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Radiological Exposure Devices (RED) Technical Basis for Threat Profile

Jesse Bland

Charles "Gus" Potter

Sandia National Laboratories

Steven Homann

Lawrence Livermore National Laboratory

Sandia National Laboratories

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Jesse Bland
Charles "Gus" Potter
Sandia National Laboratories

Steven Homann
Lawrence Livermore National Laboratory

Sandia National Laboratories
P. O. Box 5800
Albuquerque, New Mexico 87185-MS1371

Abstract

Facilities that manufacture, store or transport significant quantities of radiological material must protect against the risk posed by sabotage events. Much of the analysis of this type of event has been focused on the threat from a radiological dispersion device (RDD) or "*dirty bomb*" scenario, in which a malicious assailant would, by explosives or other means, loft a significant quantity of radioactive material into a plume that would expose and contaminate people and property. Although the consequences in cost and psychological terror would be severe, no intentional RDD terrorism events are on record. Conversely, incidents in which a victim or victims were maliciously exposed to a Radiological Exposure Device (RED), without dispersal of radioactive material, are well documented. This paper represents a technical basis for the threat profile related to the risk of nefarious use of an RED, including assailant and material characterization. Radioactive materials of concern are detailed in Appendix A.

TABLE OF CONTENTS

NOMENCLATURE

Abbreviation	Definition
Abbreviation	Definition
ARS	Acute Radiation Syndrome
Gy	Gray
IND	Improvised Nuclear Device
Kerma	kinetic energy released per unit mass
rad	Radiation Absorbed Dose
RGD	Radiation Generating Device
RDD	Radiological Dispersal Device
RED	Radiological Exposure Device
RPD	Radiological Poisoning Device

1. THREAT PROFILE

An assailant who intends to use an RED for the malicious, harmful exposure of others to ionizing radiation would have the following attributes:

1.1. Access to radiological material

Access is defined as follows:

1) The ability to move radiological material from secure storage to a location where it would remain undetected for a duration sufficient to cause severe deterministic health effects which are fatal or life threatening or result in a permanent injury. It should also be assumed that the assailant would act to prevent detection of the material theft during the duration of the exposure event, as detection could alert authorities, draw attention to everyone with access to the material, and potentially interrupt the event; and
2) the ability to move radiological material without exposing the assailant to radiation sufficient to cause marked physical harm. Because the RED is difficult to detect, it would seem that the actor wants to complete the exposure event anonymously and without sustaining personal injury.

1.2. Targeting of a single victim or group of victims and Terrorism

It is likely that the RED threat is a criminal assault or murder perpetrated by an individual who is known to the victim and not a terrorist act. The likelihood of unintended exposure of others nearby is high, but since ionizing radiation exposure is in inverse proportion to the square of the distance from the source, victims not in proximity of the material would not receive significant dose unless the source of radiation is of extremely high activity.

A terrorist planting a highly radioactive item in a public place with the intent of violence towards a general population would need to ensure that the victims stay in the immediate vicinity of the item for a duration sufficient to cause deterministic effects. If the terrorist were able to achieve this, there would be no certainty that medical response personnel would identify an RED as the source of the symptoms or, if identified, the public would become aware of the incident.

Although this type of attack, if publicized, would intimidate the civilian population, a terrorist in possession of a quantity of radiological material sufficient to deliver a lethal dose would cause much more disruption, cost, and fear by using an explosive or other means to disperse material (RDD). Terrorists intend to commit violent acts to intimidate or coerce the civilian population, influence the policy and/or actions of the government and to affect the conduct of government (U.S. Department of Energy, 2016). The terrorist would seek the greatest possible visibility and impact to meet this goal. Therefore, it is reasonable to assume that use of an RED as a tool for terror is unlikely, as a terrorist would be more likely to create a dispersion event with radiological material.

1.3. Knowledge regarding the biological effects of radiation

An assailant determined to cause harm by means of an RED could have at least rudimentary knowledge of the biological effects of ionizing radiation exposure. Some concept of activity and duration of exposure is needed to harm another as well as knowledge specific to the physical material characteristics of the radionuclide or set of radionuclides used. The more versed the assailant is in the principles of health physics, the more efficacious the attack.

