# MANIFESTATIONS OF POWER IN UNDERSTANDING THE RISKS OF NUCLEAR AND RADIOLOGICAL TERRORISM WITH REFLECTIONS FOR A POST-FUKUSHIMA JAPAN

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**Charles Ferguson**

**May 26, 2017**

## I. INTRODUCTION

In this essay, Charles Ferguson states "that dry cask storage for spent fuel has been shown to provide a safe and secure means of storage for at least a few decades based on real world experience. How long these casks will last is not clear, but perhaps for several decades to maybe a century. This could buy time while a longer-term solution is worked out."

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The views expressed in this report do not necessarily reflect the official policy or position of the Nautilus Institute. Readers should note that Nautilus seeks a diversity of views and opinions on significant topics in order to identify common ground.

Banner Image Credit: Mobile cesium irradiation sources, IAEA image

## II. SPECIAL REPORT BY CHARLES FERGUSON

## MANIFESTATIONS OF POWER IN UNDERSTANDING THE RISKS OF NUCLEAR AND RADIOLOGICAL TERRORISM WITH REFLECTIONS FOR A POST-FUKUSHIMA JAPAN

**May 26, 2017**

> Power
>
> Living in the earth-deposits of our history
>
> Today a backhoe divulged out of a crumbling flank of earth
>
> one bottle amber perfect a hundred-year-old
>
> cure for fever or melancholy a tonic
>
> for living on this earth in the winters of this climate
>
> Today I was reading about Marie Curie:

she must have known she suffered from radiation sickness

her body bombarded for years by the element

she had purified

It seems she denied to the end

the source of the cataracts on her eyes

the cracked and suppurating skin of her finger-ends

till she could no longer hold a test-tube or a pencil

She died a famous woman denying

her wounds

denying

her wounds came from the same source as her power

--Adrienne Rich from *The Dream of a Common Language: Poems, 1974-1977* (New York: Norton, 1993).

**Fundamentals about the Physical and Psychological Aspects of Nuclear and Radiological Terrorism**

Just over a hundred years ago in *fin de siècle* France, scientists discovered powerful energetic rays emanating from heavy atoms: uranium, thorium, radium, and polonium. Polonium (named after Marie Curie's homeland Poland) and radium (named after the property of radioactivity) are more energetically potent gram for gram than uranium itself. To many non-scientists, these nuclear scientists must have seemed god-like (or like a nuclear Dr. Victor Frankenstein) tapping into mysterious, microscopic worlds. Humans tend to have a natural fear of invisible, powerful substances.[1] We cannot see radioactive rays with our eyes and thus need special scientific instruments such as Geiger counters to measure the presence of radioactivity.

Because of the hidden nature of nuclear reality and the atavistic aversion of many people to radioactive substances, terrorists would appear to want to use radioactive materials to stimulate a psychological response in targeted audiences. Terrorism is after all largely about "theater" by creating a spectacle that will prod those in political power to pay attention to the terrorists and their political objectives.[2] But terrorists are people too; that is, they also tend to fear radioactivity and would be disinclined to handle potent radioactive materials. They would need to feel highly motivated to cross a psychological threshold before seeking to use nuclear and other radioactive materials in acts of terrorism. For various political and psychological reasons, most terrorist groups are not motivated to do that.[3] Those few that are would likely want to cause massive destruction by detonating a nuclear explosive in a densely populated city or massive disruption by dispersing radioactive (but non-nuclear explosive) materials over a populated area. But massive effects can result in massive responses by the politically and militarily powerful against the terrorist group and could thus backfire against the terrorists' political aims. Unless massive effects will advance a terrorist group's objectives, the group will likely remain opposed to nuclear and radiological terrorism.

Many terrorist groups are also risk-averse when choosing their tactics and would want a high likelihood of success in an attack; consequently, they would not venture toward nuclear and radiological terrorism if these methods appeared to increase the probability of failure.  This rationale could explain (at least partially) why there have not been nuclear terrorist attacks and even why there have been few instances of non-state actors acquiring radioactive materials for potential malicious acts.

During the time period of the first discoveries of radioactivity, terrorism was a means used by anarchists to try to achieve their political goals. Having started in the late 19th century, the anarchist movement was fueled by growing disgruntlement of the huge economic disparity between the working class and the bourgeois. Anarchists believed that government was a major source of this problem, and thus they mostly targeted political leaders. But some anarchists believed that violent attacks against the larger populace of the bourgeois were needed to further their cause by "the propaganda of the deed."

