alpha particles can be stopped by an object as thin as a piece of paper. For most beta particles, it would take something more substantial such as a thin piece of aluminum or glass to stop them. Because of their weak ability to penetrate objects such as skin, both alpha and beta radiation are mainly regarded as internal health hazards. Gamma radiation is the most penetrating of the three. In contrast to alpha and beta radiation, gamma radiation requires thick concrete or lead to

11 “Radiation: Non-Ionizing and Ionizing,” *United States Environmental Protection Agency*, accessed January 7, 2012, http://www.epa.gov/radiation/understand/index.html.
12 “Radiation: Non-Ionizing and Ionizing,” *United States Environmental Protection Agency*, accessed January 7, 2012, http://www.epa.gov/radiation/understand/index.html.

block the gamma particles.[13] Unlike alpha and beta radiation, gamma radiation poses both an internal and external radiation hazard. In addition, during the process of radioactive decay, some radioisotopes emit gamma radiation accompanied by the emission of either alpha or beta radiation.[14]

Though alpha particles require very little to protect against, such as isotopes of uranium which can be held in the hand without injury, alpha particles can interact very strongly with atoms, doing a lot of damage in a very small volume. This is not a problem if the source of alpha particles is external to the body. Yet, if an alpha emitter is ingested or inhaled and exposes delicate tissue such as the linings of the lung, it can be very damaging. Conversely, beta and gamma radiation deposit their energy over longer distances and spread out their damage. The difference in the deposit of energy between alpha radiation and both beta and gamma radiation is a ratio of roughly 10:1, with alpha radiation being ten times as damaging to living organisms as beta and gamma radiation.[15] However, the probability of damage is completely dependent upon the type of interaction with the specific particles.

In terms of radiation exposure and its result, the outcome relies primarily on what radioisotope is present and what the rate of decay is. Each different isotope decays at different rates and, as aforementioned, each radioactive decay process is characterized by

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[13] Charles D. Ferguson, Tahseen Kazi, and Judith Perera, "Commercial Radioactive Sources: Surveying the Security Risks," *Center for Nonproliferation Studies, Monterey Institute of International Studies,* (January 2003): 16, accessed December 18, 2011, http://cns.miis.edu/opapers/op11/op11.pdf.

[14] It is important to note that in addition to alpha, beta, and gamma radiation, some unstable nuclei emit protons, neutrons, and deuterons. Also, there are other nuclei that become more stable by spontaneously undergoing fission, that is, splitting into two smaller mass pieces (fission products) and releasing neutrons.

[15] Allan Krass, "Nuclear Proliferation: The Basic Science and Technology," (paper presented at Brookhaven National Laboratory for the summer course on Nuclear Nonproliferation, Safeguards and Security in the 21st Century, Upton, New York, June 7, 2011).

half-life. The way this process works is that for any given isotope, "after two half-lives, one-fourth of the sample remains; three half-lives, one-eighth; and so on. After seven half-lives, the radioactive substance has decayed to less than one percent of its initial amount."[16] The length of a half-life can range from tiny fractions of a second, to as long as billions of years. Isotopes such as Uranium-235 (U-235), Uranium-238 (U-238), Thorium-232 (Th-232) and Potassium-40 (K-40), have half-lives that are comparable to the age of the solar system (approximately 4.6 billion years) and these isotopes have been slowly decaying since its creation.[17] The shorter the half-life, the more frequently the radioactive source emits ionizing radiation and the more likely it is to expend its radiation and return to a stable non-irradiating form. "Some materials decay quickly, making them sources of intense radiation, but their rapid decay rate means that they do not stay radioactive for long periods of time. Other materials serve as a weaker source of radiation because they decay slowly."[18] However, it is important to recognize that though radioactive decay is generally predictable, radioactive decay is a complex process that is both spontaneous and unpredictable. If we know that a given isotope has a half-life of 15 minutes, then there is a 50% chance that it will decay within the next 15 minutes and 50% that it will not, no matter how long it has existed.

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[16] Charles D. Ferguson, Tahseen Kazi, and Judith Perera, "Commercial Radioactive Sources: Surveying the Security Risks," *Center for Nonproliferation Studies*, Monterey Institute of International Studies, (January 2003): 16, accessed December, 18, 2011, http://cns.miis.edu/opapers/op11/op11.pdf.
[17] Allan Krass, "Nuclear Proliferation: The Basic Science and Technology," (paper presented at Brookhaven National Laboratory for the summer course on Nuclear Nonproliferation, Safeguards and Security in the 21st Century, Upton, New York, June 7, 2011).
[18] "Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations," March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.

Ionizing Radiation and People

With this basic understanding of how radiation works, it is equally important to examine the possible effects of radiation, specifically the way it reacts with human tissue. "For living organisms, the danger posed by radioactive material is contingent on two factors: the intensity of the radioactivity and length of exposure."[19] Radiation doses, or equivalent doses, are measured in what is referred to as rem, short for *roentgen equivalent man*.[20] Rem relates the "absorbed dose in human tissue to the effective biological damage of the radiation."[21] However, it is important to note that, "not all radiation has the same biological effect, even for the same amount of absorbed dose."[22]

In terms of a given year, the average person will receive 300 millirem (mrem) in natural background radiation exposure, including radiation from "cosmic rays and the uranium in granite bedrock."[23] In addition, the average person also receives small amounts of radioactivity "in the soil, in building materials, and other parts of our environment."[24] We even receive a small dose of radiation in the form of K-40 every time we eat a banana.[25]

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[19] Major Julian M. Chesnutt, "Defeating the United States with Radiological Weapons in Fourth Generation Warfare," *Air Command and Staff College Air University*, (April 2003), accessed January 7, 2012, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA476348.

[20] Other units may be used as well. In terms of their equivalence, a sievert is equal to a gray, and they are both equal to roughly 100 rem.

[21] "Radiation Related Terms," *Radiation Information Network's*, Idaho State University, accessed January 7, 2012, http://www.physics.isu.edu/radinf/terms.htm.

[22] "Radiation Related Terms," *Radiation Information Network's*, Idaho State University, accessed January 7, 2012, http://www.physics.isu.edu/radinf/terms.htm.

[23] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.

[24] "Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations," March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.

[25] In fact, some research actually posits that low doses of radiation can actually have beneficial effects.

In terms of regulation, the Environmental Protection Agency (EPA) considers "100 mrem per year beyond normal background radiation acceptable."[26] However, the EPA maintains that in any given area emitting radiation, that "cleanup actions must reduce contamination to the extent that the radiation dose from all exposure pathways, including ground water, is less than 15 mrem per year, above the background dose."[27] Conversely, U.S. federal regulations maintain a higher rate for acceptable dose for those working in the nuclear field. The U.S. Nuclear Regulatory Commission standard for maximum permissible radiation dosage for workers in a radiation environment is five rem per year.[28]

Any increase in exposure to radiation can increase the risk of developing cancer. However, the doses of radiation garnered from the sources just mentioned are quite insignificant and are not generally expected to cause any deterministic effects. Nevertheless, even small doses of radiation can be considered significant if received in a short period of time. Such doses have the ability to cause serious and demonstrable effects in living cells. And as the exposure increases, so do the effects, which can manifest in the form of nausea, skin burns, internal bleeding, hair loss, etc. These are common symptoms seen in people who have been given, or who have come in contact, with high doses of radiation such as the doses of radiation used for cancer therapy. For example, many of the firemen, soldiers and nuclear plant workers involved with the

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[26] Lieutenant Colonel Joel T. Hanson, "Radiological Dispersal Device Primer: From a Terrorist's Perspective," *Air War College Air University*, February 15, 2008, accessed March 20, 2012, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA489222.
[27] "Consistency in EPA Requirements for Ground-Water Cleanup," *U.S. Environmental Protection Agency*, Office of Solid Waste and Response, May 14, 1996, accessed March 10, 2012, http://www.epa.gov/fedfac/documents/ground_water_cleanup.htm.
[28] Richard J. Burk, "Radiation Risk in Perspective," *Health Physics Society*, (2001): 2.

Chernobyl reactor accident in 1986 in the former Ukrainian Soviet Socialist Republic suffered serious radiation sickness due to high radiation exposure. Similarly, in the more recent Fukushima Daiichi nuclear accident in Japan, two workers died after long illnesses caused by massive exposure to radiation.

In terms of exposure, even small doses of radiation can cause genetic mutations that greatly increase the risk of developing cancer, though cancer may take years to present itself. This delayed affect occurs when a cell is damaged from ionizing radiation and then replicates and passes on its damaged "blueprint" for cell reproduction. A likely result is the production of a cancerous cell. The rate at which this risk is calculated is not definitively clear. As Berkley physics professor Dr. Richard Muller purports, "results from historical exposures suggest that the increased risk of cancer is about 0.04% per rem,"[29] or 1% for every 25 rem. Moreover, "for larger doses, the danger is proportional to the dose, so a 50-rem dose gives you a 2% chance of getting cancer; 75 rem ups that to 3%."[30] At the same time, as recently as 2010, the journal *Radiology* stated that the "current rule-of-thumb" estimate for the overall radiation attributable **cancer mortality rate**, not incidence rate, is about 1.25% per 25 rem, and that the radiation attributable **cancer incidence rate** is roughly 2.5% per 25 rem, more than double Muller's estimate.[31] The difference in these figures could be partly attributed to the different rates given for different types of radiation attributable cancer. **Table-1** gives a brief picture of latency

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[29] Richard A. Muller, "Physics for Future Presidents," (New York: W.W. Norton & Company, 2008): 39.
[30] Richard Muller, "The Panic Over Fukushima," *The Wall Street Journal*, August 18, 2012, C1.
[31] Christensen et al, "Medical Response to a Major Radiologic Emergency: A Primer for Medical and Public Health Practitioners," *Radiology*, (March 2010), accessed on November 17, 2012, http://radiology.rsna.org/content/suppl/2010/02/12/254.3.660.DC1

and various types of cancer associated with ionizing radiation. Regardless, it is important to keep in mind that the increased risk of cancer due to radiation is in addition to the rate cancer from natural causes which is roughly 20%.[32]

Table 1. Long Term Medical Effects of Ionizing Radiation[33]		
Disease	**Minimum Latency Period**	**Relative Risk at 100 rem (Gamma Radiation)**
Leukemia	2 years	4.9%
Bone cancer	3 years	1.2%
Thyroid cancer	5 years	1.2%
Solid tumors	10 years	3.3%
Note: Relative risk can be simplified and summarized as the increase in likelihood of contracting the disease, thus, a person exposed to 100 rem of radiation cumulatively over a long period of time is roughly five times more likely to contract Leukemia than a person only exposed to normal background radiation.		

History provides us with two examples of the possible relationship between radiation exposure and cancer. First, is when the "incidence of leukemia in the Hiroshima area peaked five to seven years after the atomic bomb was detonated."[34] The second example is when thyroid cancer peaked in survivors of the Chernobyl meltdown, four to five years after the meltdown occurred.[35] Although, triggering cancer is largely a

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[32] Richard A. Muller, "Physics for Future Presidents," (New York: W.W. Norton & Company, 2008): 101.
[33] Major Julian M. Chesnutt, "Defeating the United States with Radiological Weapons in Fourth Generation Warfare," *Air Command and Staff College Air University*, (April 2003), accessed January 7, 2012, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA476348.
[34] Major Julian M. Chesnutt, "Defeating the United States with Radiological Weapons in Fourth Generation Warfare," *Air Command and Staff College Air University*, (April 2003), accessed January 7, 2012, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA476348.
[35] Major Julian M. Chesnutt, "Defeating the United States with Radiological Weapons in Fourth Generation Warfare," *Air Command and Staff College Air University*, (April 2003), accessed January 7, 2012, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA476348.

matter of chance, it is generally accepted that on average, "if 2,500 people are exposed to a single rem of radiation, one will die of an induced cancer."[36]

In addition, the length of time that exposure occurs also has an important effect. The more radiation received in any given period, the more substantial the effects. **Table-2** showcases a comprehensive picture of exposure to varying levels of ionizing radiation and its effects. For example, if a person received at least 100 rem of radiation, it would most likely result in radiation sickness which would require immediate medical attention. "Intense sources of gamma rays can cause immediate tissue damage, and lead to acute radiation poisoning."[37] A more significant dose of 450 rem would result in 50% of those exposed dying within 60 days.[38]

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[36] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.
[37] "Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations," March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.
[38] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.

Table 2. Radiation Exposure and the Effects[39]		
Exposure (rem)	Health Effect	Time to Onset (without treatment)
5. – 10	Changes in blood chemistry	
50	Nausea	hours
55	Fatigue	
70	Vomiting	
75	Hair loss	2-3 weeks
90	Diarrhea	
100	Hemorrhage	
400	Possible death	within 2 months
1,000	Destruction of intestinal lining, internal bleeding, and death	1-2 weeks
2,000	Damage to central nervous system, loss of consciousness; death	minutes hours to days
Note: the acute affects are cumulative. For example, a dose that produces damage to bone marrow will have produced changes in blood chemistry and be accompanied by nausea.		