1.4. Poisoning

Heuristics indicate that a credible pathway for malicious exposure is the ingestion or injection of radiological materials, especially high specific-activity alpha-emitting radionuclides. Several prominent case studies validate the efficacy of the poisoning scenario, including that of Alexander Litvinenko. A poisoning scenario could affect an individual or group but would be unlikely to affect a significant population as the amount of material required for a mass poisoning would be extremely difficult to obtain and deploy.

It is worth noting that an attempt to contaminate a public water supply or food source with a radiological material could result in mass panic if the population became aware of the threat. This could have catastrophic effects on local medical and emergency management infrastructure, even without significant health effects from the direct act. Dilution is a critical factor in the likelihood of deterministic effects from poisoning of a water supply or food source. If a water supply or food source were poisoned, the target or targets would have to ingest a significant quantity near the source of the poisoning before dilution rendered the radioactive material benign.

1.5. Radiation Generating Device (RGD)

There is no historical record of the malicious use of RGDs in an exposure event. As technology advances, the miniaturization and output of these devices will make these devices small enough to be hidden and capable of emitting sufficient radiation to cause deterministic effects. Most devices have built in interlocks designed to protect the user; an assailant would need to defeat these interlock capabilities to use the device for a nefarious exposure. Although significant work has been done to increase the output and to miniaturize these devices, it would be impractical for an assailant to use an RGD in a malicious act. However, periodic evaluation of this issue is recommended to keep the threat analysis in line with emerging technology. There is an international effort to replace radioactive material with RGDs to mitigate the risk of lost or orphaned sources and RDD events. As more resources are allocated to RGD development, the security community should be aware of this emerging issue.

2. ASSAILANT GOALS

Unlike a conventional weapon used in an assault, such as a firearm, knife, or vehicle, the biological insult delivered by a weaponized RED will leave forensic evidence that may be unclear to doctors and police. The symptoms of Acute Radiation Syndrome (ARS) can be confused with a variety of illnesses. Because the victim is likely unaware of the assault, they may seek medical treatment with no inkling of the cause. Unless medical personnel are knowledgeable in the field of radiation effects, misdiagnosis is likely.

2.1. Scenarios

Credible scenarios resulting from the weaponization of an RED are as follows:

- death or serious injury of single target known to assailant;

- death or serious injury of multiple targets known to assailant;
- death or serious injury of single target unknown to assailant;
- death or serious injury of multiple targets unknown to assailant; or
- psychological terror affecting a mass population.

These scenarios may play out in combination.

Supporting case studies are included at the end of this report.

3. MATERIAL PROFILE

Not all radiological materials are effective as an RED. Materials with low specific activities cannot emit sufficient radiation to create a dose adequate to cause deterministic effects. It is reasonable to assume that the assailant will need to move the radiological material to use it as an RED. The gross mass of the material and its associated shielding or container cannot be outside of the lifting or transportation capacity of the assailant. In most cases, the RED assailant would be attempting to avoid detection both of the material theft and of the material while the act is in progress. A scenario in which the assailant removes shielding from radioactive material to expose targets in the storage location is highly unlikely and not supported by case study. Most facilities that store highly radioactive materials have health and safety controls in place to monitor worker exposure, such as radiation area monitors and regular radiation surveys.

The International Atomic Energy Agency (IAEA) Dangerous Quantities of Radioactive Material (D-Values) IAEA-Epr-D-Values provides guidance on the quantity of radioactive material which if uncontrolled, *"could be involved in a reasonable scenario resulting in the death of an exposed individual or a permanent injury, which decreases that person's quality of life."* (IAEA, August 2006)

The D1-values listed in IAEA-EPR-D-Values 2006 are the activities of 373 distinct radionuclides which, if uncontrolled but not dispersed, could reasonably be expected to cause severe deterministic health effects if handled for a few minutes. It is worth noting that the D1 values include activity thresholds adjusted for the risk posed by a criticality incident. For the purposes of this analysis a malicious criticality event would fall under the definition of an Improvised Nuclear Device (IND) and is outside of an analysis of RED scope.

