LA-UR-16-20987
Approved for public release; distribution is unlimited.

Title: Threat Identification Parameters for a Stolen Category 1 Radioactive Source

Author(s): Ussery, Larry Eugene
Winkler, Ryan
Myers, Steven Charles

Intended for: Report

Issued: 2016-02-18

Disclaimer:
Los Alamos National Laboratory, an affirmative action/equal opportunity employer,is operated by the Los Alamos National Security, LLC for the National NuclearSecurity Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Departmentof Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Threat Identification Parameters for a Stolen Category 1 Radioactive Source

Los Alamos National Laboratory

Larry E. Ussery, Steven C. Myers, and Ryan Winkler

I. INTRODUCTION

Radioactive sources are used very widely for research and practical applications across medicine, industry, government, universities, and agriculture. The risks associated with these sources vary widely depending on the specific radionuclide used to make the source, source activity, and its chemical and physical form. Sources get categorized by a variety of classification schemes according to the specific risk they pose to the public. This report specifically addresses sources that are classified in the highest category for health risk.

II. BACKGROUND

II A. WHAT ARE CATEGORY 1 SOURCES

Category 1 sources are very highly radioactive, ranging from about 600 to 1,000,000 or more Curies in activity. These very large activity sources are normally used for medical, industrial, or research applications. A set of 16 radioactive materials currently have a defined Category 1 activity threshold[1,2]. Only six of those materials, listed in Table 1 below, are currently registered at any site within the U.S, at or above the Category 1 threshold activity, which is given in units of Curies for each material. The total number of registered U.S. Category 1 sites in 2015 was greater than 400.

Table 1. Category 1 Sources and Threshold Quantity

Radioactive Material	Category 1 Quantity (Curies)	Typical activity (Curies) of sources when new	Common Uses
Americium-241	1,620		Smoke detectors, manufacture of industrial neutron sources, density gauges, x-ray fluorescence sources. This material is typically used in very small quantities but a full site inventory, where individual sources are manufactured for the applications above may add up to a Category 1 quantity.
Cobalt-60	810	2,000 – 50,000	Research/blood irradiators, teletherapy machines, multi-beam teletherapy machine (Gamma Knife), industrial sterilization plant
Curium-244	1,350		Used primarily for scientific research. Could be used for Radioisotope Thermoelectric Generators (RTGs). Is used in alpha-particle x-ray spectrometers for Mars space missions. Typically used in very small quantities but a full site inventory may add up to a Category 1 quantity.
Cesium-137	2,700	up to 7,000	Research irradiators, blood irradiators
Iridium-192	2,160		Typically used for radiography in Category 2 (>22 Curies) quantities or less but a full site inventory may add up to a Category 1 quantity.

Radioactive Material	Category 1 Quantity (Curies)	Typical activity (Curies) of sources when new	Common Uses
Strontium-90	27,000	From about 100,000 up to 330,000	RTGs as power sources in remote locations, primarily by the U. S. Air Force.

II B. LOCATIONS OF CATEGORY 1 SOURCES

As of 2015 there were approximately 425 sites within the U.S. and Puerto Rico that had Category 1 source inventories registered with the Nuclear Regulatory Commission (NRC). Figure 1 below is a representation of how those sources are distributed throughout the country. The individual circles on the map represent registered sites and the size and color of the circles indicate the magnitude of that site's source inventory relative to a Category 1 quantity. For example, the smallest green circle represents a site that has a total inventory that is at least equal to one Category 1 quantity of radioactive material, up to a quantity that is 249 times this minimum Category 1 quantity.