Another important consideration is that, based on a National Academy of Sciences 2006 BEIR-VII report, exposure to radiation is purported to cause "50% greater incidence of cancer and 50% greater rate of death from cancer among women, compared to the same radiation dose level to men."[40] In addition, the fetuses of pregnant women are particularly susceptible to the effects of radiation. The risk of mutation in a fetus is "about 3% for each rem of exposure."[41] In terms of the effect, "mutation in one of the

[39] "Health Effects," *United States Environmental Protection Agency*, accessed January 7, 2012, http://epa.gov/radiation/understand/health_effects.html.
[40] "Atomic radiation is more harmful to women than to men," *Canadian Women's Health Network*, 2012, accessed on November 17, 2012, http://www.cwhn.ca/en/node/43947.
[41] Richard A. Muller, "Physics for Future Presidents," (New York: W.W. Norton & Company, 2008): 119.

stem cells can lead to mental retardation, malformed growth, or cancer, but usually the result is a spontaneous abortion."[42]

Radioisotopes

With this basic understanding of radiation, as well as the effects that ionizing radiation can have on human cells, we can now properly analyze and define which sources of ionizing radiation or which radioisotopes present the greatest threat, specifically in terms on an ERDD. A list of known radioisotopes is extensive, with over 3,000 different radioisotopes. Many radioisotopes are naturally occurring such as tritium, which is formed by cosmic ray interaction with atmospheric molecules. Other radioisotopes, such as uranium and thorium, were formed billions of years ago at the birth of our solar system. Radioisotopes may also be produced as a by-product in nuclear reactors and in cyclotrons and are often utilized in fields such as nuclear medicine, biochemistry, agriculture, and the manufacturing industry.[43]

As aforementioned, each different radioisotope has a specific type of radiation that is emits. Whereas the amount of radiation received is measured in units of rem, the amount of radiation emitted or the rate of decay is denoted in units of Curie (Ci).[44] Originally, one Ci was the estimate of "the activity of one gram of pure radium-226."[45] In terms of the significance of a Ci, "a one Curie source is considered large; a 100 Curie

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[42] Richard A. Muller, "Physics for Future Presidents," (New York: W.W. Norton & Company, 2008): 119.
[43] "Radioisotopes," *Canadian Nuclear Safety Commission*, accessed January 7, 2012, http://nuclearsafety.gc.ca/eng/readingroom/radiation/radioisotopes.cfm.
[44] A Curie measures the decay and equals 3.7x1010 nuclei decaying per second.
[45] Benjamin F. Visger, "Dirty Bombs: The Technical Aspects of Radiological Dispersion Devices," (Master thesis, Naval Post Graduate School, 2004).

source is considered very dangerous."[46] In addition, each radioisotope has its own specific half-life, decays at its own specific rate, and emits different levels of radiation per quantity. These factors all contribute to the overall threat posed by a given radioisotope and "knowing the type, energy, decay rate, and amount of radiation of particular radioisotopes helps to characterize the security risk."[47]

Radioisotopes and ERDD's

Out of the total available radioisotopes, a list containing those that present a definitive danger to people is actually quite small, particularly for the purpose of an ERDD. Out of the roughly 3,000 known radioisotopes, most decay very rapidly, taking less than one second. These radioisotopes pose little to no hazard to people. In addition, as Charles Ferguson and Michelle Smith note in their paper *Assessing Radiological Weapons*, isotopes with a half-life shorter than a few days or longer than several thousand years, should also be excluded when developing an ERDD. The rationale is that short half-life materials do not last long enough to pose a hazard, and that "very long half-life materials decay relatively slowly and thus would not emit as much radiation as an intermediate half-life material."[48] Most experts would thus agree that in terms of an effective ERDD, the main concern lies in strong radiation emitting radioisotopes that emit the majority of their radiation over several decades (corresponding with a typical

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[46] Lieutenant Colonel Joel T. Hanson, "Radiological Dispersal Device Primer: From a Terrorist's Perspective," *Air War College Air University*, February 15, 2008, accessed March 20, 2012, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA489222.
[47] Charles D. Ferguson, Tahseen Kazi, and Judith Perera, "Commercial Radioactive Sources: Surveying the Security Risks," *Center for Nonproliferation Studies, Monterey Institute of International Studies*, (January 2003): 16, accessed December 18, 2011, http://cns.miis.edu/opapers/op11/op11.pdf.
[48] Charles D. Ferguson and Michelle M. Smith, "Assessing radiological weapons: Attack methods and estimated effects," *Defence Against Terrorism Review*, Vol. 2, No. 2 (Fall 2009): 15-34, January 7, 2012, http://www.tmmm.tsk.tr/publications/datr4/02-CharlesFerpdf.

human lifespan). Acknowledging these factors, there are multiple isotopic candidates that would prove most effective in the construction of an ERDD. Specifically, the prevailing literature on radiological weapons denotes "nine isotopes considered candidates for an RDD,"[49] These nine isotopes are listed in **Table-3.**

Table 3. Candidate Isotopes of Greatest Concern for use in an ERDD[50]

Radioisotope	Half-Life	Specific Activity Ci/g
Americium-241 (Am-241)	433 years	3.4
Californium-252 (Cf-252)	2.7 years	536
Cesium-137 (Cs-137)	30 years	88
Cobalt-60 (Co-60)	5.3 years	1,100
Iodine-131 (I-131)	8.0 days	130,000
Iridium-192 (Ir-192)	74 days	>450
Polonium-210 (Po-210)	140 days	166,500
Plutonium-238 (Pu-238)	88 years	17.2
Strontium-90 (Sr-90)	29 years	140

Note: When Cs-137 decays, it can produce the radioisotope barium-137m (Ba-137m), which emits gamma radiation and has a short 2.6 min half-life, creating an external health hazard. When Sr-90 decays, it produces a daughter radioisotope yttrium-90 (Y-90), which has a 64-hour half-life and decays by beta emission.

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[49] "Radiological Dispersal Device (RDD)" *Human Health Fact Sheet*, Argonne National Laboratory, (August 2005), January 7, 2012, http://www.evs.anl.gov/pub/doc/rdd.pdf.

[50] Charles D. Ferguson and Michelle M. Smith, "Assessing radiological weapons: Attack methods and estimated effects," *Defence Against Terrorism Review*, Vol. 2, No. 2 (Fall 2009): 15-34, January 7, 2012, http://www.tmmm.tsk.tr/publications/datr4/02-CharlesFerpdf.

Three of the isotopes listed in **Table-3** are considered strong gamma-ray emitters. This includes Cobalt-60 (Co-60) as well as Cesium-137 (Cs-137), and Iridium-192 (Ir-192). Owing to their intense gamma radiation, these isotopes would pose a serious external hazard to individuals who came into contact with them.[51] A fourth isotope, Strontium-90 (Sr-90), emits beta particles which primarily represent an internal health hazard if ingested or inhaled. As Dr. Muller of Berkeley notes, Sr-90 does not pose a topical hazard in terms of penetrating the skin, but when it settles to the ground, "don't eat the food it settles on, and don't eat the animals that eat the grass it settles on, and don't drink their milk."[52] Also, Sr-90 poses a serious concern particularly in relation to its daughter product Yttrium-90 (Y-90), which is a short lived heavy gamma emitter. The radioisotopes Sr-90 and Cs-137 are considered to have played important roles in the long-term health effects related to the atomic bombing of Hiroshima and Nagasaki, and the dispersal of radiation from the Chernobyl nuclear reactor accident.

Other isotopes such as Americium-241 (Am-241), Californium-252 (Cf-252), Polonium-210 (Po-210), Plutonium-238 (Pu-238), and Radium-226 (Ra-226) also present a radiological danger, though considered a smaller danger in comparison to gamma emitters. Primarily alpha emitters, these latter isotopes mainly pose an internal threat and are easily shielded with only minimal amounts of material. However, it should be noted that, "if plutonium is in the environment in particles small enough to be inhaled,

[51] This includes those individuals involved in constructing an ERDD.
[52] Richard A. Muller, "Physics for Future Presidents," (New York: W.W. Norton & Company, 2008): 119.

contaminated particles can lodge in the lung for extended periods… [and that] the alpha particles produced by plutonium can damage lung tissue and lead to long-term cancers."[53]

Nevertheless, the list that is given in **Table-3** should not be considered as a comprehensive list regarding what are the dangerous radioisotopes. Additional radioisotopes would still present a radiological hazard if used in an ERDD. Specifically, isotopes such as Zinc-65 (Z-65) and Tantalum-182 (Ta-182) could also serve as the radiological component of an ERDD. Specifically, in comparison to Co-60, Z-65 has the advantage of a faster decay rate with a half-life of 243 days, and higher radiation per gram, roughly 8253.5 Ci/g.[54] In a weapon utilizing pure Zn-65, "the radiation intensity would initially be twice as much as Co-60. This would decline to be equal in 8 months [and] in 5 years Co-60 would be 110 times as intense."[55] Ta-182, which emits roughly 6271 Ci/g, would exhibit initial radiation intensity even greater than that of Zn-65.[56] However, Ta-182 has a much smaller half-life than Zn-65, 114 days, and its radiation output would drop precipitously compared to Zn-65 over a very short period of time. Thus, **Table-3** is best considered a "most wanted" list for radioisotopes for the development of an ERDD.

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[42] Charles D. Ferguson, Tahseen Kazi, and Judith Perera, "Commercial Radioactive Sources: Surveying the Security Risks," *Center for Nonproliferation Studies, Monterey Institute of International Studies*, (January 2003): 16, accessed December 18, 2011, http://cns.miis.edu/opapers/op11/op11.pdf.
[54] "What are the decay modes of zinc 65," *WolframAlpha*, accessed March 25, 2012, http://www.wolframalpha.com/input/?i=What+are+the+decay+modes+of+zinc+65&a=ClashPrefs_*Isotope.Tantalum182.IsotopeProperty.DecayModeSymbols-.
[55] "Nuclear Weapons Frequently Asked Questions," *The Nuclear Weapon Archive*, May 1, 1998, accessed December 1, 2011, http://nuclearweaponarchive.org/Nwfaq/Nfaq1.html.
[56] "What are the decay modes of tantalum 182," *WolframAlpha*, accessed March 25, 2012, http://www.wolframalpha.com/entities/isotope_decay_modes/what_are_the_decay_modes_of_tantalum_182/6t/lo/cu/.

Chapter 3: History of Radiological Weapons

WWII Era

To properly assess the value of a possible ERDD, it is important to not only understand radioisotopes and their effects, but also to look at how ERDD's have developed and been perceived over time.

The threat proposed by a weapon emitting radioactive materials was acknowledged even before the first atomic bomb was ever tested. In May 1941 a special U.S. scientific panel composed of physicists Arthur Holly Compton, J.C. Slater, Ernest O. Lawrence, and John Van Vleck, "proposed that, as a top priority, the United States develop radioactive products for use against the enemy."[57] Specifically, the panel noted how easily obtainable quantities of fission products could be used to make large areas uninhabitable. It was envisioned that radioactive particles could be used as a "particularly vicious form of poison gas."[58] At the same time, the National Academy of Sciences produced a report proposing the possible military application of "violently radioactive materials carried by airplanes to be scattered as bombs over enemy territory."[59] The severity of these weapons was once again highlighted in 1942 when Dr. Compton warned the Manhattan Project's Dr. James Conant that there was "a real danger

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[57] Barton J. Bernstein, "Radiological Warfare: The path not taken," *Bulletin of the Atomic Scientists*, (August 1985): 44-49.
[58] Barton J. Bernstein, "Radiological Warfare: The path not taken," *Bulletin of the Atomic Scientists*, (August 1985): 44-49.
[59] "Chapter 11: What We Now Know," *ACHRE Report*, Department of Energy, accessed January 22, 2012, http://www.hss.doe.gov/healthsafety/ohre/roadmap/achre/chap11_2.html; Quoted in Richard Rhodes, The Making of the Atomic Bomb (New York: Simon and Schuster, 1986): 365.

of bombardment [against Americans] by the Germans within the next few months using bombs designed to spread radio-active material in lethal quantities."[60]

Though the Germans never reached the same level of nuclear achievement as the Americans and the British during WWII, it is argued that they made endeavors into both nuclear weapons and radiological weapons. WWII German endeavors in enriching uranium have been explored by numerous people. However, Geoffrey Brooks, author of *Hitler's Nuclear Weapons*, posits that in addition to the German nuclear weapons program, the Germans also investigated radiological warfare and possibly developed radiation bombs at the SS-Mittelwerk underground concentration camp.

These radiation bombs were said to be a variation on the Germans V-series rocket, and were dubbed the V-4: a "one-ton aerial bomb containing 850 kilos of high explosive in a warhead packed around by twelve pumpkin-sized bomblets holding the radioactive matter."[61] The V-4 reportedly had the ability to "exterminate all human life within two to three kilometres from the point of impact."[62] A significant aspect of this bomb design is that it was intended to utilize nuclear waste from the uranium fuel based fission cycle. Brooks notes that during the final years of the war, Germany purportedly conducted rocket tests to produce a "launcher to fire a battery of rockets, each fitted with one or two radiation bombs around a warhead, [to] spread across an American city."[63] Despite Brooks' assertions, the U.S. never witnessed the usage of radiological weapons by the Germans. However, if these claims were true, then the Germans would have

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[60] Barton J. Bernstein, "Radiological Warfare: The path not taken," Bulletin of the Atomic Scientists, (August 1985): 44-49.
[61] Geoffrey Brooks, "Hitler's Nuclear Weapons," (Michigan: Leo Cooper, 1992): 37.
[62] Geoffrey Brooks, "Hitler's Nuclear Weapons," (Michigan: Leo Cooper, 1992): 37.
[63] Geoffrey Brooks, "Hitler's Nuclear Weapons," (Michigan: Leo Cooper, 1992): 125.

developed the first radiological weapon whose sole purpose was the dispersion of radioactive material.

Nevertheless, the growing fear that Germany might utilize such a weapon prompted a detailed report issued by Drs. James B. Conant, A. H. Compton, and H. C. Urey in 1943 on the "Use of Radioactive Materials as a Military Weapon." Both Compton and Urey believed strongly that the Germans might use radioactive material against the United Nations. Their report recommended investigation into the use of radioactive materials so that the U.S. would be ready to either "use such materials or be ready to defend itself against the use of such materials."[64] Their report further suggested that "theoretical studies pertaining to the methods, means and equipment for disseminating radioactive material as a weapon of warfare,"[65] begin immediately. Not only did the scientists feel it was imperative to begin to study the military possibilities of radioactive material, but they also believed there was a real possibility that a radioactive attack would occur against the Allies. To that end, the report advocated that an instruction manual be prepared for the defense against radioactive weapons.

This report included possible applications of radiological weapons. The initial example was that of a gas warfare unit whose function would be to distribute microscopic particles that would be inhaled by fighting personnel. They estimated that "one millionth of a gram accumulating in a person's body would be fatal [with] no known methods of

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[64] "Memorandum to: Brigadier General L. R. Groves From: Drs. Conant, Compton, and Urey," *United States War Department*, Declassified June 5, 1974, accessed January 22, 2012, http://www.american-buddha.com/planet.memobrigadiergengrovesconant.htm.