4. RED MATERIAL INVENTORY RADIONUCLIDE DOWN SCREENING

In support of the Global Threat Reduction Initiative, a comprehensive down screening analysis has already been performed, *Radioactive Material Downselection and Source Prioritization Methodology* (Rhodes, 2009). Although this work briefly discusses the RED threat, the radionuclide down screening was performed with RDD threat in mind; consequently, the attributes for an RED threat contained in this report differ somewhat from the attributes for an RDD from the Rhodes report. A comprehensive understanding of the risk posed by sabotage using radiological materials requires evaluation of both technical bases. Evaluation of facility inventory for material that poses an RED risk should consider two factors:

- Whether the presence or theft of the material would not be detected for a duration sufficient to create an exposure resulting in the death or permanent injury of the victim or victims.
- Whether the material is of a size and mass that would not inhibit concealed movement from its storage location or intermediate hiding place to the location of the exposure.

These factors permit elimination of radionuclides that would require more than 10kg of raw material to create a radiation field sufficient to cause deterministic effects in the victim. This paper will consider RED concern any radiological material that produces a dose rate of 100 rad per hour at one meter from the source material. This is in line with the IAEA D1 value determination, which is stated as:

> "The value is the minimum reference dose for developing any severe deterministic effect from uniform irradiation of the whole body. The reference level of 1 Gy was selected because it is the lower bound of the reference levels for onset of severe deterministic effects in the red bone marrow, thyroid, lens of the eye and reproductive organ." (IAEA, August 2006)

It is reasonable that the assailant would be able to place the source within one meter of the victim without awareness by the victim. An exposure of one hour would allow for the removal, transfer, irradiation, and replacement during a one-day window, minimizing the chance of discovery.

Although longer irradiation times are possible and could cause deterministic effects, for the purpose of material down screening, this analysis will be limited to radionuclides which could inflict a 100 rad dose at one meter from the source in one hour based on DOE Design Basis Threat requirements (U.S. Department of Energy, 2016).

The assailant must be physically able to move the material to the exposure location. This analysis considers incredible for RED use any materials that require a mass of 10 kilograms or greater to create the requisite dose rate of 100 rad/hr 1 meter from the source. Materials used for an RED would be extremely radioactive and require significant shielding to protect the assailant during transfer, so the probability that an assailant could discretely move 10 kg of material and associated shielding is low.

Radionuclides with short half-lives should not be considered RED materials, as the acquisition, planning, and execution of an RED event with a short-lived radionuclide would be difficult if not impossible. For the purpose of this analysis, asset characterization as related to RED risk will screen out radionuclides with a half-life less than one week. This is in line with the Rhodes downselection analysis (Rhodes, 2009).

RED material downscreening attributes in summary:

- Dose rate equal to 100 rad (1 Gy) per hour at one meter from the source
- Mass less than or equal to10 kg
- Half-life greater than or equal to one week

This analysis does not account for attenuation, self or otherwise.

5. RISK ANALYSIS CASE STUDY

Malicious RED-related acts vary in methodology and form of radionuclides. Summarized below are a subset of case studies that outline the range of risk. These case studies were used as a roadmap to develop a technical basis for the identification of RED risk in the current threat environment.

5.1. 1974 - Texas Petroleum Engineer Irradiates Son

A male petroleum engineer used one or two Cs-137 (cesium-137) licensed oil and gas well logging sources (1-2 Curies each) to intentionally irradiate his 11-year-old son on multiple occasions, resulting in serious skin lesions requiring multiple grafts and castration. The man repeatedly drugged his son and, while the boy was unconscious, placed the small metal cylindrical sources near his son. On occasion, the boy was left alone after being told to listen to the television only with earphones. Inside the earphones, he found the metal cylinders which he later identified in court as the well logging sources in question (Bailey, 1977).