These anarchists had at hand a relatively newly invented explosive: dynamite. In 1866, Alfred Nobel invented dynamite, a compact, portable, highly energetic explosive that found ready use in civilian and military applications. (Nobel had his estate endow a set of prizes in his name; while in late 1945 after the first atomic bombs were detonated, Albert Einstein expressed his belief that the Nobel Peace Prize was established in Nobel's will in order to "atone for [Nobel's] accomplishments" in weapons technologies, it is unclear based on Nobel's own writings whether he believed that, but he did mention his hope for a type of deterrence in that "on the day that two army corps can mutually annihilate each other in a second, all civilized nations will surely recoil with horror and disband their troops."[4] That day has yet to come.) The notorious German anarchist Johann Most reveled, "It is within the power of dynamite to destroy the capitalist regime just as it had been within the power of gunpowder and the rifle to wipe feudalism from the face of the earth. A girdle of dynamite encircles the world."[5] He fomented rebellion among many downtrodden workers and encouraged those with access to dynamite to steal and detonate it against their oppressors.

Not far from where Marie and Pierre Curie would perform their revolutionary scientific experiments in the late 1890s and early 1900s, Emile Henry, an anarchist and an accountant who was the son of a disaffected engineer, detonated on February 12, 1894, a bomb in Café Terminus in the Parisian Gare Saint-Lazare killing one person and wounding twenty people. Henry said that he wished that he had had a bomb big enough to blow up the whole of Paris.[6] Thus, the desire for massive destruction among certain terrorists is not a new phenomenon. About 45 years after that crude bombing, nuclear scientists in Europe would discover fission of uranium in which the heavy uranium nucleus was split into two medium mass parts and release considerable energy (about ten million times greater than a typical chemical reaction between two atoms). This discovery soon paved the way for the creation of the atomic bomb that showed that one bomb could blow up the core of a city. The scientific research preceding that development would also lead toward production of the radioactive substances such as radium that offer benefits as well as pose risks to humanity.

Working outside the realm of politics, the Curies labored like Hercules to move many tons of uranium ore to extract even one gram of radium. Radium seemed like a gift from a modern-day Prometheus and would soon find a variety of applications that people would today find strange such as in tonics and luminous watch dials. But like Prometheus' fire stolen from the gods, radium was a double-edged sword. As the poem by Adrienne Rich mentions, Marie Curie suffered from the ravages of radiation sickness. (Many of the young women who painted radium-laced paint on watch dials developed cancer.)

Also as Rich alludes, radioactivity bestowed intellectual and technological power on Marie Curie and others laboring in that field of knowledge. For instance, J. Robert Oppenheimer, the Scientific Director of the Manhattan Project, was called upon to advise the government in many aspects of nuclear energy and weapons after the war until his security clearance was revoked in 1954. In the spring of 1946 in a closed congressional hearing, Oppenheimer was asked whether a few men could smuggle in atomic bombs to New York. He said, "Of course it could be done, and people could destroy New York." When an anxious senator asked how this smuggling could be detected, Oppenheimer quipped, "With a screwdriver." This is because the radioactive signature of the uranium or plutonium in the nuclear weapons would likely not be strong enough to signal radiation detectors and that each and every container would have to be opened by screwdrivers.[7] Thus, from the start of the nuclear weapons age, at least one scientific leader knew that the United States and other countries were vulnerable to clandestine nuclear attack and knew that radiation detectors are not to be counted on to defend against this threat.

Oppenheimer was also the lead writer for the Acheson-Lilienthal Report of spring 1946 that warned that a system of national controls or safeguards was not sufficient to guard against proliferation of nuclear weapons. Here again, Oppenheimer was prescient and believed that an international regime was needed. International cooperation is certainly essential to reduce the risks of nuclear and radiological terrorism.

Despite these nuclear dangers, Oppenheimer and numerous nuclear scientists favored the flourishing of the peaceful use of nuclear technologies. In addition to applications for commercial and scientific nuclear reactors, more and more uses for radioactive sources were developed after the Second World War. Commercial radioactive sources for beneficial applications included medical diagnostics, cancer treatment, blood irradiation, oil-exploration, industrial radiography, and remote sources of electrical generation, to name some prominent uses. Radium-226 was a workhorse, naturally occurring radioisotope for several decades until replaced by many other radioisotopes produced by nuclear reactors and particle accelerators after the war.

Different isotopes of an element have the same number of protons (which determine the chemical properties of the element) but different numbers of neutrons (which change the nuclear properties of the element). For example, H-1 (the most abundant isotope of hydrogen) has one proton and is the most common isotope of hydrogen; H-2 (deuterium) has one proton and one neutron and does not experience radioactive decay but has a greater likelihood to undergo nuclear fusion than H-1; H-3 (tritium) has one proton and two neutrons and does decay with a decay half-life of about 12 years for one half of a sample of H-3 to decay to helium-3.