[65] "Memorandum to: Brigadier General L. R. Groves From: Drs. Conant, Compton, and Urey," *United States War Department*, Declassified June 5, 1974, accessed January 22, 2012, http://www.american-buddha.com/planet.memobrigadiergengrovesconant.htm.

treatment for such a casualty."[66] They specifically noted that such a weapon would have the unique qualities of being undetectable by the senses as well as the ability to be so finely distributed as to permeate even a standard gas mask. The doctors also noted that characteristics of the particles would result in a quickly dissipating gas whereby heavy concentrations would be difficult to maintain. Nevertheless, the fine dust of radiological material left in the terrain could be easily reactivated "by winds, movement of vehicles or troops, etc., and would remain a potential hazard for a long time."[67]

The report also posited that a radiological weapon could be used to make an area uninhabitable through terrain contamination, denying militarily significant areas such as railroad yards and airports to all parties "at the expense of exposing personnel to harmful radiations."[68] The committee estimated that radiological material of this type could be produced by the Germans in "such quantities that each four days, two square miles of terrain could be contaminated to an average intensity of radiation three feet above ground level of one hundred [rem] per day."[69] At a daily exposure of 100 rem, the report expected that for those present in the area would suffer temporary incapacitation with one

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[66] "Memorandum to: Brigadier General L. R. Groves From: Drs. Conant, Compton, and Urey," *United States War Department*, Declassified June 5, 1974, accessed January 22, 2012, http://www.american-buddha.com/planet.memobrigadiergengrovesconant.htm.
[67] "Memorandum to: Brigadier General L. R. Groves From: Drs. Conant, Compton, and Urey," *United States War Department*, Declassified June 5, 1974, accessed January 22, 2012, http://www.american-buddha.com/planet.memobrigadiergengrovesconant.htm.
[68] "Memorandum to: Brigadier General L. R. Groves From: Drs. Conant, Compton, and Urey," *United States War Department*, Declassified June 5, 1974, accessed January 22, 2012, http://www.american-buddha.com/planet.memobrigadiergengrovesconant.htm.
[69] "Memorandum to: Brigadier General L. R. Groves From: Drs. Conant, Compton, and Urey," *United States War Department*, Declassified June 5, 1974, accessed January 22, 2012, http://www.american-buddha.com/planet.memobrigadiergengrovesconant.htm.

week's exposure resulting in death.[70] An area contaminated in this manner, would take weeks or months before the area would once again be safe due to the natural decay process. Lastly, there was concern that these weapons could be used against large cities to promote panic, and create casualties among civilian populations.[71]

Though many theories were put forth for how radioactive materials could be used offensively, there isn't any strong evidence to suggest that these weapons were seriously pursued by either the U.S. or the British during World War II. This can be attributed to the overall focus given to the completion of the atomic bomb, as well as the difficulties involved in the creation of a radiological weapon. As the director of the Office of Scientific Research and Development Vannevar Bush explained to General Groves in late 1943, "the handling of large amounts of [radioactive material] in a single package involves enormous difficulties due to the heat generated, and to the problem of dissipation."[72]

Post WWII

Following World War II, interest in radiological weapons and radiological warfare still remained. General Curtis Lemay, the deputy chief of the Air Force for research and development in 1946, posited that the dispersal of radioactive material could even prove more effective than "using plutonium in atomic bombs."[73] Physicists at

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[70] It is important to recognize that an area contaminated in such a manner would require a significant amount of radioactive material, so much so that the efficacy of such an attack could be called into question.
[71] "Memorandum to: Brigadier General L. R. Groves From: Drs. Conant, Compton, and Urey," *United States War Department*, Declassified June 5, 1974, accessed January 22, 2012, http://www.american-buddha.com/planet.memobrigadiergengrovesconant.htm.
[72] Barton J. Bernstein, "Radiological Warfare: The path not taken," Bulletin of the Atomic Scientists, (August 1985): 44-49.
[73] Barton J. Bernstein, "Radiological Warfare: The path not taken," Bulletin of the Atomic Scientists, (August 1985): 44-49.

Berkeley suggested that radiological weapons could in fact be used to not only deny territory, but to disrupt economies and morale, essentially putting forth the first idea of radiological weapons as "weapons of disruption."[74] In addition, Joseph Hamilton of the Army Chemical Corps wrote in 1948 that all of the "potentialities, including the rather repellent concepts of the use of fission products and other radioactive materials as internal poisons, should be explored up to and including a level of pilot experiments on a fairly large scale."[75] Hamilton felt that lacking exploration of radioisotopes in use as military weapons, the U.S. would have "failed to explore the necessary measures which may be desperately needed for the protection of our own people".[76]

This continued interest spawned competing research programs within the U.S. government. Along with the newly created Atomic Energy Commission (AEC), "the Armed Forces Special Weapons Project, the Air Force, and the Army's Chemical Corps were interested in both offensive and defensive radiological warfare, while the Naval Radiological Defense Laboratory focused on defense."[77] Research was coordinated between these groups and divided into three areas:

1. **The effects of radiation and radioactive materials**
2. **Studies on the production of radioactive materials**
3. **Military studies of possible RW munitions.**[78]

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[74] Barton J. Bernstein, "Radiological Warfare: The path not taken," Bulletin of the Atomic Scientists, (August 1985): 44-49.
[75] "The Human Radiation Experiments," *Final Report* of *the Advisory Committee on Human Radiation Experiments*, (New York: Oxford University Press, 1996).
[76] "The Human Radiation Experiments," *Final Report* of *the Advisory Committee on Human Radiation Experiments*, (New York: Oxford University Press, 1996).
[77] "The Human Radiation Experiments," *Final Report* of *the Advisory Committee on Human Radiation Experiments*, (New York: Oxford University Press, 1996).
[78] "The Human Radiation Experiments," *Final Report* of *the Advisory Committee on Human Radiation Experiments*, (New York: Oxford University Press, 1996).

David Lilienthal, the AEC Chairman, called the weapons both "fascinating and horrible."[79] However, even though "a program on radiological warfare [was considered] essential,"[80] most of the AEC budget was allocated for research on fission weapons. In addition, further investigation by the AEC revealed that a "fission bomb detonated near the surface would be radiologically more effective than a bomb loaded with radiological agents."[81] Equally significant, in 1948 the AEC noted that that there was both a shortage of material and lack of methods of dissemination to make radiological weapons plausible, further compounding the difficulties of utilizing a radiological weapon

At this point, the Army remained the only branch of the service interested in continuing research, believing that radiological warfare may be useful in the defense of Europe from the Soviet Union. Even as the AEC was reporting the shortcomings of creating and utilizing radiological weapons, the Army Chemical Corps was beginning to conduct field tests. From 1949 to 1952, sixty-five field tests were conducted at Dugway Proving Ground. The tests consisted of intentionally releasing roughly 13,000 Curies (Ci) of radioactive tantalum in the form of dust, small particles, and pellets. These initial prototype tests were designed to test a more "benign" radioactive distribution to garner a better understanding of radioactive warfare, "releasing much smaller quantities of radioactive material than the millions of Ci per square mile that an operational

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[79] Barton J. Bernstein, "Radiological Warfare: The path not taken," Bulletin of the Atomic Scientists, (August 1985): 44-49.
[80] Barton J. Bernstein, "Radiological Warfare: The path not taken," Bulletin of the Atomic Scientists, (August 1985): 44-49.
[81] Barton J. Bernstein, "Radiological Warfare: The path not taken," Bulletin of the Atomic Scientists, (August 1985): 44-49.

radiological weapon would need to render territory temporarily uninhabitable."[82] The initial tests were concluded by 1952 at which time "the Chemical Corps proposed a significant expansion of the radiological warfare program, with a large test of 100,000 Ci planned for 1953 and still larger tests proposed for later."[83] However, despite the Chemical Corps' proposal, further testing, as well as the whole radiological warfare test program, was canceled.

It is argued that a military budget conflict with the Korean War played a significant part in the decision to end the radiological warfare program. The expansion of the radiological warfare program would have necessitated an investment into new radioisotope production facilities, as well as the continued operating costs both in dollars and scientific manpower. Regardless, this is the last publicly available information relating to a serious investigation by the U.S. into a radiological warfare program.

The Cobalt and Neutron Bomb

It should be noted that although U.S. research into purely radiological weapons stagnated in the early 50's, the idea of dispersing radioisotopes through a nuclear explosion continued to be pursued. As early as the Korean War, there was a debate within the U.S. over the use of the radiological dispersal device known as the Cobalt Bomb whose purpose was to contaminate an area with radioactive material utilizing a relatively small blast. The original concept of a Cobalt Bomb was first put forth by

[82] "The Human Radiation Experiments," *Final Report* of *the Advisory Committee on Human Radiation Experiments*, (New York: Oxford University Press, 1996).
[83] "The Human Radiation Experiments," *Final Report* of *the Advisory Committee on Human Radiation Experiments*, (New York: Oxford University Press, 1996).

physicist Leó Szilárd in February 1950.[84] Szilárd posited that by "wrapping natural cobalt around a fission device, the resulting detonation would create a cloud of intensely radioactive Co-60."[85] In terms of its affects related to a normal fission bomb, the initial radiation from a Cobalt Bomb would be less intense but would lose its intensity far less rapidly (see **Table-4**). The Air Force Research and Development Command argued that a "15-megaton hydrogen bomb seeded with cobalt could contaminate 10,000 to 20,000 square miles for half a decade or longer."[86] Nevertheless, the Cobalt Bomb is reported to have never been put into construction.

Table 4. Long Term Cobalt radiation vs. fission bomb radiation[87]

Time	Radiation Intensity
1 hour	15,000 times less
1 week	35 times less
1 month	5 times less
6 months	Equal
1 year	8 times more
5 years	150 times more

Like the Cobalt Bomb, the Neutron Bomb was a bomb that combined traditional nuclear explosions with the dispersal of deadly radiation. In this instance, unlike a traditional nuclear weapon, the bombs design assists rather than inhibits the escape of neutrons. The Neutron Bomb was designed for use in Western Europe to offset the

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[84] "Nuclear Weapons Frequently Asked Questions," The Nuclear Weapon Archive, May 1, 1998, accessed December 1, 2011, http://nuclearweaponarchive.org/Nwfaq/Nfaq1.html.
[85] Richard Lee Miller, "Under the Cloud: the Decades of Nuclear Testing," (Texas, Two Sixty Press, 1999): 505.
[86] Barton J. Bernstein, "Radiological Warfare: The path not taken," Bulletin of the Atomic Scientists, (August 1985): 44-49.
[87] "Nuclear Weapons Frequently Asked Questions," The Nuclear Weapon Archive, May 1, 1998, accessed December 1, 2011, http://nuclearweaponarchive.org/Nwfaq/Nfaq1.html.

Warsaw Pact's advantage in tank forces.[88] Samuel T. Cohen is credited with the invention of the Neutron Bomb, a weapon whose purpose was to expand the U.S. theater nuclear capability through the dispersal of neutrons as opposed to relying on damage from an explosion.[89] The rationale for such weapons stemmed from President Eisenhower who said, "Where these things are used on strictly military targets and for strictly military purposes, I see no reason why they shouldn't be used just exactly as you would use a bullet or anything else."[90] This mentality was outlined in the NSC 162/2 where Eisenhower's New Look strategy was put forth.

Nevertheless, Washington rejected the bomb repeatedly. "The Kennedy administration said it might jeopardize a test-ban moratorium. The Johnson administration said its use in Vietnam might raise the specter of Hiroshima — Asians again slaughtered by American nuclear bombs — drawing worldwide condemnation."[91] Likewise in 1978, President Jimmy Carter decided to scrap the project due to growing public pressure, which Secretary of State Zbigniew Brzezinski called "a political explosion that reverberated throughout the United States and Europe."[92] However, a push for the Neutron Bomb was tried once more in 1981. President Ronald Reagan

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[88] Lawrence S. Wittner, "Confronting the Bomb: A short history of the world nuclear disarmament movement," (California: Stanford University Press, 2009): 130.
[89] Robert D. McFadden, "Samuel T. Cohen, Neutron Bomb Inventor, Dies at 89," *The New York Times*, December 1, 2010, accessed March 25, 2012. http://www.nytimes.com/2010/12/02/us/02cohen.html?_r=1&ref=science&pagewanted=all.
[90] President Dwight D. Eisenhower, *Unites States Department of State Bulletin*, 32, March 21, 1955: 459-60.
[91] Robert D. McFadden, "Samuel T. Cohen, Neutron Bomb Inventor, Dies at 89," *The New York Times*, December 1, 2010, accessed March 25, 2012. http://www.nytimes.com/2010/12/02/us/02cohen.html?_r=1&ref=science&pagewanted=all.
[92] Lawrence S. Wittner, "Confronting the Bomb: A short history of the world nuclear disarmament movement," (California: Stanford University Press, 2009): 130.

ordered 700 neutron warheads to counter the Soviet tank forces in Europe.[93] However, once again public outcries led to the cancellation of deployment to the NATO allies, and eventually President George Bush ordered the stockpile scrapped.[94] The Neutron Bomb stands as closest actualization of a radiological weapon developed by the U.S.

ERDD Research in Russia

Like the United States, it is reported that the Soviet Union also explored the use of radiological weapons. However, information on these tests remains sparse. It is reported that the "Soviets tested 456 nuclear devices as well as radiological weapons at the Semipalatinsk Test Site in Kazakhstan."[95] Specifically, these reports note that the Soviets experimented with the dispersal of radioactive isotopes in R-2 (SS-2) missiles.[96]

Codenamed Geran and Generator, these missiles were reportedly designed to carry a warhead "filled with a radioactive liquid that was to be dispersed over a target,"[97] and settle in the form of radioactive rain. The difference between the Generator and Geran design was that the R-2 Geran missile utilized a warhead container with a single chamber for the radioactive liquid and the R-2 Generator utilized a warhead container with a larger number of smaller containers. In addition to these R-2 missile experiments, there are also records that show that by the fall of the Soviet Union, there were 38 Soviet

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[93] Robert D. McFadden, "Samuel T. Cohen, Neutron Bomb Inventor, Dies at 89," *The New York Times*, December 1, 2010, accessed March 25, 2012. http://www.nytimes.com/2010/12/02/us/02cohen.html?_r=1&ref=science&pagewanted=all.
[94] Robert D. McFadden, "Samuel T. Cohen, Neutron Bomb Inventor, Dies at 89," *The New York Times*, December 1, 2010, accessed March 25, 2012. http://www.nytimes.com/2010/12/02/us/02cohen.html?_r=1&ref=science&pagewanted=all.
[95] Kenley Butler, "Weapons of Mass Destruction in Central Asia," *Monterrey Institute of International Affairs*, October 1, 2002, March 25, 2012, http://www.nti.org/e_research/e3_19.html.
[96] Boris Evseevich Chertok, "Rockets and People," National Aeronautics and Space Administration, Vol. 1, (January 2005): 244.
[97] A. DeVolpi, et al., "Nuclear Shadowboxing: Cold War Redux," (Michigan: DeVolpi, Inc., 2004): 38.

Alazan missiles in the Transdniester Moldovan Republic that were "modified to carry radioactive material."[98] 24 of these Alazan missiles were said to be already prepared with radiological material, though the type of radiological material is not given. Nonetheless, there is very little public information available about these reported Soviet programs.

ERDD research in Iraq

The most recent and clear example of ERDD research occurred in Iraq. During the 1980's it was believed that Iraq was working to acquire nuclear weapons, as well as ERDD's. As early as 1987 there were reports that Iraq had actually tested its own ERDD. However, it wasn't until the conclusion of the Gulf War that there was any definitive indication of this research.

A secret Iraqi report on Iraqi ERDD construction and testing was given to the United Nations in 1996 by the Iraqi government during the time the UN special commission was monitoring Iraq's disarmament. The document described a bomb that was 12 feet long and over 2000 lbs., with the flexibility to be used against troop areas, industrial centers, airports, railroad stations, bridges and other areas of interest. The test of the ERDD was reportedly conducted at Iraq's Western Firing Range during Iraq's war of attrition against Iran. The ERDD was being developed to strike and disable Iranian military forces. The development of this ERDD was completed by Iraq's Atomic Energy Agency in conjunction with the Al Qa-Qa and Al Muthanna centers of the Iraqi Military Industrial Commission.

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[98] Joby Warrick, "Dirty Bomb Warheads Disappear," *The Washington Post,* December 7, 2003, March 25, 2012, http://www.washingtonpost.com/ac2/wp-dyn/A41921-2003Dec6?language=printer.