Consequence: one injury

5.2. 1993 - Russian Man Dies from Radioactive Material Planted in Chair

In Moscow, a radioactive substance, probably cesium-137 and/or cobalt-60, was hidden in the chair of Vladimir Kaplun, director of the Kartontara packing company. Over several weeks Kaplun contracted radiation sickness and was hospitalized for a month before his death. Only after his death was the source of the radiation identified only by colleagues. No specifics of the criminal act were found in the references reviewed for this analysis. (Johnston, 2014)

Consequence: one fatality

5.3. 1995-97 - Russian Man Dies from Cs-137 Source in Pocket of Truck Door

In Zheleznodorozhny, Russia, a man suffered injury and eventual death as a result of exposure to a 1.3-curie cesium-137 source that had been placed in a door pocket of his truck. The driver was exposed for 5 months before the source was discovered. The estimated total dose was 800 rad whole body and 6,500 rad to the thigh. After 8 months of treatment, the man developed myelodsplastic syndrome (malformed blood cells or ones that don't work properly), which progressed to leukemia at 15 months. (Mayo Clinic Staff, 2017) He was hospitalized periodically from 7 July 1995 to 27 April 1997, when he died. No specifics in regards to the criminal act existed in the references reviewed for this analysis. (Johnston, 2014)

Consequence: one fatality

5.4. 2003 - Chinese Nuclear Researcher Irradiated Colleague and Other Hospital Staff

In Guangzhour, China, nuclear medicine researcher Gu Jiming stashed an industrial radiography camera containing pellets of iridium-192 above ceiling panels at a hospital. The target, identified only by his surname Liu, began complaining of fatigue, loss of appetite, headaches, and vomiting. A medical checkup two months later revealed serious irregularities in his white blood cell count. At this point, his office was searched and the radioactive materials discovered. Others at the hospital also complained of fatigue, memory loss, bleeding gums, and other symptoms. A nurse who was five months pregnant reportedly nearly suffered a miscarriage due to radiation exposure.

Gu's research institute and Liu's hospital had cooperated in forming a laser treatment center in 1997, but the two men had feuded over management, bonuses, economic benefits and other matters. Gu obtained the substance by falsifying documents to buy an industrial machine that uses iridium-192 to check welded joints. Gu Jiming was convicted on Sept. 29, 2003, given a suspended death sentence (life in prison), and an assistant was sentenced to a 15-year prison term. (Department of Homeland Security, Office for Domestic Preparedness, 2004)

Consequences: 75 injuries

5.5. 2006 - Homicide of Alexander Litvinenko

The November 2006 poisoning of former KGB agent Alexander Litvinenko by ingestion of an estimated five millicuries of the alpha-emitting radionuclide Po-210 (polonium-210) was publicized globally and brought the risk of RED into the public spotlight (Ricon, 2006). Reports suggest that Litvinenko was poisoned by microgram quantities of Po-210 added to his tea. Litvinenko was a critic of Russia's Putin administration and reportedly accused the administration of his poisoning in the last days of his life. Although no formal determination of guilt was ever made, the use of Po-210 in a poisoning would require access to the product from a nuclear research-type reactor and/or sophisticated laboratory separation techniques. This is due to the amount of pure Po-210 required, its relatively short half-life of 138 days, and the difficulties associated with transportation, storage, and handling.

UK authorities reported results of tests for Po-210 contamination on 735 people: 596 were not contaminated; 120 showed probable contact with Po-210 but with levels indicating no health risk; and 17 people (one relative of Litvinenko, probably his wife, and 16 motel staff) with Po-210 levels "not significant enough to cause any illness in the short term and any increased risk in the long term is likely to be very small." (Goldfarb & Livenko, 2007)

Consequences: one death

6. DEFINITIONS

Acute Radiation Syndrome (ARS)
An acute illness caused by irradiation of the entire body (or most of the body) by a high dose of penetrating radiation in a very short period of time (usually a matter of minutes). The major cause of this syndrome is depletion of immature parenchymal stem cells in specific tissues. Conditions for Acute Radiation Syndrome (ARS) are:

- The radiation dose must be large (i.e., greater than 0.7 Gray (Gy)1,2 or 70 rads).
- Mild symptoms may be observed with doses as low as 0.3 Gy or 30 rads.
- Radioactive materials deposited inside the body have produced some ARS effects only in extremely rare cases.
- The radiation must be penetrating (i.e., able to reach the internal organs).
- The entire body (or a significant portion of it) must have received the dose.
- Most radiation injuries are local, frequently involving the hands, and these local injuries seldom cause classical signs of ARS.
- The dose must have been delivered in a short time (usually a matter of minutes).