Knowing the half-life of a radioisotope, one can determine whether the radioactive material is something that can pose a significant harm to human health. Think of the half-life as determining the setting on a valve connecting a pipe to a vat of radioactivity. The vat represents the radioactivity latent in the nuclei of the sample of the radioisotope. If the half-life is short (say microseconds to a few days), the setting on the valve is nearly fully open, and the radioactivity is released in a relatively short period of time. These substances if dispersed into a populated area will decay relatively quickly and will not pose a major threat to human health if people are kept away from the contaminated area for a relatively brief period of time. If the half-life is long (say hundreds to billions of years), the valve is nearly closed, and the radioactivity is released slowly in a trickle. Intermediate half-lives (say a week to about a few hundred years) indicate that all or almost the entire radioactivity in that sample of radioisotope will be released within a typical human lifetime.[8]

More than 3,000 different isotopes can exist in the universe, but most of them have very short half-lives; about 900 isotopes are stable or have half-lives longer than 60 minutes. Only a few dozen radioisotopes have half-lives in the intermediate range of several days to several hundred years. Of those, only about ten are used prevalently in commercial applications. Consequently, in terms of concerns about radiological dispersal devices or so-called “dirty bombs” or releases of radioisotopes resulting from sabotage of or accidents at nuclear facilities, the radioisotopes of half-lives ranging from about eight days (iodine-131) to radium-226 (1600 years) are at the top of the list of greatest potential for harm to human health. If these materials cannot be adequately cleaned up after a dispersal, the contaminated area may have to be isolated for several years to perhaps decades depending on the level of radiation in this zone. A later section on the definition of radiological terrorism provides two tables of several radioisotopes of security concern, their properties, and commercial radioactive sources that use these radioisotopes.

**Defining Nuclear and Radiological Terrorism**

***Two Types of Nuclear Terrorism***

Nuclear and radiological terrorism can be classified in four categories: two types of nuclear terrorism and two types of radiological terrorism.[9] The two types of nuclear terrorism involve acquisition and then likely detonation of one or more nuclear explosives. Because nuclear explosives are a million times or more energetic than conventional explosives on a per mass basis, nuclear terrorist acts that result in a nuclear explosive yield are many orders of magnitude more devastating than conventional acts of terrorism or even radiological terrorism that involves dispersal of radioactive materials through non-nuclear explosive dispersal methods. Nonetheless, acts of radiological terrorism could be considered in the minds of members of the public as acts of nuclear terrorism or might be portrayed as such by the news media.

First, a terrorist group or non-state actors could obtain an intact nuclear weapon from a nuclear-armed state’s arsenal. There are approximately 15,700 nuclear warheads in nine states with Russia and the Unites States having about 90 percent or more of the total warheads.[10] A terrorist group or non-state actor could steal or be given a warhead through a gift or purchase from the controlling government or state-level custodian. A government might want to perpetrate a nuclear attack against an enemy by giving one or more nuclear weapons to non-state actors who will carry out the attack. A motivation of the government would be to deny that it is the source of the weapon while wreaking massive damage on an enemy. This is highly risky. If that government is discovered as the source, it could be subject to retributive attack. Also, it runs the risk of having the non-state actors use the weapon or weapons against the provider or other targets not approved by the provider. In the case of Japan, one can imagine that in an extremis circumstance in which the North Korean government wants to initiate a nuclear attack against Japan, it could give North Korean controlled-agents such as commandos or even non-state actors with little affiliation to North Korea a nuclear weapon to detonate on Japanese soil. To convince the non-state actors to do the deed, the North Korean government could pay the loosely affiliated non-state actors a considerable amount of money to carry out this deadly and risky act.

Security experts generally assess that the acquisition of an intact nuclear weapon by a non-state actor is highly unlikely because nation-states would tend to ensure that they have strong physical security and strong personnel access controls over these weapons that have cost a state considerable effort and national resources to make. Nonetheless, nuclear weapons have at times been outside of firm accountability by even very experienced nuclear-weapon states. For example, on August 30, 2007, six nuclear-armed cruise missiles were inadvertently loaded onto a strategic bomber and flown across the United States.[11]

The second type of nuclear terrorism involves manufacture of an “improvised nuclear device,” a crude (but still potentially devastating) nuclear explosive. Non-state actors would need adequate amounts of fissile material and enough technical skills to make such a device. Acquiring the fissile material is the most challenging step. Fissile means that the material has a relatively high probability of undergoing fission when neutrons interact with that material's nuclei.