The Iraqi bomb design revolved around the use of a radioisotope of zirconium. At the time in Iraq, there was already a production process in place for the use of zirconium in incendiary bombs. The zirconium was produced in Iraq's Tuwaitha reactor in a mixture that included hafnium, uranium and iron. The isotope of zirconium produced was Zirconium 95 (Zr-95), which has a half-life of 75.5 days. The short period of radioactive decay was important because it helped "to dissipate the effect of the bomb after several weeks so that it [would be] difficult to track, analyze, or recognize."[99] In addition, the short period of decay would allow for the movement of Iraq troops through bombed areas without significant delay. The report related that the purpose of this zirconium-laden weapon was to add a biological effect to a traditional explosion, which would "strike the enemy in the first degree with regard to external exposure"[100] the degree to which would increase with inhalation and internal exposure.

The weapon was purportedly tested three times in 1987. These tests were meant to test both the functionality of the bomb design as well as its deliverability. It was expected that the explosion would cast a radioactive cloud that would "cause vomiting, cancer, birth defects and slow death."[101] In addition, the weapons used in combination were expected to cause radiation related fatalities of "all personnel within a ten-meter

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[99] William J. Broad, "Document Reveals 1987 Bomb Test by Iraq," *The New York Times*, April 29, 2001, March 25, 2012, http://www.iraqwatch.org/wmd/radbomb.htm.
[100] "Iraq's Radioactive Bomb Project," *The Baltimore Sun*, May 2, 2001, accessed March 25, 2012, http://articles.baltimoresun.com/2001-05-02/news/0105020152_1_zirconium-research-reactor-radioactive/2.
[101] "Applications of Nuclear Physics," *Atomic Energy Agency of Iraq*, (1987), accessed March 25, 2012, http://www.iraqwatch.org/government/Iraq/UN-iraq-bomb.htm.

radius of the center, given normal weather conditions."[102] Nonetheless, though the report described one of the test explosions as "awesome," the results were found wanting with radiation readings on the ground only "290 times above the highest level allowed nationally for foodstuffs."[103]

Ironically, the document revealed that no readings were taken in the air during the test. Concurrently, the report indicated during testing "that a significant part of the fallout went with the cloud into the air and it was not possible to follow this small amount of radioactive matter by means of the portable equipment."[104] This can be perceived as a "critical oversight for a weapon meant to hurt and kill people largely through the inhalation of radioactive particles."[105] In the end, the evidence suggests that the weapons were never put into production and that the project was eventually abandoned.[106] These findings appear to affirm the 1991 National Intelligence Council report that posited that while it would be feasible for the Iraqis to "build a functioning radiological weapon [that] it would create no special blast effect, and it could not cause widespread radiation sickness."[107]

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[102] "Iraq's Radioactive Bomb Project," *The Baltimore Sun*, May 2, 2001, accessed March 25, 2012, http://articles.baltimoresun.com/2001-05-02/news/0105020152_1_zirconium-research-reactor-radioactive/2.
[103] "Applications of Nuclear Physics," *Atomic Energy Agency of Iraq*, (1987), accessed March 25, 2012, http://www.iraqwatch.org/government/Iraq/UN-iraq-bomb.htm.
[104] "Applications of Nuclear Physics," *Atomic Energy Agency of Iraq*, (1987), accessed March 25, 2012, http://www.iraqwatch.org/government/Iraq/UN-iraq-bomb.htm.
[105] William J. Broad, "Document Reveals 1987 Bomb Test by Iraq," *The New York Times*, April 29, 2001, March 25, 2012, http://www.iraqwatch.org/wmd/radbomb.htm.
[106] William J. Broad, "Document Reveals 1987 Bomb Test by Iraq," *The New York Times*, April 29, 2001, March 25, 2012, http://www.iraqwatch.org/wmd/radbomb.htm.
[107] "Memorandum: Possible Iraqi Radiological Weapons," *United States Central Intelligence Agency*, January 1991, accessed March 25, 2012. http://www.fas.org/irp/gulf/cia/960702/73887_01.htm.

Conclusions

In reviewing the historical approaches to developing an ERDD, we find that there has not been much research into their usage in over five decades, apart from the aborted Iraqi program. Part of the reason is that as a military weapon, a radiological weapon has historically been viewed in a negative light owing to the fact that the TNT in a dirty bomb may still be more dangerous than the release of radiological isotopes. This certainly appears to be the case with the weapons in the Iraqi program. In addition, radiological weapons have long been considered inappropriate for military purposes because "their effect is too delayed and unpredictable to sway a battle."[108] Also, in terms of the U.S., technical impediments and expenses during and after World War II stagnated U.S. research.

Nevertheless, the importance of this early history is that it shows that even in the preconception of radiological weapons, the distinct dangers and possibilities were understood and taken to be significant national threats. Specifically, it was noted that such weapons would have the capacity to be used against large cities, causing economic damage and promoting panic as well as creating casualties among civilian populations. It is also important to consider that the initial reservations put forth were not in the context of a terrorist attack on the United States but more specifically were based on the concern that Germany would use radiological weapons in international warfare, meaning there was perceived value for states to acquire such weapons.

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[108] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.

Equally significant is that these early scientific premonitions were predicated upon a dearth of radioisotope understanding. Since that time, the available scientific knowledge has grown considerably. The initial concern over territory being denied for weeks to months has easily been overshadowed by the radiological accidents which occurred in Chernobyl and now Fukushima, where territory loss due to radiation is calculated in decades instead of weeks. Moreover, the capacity to handle radioactive material has increased considerably since the 1940's. These are clear indicators that there may be a definitive value for states possessing radiological weapons.

Chapter 4 - Dispersion Scenarios and ERDD Outcomes

With our understanding of radioisotopes and their effects, and our review of history, it is important to now consider the wealth of contemporary research that have analyzed the effects of hypothetical terrorist driven ERDD attacks. Though history has a dearth of real life ERDD explosion examples to garner information from, there have been various hypothetical scenarios whose findings may provide definitive insight, specifically in ascertaining the value an ERDD may possess for an interested state.

Dynamics of an ERDD

First, as a matter of distinction, most researchers would agree that an ERDD is not a weapon of mass destruction in that while a radiological attack may result in some deaths, "it is very nearly impossible to disperse radioactive material from an explosively powered dirty bomb in such a way that victims externally absorb a lethal dose of radiation from the source before they are able to leave the affected area."[109] More importantly, the issue of the dispersion of radioisotopes and the proceeding radiological effect on a populace is only one factor in what should be considered when trying to evaluate and ERDD attack. Any attack that distributes radioisotopes has the propensity to "contaminate large urban areas with radiation levels that exceed EPA health and toxic material guidelines,"[110] and so have demonstrative economic effects as well as

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[109] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.

[110] "Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations," March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.

psychological effects on any given populace. Instead of a weapon of mass destruction, it is more appropriate to label an ERDD as a **weapon of mass disruption.**

In terms of the process, an ERDD explosion releases radioactive material into the environment whose transport is influenced by three mechanisms: ballistics, advection, and diffusion.[111] Ballistics account for how the explosion causes the radioactive particles to eject in random directions and then proceed to fall to earth by way of gravity. For example, in a scenario outlined in research by U.S. Department of Homeland Security, the detonation aerosol contained 90% of the original source material, which was then dispersed.[112] Diffusion refers to the dispersal of very fine particles during their movement. Lastly, advection refers to the dispersal of particles being carried by the wind. This latter category is what some experts feel is the prominent danger from the explosion of an ERDD. Dr. Michael Levi and Dr. Henry Kelly, formerly of the Federation of American Scientists, dubbed this effect the "Dread Wind."[113] They essentially posit that the greatest danger of an ERDD explosion is from the radioactive particles that the explosion projects into the air and which are subsequently carried to greater distances through the passing winds. Though most particles will fall out near the initial blast zone, in some instances small particles could be carried distances as great as hundreds of miles.[114]

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[111] Chris Robbins, "Radioactive Particle Transport," *Grallator*, accessed January 14, 2012, http://www.ionactive.co.uk/pdfs/Chris%20Robbins-RDD-ParticleTransport-1.pdf.
[112] "Homeland Security Planning Scenarios," *Global Security*, accessed January 10, 2012, http://www.globalsecurity.org/security/ops/hsc-scen-11.htm.
[113] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.
[114] "Homeland Security Planning Scenarios," *Global Security*, accessed January 10, 2012, http://www.globalsecurity.org/security/ops/hsc-scen-11.htm.

An additional consideration is how radioisotopes interact and incorporate into the environment. In metropolitan areas, dispersed radioisotopes from an explosion could "remain trapped for extended periods in cracks and crevices on the surfaces of buildings, sidewalks and streets."[115] Also, certain radioisotopes such as Cs-137, chemically bind to glass, concrete and asphalt. For example, "more than 15 years after the 1986 Chernobyl disaster, in which a Soviet nuclear power plant underwent a meltdown, cesium is still affixed to the sidewalks of many Scandinavian cities that were downwind of the disaster."[116]

This presents a real dilemma in terms of decontamination because "under present [U.S.] regulations and applicable laws, any building that cannot be decontaminated so that the dose rate from residual radioactive debris from any radiation accident is below the limits set by either EPA and NRC may not be occupied."[117] As was noted in Part 1 of this research, this level is currently set at 15 mrem per year over normal background radiation levels. Structures unable to comply with these regulations would therefore have to be abandoned, restricted, and eventually demolished with the subsequent debris being removed to a low-level radioactive waste dump. It would be a very expensive outcome, as will be evidenced later in this research.

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[115] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.
[116] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.
[117] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.

Kelly and Levi Scenarios

The Federation of American Scientists proposed a number of scenarios in 2002 demonstrating the likely effects of an ERDD. These were based on the work of Dr. Henry Kelly and Dr. Michael Levi. The findings of their work was both the basis of a the testimony that Kelly gave to the Senate in March 2002, as well as the basis for an article entitled "Weapons of Mass Disruption," which was published in *Scientific American* in November of the same year. The scenarios that they put forth were developed as an instrument that would highlight a range of possible impacts.

Each of these scenarios was built with the idea that the ERDD in question would utilize a small quantity of a radioactive material. The authors acknowledged that the outcomes of each of these scenarios would necessarily depend on a number of factors that were not predictable. Specifically, the consequences would depend on "the amount of material released, the nature of the material, the details of the device that distributes the material, the direction and speed of the wind, other weather conditions, the size of the particles released (which affects their ability to be carried by the wind and to be inhaled), and the location and size of buildings near the release site."[118] Acknowledging these factors, they posited that the results of their scenarios were better understood to be "fairly accurate illustrations, rather than precise predictions."[119] With these conditions, they outlined four specific scenarios using the HOTSPOT computer code developed at

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[118] "Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations," March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.
[119] "Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations," March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.

Lawrence Livermore National Laboratory, which simulates the movement of radioactive particles. In each scenario, a conventional explosion releases radioisotopes, which are then distributed by the prevailing winds. The results derived from Hotspot were then "combined with experimental and theoretical data on the effects of radiation to produce estimates of health risks and contamination."[120]

The first scenario focused on Washington, DC and the explosion of an ERDD comprised of ten pounds of TNT and a pea-sized amount of Cs-137.[121] In this scenario, an area of forty city blocks would be contaminated to a point that exceeded EPA limits. Over the long term, there would be a 1/10 thousand chance of getting cancer for those within forty blocks and a 1/1000 chance of getting cancer for those within five blocks. For these areas, decontamination would be necessary, subsequently leaving the areas abandoned for decades.

The second scenario focused on Manhattan, New York and a weapon comprised of a cobalt rod containing Co-60. "Based on FAS assumptions the rod has been made into particulate form,"[122] containing roughly 1374.5 grams of Co-60 coupled with an unspecified amount of explosives. In this example, "an area of approximately one-thousand square kilometers, extending over three states"[123] would be contaminated with radiation, resulting in increased risk of cancers for residents. In the long term, there

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[120] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.
[121] Noah Shachtman, "How Bad Can a 'Dirty Bomb' Be?" *Wired Magazine*, June 10, 2002, February, 11, 2012, http://www.wired.com/politics/law/news/2002/06/53110.
[122] Benjamin F. Visger, "Dirty Bombs: The Technical Aspects of Radiological Dispersion Devices," (Master thesis, Naval Post Graduate School, 2004).
[123] "Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations," March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.

would be a 1/10 risk of death from cancer for those in an area of about three hundred typical city blocks and a 1/100 chance of dying from cancer for the entire borough of Manhattan. Decontamination and demolition would be necessary in these areas and it would take decades “before the city was inhabitable again.”[124] Kelly and Levi also noted that an area equivalent to fifteen miles may need periodic controls on human use including restrictions on food, clothing, and time spent outdoors.

The third scenario also focused on Manhattan, New York but with a weapon comprised of Am-241 and one pound of TNT. Because of the danger of alpha emitters, people in a region roughly equal to ten times “the area of the initial bomb blast would require medical supervision and monitoring.”[125] An area of roughly twenty city blocks would need to be evacuated within half an hour. A region two km long and covering sixty city blocks would be contaminated in excess of EPA safety guidelines. In the long term, there would be a 1/1000 risk of death from cancer for those in a ten-block area. The authors also suggest that the decontamination and demolition costs could exceed fifty billion dollars.

The fourth scenario focuses again on Manhattan, New York but with a weapon comprised of 3,500 Ci, or roughly 40 grams of Cs-137. In this scenario, an area roughly 800 km^2 would be contaminated above EPA decontamination guidelines. In the long term, there would be a 1/10 increased risk of death from cancer for those in a 20 block

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[124] “Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations,” March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.

[125] “Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations,” March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.

radius, and “a broader area of 15 square kilometers— varying from four to 20 square kilometers, depending on the weather—would be contaminated above the relocation threshold recommended by the International Commission on Radiological Protection and accepted by the NRC.”[126] Also, estimates showed that decontamination and demolition costs could exceed hundreds of billions of dollars for just a 100-block radius alone.

CSIS Scenario

In 2004, the Center for Strategic and International Studies (CSIS) conducted its own ERDD explosion scenario. Similar to that of Kelly and Levi’s, the CSIS scenario focused on Washington, DC. The ERDD was comprised of 1.5 pounds (680 grams) of Cs-137 coupled with 4,000 pounds of TNT. The scenario had detonation taking place in a school bus parked outside of the National Air and Space Museum. As with the examples from Kelly and Levi, immediate damage within the blast vicinity was to be expected owing to the explosives, and for the purpose of this research was excluded in the findings. Contamination was projected to spread as far as southern Pennsylvania. Those individuals located within a few blocks would be exposed to roughly five rem of radiation in one hour, the “equivalent to the occupational dose for one year set by the EPA and NRC.”[127] People located outside of the most contaminated areas and stretching roughly a mile would exceed the recommended yearly occupational radiation dose of five rem within weeks.

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[126] Michael A. Levi and Henry C. Kelly, “Weapons of Mass Disruption,” *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.
[127] “20.1201 Occupational dose limits for adults,” *Standards for Protection Against Radiation*, U.S. Nuclear Regulatory Commission, accessed January 31, 2012, http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1201.html.