Deterministic Effects
A health effect of radiation for which, generally, a threshold level of dose exists above which the severity of the effect is greater for a higher dose. Such an effect is described as a 'severe deterministic effect' if it is fatal or life threatening or results in a permanent injury that reduces the quality of life.

Gray (Gy):
International unit of absorbed radiation dose. One Gy is equivalent to 100 rad. See rad.

Half-life
The time required for half the atoms of a given radioisotope to transform by radioactive decay.

Improvised Nuclear Device (IND)
A crude device, assembled by the adversary using SNM, capable of producing nuclear yield.

kinetic energy released per unit mass (Kerma)
The quantity of energy transferred from initial particles (often photons, which are uncharged) to charged particles in the medium.

Radiation Generating Device (RGD)
A device that creates a radiation field without the use of radioactive material (e.g. an x-ray machine).

Plume
Airborne material spreading from a particular source; the dispersal of particles, gases, vapors and aerosols in the atmosphere.

Stochastic Effects
A radiation induced health effect, the probability of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose.

rad (radiation absorbed dose):
A basic unit of absorbed radiation dose. One rad equals the dose delivered to an object of 100 ergs of energy, per gram of material.

Radiological Dispersal Device (RDD)
A device or mechanism that is intended to spread radioactive material from the detonation of conventional explosives or other means. An RDD is commonly known as a "dirty bomb."

Radiological Exposure Device (RED)
A radiation emitting item used to maliciously expose people, without dispersal of radioactive material.

Radiological Poisoning Device (RPD)
Radioactive material used to cause harm by malicious ingestion or injection.

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APPENDIX A: RED EXTERNAL DOSE SCREENING TABLE

As calculated April 12, 2018

This appendix describes the methodologies used to determine the hourly external photon and neutron ionizing radiation dose delivered to an individual remaining 1 meter from an unshielded hypothetical point source. The external dose uses the air-kerma coefficient (Γ_{air}) values from ICRP Publication 107 ((ICRP, 2008)), Gy m^2 Bq^{-1} s^{-1}. Kerma is the acronym for "kinetic energy released per unit mass." The Γ_{air} values include all photons of energy greater than 10 keV, including annihilation photons arising from position emission, delayed and prompt gamma rays accompanying spontaneous fission, and neutrons accompanying spontaneous fission. Only neutrons of energy greater than 10 keV are included.

IAEA publication "Dangerous quantities of radioactive material (D-values)" (IAEA, August 2006), includes criticality considerations in determining D values, and lists specific mass limits not to be exceeded (Table 28 Appendix VIII). The following radionuclides have been omitted from the RED External Dose Screening Table, as the mass associated with the D values exceeded the Table 28 radionuclide-specific criticality mass limit:

Am-242m
Cm-245
Bk-247
Cf-248
Cf-249
Cf-251

Radionuclide	Halflife (year)	Activity (Ci)	Mass (kg)
Ac-225	2.74E-02	1.1E+03	1.9E-05
Ac-227	2.18E+01	2.1E+02	2.9E-03
Ag-105	1.13E-01	2.7E+02	8.9E-06
Ag-106m	2.27E-02	6.9E+01	4.6E-07
Ag-108m	4.18E+02	1.1E+02	1.4E-02
Ag-110m	6.84E-01	7.6E+01	1.6E-05
Ag-111	2.04E-02	7.5E+03	4.8E-05
Al-26	7.17E+05	8.5E+01	4.4E+00
Am-241	4.32E+02	7.7E+02	2.2E-01
Am-243	7.37E+03	1.2E+03	5.8E+00
As-73	2.20E-01	1.2E+03	5.5E-05
As-74	4.87E-02	2.5E+02	2.6E-06
Au-195	5.10E-01	5.1E+02	1.4E-04
Ba-131	3.15E-02	2.9E+02	3.4E-06
Ba-133	1.05E+01	3.8E+02	1.5E-03
Ba-140	3.49E-02	9.8E+01	1.3E-06
Be-7	1.46E-01	4.0E+03	1.1E-05
Bi-205	4.19E-02	1.0E+02	2.5E-06
Bi-207	3.29E+01	1.1E+02	2.1E-03
Cd-109	1.26E+00	6.9E+02	2.6E-04
Cd-113m	1.41E+01	1.1E+06	4.7E+00
Cd-115m	1.22E-01	6.5E+03	2.5E-04
Ce-139	3.77E-01	9.3E+02	1.4E-04
Ce-141	8.91E-02	2.6E+03	9.0E-05
Ce-144	7.81E-01	8.8E+03	2.8E-03
Cf-250	1.31E+01	2.6E+03	2.4E-02
Cf-252	2.65E+00	1.0E+02	1.9E-04
Cf-253	4.88E-02	2.2E+03	7.5E-05
Cf-254	1.66E-01	3.0E+00	3.5E-07
Cm-240	7.40E-02	3.1E+03	1.5E-04
Cm-241	8.99E-02	2.0E+02	1.2E-05
Cm-242	4.46E-01	3.5E+03	1.0E-03
Cm-243	2.91E+01	5.0E+02	9.9E-03
Cm-244	1.81E+01	4.0E+03	5.0E-02
Cm-250	8.30E+03	5.2E+00	3.0E-02
Co-56	2.12E-01	6.4E+01	2.1E-06
Co-57	7.44E-01	1.2E+03	1.4E-04
Co-58	1.94E-01	2.1E+02	6.6E-06
Co-60	5.27E+00	8.8E+01	7.8E-05
Cr-51	7.59E-02	6.4E+03	6.9E-05
Cs-131	2.65E-02	1.8E+03	1.7E-05

Radionuclide	Halflife (year)	Activity (Ci)	Mass (kg)
Cs-134	2.06E+00	1.3E+02	1.0E-04
Cs-136	3.61E-02	9.8E+01	1.3E-06
Cs-137	3.02E+01	3.3E+02	3.8E-03
Dy-159	3.96E-01	2.7E+03	4.7E-04
Er-169	2.58E-02	6.7E+07	8.2E-01
Es-253	5.61E-02	1.6E+04	6.4E-04
Es-254	7.55E-01	4.9E+02	2.6E-04
Es-255	1.09E-01	7.3E+04	5.7E-03
Eu-147	6.60E-02	4.0E+02	1.1E-05
Eu-148	1.49E-01	9.0E+01	5.6E-06
Eu-149	2.55E-01	1.9E+03	2.0E-04
Eu-150	3.69E+01	1.3E+02	2.0E-03
Eu-152	1.35E+01	1.8E+02	1.0E-03
Eu-154	8.59E+00	1.7E+02	6.3E-04
Eu-155	4.76E+00	3.3E+03	6.8E-03
Eu-156	4.16E-02	1.8E+02	3.3E-06
Fe-59	1.22E-01	1.8E+02	3.7E-06
Fm-257	2.75E-01	3.7E+02	7.3E-05
Gd-146	1.32E-01	7.7E+01	4.1E-06
Gd-149	2.54E-02	3.6E+02	3.8E-06
Gd-151	3.40E-01	1.8E+03	2.6E-04
Gd-153	6.59E-01	1.4E+03	3.9E-04
Ge-68	7.42E-01	2.7E+03	3.8E-04
Ge-71	3.13E-02	2.6E+03	1.6E-05
Hf-172	1.87E+00	9.4E+02	8.4E-04
Hf-175	1.92E-01	5.3E+02	4.9E-05
Hf-178m	3.10E+01	8.9E+01	1.4E-03
Hf-179m	6.86E-02	2.1E+02	7.3E-06
Hf-181	1.16E-01	3.7E+02	2.2E-05
Hg-194	4.40E+02	1.6E+02	3.9E-02
Hg-203	1.28E-01	6.8E+02	4.9E-05
Ho-166m	1.20E+03	1.3E+02	7.0E-02
I-125	1.63E-01	7.6E+02	4.3E-05
I-126	3.54E-02	4.0E+02	5.0E-06
I-131	2.20E-02	5.2E+02	4.2E-06
In-114m	1.36E-01	1.3E+03	5.6E-05
Ir-189	3.62E-02	5.7E+02	1.1E-05
Ir-190	3.23E-02	1.2E+02	2.0E-06
Ir-192	2.02E-01	2.4E+02	2.6E-05
Ir-192m	2.41E+02	5.0E+02	6.4E-02
Ir-193m	2.88E-02	3.0E+03	4.6E-05