The fissile material would be either highly enriched uranium (HEU) or plutonium. HEU is defined as uranium with 20 percent or greater concentration of the fissile isotope uranium-235, which has 92 protons plus 143 neutrons in its nucleus for a total atomic mass of 235. The greater the concentration of uranium-235, the less material is needed for making a critical mass. Weapons-grade uranium is typically 90 percent or greater in the concentration of uranium-235. Uranium-233 is also fissile, but it tends to be a lesser security concern than uranium-235 because there are relatively large stockpiles of HEU in various nations and comparatively little stockpiled uranium-233. HEU can be found in nuclear weapon arsenals (in nine countries), naval nuclear propulsion programs (in four countries), and civilian applications (in about a dozen countries). The International Panel on Fissile Materials has the most up-to-date unofficial estimates of these stockpiles in its reports.[12] Worldwide, there are about 1,350 metric tons (1,350,000 kilograms) of HEU in various stockpiles: approximately 936 metric tons for weapons purposes, 290 metric tons for naval propulsion, 57 metric tons declared as excess to military purposes, and 61 metric tons for civilian applications such as research reactors and isotope production reactors.[13] It is noteworthy that there is significant uncertainty in the military HEU stockpile (mostly due to lack of accurate accounting of the Russian HEU) and that the vast majority of the HEU is dedicated to military purposes either for weapons or naval propulsion.

An improvised nuclear device would need about 40 kilograms of weapons-grade HEU for a first-generation gun-type device and about 25 kilograms of weapons-grade HEU for a first-generation implosion-type device. A gun-type device consists essentially of two subcritical pieces of HEU at two ends of a metallic tube. To ignite the bomb, one piece of HEU is fired with conventional explosives into the other piece to quickly form a supercritical mass of HEU. A burst of neutrons can be used to trigger the nuclear explosion once this mass is formed. It takes a few milliseconds for the two subcritical pieces to be assembled into the supercritical mass, which once triggered detonates in mere microseconds. This type of bomb was detonated over Hiroshima on August 6, 1945, and had an explosive yield equivalent to about 13,000 tons of TNT. It used an average uranium enrichment of about 80 percent of uranium-235.

The "Nagasaki bomb" was based on the principle of implosion in which a sphere of fissile material was squeezed rapidly and smoothly by a spherical shock wave created by detonating layers of conventional explosives. The implosive shock wave increases the density of the fissile material and thus results in a supercritical dense-state of fissile material that can be triggered by a burst of neutrons. While about 25 kilograms of HEU is needed for a first-generation implosion design, more sophisticated designs that use effective neutron reflecting material such as beryllium and use levitated spherical pits of fissile material can reduce the required amount of fissile material by a factor of two or more. The Nagasaki bomb actually used plutonium for the fissile material and had an explosive yield equivalent to about 20,000 tons of TNT. Because plutonium is a more efficient fissile material than HEU, only six kilograms were used.

An improvised nuclear *implosion* device would pose significant technical challenges for non-state actors because of the technical complexity of this design as compared to the gun-type device, and thus security experts tend to agree that the gun-type device presents the greatest nuclear terrorist concern. Consequently, most security experts have emphasized that the security focus should give top priority to HEU. However, plutonium in a gun-type device could result in a low explosive yield and substantial dispersal of radioactive materials.[14] Therefore, plutonium needs to have high security to prevent non-state actors from acquiring it.

Weapons-grade plutonium typically has at least 90 percent concentration of plutonium-239 while minimizing the proportions from the non-plutonium-239 isotopes, which in higher proportions would complicate the manufacture of a nuclear weapon. However, it is very important to underscore that so-called reactor-grade plutonium is also weapons-usable, as officially stated by the U.S. Department of Energy.[15] According to former nuclear weapon designer Richard Garwin, it is wrong to rule out the use of a plutonium (Pu) mixture that has less than 85 percent fissile content. His calculations show that even a fissile content of about 66 percent is weapon-usable and has a "bare" critical mass of about 13 kilograms as compared to about 10 kilograms bare critical mass for weapons-grade plutonium (Bare means a sphere of this material by itself in a vacuum without being surrounded by a neutron reflector that would reduce the critical mass). He outlines in a 1998 article the relatively simple engineering steps that would be needed to be able to use reactor-grade plutonium of 66 percent or greater fissile content. He also points out that Pu-240 would add to the fissile yield because high-energy neutrons, produced during the fission of Pu-239 and Pu-241, can fission Pu-240. Thus, he argues that the explosive yield of a reactor-grade plutonium bomb would be comparable to a weapons-grade plutonium bomb because of approximately the same number of fissions in each bomb, assuming similar number of critical masses.[16] Moreover, there should be no doubt because the United States demonstrated via a nuclear test during the Cold War that reactor-grade plutonium is usable in nuclear explosives and will produce powerful nuclear yields.[17] Also, it is believed that India demonstrated during its May 1998 tests that it used reactor-grade plutonium. The Indian pressurized heavy water reactors were the likely source of that fissile material for at least one of the tests.[18]

But reactor-grade plutonium is only a potential security concern for nuclear terrorism when it has been chemically separated from highly radioactive fission products in spent (or irradiated) nuclear fuel. These fission products form a protective barrier around the plutonium. A thief would suffer from acute radiation sickness and most likely death if he were exposed to unshielded fission products in spent fuel at a short distance of about a meter. Not until a state with the right type of facility known as a reprocessing plant has safely removed the plutonium from fission products would there be the potential for theft or diversion of the plutonium.