CSIS concluded from their study that the effects from radiation would not pose the most serious concern in the event of an ERDD explosion. The initial explosion was expected to dilute the embedded Cs-137, making it almost impossible for a person "to get a large enough radiation dose to cause acute illness."[128] More so, the explosion was expected to "only increase the amount of radiation that most of the affected people are normally exposed to by 25 percent,"[129] taking long periods of time before people encountered a significant risk from the ambient radiation. With that being said, the study did note that the fact that radiation involved in the blast would have "an enormous psychological impact on the public."[130] Additionally, it could be assumed that even without high levels of radiation, many irradiated areas would be left vacant due to radiation concerns from the populace.

Rhodes and Pennington Scenario

William Rhodes III, along with Heather Pennington offer an analysis of an ERDD attack in Washington, DC featuring a weapon comprised of 1,000 Ci (about 50 grams) of cesium chloride, an easily dispersal substance containing Cs-137 and in particulate form. The model they put forth assumes that all material used is dispersed, but that it is dispersed unevenly over the area. They also assume a wind speed of 7 mph coming from the east.

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[128] Matthew L. Wald, "Fear Itself Is the Main Threat of a Dirty Bomb, Experts Say," *The New York Times*, June 11, 2002, February 12, 2012, http://www.nytimes.com/2002/06/11/national/11BOMB.html.
[129] Benjamin F. Visger, "Dirty Bombs: The Technical Aspects of Radiological Dispersion Devices," (Master thesis, Naval Post Graduate School, 2004).
[130] Erik Schechter, "Weapon of Mass Hysteria," *Jerusalem Post*, March 2, 2006, February 12, 2012, http://www.jpost.com/Magazine/Features/Article.aspx?id=14868.

The model shows that there would be contamination of different levels, in zones ranging in area from 0.81 to 5.10 square miles. In this scenario immediate damage within the blast vicinity is excluded from the results. The significance of this scenario is that, as current regulations go, roughly 13.2 km^2 would exceed radiation levels deemed acceptable in the Protective Action Guide (PAG) set forth by the U.S. government. This area would need to be decontaminated before it would be suitable for habitation again. Without decontamination, an area of 2.10 km^2 would have a roughly 1/100 cancer incident rate within the first year. An area of 7.60 km^2 would have a roughly 1/350 cancer incident rate for every subsequent year. And, an area of 13.2 km^2 would have a roughly 1/271 cancer incident rate after 50 years of accumulation.

What Rhodes and Pennington concluded was that while an attack would have a large impact on Washington, DC, the response may not be the same as the previous scenarios we have outlined. Faced with the choice of costly decontamination and large restricted areas, the government may choose to relax current regulations and accept an increased risk of radiation. Specifically, the U.S. might choose to adopt NRC guidelines, "which require cleanup of all areas where contamination would deliver a dose greater than five rem over 50 years, increasing the risk of cancer death by more than one in 500 (equivalent to a reduction of each person's life expectancy by roughly 15 days)."[131]

Radiation and Decontamination

What we find by comparing these initial scenarios is that by using a relatively small amount of radioactive material coupled with an explosion, a widespread area can be

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[131] Jonathan Medalia, "Dirty Bombs": Technical Background, Attack Prevention and Response, Issues for Congress," *Congressional Research Service*, June 24, 2011, accessed February 16, 2012, http://www.fas.org/sgp/crs/nuke/R41890.pdf.

contaminated. Depending on the amount of explosives and the type of radioactive material, the effects outlined by the scenarios could be as severe as a 1/10 risk of death from cancer in a contamination zone that could stretch for 1000 km^2. Now it should be noted that in the Kelly and Levi scenario, the risk of cancer is based on a person living 30 years within the contaminated zone, which would more than likely not transpire.[132] A likely scenario is that an exclusion zone would be created after the explosion, much like the exclusion zone currently surrounding the area of the 1986 Chernobyl disaster and the recent Fukushima Daiichi accident. For Chernobyl, even decades after the incident a 30 km region surrounding the plant has been permanently closed due to the threat of radiation.[133] If such an incident occurred in the U.S., and if decontamination could not reduce the danger of cancer death to less than 1/10,000, then "the EPA would recommend the contaminated area be eventually abandoned."[134] In their second example, Kelly and Levi posit that much of Manhattan would be similarly restricted. This could be further complicated by the fact that certain isotopes such as Cs-137, chemically bind to concrete and asphalt.

Further compounding this problem is the fact that in terms of decontamination, we can only truly rely on hypothetical figures and best guesses. The removal of "urban radioactive contamination has never been performed on a large scale because no one has

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[132] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American,* Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.
[133] "Frequently Asked Chernobyl Questions," *International Atomic Energy Agency,* accessed March 25, 2012, http://www.iaea.org/newscenter/features/chernobyl-15/cherno-faq.shtml.
[134] "Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations," March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.

ever had to deal with the consequences of a radiological attack."[135] An attack utilizing Cs-137, Co-60, Ir-192, or Sr-90, all of which release some form of gamma radiation, could effectively render large urban areas useless. The cleanup would involve not only the removal of loose contamination, but also more invasive techniques to remove radioisotopes that had penetrated more porous material. This could involve demolition, particularly where Cs-137 had bound to concrete and asphalt, as well as the removal of the top layer of soil and vegetation. Though the authors of these scenarios disagree on the overall impact of an ERDD explosion, the issue of decontamination remains consistently severe throughout, with a period of years or even decades necessary before areas would once again be deemed safe and legally inhabitable.[136]

Economic Costs

As aforementioned, in the 1940's U.S. physicists suggested that radiological weapons could be used to disrupt economies. This idea is further exemplified by the proceeding hypothetical ERDD explosion scenarios, which posit that any restrictions and exclusions due to radiological contamination would have huge financial costs for an economy related to an affected area. However, the magnitude of the economic impact of an ERDD attack remains a very serious and widely debated topic.

As then U.S. Senator Joseph Biden stated, "The economic impact that could result from such an attack could be devastating. We all know what the economic impact was when the World Trade Towers came down, beyond the impact of the loss of the towers,

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[135] Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American*, Vol. 287, Issue 5 (2002): 76-82, accessed January 7, 2012, http://www.fas.org/ssp/docs/021000-sciam.pdf.
[136] "Testimony of Dr. Henry Kelly, President Federation of American Scientists before the Senate Committee on Foreign Relations," March 6, 2002, accessed December 12, 2011, http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf.

as well as the loss of the personnel and the businesses that were contained in the towers."[137] To give some context, the September 11, 2001 attack on New York City cost the insurance industry $40 billion, according to the Insurance Information Institute.[138] The New York Times estimates that the total economic impact of the September 11, 2001 attack totaled roughly $178 billion.[139] Given the radiological threat posed by an ERDD and the subsequent need to decontaminate and exclude certain areas, we would expect the costs associated with an ERDD to be substantially greater than those produced from the 9/11 attack.

Research conducted by University of Southern California's Center for Risk and Economic Analysis of Terrorism (CREATE) in 2008, seems to take a more conservative approach to their projections. Their research entitled the "Economic Impact Analysis of Terrorism Event: Recent Methodological Advances and Findings" evaluates the economic impact of an ERDD attack, particularly focused on the twin ports of Los Angeles and Long Beach. Their research particularly focuses on the impact trade. They note that in 2004, the combined import and export trade of these ports accounted for roughly $300 billion, the "equivalent to about 30 percent of the greater Los Angeles area gross regional product."[140] CREATE's research posits that the "economic disruptions

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[137] "Dirty bombs and basement nukes: the terrorist nuclear threat," Hearing before the Committee on Foreign Relations, United States Senate, One Hundred Seventh Congress, second session, March 6, 2002, Vol. 4, accessed February 20, 2012, http://ftp.resource.org/gpo.gov/hearings/107s/80848.txt.
[138] Edward Iwata, "State Farm won't cover nuke losses," *USA Today*, February 27, 2003, accessed March 25, 2012, http://www.usatoday.com/money/industries/insurance/2003-02-27-statefarm_x.htm.
[139] David E. Sanger, "The Price of Lost Chances," *The New York Times*, September 8, 2011, accessed February 19, 2012, http://www.nytimes.com/2011/09/08/us/sept-11-reckoning/cost.html.
[140] Peter Gordon, James E. Moore and Harry W. Richardson, "Economic Impact Analysis of Terrorism Event: Recent Methodological Advances and Findings," *Center for Risk and Economic Analysis of Terrorist Events*, University of Southern California, (November 2008), accessed February 21, 2012, http://www.internationaltransportforum.org/jtrc/discussionpapers/DP200822.pdf.

resulting from closure of America's largest port complex (in terms of $ of trade) would be far greater than a disruption to Los Angeles' modest financial and office sector."[141] Given these assumptions, CREATE purports that the worst-case scenario of the explosion of an ERDD utilizing five pounds of explosives on the twin ports of Los Angeles and Long Beach would cost the U.S. economy roughly $49 billion.

Similarly, research conducted by Tom Cousins and Barbara Reichmuth investigated the economic costs associate with an ERDD attack occurring in Vancouver, Canada. The report outlined the economic consequences of an ERDD attack consisting of 1,000 Ci (11.5 grams) of Cs-137 exploded at BC Place Stadium in Vancouver, Canada. Using U.S. methodology and assumptions as a proxy for a similar event in Canada, their scenario projected that the outermost plume of radiation would be 15 mrem per year over 99 mi^2 (256 km^2), which is the maximum background radiation for allowed in habitable areas within the U.S. At the same time the innermost plume of radiation would be .5 rem per year over 2.3 mi^2 (6 km^2).[142] Cousins and Reichmuth found that the costs associated with dealing with these irradiated areas would total roughly $90 billion, the majority of which would be spent on cleanup and reconstruction.[143]

At the same time, very similar research to the CREATE report was conducted by Rosoff and Von Winterfeldt in 2007. Their report also explored the effect of an ERDD

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[141] Peter Gordon, James E. Moore and Harry W. Richardson, "Economic Impact Analysis of Terrorism Event: Recent Methodological Advances and Findings," *Center for Risk and Economic Analysis of Terrorist Events*, University of Southern California, (November 2008), accessed February 21, 2012, http://www.internationaltransportforum.org/jtrc/discussionpapers/DP200822.pdf.

[142] Jonathan Medalia, "Dirty Bombs": Technical Background, Attack Prevention and Response, Issues for Congress," *Congressional Research Service*, June 24, 2011, accessed February 16, 2012, http://www.fas.org/sgp/crs/nuke/R41890.pdf.

[143] Jonathan Medalia, "Dirty Bombs": Technical Background, Attack Prevention and Response, Issues for Congress," *Congressional Research Service*, June 24, 2011, accessed February 16, 2012, http://www.fas.org/sgp/crs/nuke/R41890.pdf.

attack on the twin ports of Los Angeles and Long Beach. However, Rosoff's and Von Winterfeldt's research posited that the economic costs of an ERDD attack on these ports could result in economic costs as high as $252 billion.[144] An important consideration is that in both the CREATE and Rosoff and Von Winterfeldt studies, the projected economic losses were based on a shut down time frame of 120 days to a one year. Given the nature of the cleanup and the fact that such a cleanup has never been conducted, these estimates may be very conservative projections of cleanup time, and thus actually understate the economic impact of an ERDD attack. In addition, the findings of Rosoff and Von Winterfeldt denote only the localized effect of an ERDD attack. It is important to consider that any attack may present an additional ripple effect throughout the whole U.S. economy.

Rosoff and Von Winterfeldt also highlight that other research has suggested that if rigorous standards were used in terms of cleanup, such as those held by the EPA, that cleanup costs could amount to trillions of dollars.[145] This is in fact the idea put forth in a study by Pacific Northwest National Laboratory (PNNL). In 2005, PNNL produced a study that suggested that if 10,000 Ci (115 grams) of Cs-137 were released in Manhattan, New York that the costs associated with such an attack, including cleanup, could total

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[144] Barbara Reichmuth, et al., "Economic Consequences of a Rad/Nuc Attack: Cleanup Standards Significantly Affect Cost," *Pacific Northwest National Laboratory*, (April 2005), accessed February 19, 2012, http://www.nuclearfiles.org/menu/key-issues/nuclear-weapons/issues/effects/PDFs/economic_consequences_report.pdf.

[145] Barbara Reichmuth, et al., "Economic Consequences of a Rad/Nuc Attack: Cleanup Standards Significantly Affect Cost," *Pacific Northwest National Laboratory*, (April 2005), accessed February 19, 2012, http://www.nuclearfiles.org/menu/key-issues/nuclear-weapons/issues/effects/PDFs/economic_consequences_report.pdf.

roughly $4.5 trillion if the contaminated area were to be decontaminated to the level of 15 mrem of radiation per year as designated by the EPA.

The PNNL report also suggested that by utilizing a "RADTRAN 5" economic model, that the evacuation costs alone would equal roughly $4500 per person in the affected area.[146] Given Manhattan's population of 1,629,054 people,[147] this would amount to $7,330,743,000 in solely relocation costs. More tellingly, the PNNL report suggests that the RADTRAN 5 economic model underestimates the actual costs of relocation for a location as densely populated as Manhattan, and that the true estimate could be substantially higher.

These studies present important findings relating to the possible economic costs of an ERDD explosion. Specifically, they highlight the issue of the time frame associated with decontamination and the question of what, given the event of an ERDD attack, is the acceptable time frame before resuming business as usual. Kelly and Levi as well as Rhodes and Pennington have suggested that faced with the choice of decontamination and area exclusion, a country such as the U.S. might choose to relax current guidelines related to radiation exposure or adopt new guidelines. A contemporary example of this would be the guidelines in Japan where in the wake of the Fukushima Daiichi incident, the occupational radiation dose limit was reportedly raised to 25 rem per year, which as we noted earlier would increase the risk of excess cancers by at least 1% annually for

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[146] Barbara Reichmuth, et al., "Economic Consequences of a Rad/Nuc Attack: Cleanup Standards Significantly Affect Cost," *Pacific Northwest National Laboratory*, (April 2005), accessed February 19, 2012, http://www.nuclearfiles.org/menu/key-issues/nuclear-weapons/issues/effects/PDFs/economic_consequences_report.pdf.

[147] "Population," *New York City Department of Planning*, accessed February19, 2012, http://www.nyc.gov/html/dcp/html/census/popcur.shtml.

those residing within the exposed area. This is "five times the maximum exposure permitted for American nuclear plant workers."[148] The significance of such a decision would invariable alter the calculus of the economic costs of a given ERDD attack.