Radionuclide	Halflife (year)	Activity (Ci)	Mass (kg)
Ir-194m	4.68E-01	8.3E+01	2.1E-05
Kr-85	1.08E+01	8.8E+04	2.3E-01
Lu-171	2.26E-02	2.8E+02	3.0E-06
Lu-173	1.37E+00	1.0E+03	6.6E-04
Lu-174	3.31E+00	1.6E+03	2.6E-03
Lu-174m	3.89E-01	1.7E+03	3.3E-04
Lu-177m	4.39E-01	2.0E+02	4.3E-05
Mn-54	8.55E-01	2.5E+02	3.2E-05
Mo-93	4.00E+03	5.1E+02	5.3E-01
Na-22	2.60E+00	9.6E+01	1.5E-05
Nb-91	6.80E+02	5.3E+02	9.2E-02
Nb-91m	1.67E-01	6.6E+02	2.8E-05
Nb-92m	2.78E-02	1.5E+02	1.1E-06
Nb-93m	1.61E+01	3.4E+03	1.4E-02
Nb-94	2.03E+04	1.3E+02	7.0E-01
Nb-95	9.59E-02	2.7E+02	6.7E-06
Nd-147	3.01E-02	1.2E+03	1.5E-05
Np-235	1.09E+00	8.9E+02	6.3E-04
Os-185	2.56E-01	2.3E+02	3.1E-05
Os-191	4.22E-02	5.4E+02	1.2E-05
Os-194	6.00E+00	9.3E+02	3.0E-03
Pa-230	4.77E-02	1.9E+02	5.8E-06
Pa-231	3.28E+04	4.5E+02	9.6E+00
Pa-233	7.39E-02	3.7E+02	1.8E-05
Pb-202	5.25E+04	2.2E+02	6.6E+00
Pb-210	2.22E+01	7.7E+02	1.0E-02
Pd-103	4.66E-02	7.5E+02	1.0E-05
Pm-143	7.26E-01	5.6E+02	1.6E-04
Pm-144	9.95E-01	1.2E+02	5.0E-05
Pm-145	1.77E+01	2.6E+03	1.8E-02
Pm-146	5.53E+00	2.6E+02	5.8E-04
Pm-148m	1.13E-01	1.0E+02	4.7E-06
Po-206	2.41E-02	1.1E+02	1.5E-06
Po-208	2.90E+00	5.1E+06	8.6E+00
Po-209	1.02E+02	2.3E+04	1.4E+00
Po-210	3.79E-01	2.1E+07	4.6E+00
Pt-188	2.79E-02	8.1E+01	1.2E-06
Pt-193	5.00E+01	1.6E+03	4.3E-02
Pu-236	2.86E+00	2.6E+03	5.0E-03
Pu-237	1.24E-01	6.2E+02	5.1E-05
Pu-238	8.77E+01	2.8E+03	1.7E-01