According to the IPFM's 2015 report, the world has about 500 metric tons of separated plutonium with approximately 142 tons set aside for military purposes, 89 tons of previous military plutonium as declared excess for those purposes and slated for disposition, and 267 tons in the civilian sector. Notably, presently the civilian sector has more plutonium than the military sector; this is unlike the situation with HEU. This excess of civilian plutonium has come about because certain countries such as France, Japan, and Russia have policies to recycle plutonium as fuel, but the rate of consumption has been significantly less than the rate of production. Consequently, civilian plutonium stockpiles have been rising. As a result of its policy on reuse of plutonium but its experiencing roadblocks to consume plutonium as recycled fuel, Japan has accumulated more than 47 metric tons of reactor-grade plutonium with 36.3 metric tons in France and the United Kingdom (coming from reprocessing for Japan performed in those countries but not yet having shipped back the plutonium to Japan) and 10.8 metric tons residing in Japan.

Non-state groups would not have the requisite resources to enrich their own uranium or produce their own plutonium. Enrichment requires a facility that could cost at least tens of millions of dollars, highly specialized equipment, and a team of technically trained engineers. Plutonium production requires a nuclear reactor of a power rating of about 20 Megawatts thermal power in order to make a weapon's worth of plutonium annually and a reprocessing facility. These are expensive and highly specialized items. Thus, non-state actors would have to acquire fissile material from already existing stockpiles.

Civilian stockpiles of both HEU and plutonium are usually considered more vulnerable to theft or diversion because of the typically rigorous security culture present in militaries. This is not to imply that militaries do not have security vulnerabilities or that nuclear material produced for military purposes has not gone unaccounted for; a recent book published by the Nonproliferation Policy Education Center recounts several concerns with missing or unaccounted for fissile material in both military and civilian nuclear programs.[19]

There is considerable good news in reducing the threat from nuclear terrorism. Since the late 1990s, several hundred metric tons of HEU have been eliminated through a process termed down-blending to make low enriched uranium for reactors' fuel. In particular, the Megatons-to-Megawatts Program down-blended 500 metric tons of Russian weapons-origin uranium, and the United States has down-blended about 160 metric tons of its HEU that was deemed excess to weapons purposes. Through the U.S. National Nuclear Security Administration working in cooperation with several countries, HEU has been substantially reduced or entirely removed from at least two-dozen nations in the past two decades. Much of that material was returned or repatriated to the United States and Russia, which had supplied the HEU to client states. In parallel, dozens of HEU-using research and isotope production reactors have been shut down or converted to use low enriched uranium. Civilian HEU has been the primary focus of the Nuclear Security Summits (NSS), which began in spring 2010 in Washington, DC. While the summits have also encouraged participating nations to also improve the security of radioactive sources, the NSS leadership has been careful in its discussion of military HEU and plutonium due to the political sensitivities of certain governments and the choice from the start of the NSS process to emphasize the common threat of nuclear terrorism and not the more controversial issue of nuclear disarmament. Even reactor-grade plutonium has been a sensitive political issue in the NSS process. Certain governments are concerned that too much emphasis on potential security vulnerabilities of this material could complicate domestic political and economic interests that want to keep continuing reprocessing programs.

As part of the NSS process, Japan in 2014 committed to send to the United States hundreds of kilograms of weapons-grade uranium and plutonium it had acquired decades ago from the United States and the United Kingdom. The fissile material had been used at the Fast Critical Assembly of the Japan Atomic Energy Research Institute in Tokai-mura. According to the communiqué issued by Japan and the United States, the removal of the material will "help prevent unauthorized actors, criminals, or terrorists from acquiring such materials. This material, once securely transported to the United States, will be sent to a secure facility and fully converted into less sensitive forms." This was the largest commitment in terms of amount of material so far in the NSS process for securing fissile material. Japan should be highly commended for this commitment; however, it took many years for the seriousness of the security vulnerability to be recognized in Japan; many U.S. observers of that facility had noted that guards appeared unarmed and that the overall security seemed light.[20] Globally, much more remains to be done to secure HEU and plutonium. For a detailed agenda of what remains to be accomplished in ending the use of civilian HEU, please read the paper by Miles Pomper and Philippe Mauger.[21]