Psychological Fallout

In addition to the contamination problem and the subsequent costs for decontamination, an ERDD attack would also likely produce psychological fallout arising from the panic of the populace. Dr. Walter Scheider, a professor of physics at the University of Michigan, stated that radioactivity "evokes feelings of fear and apprehension. That the effects of radioactivity are delivered by stealthy, invisible, silent forces only intensifies these feelings." Similarly, as Ferguson and Smith note, "a radiological attack carried out in any method, even if it does not succeed in exposing or killing large numbers of people, will still foster fear, uncertainty, and other social and economic disruptions."[149]

Any ERDD incident would require a need to evacuate contaminated areas and would leave many citizens concerned over the effects of radiation. The National Council on Radiation Protection suggests that the fear of an ERDD attack would be compounded by the fact that radiation and radioactivity are invisible toxins which people can neither see nor sense, yet know are potentially hazardous.[150] The reaction to this fear alone

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[148] Keith Bradsher and Hiroko Tabuchi, "Last Defense at Troubled Reactors: 50 Japanese Workers," *New York Times,* March 16, 2011, accessed March 25, 2012, http://www.nytimes.com/2011/03/16/world/asia/16workers.html?pagewanted=all.
[149] Charles D. Ferguson and Michelle M. Smith, "Assessing radiological weapons: Attack methods and estimated effects," *Defence Against Terrorism Review*, Vol. 2, No. 2 (Fall 2009): 15-34, January 7, 2012, http://www.tmmm.tsk.tr/publications/datr4/02-CharlesFerpdf.
[150] Matthew L. Wald, "Fear Itself Is the Main Threat of a Dirty Bomb, Experts Say," *The New York Times,* June 11, 2002, February 12, 2012, http://www.nytimes.com/2002/06/11/national/11BOMB.html.

would in turn lead to injuries and deaths from both the flow of people trying to evacuate, as well as the overflow of citizens into medical facilities demanding medical attention and screening for treatment of real and imagined radiation sickness. As Dr. John W. Poston Sr., a professor of nuclear engineering at Texas A&M University, notes, "you can think of all kinds of things, people panicking, killing each other in automobiles, arguing over who has the right of way, crazy things that would have nothing to do with radioactivity but would be caused by psychological effects."[151] As Dr. Muller of Berkley notes, "the psychological impact of such weapons can be greater than the limited harm they are likely to cause."[152]

The Department of Homeland Security analyzed this issue and put together a planning scenario for an ERDD attack, assuming the outcome of an explosion of three ERDD's in three different but similar moderate-to-large cities, covering 36 city blocks. Their research posited that beyond the initial injuries, there would not be incidents of acute radiation syndrome. "Approximately 20,000 individuals are likely to become externally contaminated at each site"[153] with the sum of the cumulative exposures resulting in an increased lifetime cancer risk proportionate to the dose. However, the hospitals in each region would be inundated with upwards of 50,000 "worried well" citizens, in addition to those needing care. Equally important, "panic would be unlikely to remain localized but probably spread nationally, and would easily be fuelled by dirty

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[151] Matthew L. Wald, "Fear Itself Is the Main Threat of a Dirty Bomb, Experts Say," *The New York Times*, June 11, 2002, accessed February 12, 2012, http://www.nytimes.com/2002/06/11/national/11BOMB.html.
[152] Richard A. Muller, "Physics for Future Presidents," (New York: W.W. Norton & Company, 2008): 38.
[153] "Homeland Security Planning Scenarios," *Global Security*, accessed January 10, 2012, http://www.globalsecurity.org/security/ops/hsc-scen-11.htm.

and conventional bomb alerts - genuine or hoax."[154] In addition to the local direct economic losses, the scenario posits that an ERDD attack could have an effect on the psychology of the nation as a whole and that "an overall national economic downturn may occur in the wake of the attack due to a loss of consumer confidence."[155]

Conclusions

Reviewing these hypothetical ERDD scenarios is important in trying to understand what value these weapons may possess for states. Though the authors may not agree on the significance or the outcome, it is clear that with just a small amount of radiological material, an explosive weapon can be constructed, whose effects would be dramatic and widespread. The distribution of radioisotopes would be widespread and difficult to determine due to the variability of the explosion, ballistics, diffusion, and the weather.

However, it is clear that the initial reaction would be an effort to limit the possible damages of such an ERDD attack, which would necessitate widespread evacuation. This would neither be easy nor would it likely be efficient. Once completed, there would begin a long process of determining how the affected site could be safely managed and if it could once again be suitable for habitation. If so, it would necessitate never before performed large scale decontamination. During that time, the affected area would be subject to major economic losses whose effects may bleed over into the national economy. Concurrently, there would likely be widespread psychological issues, in terms

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[154] Mark Burgess, "Pascal's New Wager: The Dirty Bomb Threat Heightens," *Center for Defense Information*, February 4, 2003, accessed February 12, 2012, http://www.cdi.org/terrorism/dirty-bomb.cfm.
[155] "Homeland Security Planning Scenarios," *Global Security*, accessed January 10, 2012, http://www.globalsecurity.org/security/ops/hsc-scen-11.htm.

which could manifest in a number of ways but whose effect is likely to negatively impact the economy and overburden the local and national health systems.

These are clear indicators that there may be a definitive value for states possessing radiological weapons, in that this description presents a vivid picture of a situation that any country would work strongly to prevent.

Chapter 5 – Radioactive Incidents

History provides very little information on the effects following a radiological attack. Contemporary research relies mainly on assumptions gathered from hypothetical scenarios. Given this position, it is imperative that we broaden the scope of our research. Specifically, there are a number of examples of the dispersion of radioisotopes and their effects from history in the form of radiological accidents. Specifically, I would like to highlight three of these incidents: the Chernobyl accident, the Goiânia event, and the Fukushima Daiichi accident. Each of these unique incidents gives definitive insight into the outcome of the dispersal of radioisotopes and thus the value of an ERDD.

Chernobyl Accident

On April 26, 1986, what is arguably the world's most severe radiological accident occurred at the Chernobyl nuclear power plant in Ukraine. A combination of operational errors, as well as poor reactor design turned what was supposed to be a routine exercise into a situation that "provoked a sudden and uncontrollable power surge which resulted in violent explosions and almost total destruction of the reactor."[156] This in turn, caused material fires within the plant that "contributed to a widespread and prolonged release of radioactive materials to the environment."[157]

Over a ten-day period, these fires released a large portion of the radioactive product inventory of Chernobyl's nuclear reactor. During that time, the dispersion of the

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[156] "Chernobyl: Assessment of Radiological and Health Impacts," *Nuclear Energy Agency Organisation for Economic Co-operation and Development*, (2002), accessed March 17, 2012, http://www.oecd-nea.org/rp/reports/2003/nea3508-chernobyl.pdf.

[157] "Chernobyl: Assessment of Radiological and Health Impacts," *Nuclear Energy Agency Organisation for Economic Co-operation and Development*, (2002), accessed March 17, 2012, http://www.oecd-nea.org/rp/reports/2003/nea3508-chernobyl.pdf.

radioactive materials reached an altitude of approximately 1 km high. With frequent changes in wind direction, the resulting area of exposure encompassed the whole Northern hemisphere. However, it should be noted that "significant contamination outside the former Soviet Union was only experienced in part of Europe."[158]

Although a number of materials were released during the accident, there was only a small subset that proved the most deleterious, including: I-131, Cs-134, Cs-137, Sr-90, Pu-238, and Pu-239. Surprisingly, the overall combined mass of these specific isotopes only measured 41 kgs, weighing roughly 91 lbs. The deposition of the released particles "depended highly on the dispersion parameters, the particle sizes, and the occurrence of rainfall."[159] The largest particles, consisting primarily of fuel particles such as Sr-90 and Pu-239, fell within the zone near the reactor. The smaller particles, such as I-131 and Cs-137 were carried farther distances and deposited primarily by rainfall. Ground depositions of Cs-137 measured over .000001081 Ci/m^{2}, covering large areas of the Northern Ukraine and Southern Belarus. "The most highly contaminated area was the 30-km zone surrounding the reactor, where [Cs-137] ground depositions generally exceeded [.000040541 Ci/m^{2}]."[160]

An important aspect of the effects of this radiological accident was in in how the radionuclides interacted with the environment. Resuspension of radioactive particles

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[158] "Chernobyl:Assessment of Radiological and Health Impacts," *Nuclear Energy Agency Organisation for Economic Co-operation and Development*, (2002), accessed March 17, 2012, http://www.oecd-nea.org/rp/reports/2003/nea3508-chernobyl.pdf.

[159] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.

[160] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.

became a long-term issue. A year after the accident both storms as well as fires resulted in the resuspension of radiation from within the exclusion zone, raising the levels of radiation in nearby areas. In addition, radionuclides deposited on soil generally tend to migrate downwards towards the part of soil containing roots. However, after the incident, the vertical migration of these radioisotopes was noted to be slow with a significant fraction of the radioisotopes residing in the upper soil layers.[161] "As a result of the accumulation of Cesium-137 (Cs-137), Strontium-90 (Sr-90), Plutonium (Pu) and Americium (Am) in the root soil layer, radionuclides [continued] to build in plants."[162] For example, Sr-90, which accumulates into plants easier than Cs-137, led to "grazing animals [concentrating] Sr-90 in their milk, and then into the food supply."[163]

This had the effect of increased levels of internal irradiation and dose rates in consumers of affected foodstuffs. This problem was further compounded by the fact that moving water continued to redistribute radionuclides to areas of topsoil where radionuclides had already migrated from. Although "the contribution of aquatic pathways to the dietary intake of [Cs-137] and [Sr-90] is usually quite small,"[164] the issue of runoff presented an ongoing challenge creating radioactive hotspots.

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[161] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.
[162] Janette D. Sherman and Alexey V. Yablokov, "Chernobyl: Consequences of the catastrophe 25 years later," *San Francisco Bay View*, April 27, 2011, accessed March 17, 2012, http://www.ratical.org/radiation/Chernobyl/CCofC25YL.html.
[163] Janette D. Sherman and Alexey V. Yablokov, "Chernobyl: Consequences of the catastrophe 25 years later," *San Francisco Bay View*, April 27, 2011, accessed March 17, 2012, http://www.ratical.org/radiation/Chernobyl/CCofC25YL.html.
[164] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.

Owing to the threat of these radioisotopes, the Soviet Union evacuated roughly "116,000 people from areas surrounding the reactor during 1986."[165] However, in the years that followed the accident, roughly 220,000 people were relocated from the areas of what are now, Belarus, the Russian Federation, and Ukraine.[166] After the accident, a 30 km exclusion zone was put into effect around the reactor. However, this was eventually extended for an area roughly 4300 km^2 due to concerns over residual radiation exposure.

In terms of exposure, radiation resulting from the Chernobyl accident came initially from the I-131. However, because of I-131's short half-life, the long-term exposure of radiation resulted from exposure to isotopes of Cs-134 and Cs-137. Long-term radiation exposure functioned as a byproduct of both "external irradiation and the consumption of foods contaminated with these radionuclides,"[167] and is expected to continue at low dose rates, for a period of several decades following the event.

The effects of the radiation present in a number of ways. Specifically, "I-131 and I-129 concentrate in the thyroid, Cs-137 in soft tissue, and Sr-90 in teeth and bones."[168] Notwithstanding, research has posited that, "apart from the substantial increase in thyroid cancer after childhood exposure, there is no evidence of a major public health impact related to the ionizing radiation 14 years after the Chernobyl accident."[169] Similarly, the

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[165] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.
[166] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.
[167] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.
[168] Janette D. Sherman and Alexey V. Yablokov, "Chernobyl: Consequences of the catastrophe 25 years later," *San Francisco Bay View*, April 27, 2011, accessed March 17, 2012, http://www.ratical.org/radiation/Chernobyl/CCofC25YL.html.
[169] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.

World Health Organization (WHO) stated that the accident only caused an additional 4,000 cancer deaths, among the 626,000 most highly exposed people, roughly 4% higher than the normal rate.[170] Dr. Muller suggests a higher number, estimating the number of excess cancers caused by this radiation at 24,000.[171] At the same time, it is important to note that these conclusions are still debated. Other sources purport that the overall mortality from the Chernobyl catastrophe was in fact "a hundred times more than the WHO/IAEA estimate."[172]

Yet despite the lack of consensus on overall deterministic effects from exposure, there are other effects beyond the physiological to consider. "The Chernobyl Forum report says that people in the area have suffered a paralysing fatalism due to myths and misperceptions about the threat of radiation, which has contributed to a culture of chronic dependency."[173] In fact, the World Health Organization said that psychological distress was the largest public health problem resulting from the accident. Specifically, they noted that, "populations in the affected areas exhibit strongly negative attitudes in self-assessments of health and wellbeing and a strong sense of lack of control over their own

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[170] Jonathan Watts, "Fukushima disaster: it's not over yet," *The Guardian*, September 9, 2011, accessed March 4, 2012, http://www.guardian.co.uk/world/2011/sep/09/fukushima-japan-nuclear-disaster-aftermath.

[171] Richard Muller, "Comparing Fukushima to Chernobyl," *The Wall Street Journal*, August 17, 2012, accessed on November 18, 2012, http://online.wsj.com/article/SB10000872396390443324404577595221606754192.html.

[172] Janette D. Sherman and Alexey V. Yablokov, "Chernobyl: Consequences of the catastrophe 25 years later," *San Francisco Bay View*, April 27, 2011, accessed March 17, 2012, http://www.ratical.org/radiation/Chernobyl/CCofC25YL.html.

[173] "Chernobyl Nuclear Accident," *World Nuclear Association*, accessed March 26, 2012, http://www.world-nuclear.org/info/chernobyl/inf07.html.

lives. Associated with these perceptions is an exaggerated sense of the dangers to health of exposure to radiation."[174]

Decontamination was also a problem. Following the accident, cleanup was initiated on a massive scale. "Decontamination procedures performed by military personnel included the washing of buildings, cleaning residential areas, removing contaminated soil, cleaning roads and decontaminating water supplies."[175] At the same time, there were immediate efforts to handle contaminated food as well. "Mechanisms to handle locally produced as well as imported contaminated food had to be put in place within a few weeks of the accident,"[176] both for the Soviet Union as well as surrounding countries. A number of countries banned any food containing any radionuclides whatsoever. In many instances even "slightly contaminated food was destroyed or refused importation to avoid only trivial doses." [177] This reaction contributed substantially to the economic effects of the Chernobyl accident.