Radionuclide	Halflife (year)	Activity (Ci)	Mass (kg)
Pu-246	2.97E-02	5.2E+02	1.1E-05
Ra-223	3.13E-02	5.7E+02	1.1E-05
Ra-225	4.08E-02	1.5E+03	3.7E-05
Ra-226	1.60E+03	6.5E+01	6.5E-02
Ra-228	5.75E+00	1.7E+02	6.3E-04
Rb-83	2.36E-01	2.0E+02	1.1E-05
Rb-84	8.98E-02	1.6E+02	3.4E-06
Rb-86	5.11E-02	2.3E+03	2.8E-05
Re-183	1.92E-01	9.9E+02	9.7E-05
Re-184	1.04E-01	2.2E+02	1.2E-05
Re-184m	4.63E-01	3.7E+02	8.9E-05
Rh-101	3.30E+00	3.7E+02	3.4E-04
Rh-102	5.67E-01	3.0E+02	4.9E-05
Rh-102m	3.74E+00	8.5E+01	9.0E-05
Rh-99	4.41E-02	2.2E+02	2.7E-06
Ru-103	1.08E-01	4.0E+02	1.2E-05
Ru-106	1.02E+00	9.8E+02	3.0E-04
Sb-124	1.65E-01	1.2E+02	6.8E-06
Sb-125	2.76E+00	2.7E+02	2.6E-04
Sb-126	3.38E-02	7.3E+01	8.7E-07
Sc-46	2.30E-01	1.1E+02	3.1E-06
Se-72	2.30E-02	1.9E+02	8.9E-07
Se-75	3.28E-01	1.8E+02	1.2E-05
Sm-145	9.32E-01	9.2E+02	3.5E-04
Sn-113	3.15E-01	1.1E+03	1.1E-04
Sn-117m	3.77E-02	7.5E+02	9.3E-06
Sn-119m	8.03E-01	1.5E+03	4.1E-04
Sn-121m	4.39E+01	6.2E+03	9.1E-02
Sn-123	3.54E-01	3.1E+04	3.8E-03
Sn-125	2.64E-02	6.4E+02	5.9E-06
Sn-126	2.30E+05	1.2E+02	9.7E+00
Sr-82	6.95E-02	4.2E+02	6.6E-06
Sr-85	1.78E-01	2.0E+02	8.5E-06
Sr-89	1.38E-01	2.4E+06	8.2E-02
Ta-179	1.82E+00	4.3E+03	3.9E-03
Ta-182	3.14E-01	1.7E+02	2.6E-05
Tb-157	7.10E+01	2.4E+04	7.4E-01
Tb-158	1.80E+02	2.5E+02	2.0E-02
Tb-160	1.98E-01	1.9E+02	1.7E-05
Tc-95m	1.67E-01	2.1E+02	9.1E-06
Tc-97m	2.47E-01	9.6E+02	6.4E-05

Radionuclide	Halflife (year)	Activity (Ci)	Mass (kg)
Te-121	5.25E-02	2.8E+02	5.0E-06
Te-121m	4.22E-01	2.0E+02	2.9E-05
Te-123m	3.27E-01	9.9E+02	1.1E-04
Te-125m	1.57E-01	9.2E+02	5.1E-05
Te-127m	2.99E-01	2.8E+03	2.9E-04
Te-129m	9.21E-02	2.5E+03	8.4E-05
Th-227	5.12E-02	3.6E+02	1.2E-05
Th-228	1.91E+00	5.5E+02	6.7E-04
Th-229	7.34E+03	2.8E+02	1.3E+00
Th-234	6.60E-02	2.6E+03	1.1E-04
Ti-44	6.00E+01	1.7E+03	1.2E-02
Tl-202	3.35E-02	3.2E+02	6.1E-06
Tl-204	3.78E+00	3.9E+04	8.4E-02
Tm-167	2.53E-02	1.3E+03	1.5E-05
Tm-168	2.55E-01	1.6E+02	2.0E-05
Tm-170	3.52E-01	5.0E+04	8.4E-03
Tm-171	1.92E+00	2.7E+05	2.5E-01
U-230	5.70E-02	2.4E+03	8.7E-05
U-232	6.89E+01	2.5E+03	1.1E-01
V-48	4.38E-02	7.3E+01	4.3E-07
W-178	5.92E-02	5.8E+03	1.7E-04
W-181	3.32E-01	3.4E+03	5.6E-04
W-185	2.06E-01	1.5E+06	1.6E-01
W-188	1.91E-01	6.1E+02	6.1E-05
Xe-127	9.97E-02	5.2E+02	1.8E-05
Xe-129m	2.43E-02	9.5E+02	8.3E-06
Xe-131m	3.24E-02	2.3E+03	2.7E-05
Y-88	2.92E-01	7.2E+01	5.2E-06
Y-91	1.60E-01	7.0E+04	2.8E-03
Yb-169	8.77E-02	5.9E+02	2.4E-05
Zn-65	6.69E-01	3.7E+02	4.5E-05
Zr-88	2.28E-01	5.6E+01	3.1E-06
Zr-95	1.75E-01	1.4E+02	6.3E-06

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