Returning to the question of whether certain non-state actors or terrorist groups would want nuclear explosives, notably, the possession of nuclear weapons bestows political and military power. A terrorist group that has aspirations to form a nation-state (or a caliphate, for example) would thus be inclined to acquire these weapons. The group might not want to detonate the weapons if the group's leadership perceives the weapons' value from the perspective of deterrence. A detonation of a weapon, however, might be deemed necessary by the group's leadership to demonstrate the capability. The detonation site would be carefully chosen for optimal political effect. If the group can convincingly show (or at least raise the potential) that it has more than one nuclear weapon, it can leverage this capability to instill tremendous fear and panic.

### *Two Types of Radiological Terrorism*

First, radioactive materials could be dispersed by a variety of methods. The popular conception is a so-called dirty bomb that would couple a conventional explosive such as dynamite to a radioactive substance. The more technical term is a radiological dispersal device (RDD). (Table 1 shows many of the radioisotopes of security concern that could fuel potent RDDs.) While the explosion would attract attention and likely do damage to people and property, this might not be an effective means to spread radioactive substances, but it might suit the purposes of the non-state actors if their intention is primarily to create a disruptive spectacle. Dispersal might not be necessary to achieve the aims of the perpetrators; that is, they might want to place a radiation source in a public place such as a train station or stadium or just put the source in one location so as to target a particular person.

But dispersal methods are a main concern of authorities' wanting to prevent massive disruption. Depending on the chemical properties of the radioactive substance, just letting winds blow on it might be an inexpensive but relatively effective dispersal method. For example, many security experts, in general, and the U.S. National Research Council, in particular, have called attention to cesium chloride, which has a talcum powder-like form and thus subject to relatively easy dispersal.[22] This substance is used in several different commercial radioactive sources. See Table 2 for a list of commercial radioactive sources and their typical radioactivity content. Category 1 sources are considered based on human health consequences to be more of a concern than category 2, which is a greater concern than category 3 sources.

The types of radiation emitted affect whether the radioisotope would be considered an internal or external human health hazard. A radioactive substance would pose an internal-to-the-body hazard only when it is ingested or inhaled and would stay resident long enough in the body to result in substantial damage to cells, tissues, organs, or bones. For example, alpha emitting substances release charged helium nuclei (which are known as alpha particles), which are stopped by the dead outer layer of skin and thus would not be an external health hazard and would only be a health concern if ingested or inhaled. Beta emitting radioisotopes emit fast moving electrons or sometimes positrons that would pose potential harm to soft tissues such as eyes when external to the body but otherwise would mostly be considered an internal health hazard. Gamma emitting substances release gamma rays, which are high-energy light particles and are highly penetrating; consequently, they are both internal and external health hazards.

| **Radioisotope** | **Half-life** | **Specific Activity GBq/g (Ci/g)** | **High Energy Alpha Emissions** | **High Energy Beta Emissions** | **High Energy Gamma Emissions** |
|---|---|---|---|---|---|
| Americium-241 (Am-241) | 433 years | 125.8 (3.4) | Yes | No | Low energy |
| Californium-252 (Cf-252) | 2.7 years | 19,832 (536) | Yes | No | Low energy |
| Plutonium-238 (Pu-238) | 88 years | 636.4 (17.2) | Yes | No | Low energy |
| Radium-226 (Ra-226) | 1,600 years | 37 (1) | Yes | No | Low energy |
| Cesium-137 (Cs-137) [Barium-137m (Ba-137m)] | 30 years [2.6 min] | 3,256 [19,980 million] (88 [540 million]) | N/A | Low energy [Low energy] | N/A [Yes] |

| | | | | | |
|---|---|---|---|---|---|
| Cobalt-60 (Co-60) | 5.3 years | 40,700 (1,100) | N/A | Low energy | Yes |
| Iridium-192 (Ir-192) | 74 days | >16,650 (>450) std >37,000 (>1,000) high | N/A | Yes | Yes |
| Strontium-90 (Sr-90) [Yttrium-90 (Y-90)] | 29 years [64 hours] | 5,180 [20.35 million] (140 [550,000]) | N/A | Yes [Yes] | N/A [Low energy] |