In terms of economic costs, Ivan Kenik, Belarus's Chernobyl minister, estimates that within the borders of Belarus the total damages from the Chernobyl catastrophe will have cost roughly $235 billion.[178] This estimate incorporates the total cost of "resettling

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[174] Jonathan Watts, "Fukushima disaster: it's not over yet," *The Guardian*, September 9, 2011, accessed March 4, 2012, http://www.guardian.co.uk/world/2011/sep/09/fukushima-japan-nuclear-disaster-aftermath.
[175] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.
[176] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.
[177] Burton Bennett, et al., "Chernobyl Accident: Exposures and Effects," *Epidemiologic Reviews*, Vol. 27, Issue 1, (July 2005):56-66, accessed March 17, 2012, http://epirev.oxfordjournals.org/content/27/1/56.full.
[178] "Chernobyl: Understanding Some of the True Costs of Nuclear Technology," *Ratical World*, accessed March 24, 2012, http://www.ratical.org/radiation/Chernobyl/.

inhabitants, cleaning and sealing the area and paying off medical claims."[179] In fact, Belarus reportedly spends 20% of its national annual budget on dealing with the costs of Chernobyl. The total figure for the region of Belarus, Ukraine and Russia, combined is said to more than double that of Belarus, with total estimates exceeding $500 billion.[180]

Goiânia Incident

On September 13, 1987, scavengers in Goiânia, Brazil broke into a building that formerly housed the Goiânia Institute of Radiotherapy. The scavengers then stole a capsule of cesium chloride containing 1,375 Ci (93 grams) of Cs-137 from an abandoned teletherapy machine.[181] The scavengers then took the capsule to a domicile over a distance of half a kilometer. Though the Cs-137 remained in the source capsule, both men began exhibiting signs of radiation sickness within a day.[182] Less than five days later, the men punctured the capsule allowing the Cs-137 to spread. An interesting facet about the cesium chloride is that it comes in a powder form that gives off a blue glow.[183]

This special attribute had an allure to the scavenger and locals of Goiânia. Not knowing about the accompanying threat of radiation, the powder was distributed amongst family members and friends, some of which "sprinkled or rubbed the material on their

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[179] Mikka Pineda, "Fukushima Vs. Three Mile Island Vs. Chernobyl," *Forbes*, March 17, 2011, accessed March 17, 2012, http://www.forbes.com/2011/03/16/japan-disaster-nuclear-opinions-roubini-economics.html.

[180] Janette D. Sherman and Alexey V. Yablokov, "Chernobyl: Consequences of the catastrophe 25 years later," *San Francisco Bay View*, April 27, 2011, accessed March 17, 2012, http://www.ratical.org/radiation/Chernobyl/CCofC25YL.html.

[181] "The Radiological Accident in Goiania," *International Atomic Energy Agency*, (1988): 22, accessed March 3, 2012, http://www-pub.iaea.org/mtcd/publications/pdf/pub815_web.pdf.

[182] Both men were vomiting with diarrhea, and shows signs of swelling tissue.

[183] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.

bodies as they might have done with Carnival glitter."[184] The powder was even ingested by two people, one of which was a child who later died. It wasn't until September 28, 1987, that a doctor recognized the signs of acute radiation sickness in one of the individuals. However, in an effort to confirm the source of the radiation, the material was further distributed in route to the clinic of the Vigilancia Sanitária.

The outcome of this incident involving this relatively small source of Cs-137 was that Brazilian authorities, in partnership with the IAEA were forced to monitor over "112,000 people in the city's Olympic-sized soccer stadium for radiation exposure and sickness."[185] A report later produced by the IAEA notes that "a total of 249 people were identified as contaminated by the Cesium-137, 151 people exhibited both internal and external contamination, 49 people were admitted to hospitals, with the 20 most seriously irradiated having received doses from 100 to 800 rads [100 to 800 rem]."[186] Compounding the problem of the radiation exposure was the fact that those that were internally contaminated were themselves radioactive.[187] Interestingly, many of those contaminated never came in direct contact with the source; they had secondary contact

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[184] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.
[185] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.
[186] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.
[187] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.

only. Moreover, there were even a number of individuals exposed to radiation through tertiary contact.[188]

The event resulted in five deaths, with 28 people suffering radiation burns. In addition, authorities found a number of buildings with significant levels of contamination. In the downtown area there was significant contamination across "85 houses, of which 41 were evacuated."[189] Beyond the downtown region, before the incident could be controlled, people had also "cross-contaminated houses nearly 100 miles away."[190] Even once the Brazilian government was handling the radiation incident, that dissemination of radioactive material still continued. "Both patients and technicians spread radioactive contamination,"[191] not only in Goiânia but all the way to Rio de Janeiro. The cleanup of the radiation generated 3,500 metric tons of waste at a cost of over $20 million.[192]

In addition, "the long-term socio-economic effects were devastating."[193] After the incident, Goiânia and its 800,000 residents quickly went into an economic recession. As Peter Zimmerman and Cheryl Loeb note, "The majority of the damage done to the Goiânia region was caused by the nearly total cessation of economic intercourse with the

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[188] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.
[189] "The Radiological Accident in Goiania," *International Atomic Energy Agency*, (1988): 22, accessed March 3, 2012, http://www-pub.iaea.org/mtcd/publications/pdf/pub815_web.pdf.
[190] "Radiological Dispersal Device (RDD)" *Human Health Fact Sheet*, Argonne National Laboratory, (August 2005), January 7, 2012, http://www.evs.anl.gov/pub/doc/rdd.pdf.
[191] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.
[192] "Radiological Dispersal Device (RDD)" *Human Health Fact Sheet*, Argonne National Laboratory, (August 2005), January 7, 2012, http://www.evs.anl.gov/pub/doc/rdd.pdf.
[193] Louis Charbonneau, "A dirty bomb may not kill, but it sure would hurt," *Reuters*, March 17, 2003, accessed March 2, 2012, http://nuclearno.com/text.asp?5347.

rest of Brazil."[194] At the time, Goiânia's primary business was agriculture. After the incident, farmers in the area were unable to sell their produce to the rest of Brazil. Fear of radioactive contamination spurred a boycott of products from Goiânia, with the price of manufactured goods dropping by roughly 40%.[195] Also, the local tourism industry was eradicated. For months after the event, a significant portion of the downtown area was put under quarantine. The Brazilian government even forbade travel by Goiânians outside the region unless certificated uncontaminated. Proceeding from the incident, Goiânia's GDP dropped roughly 20 percent, taking roughly five years to return to normal levels.[196] "Total economic losses were estimated at hundreds of millions of dollars."[197]

Fukushima Accident

On March 11, 2011, Japan was struck by a magnitude 9.0 earthquake named the Great East Japan Earthquake. The quake caused considerable damage, most notably to Japan's Fukushima Daiichi nuclear power plant. At the time of the earthquake, eleven reactors at four of Japan's nuclear power plants shut down automatically. However, owing to the seismic force of the earthquake, shortly after a tsunami struck the Fukushima Daiichi plant, disabling the power supply and cooling of three of the

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[194] Peter D. Zimmerman and Cheryl Loeb, "Dirty Bomb – Threats Revisited," *Defense Horizons*, Center for Technology and National Security Policy, National Defense University, No. 38, (January 2004), accessed March 2, 2012, http://hps.org/documents/RDD_report.pdf.
[195] "Radiological Dispersal Device (RDD)" *Human Health Fact Sheet*, Argonne National Laboratory, (August 2005), January 7, 2012, http://www.evs.anl.gov/pub/doc/rdd.pdf.
[196] Louis Charbonneau, "A dirty bomb may not kill, but it sure would hurt," *Reuters*, March 17, 2003, accessed March 2, 2012, http://nuclearno.com/text.asp?5347.
[197] "Radiological Dispersal Device (RDD)" *Human Health Fact Sheet*, Argonne National Laboratory, (August 2005), January 7, 2012, http://www.evs.anl.gov/pub/doc/rdd.pdf.

Fukushima Daiichi nuclear reactors, including disabling back-up generators, heat exchangers, and electrical switchgears, all of which lead to a nuclear accident.[198]

The impact of the tsunami "rendered the loss of all instrumentation and control systems at reactors 1-4."[199] As a result, the reactors lost the ability to remove heat and to cope with overheating spent fuel ponds. "All three cores largely melted in the first three days,"[200] causing severe damage to the fuel as well as a series of explosions. These explosions caused further destruction at the site, and precipitated the spread of radiological contamination into the environment, which together "released more radiation than any accident since Chernobyl."[201] It took weeks for workers to reach any type of stability again. However, it wasn't until mid-December that "an official 'cold shutdown condition' was announced."[202]

Following this accident, the Japanese government has had to evacuate a large portion of the region surrounding the Fukushima Daiichi nuclear plant, owing to the threat posed by the residual radiation that was deposited from the nuclear accident. The overall radiation released from the plant equated to roughly 20,790,000 Ci across the

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[198] "Fukushima Accident 2011," *World Nuclear Association,* accessed March 4, 2012, http://www.world-nuclear.org/info/fukushima_accident_inf129.html.

[199] "Preliminary Summary," *IAEA International Fact Finding Expert Mission of the Nuclear Accident Following the Great East Japan Earthquake and Tsunami*, International Atomic Energy Agency, May 24 - June 1, 2011, accessed March 4, 2012, http://www.iaea.org/newscenter/focus/fukushima/missionsummary010611.pdf.

[200] "Fukushima Accident 2011," *World Nuclear Association,* accessed March 4, 2012, http://www.world-nuclear.org/info/fukushima_accident_inf129.html.

[201] Jonathan Watts, "Fukushima disaster: it's not over yet," *The Guardian,* September 9, 2011, accessed March 4, 2012, http://www.guardian.co.uk/world/2011/sep/09/fukushima-japan-nuclear-disaster-aftermath.

[202] "Fukushima Accident 2011," *World Nuclear Association,* accessed March 4, 2012, http://www.world-nuclear.org/info/fukushima_accident_inf129.html.

various radioisotopes.[203] This radiation was comprised in part by I-131, which tends to accumulate in the thyroid gland, Cs-134 and Cs-137, which affects the bladder and liver, and Sr-90, which tends to accumulate in the bones and causes leukemia.

The Japanese government reported in June 2011 that the Fukushima Daiichi nuclear plant "released 1.5×10^{16} bequerels [4.6 kgs] of caesium-137 [and] a far larger amount of xenon-133, 1.1×10^{19} Bq [1.59]."[204] However, other studies suggest that in fact there was 3.5×10^{16} Bq [10.9 kgs] of Cs-137 released, more than double the Japanese government's official estimate.[205] The Cs-137, though now diluted and dissipated, presents an ongoing problem particularly in terms of seepage into the soil, contamination of the leaves in the forests, and "being passed through the food chain to cattle, fish, vegetables – and humans."[206] With a half-life of roughly 30 years, this threat posed by Cs-137 will last longer than a generation.

Owing to this large output of radiation, a circular area roughly 40 km in circumference has been designated a restricted zone, prohibiting all but emergency workers.[207] In addition, a larger portion of additional land stretching to the northwest, has been designated a deliberate evacuation zone owing to concerns that the cumulative

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[203] Jonathan Watts, "Fukushima disaster: it's not over yet," *The Guardian*, September 9, 2011, accessed March 4, 2012, http://www.guardian.co.uk/world/2011/sep/09/fukushima-japan-nuclear-disaster-aftermath.
[204] Geoff Brumfiel, "Fukushima Nuclear Plant Released Far More Radiation Than Government Said," *Nature Magazine*, October 25, 2011, accessed March 4, 2012, http://www.scientificamerican.com/article.cfm?id=fukushima-nuclear-planet-released-more-radiation-government-said.
[205] Geoff Brumfiel, "Fukushima Nuclear Plant Released Far More Radiation Than Government Said," *Nature Magazine*, October 25, 2011, accessed March 4, 2012, http://www.scientificamerican.com/article.cfm?id=fukushima-nuclear-planet-released-more-radiation-government-said.
[206] Jonathan Watts, "Fukushima disaster: it's not over yet," *The Guardian*, September 9, 2011, accessed March 4, 2012, http://www.guardian.co.uk/world/2011/sep/09/fukushima-japan-nuclear-disaster-aftermath.
[207] "Fukushima Daiichi Status Report," *International Atomic Energy Agency*, February 23, 2012, accessed March 4, 2012, http://www.iaea.org/newscenter/focus/fukushima/statusreport230212.pdf.

dose of radiation that could be received within one year in these areas exceeded acceptable amounts. This region stretches roughly 60 km away from the Fukushima Daiichi nuclear plant.[208]

As it stands, roughly "2 million people in Fukushima are living in areas where the annual radiation dose exceeds the one millisievert [100 mrem] per year safety target set by the government for the general population."[209] Yet, the effects of the Fukushima Daiichi accident extend well beyond the immediate region. As with the case of Goiânia in Brazil, rain and weather have redistributed the radioactive material. "Even in downtown Tokyo – 240km from the reactor – levels have [reportedly] risen close to the point where they would have to be marked with a "Radiation Hazard" warning if they were found in a workplace."[210]

The economic costs of the accident, though still unclear, appear enormous. "The area in need of cleanup could be 1,000 to 4,000 square km, about 0.3 to 1 percent of Japan's total land area, and cost several trillion to more than 10 trillion yen ($130 billion)."[211] At the same time the estimated costs of the Fukushima accident have been suggested to range as high as $250 billion. As time goes on and the problem of the

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[208] "Fukushima Daiichi Status Report," *International Atomic Energy Agency*, February 23, 2012, accessed March 4, 2012, http://www.iaea.org/newscenter/focus/fukushima/statusreport230212.pdf.
[209] Jonathan Watts, "Fukushima disaster: it's not over yet," *The Guardian*, September 9, 2011, accessed March 4, 2012, http://www.guardian.co.uk/world/2011/sep/09/fukushima-japan-nuclear-disaster-aftermath.
[210] Jonathan Watts, "Fukushima disaster: it's not over yet," *The Guardian*, September 9, 2011, accessed March 4, 2012, http://www.guardian.co.uk/world/2011/sep/09/fukushima-japan-nuclear-disaster-aftermath.
[211] "Yoko Kubota , "Japan faces costly, unprecedented radiation cleanup," *Reuters*, August 25, 2011, accessed March 4, 2012, http://www.reuters.com/article/2011/08/25/us-japan-nuclear-decontamination-idUSTRE77O3LI20110825.

radiation persists, these projections are only likely to increase.[212] It has been estimated to cost roughly $54 billion just to buy up all the contaminated land within 20 kilometers of the plant in the just area that makes up the restricted zone.[213]

The issue is compounded by the fact that Japan faces the problem of limited land space, "unlike in Chernobyl, where the then-Soviet Union moved residents elsewhere."[214] The limited land space calls into question the option of decontamination to let residents return. In terms of the effect on agriculture, analytical results have shown that roughly 1% of all samples indicated that Cs-134 and Cs-137 were "found to be above the provisional regulation values for radioactive caesium (Cs-134 and Cs-137)."[215]

Conclusions

These radiological incidents present very interesting findings, most notably in demonstrating how radiation interacts with the environment, as well as demonstrating the types of costs that could be expected from the dispersal of a large amount of radiation. In the first example, Chernobyl shows how incidents of radioactive contamination have led to large swaths of territory being cordoned off due to the risk of contamination. Almost three decades later, the same 30 km exclusion zone remains in place. We could expect a similar result as the outcome of an ERDD attack. Also, an important consideration in the context of relating the incident to the effects of an ERDD is the positioning of the

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[212] Mark Cooper, "Nuclear liability: The market-based, post-Fukushima case for ending Price-Anderson," *Bulletin of Atomic Scientists*, October 5, 2011, accessed March 4, 2012, http://www.thebulletin.org/web-edition/features/nuclear-liability-the-market-based-post-fukushima-case-ending-price-anderson.
[213] "Fukushima cleanup could cost up to $250 billion," *News on Japan,* accessed March 4, 2012, http://newsonjapan.com/html/newsdesk/article/89987.php.
[214] "Yoko Kubota , "Japan faces costly, unprecedented radiation cleanup," *Reuters*, August 25, 2011, accessed March 4, 2012, http://www.reuters.com/article/2011/08/25/us-japan-nuclear-decontamination-idUSTRE77O3LI20110825.
[215] "Fukushima Daiichi Status Report," *International Atomic Energy Agency*, February 23, 2012, accessed March 4, 2012, http://www.iaea.org/newscenter/focus/fukushima/statusreport230212.pdf.