**Table 1: Radioisotopes of Security Concern**

An RDD is considered a weapon of mass disruption in that it is not expected to cause massive deaths to people (at least over the near term) or even massive blast damage. But for the worst-case plausible scenarios, an RDD could result in significant radioactive contamination that would disrupt people's lives and livelihoods, likely meaning mass evacuations for a period of time depending on the chemical and radioactive properties and the amounts of the material needing to be cleaned up. For example, cesium-137 has a 30-year half-life and has chemical properties that give it an affinity to bind to concrete and building materials; thus, a highly contaminated zone with cesium-137 might require isolation for decades if the decontamination were not successful.

| **Type of Source or Application** | **Radioisotope** | **Typical Radioactivity Level GBq (Ci)** | **Source Categorization** |
|---|---|---|---|
| Sterilization and food irradiation | Cobalt-60 | 148 million (Up to 4 million) | 1 |
| | Cesium-137 | 111 million (Up to 3 million) | |
| Radioisotope thermoelectric generator (RTG) | Strontium-90 | 740,000 (20,000) | 1 |
| | Plutonium-238 | 10,360 (280) | |
| Research and blood irradiators | Cobalt-60 | 88,800-925,000 (2,400-25,000) | 1 |
| | Cesium-137 | 259,000-555,000 (7,000-15,000) | |
| Single-beam teletherapy | Cobalt-60 | 148,000 (4,000) | 1 |
| | Cesium-137 | 18,500 (500) | |
| Multi-beam teletherapy (gamma knife, e.g.) | Cobalt-60 | 259,000 (7,000) | 1 |
| Industrial radiography | Cobalt-60 | 2,220 (60) | 2 |
| | Iridium-192 | 3,700 (100) | |

| | | | |
|---|---|---|---|
| High- and medium-dose brachytherapy | Cobalt-60 | 370 (10) | 2 |
| | Cesium-137 | 111 (3) | |
| | Iridium-192 | 222 (6) | |
| Well logging | Cesium-137 | 0.74-74 (0.02-2) | 3 |
| | Americium-241/Beryllium | 0.74-74 (0.02-2) | |
| | Californium-252 (rare use) | 37 (1) | |
| Level and conveyor gauges | Cobalt-60 | 0.74-74 (0.02-2) | 3 |
| | Cesium-137 | 0.74-74 (0.02-2) | |

Table 2: High-Risk Radioactive Sources[23]

The good news is that many nations have acted to reduce the risk of this type of radiological terrorism. More than 100 countries have pledged to uphold the safety and security guidelines for radioactive sources that the International Atomic Energy Agency has published. The U.S. government has cooperated with dozens of other governments and companies around the world to round up orphaned or disused potent radioactive sources and has applied stronger security measures at hundreds of facilities that still use such sources. The U.S. Nuclear Regulatory Commission (NRC) has promulgated enhanced rules including requiring personnel background checks for users of the higher category sources in the United States. The Group of Eight industrialized nations in 2003 pledged to tighten security on and export controls for these sources; many of the nations that are major producers of these sources belong to this group. (Russia was booted out of the G8 in 2014 but is still a major producer of radioactive sources.) Despite the enhanced security efforts, much more work needs to be done given the thousands of higher risk commercial radioactive sources still used worldwide.

However, if alternative technologies such as X-ray irradiation generated by electrical power can substitute for or replace radioactive sources, then the risk can be reduced to zero in the applications where the substitution technology has been put in place. For example, in Japan, Hitachi Medical has been a leader for more than 20 years in developing and selling X-ray technology to irradiate blood. Most countries use radioactive sources such as cesium chloride in blood irradiators to treat blood before it is transfused. Depending on the type of blood from the donor, transfusion recipients can develop a disease called Graft Versus Host Disease (GVHD). Irradiation of the blood can prevent GVHD. In the early 1990s, Japan enacted the policy to irradiate all blood because of a few cases in which untreated blood caused GVHD. Hitachi Medical saw this as a commercial opportunity and decided to invest in making high quality irradiators that did not use radioactive sources. This decision was influenced by Japanese people’s aversion to radioactive materials and by not wanting to be dependent on outside suppliers for radioactive sources. The X-ray irradiator operates on stable electricity generation, which Japan and other developed countries have. Japan’s path breaking commercial work in this area could lead the way for other countries to adopt this alternative technology and others like it in order to reduce the demand for and prevalence of higher risk radioactive sources.

The second type of radiological terrorism involves attacks on or sabotage of nuclear facilities such as nuclear power plants, radioactive waste storage sites, and reprocessing plants. While many attackers or saboteurs would likely want to cause release of radiation or dispersal of radioactive substances from these facilities, their motivations can focus on less destructive objectives. For example, anti-nuclear activists who are attracted to an extreme form of protest might want to draw attention through a mock attack to the security vulnerabilities of nuclear power plants in order to undermine public acceptance of nuclear power. The prime security concern, though, is that a group exploits vulnerabilities for the purposes of causing substantial damage to the facilities and releasing radioactive materials to the environment.