Chernobyl nuclear plant and the area's population density. The Chernobyl nuclear plant was located in an area of low population density. Roughly 3 km away from the reactor, 49,000 people lived in the city Pripyat; 15 km away, there was another town of roughly 12,500 people. "Within a 30 km radius of the power plant, the total population was between 115,000 and 135,000."[216] Similarly, the event at Fukushima occurred in areas of low population density relative to larger urban areas. If a similar accident had occurred in a more populated area such as Manhattan, the amount of people affected and thus needing to be relocated could easily have reached into the millions.

In addition, the more people in the area of the dispersal, the more people that would likely seek medical attention. The Goiânia incident shows that in a region of 800,000, with limited distribution of radioactive material that over 130,000 sought medical attention. It can be assumed that with a much larger distribution of material, that an equally greater number of people would seek medical attention. In the scenario outlined by Kelly and Levi in the preceding section, an ERDD could lead to all of Manhattan being exposed to some form of radiation. If similar concerns of radiation exposure prompted the people of Manhattan to also seek medical attention, then a large percentage if not all of Manhattan's population of 1,629,054 people[217] could similarly seek medical assistance.

Moreover, though the 99.8% that sought medical attention during the Goiânia incident were not contaminated, "8% had psychosomatic reactions mimicking radiation

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[216] "Chernobyl Nuclear Accident," *World Nuclear Association*, accessed March 26, 2012, http://www.world-nuclear.org/info/chernobyl/inf07.html.
[217] "Population," *New York City Department of Planning*, accessed February 19, 2012, http://www.nyc.gov/html/dcp/html/census/popcur.shtml.

exposure."[218] Again, in a scenario involving Manhattan, that could mean dealing with roughly 122,000 people suffering from psychosomatic reactions alone. This would have a definitive impact in terms of the cost of an ERDD attack.

The example of Goiânia also highlights the complexities of dispersion. The extent of the radiological incident was largely dependent on the exposure from contact by people. A number of those that were exposed to radiation in the Goiânia incident were through secondary or tertiary contact, never actually coming in contact with the original radiological source deposit. In fact, radiation was spread from Goiânia all the way to Rio de Janeiro, over 1,200 km away, all through residual contact. Even when actual decontamination had begun in Goiânia, repeated washing of contaminated clothing in several soap and water baths only proved to be 50-80% effective, further emphasizing the propensity for radiation to continue to be disseminated after an event.[219]

In addition, both the Chernobyl and Goiânia events show how the redistribution of particles owing to weather can create additional problems. Specifically, cesium chloride is highly soluble, and its dispersion through an environment is increased by rainfall, with winds causing resuspension and dispersion.[220] In Chernobyl, this resuspension spread contamination across the northern part of Europe and continued to create new radioactive hotspots. In Goiânia, when decontamination began in the city it was found that contamination, which was resuspended by winds and rain fall and then

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[218] Dr. Leonard A. Levy, "Japan's Nuclear Disaster, Implications on the U.S.: A Public Health Perspective," *Nova Southeastern University College of Osteopathic Medicine*, (November 2011), accessed March 3, 2012, http://qol.nova.edu/pdf/Levy_nov2011.pdf.

[219] "The Radiological Accident in Goiania," *International Atomic Energy Agency*, (1988): 42, March 3, 2012, http://www-pub.iaea.org/mtcd/publications/pdf/pub815_web.pdf.

[220] "The Radiological Accident in Goiania," *International Atomic Energy Agency*, (1988): 42, March 3, 2012, http://www-pub.iaea.org/mtcd/publications/pdf/pub815_web.pdf.

deposited on roofs. Surprisingly, this type of dispersal "was the major contributor to dose rates indoors."[221]

The hypothetical scenarios outlined earlier do not appear to adjust for the effect of the redistribution of material and its persistent propensity to spread over vast amounts of territory through weather and simple physical contact. Understanding this concept, if the need arose to evacuate an affected urban population of millions of people, resuspension, residual contact, and redistribution may spread radiation across the whole country, easily turning what would appear to be an isolated incident into a national incident. These costs and consideration are clear indicators that there may be a definitive value for states possessing radiological weapons.

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[221] "The Radiological Accident in Goiania," *International Atomic Energy Agency*, (1988): 42, March 3, 2012, http://www-pub.iaea.org/mtcd/publications/pdf/pub815_web.pdf.

Chapter 6 – Conclusions

In this research, we have developed a baseline understanding of radioisotopes and their effects. We have reviewed the history of the development of radiological weapons. We have also reviewed the prevailing literature regarding the explosion of an ERDD and explored the hypothetical effects. Lastly, we have reviewed three of the worst cases of the dispersion of radioisotopes in world history.

After reviewing this literature it is clear that an ERDD has considerable value in terms of the costs which it can exact from a given territory. What my research has shown is that with a limited amount of material, an ERDD can disperse significant amount of radiation over a large area and that this radiation will most likely continue to be redispersed after the fact. This radiation would not lead to significant immediate casualties. However, the value of this type of attack is not realized in immediate casualties. Instead, such an explosion would foster widespread fear concerning exposure to radiation, which would exist as an ongoing threat to the health and well being of those continually exposed. In the short term, this would prompt large scale evacuation of the inhabitants of the affected area. Moreover, these evacuations would be indefinitely maintained until large scale decontamination could be conducted. In some instances, radioisotopes would bind with surfaces such as concrete and asphalt with some areas likely excluded permanently due to residual radiation. Regardless of the cleanup, concerns over exposure to radiation would deter many from returning to the affected are, while at the same time discouraging any new residents. All of these factors would contribute to extreme and likely insurmountable economic costs for any affected territory, city, or nation. It is with this developed understanding that we now have a basis for answering our initial question, “what value would an ERDD have for a state actor?”

Any state wishing to exact large economic costs on another state could, with relative simplicity compared to the development of a nuclear weapon, choose to couple a limited amount of radioactive material with explosives and carry out an ERDD attack levying significant costs against an adversary state, costs which would only increase with the amount of radioactive material and explosives used. The ability for one state to take away from an adversary state essential territory, a city, or multiple cities due to radiological contamination would be limited only by the availability of radioisotopes and the specific means of delivery. Understanding this value makes it clear that possession of these types of weapons by any state would pose a clear and significant threat to an adversary state.

Moreover, the hypothetical scenarios evaluating the possible explosion of an ERDD, which serve as our basis for conceptualizing the reality of such an attack, have been wholly focused on a terrorist contrived event, and more importantly, a terrorist contrived weapon. Therefore, these examples are inadequate for determining the value of these types of weapons for states because they ignore the advanced capabilities available to a given state for developing and distributing such weapons. A given state has a greater opportunity to: 1) acquire a significant quantity of radiological material; 2) utilize more highly radioactive material; 3) couple that highly radioactive material with a more effective means of dispersal; and 4) develop an effective arsenal of ERDD for the threat of repeated dispersal.

First, a state would have superior access to the means of acquiring radioisotopes in far larger quantities than could a terrorist organization. Radioactive material is present in almost every country in the world. Radioisotopes are commonly used in hospitals and universities, as well as numerous commercial and industrial products "from cancer treatment, food and medical sterilization, oil exploration, smoke detectors, to laboratory research."[222] Specifically, many of these dangerous isotopes are readily available because of their use in medical diagnosis and radiotherapy. As noted by the IAEA, a given food irradiator alone may contain 3,000,000 Ci (34.5 kg) of Cs-137.[223] In addition, these radioisotopes are also byproducts of research reactors and the nuclear fuel cycle. The importance of this information is that while a terrorist organization may have difficulty in acquiring radioactive material, a state has numerous avenues to develop or to acquire and utilize not just grams of source material, but kilograms of source material, doing so without difficulty or restriction, and affording the opportunity to increase the threat of radiation by thousands.

Second, a state would have a superior capability for utilizing and weaponizing highly radioactive material, enabling the effective use of far more dangerous radioisotopes. Case in point, most of the aforementioned dispersal scenarios posit the dispersal of Cs-137 because it is commonly found in a readily dispersible particulate form known as cesium chloride, in contrast to Co-60 which is commonly found in small

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[222] Benjamin F. Visger, "Dirty Bombs: The Technical Aspects of Radiological Dispersion Devices," (Master thesis, Naval Post Graduate School, 2004).

[223] "3,000,000 curies cesium-137," *WolframAlpha*, accessed March 25, 2012, http://www.wolframalpha.com/input/?i=3%2C000%2C000+curies+cesium-137; "International Atomic Energy Agency Safety Standard Series No. RS-G-1.9: Categorization of Radioactive Sources," *International Atomic Energy Agency*, (August 2005), March 2, 2012, http://www-pub.iaea.org/MTCD/publications/PDF/Pub1227_web.pdf.

metallic rods used in irradiators. During the initial explosion of an ERDD, radioisotopes in metallic form would have a very limited distribution capability compared to materials in particulate form. However, Co-60 is far more radioactive than Cs-137 by a magnitude of ten, making it a more attractive material for utilization in an ERDD. For a terrorist organization with a limited nuclear infrastructure and advanced scientific capabilities, this is likely an insurmountable hurdle. This in fact was an argument against the aforementioned scenario by Kelly and Levi, which speculated on a terrorist explosion of roughly 1.3 kgs of Co-60. The argument being that their scenario did not account for the limited dispersal of radioisotopes in metallic form. However, a state which possesses a nuclear infrastructure and advanced scientific capabilities could effectively alter Co-60 from its metallic state to a particulate form and weaponize it to allow for a more effective dispersal in an ERDD.[224]

Third, a state would have a more advanced technical capability for coupling radioactive material with a delivery system such as a missile. The significance of this is two-fold. First, utilizing a missile as the delivery system for an ERDD allows the ERDD wielding state to disperse the harmful radiation without realizing any of the effects of the explosion due to the distance the missile would allow the ERDD to traverse. Second, it also allows for the controlled and verifiable coupling of dangerous radioisotopes with, in some cases, thousands of kilograms of explosives. The significance of this last point is that as the explosive payload of the weapon is increased, so is the effective dispersal radius or plume, which in turn, significantly multiplies the effects of the explosion.

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[224] This assertion was affirmed to the author by a credible scientific source who wishes to remain off the record.

Fourth, the significance of being able to utilize a more effective means of delivery could also signify the ability to develop a multiplicity of ERDD weapons. For example, coupling an ERDD with a missile delivery system would allow for a safe and repeated delivery mechanism. This means that any state wishing to do so, could pursue the development of ERDD weapons which would have the ability and means to create far more damage in the form of economic costs, territory denial, and psychological trauma, as well as the capability to do so repeatedly.

The significance of these four points is that they considerably alter the calculus behind the aforementioned ERDD scenarios. As was highlighted in the section of this paper on dispersal scenarios, a terrorist organization would be most likely to construct a weapon utilizing conventional explosives coupled with a few grams of source material to cause widespread contamination. The worst case economic scenario by PNNL was only based on a weapon utilizing 115 grams of Cesium-137, equivalent to a quarter pound of material. However, when considering the ability of a state, the outcomes of such a scenario must now be altered to account for the possibility of greater quantities of material, explosives, a more sophisticated means of delivery, and the possibility of repeated use. Therefore, this clearly indicates that a state could develop an ERDD with a far greater value than that of a terrorist.

At the same time, it is important to recognize that through our review of the history of these weapons that time and time again they have generally been found to be lacking as effective military tools in an offensive military campaign.[225] As Kelly and Levi so aptly denote, these weapons do not operate as weapons of mass destruction weapons, but as weapons of mass disruption. In a military conflict they would be unable to cause the type of immediate damage that would be necessary to affect a military victory. This appears to be the understood and accepted idea by most researchers and policy practitioners and I do not call that presumption into question.

Yet at the same time, recent focus on radiological weapons has shifted from their military efficacy to their use by non-state actors whose actions are more about creating terror and disruption, rather than destruction. Using that logic, researchers have shown repeatedly that there is a significant risk posed by such weapons and that the use of an ERDD would exact massive economic costs, related to the loss of essential territory and the need for relocation, quarantine, decontamination, destruction, and reclamation for any targeted state, not to mention the psychological impact. The scenario put forth by PNNL projected costs as high **$4.5 trillion**, which again was based on the one time explosion of a terrorist developed weapon.

Therefore, though a state may not be able to use radiological weapons as effective tools in a military campaign, they could pursue radiological weapons for the inherent threat they possess, particularly the economic threat, which for a state designed weapon, could range well beyond trillions of dollars. In this sense, a state could develop a radiological weapon or an arsenal of radiological weapons specifically to have the ability to pose this threat. “While RDDs may not be well suited as "military weapons" in the

[225] The military efficacy of such weapons was explored as recently as 1987 and have repeatedly been found wanting.

classic sense, the use of RDDs could be powerfully coercive and could trigger enormous political reactions within host countries or among allies in a coalition."[226] In addition, "these reactions could produce major strategic consequences."[227] In that sense, state actors could acquire radiological weapons for their deterrent value.

As noted by former Deputy Undersecretary of the U.S. Army Amoretta M. Hoeber, "deterrence can be more fully defined as the maintenance of such a posture that the opponent is not tempted to take any action which significantly impinges on his adversary's vital interests."[228] Threatening significant territory denial and massive economic losses to an opposing state would satisfy just that concept. Understanding the impact that such an arsenal of weapons could have, it is safe to assume that the threat of their use would be an extremely powerful tool for the possessor and would give any threatened adversary state considerable pause, quite possibly creating the "maintenance of such a posture that the opponent is not tempted to take any action." In a sense, the development of such weapons by a non-nuclear weapon wielding nation could serve as a "poor man's" nuclear deterrent against even a nuclear weapons state, with the idea not being ***mutually assured destruction***, but instead possibly ***mutually assured disruption***.

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[226] James L. Ford, "Radiological Dispersal Devices: Assessing the Transnational Threat," *Strategic Forum*, No. 136, (March 1998), March 29, 2012, http://www.au.af.mil/au/awc/awcgate/ndu/forum136.htm.
[227] James L. Ford, "Radiological Dispersal Devices: Assessing the Transnational Threat," *Strategic Forum*, No. 136, (March 1998), March 29, 2012, http://www.au.af.mil/au/awc/awcgate/ndu/forum136.htm.
[228] Amoretta M. Hoeber, "Strategic Stability," *Air University Review*, (July - August 1968), September 9, 2012, http://www.airpower.au.af.mil/airchronicles/aureview/1968/jul-aug/hoeber.html.

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