A major concern is a prolonged loss (typically more than one day) of electrical power at a nuclear power plant. If a nuclear plant does not have power to run coolant pumps, the reactor's core can heat up to high enough temperatures to melt the fuel and result in hydrogen gas generation that could lead to a non-nuclear explosion that can further damage the plant and provide pathways for radioactive materials to be released to the environment. In a normal shutdown, the plant would have back up sources of power such as emergency diesel generators and batteries even in the event of a loss of offsite electrical power. Decades prior to the March 2011 nuclear reactor meltdowns at Fukushima Daiichi, concerns were raised about the potential vulnerability of nuclear plants to prolonged loss of electrical power. (Indeed, in 1975, the WASH-1400 Reactor Safety Study "indicated that station blackout (SBO) could be an important contributor to the total risk from nuclear power plant accidents."[24]) In particular, soon after the 9/11 terrorist attacks, the NRC promulgated enhanced B.5.b accident mitigation rules that ordered power plant operators to take the necessary measures to ensure that their plants can withstand prolonged loss of electrical power from various causes such as terrorist attacks, fires, flooding, etc. The NRC's focus was assuredly on the potential for terrorist attacks, but the rules were written to take into account other extraordinary but still plausible events. The Japanese nuclear regulatory authorities knew about the NRC's enhanced B.5.b rules, but these were not implemented across Japanese nuclear power plants. Analyzing why is beyond the scope of this paper, but views are readily available from Japanese researchers.[25] As is well known, the tsunami waves generated by the extremely powerful earthquake on March 11, 2011, flooded the emergency diesel generators at the Fukushima Daiichi reactors. The batteries did not have sufficient electrical storage before offsite electrical power could be restored. The extensive damage from the earthquake and tsunami tremendously complicated efforts to restore power before the sequence of reactor meltdowns.

While the major problems at Fukushima Daiichi were nuclear reactors' experiencing meltdowns with the subsequent release of radioactive materials to the environment, another major concern was the potential for the pools of water containing spent nuclear fuel to drain and then loss of the capacity to keep the spent fuel cool. If the spent fuel were to heat up to high enough temperatures, radioactive materials could have been further released to the environment.[26] Fortunately, the spent fuel pools did not drain and uncover the spent fuel although during the first week of the tragedy there were concerns (especially among some people at the NRC) about the pool at reactor unit 3.

A recent report by Peter Hayes underscores the continuing concerns and risks of spent fuel management in Japan and discusses the "multiple constraints that work against open enquiry and policy change" among them being the "ongoing impact on civil society arising from the [Fukushima] event itself" and most important the continuing impasse in reconstituting or revising "the fundamental political deal between the state, the nuclear utilities, and local host communities" for the spent fuel and associated radioactive waste as well as plutonium slated for recycling.[27] Hayes' further assesses the complex set of political, societal, economic, technical, and security questions Japan needs to reconcile especially concerning the policy to return to recycling plutonium as mixed oxide (MOX) fuel once MOX-certified reactors are restarted. His analysis brings us back to the threat of genuine nuclear terrorism involving fissile material and connects this threat to the radiological terrorism threat of potentially vulnerable spent fuel stored outside of strong storage casks.

This present paper does not offer any definite solutions to this set of issues, but it will close by reminding readers that dry cask storage for spent fuel has been shown to provide a safe and secure means of storage for at least a few decades based on real world experience. How long these casks will last is not clear, but perhaps for several decades to maybe a century. This could buy time while a longer-term solution is worked out. Notably, the tsunami waves struck the dry storage casks at Fukushima Daiichi (one of the few places where these casks have been used in Japan) and were unscathed. News reports in 2014 stated that the Japanese government plans to encourage utilities to expand use of dry cask storage.[28]

## III. ENDNOTES


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[24] http://www.nrc.gov/reading-rm/doc-collections/commission/slides/2011/20110428/staff-slides-20110428.pdf

[25] See, for example, *The Fukushima Nuclear Accident and Crisis Management: Lessons for Japan-U.S. Alliance Cooperation* (Tokyo: The Sasakawa Peace Foundation, September 2012), which examines starting on page 78 the different threat perceptions between Japan and the United States and discusses on page 79, "As a result, even when senior officials in the safety division at the NISA were informed that the United States had issued the B5b order for the purpose of counterterrorism, they did not recognize that such measures were relevant to their own work. Additionally, due to a general perception that the risk of terrorist attacks like 9/11 occurring in Japan is low, one can assume that the NISA failed to consider this when conveying information to the divisions that are in charge of acts of sabotage against nuclear facilities."

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