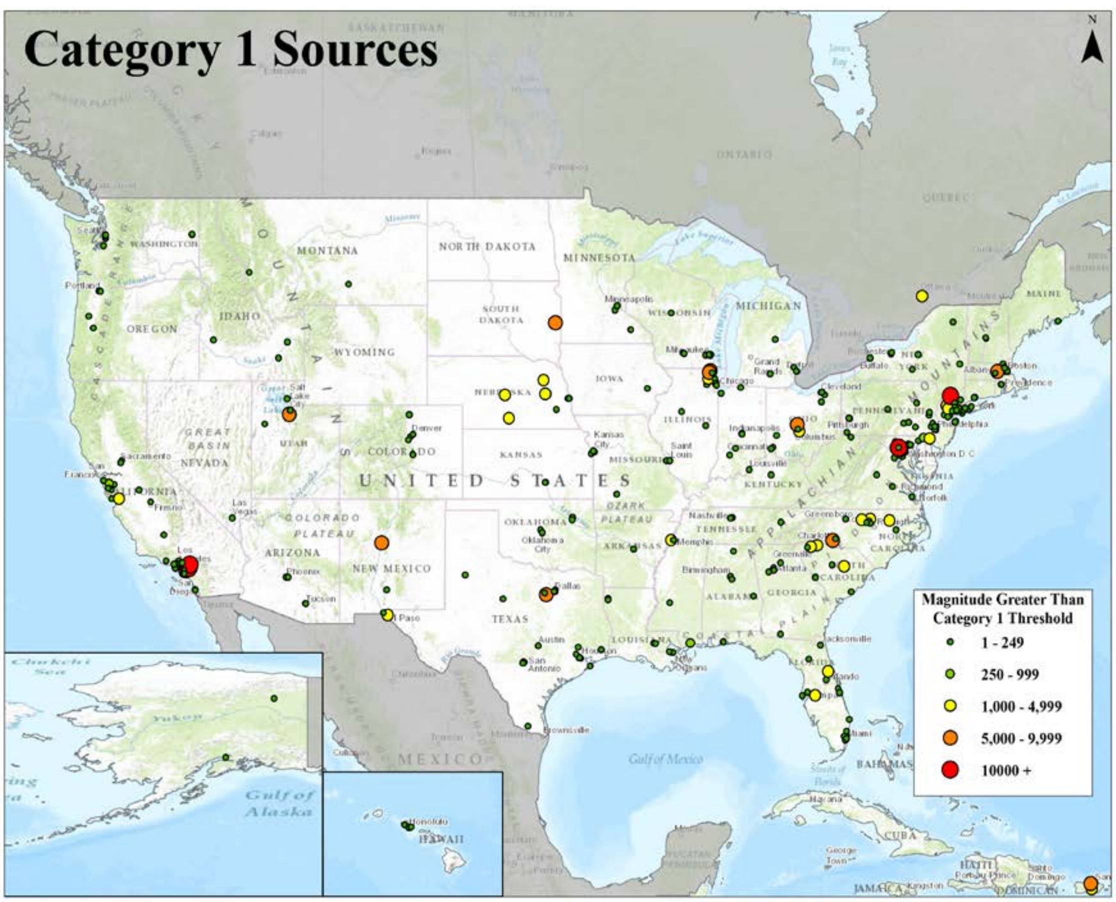


Figure 1. Distribution of registered Category 1 source inventories within the United States as of 2015.

II C. TYPICAL CONFIGURATIONS OF CATEGORY 1 SOURCES

Virtually all Category 1 radioactive source applications fall into six categories described in Table 2. This table provides approximate physical dimensions and weights for these sources, as typically used, and the physical dimensions for individual source holders that are either used alone or as a collection that results in a total activity above the Category 1 limit for the isotopes of interest. In addition, the table includes very approximate dimensions and weights for configurations that might be used when shipping these sources between a vendor and the ultimate user. The shipping configuration can vary significantly depending on whether one is shipping only radioactive material or a fully loaded instrument such as a research irradiator or blood irradiator.

Table 2. Typical Configurations of Category 1 Sources

Application	Typical Configuration	Isotope & Typical Activity (Curies)	Typical Dimensions for Individual Source	Approximate Shipping Configuration*
Industrial Sterilization Plant	Building approximately 330ft by 660ft by 20ft high. (from reference 3, section 5)	^{60}Co, 12,000-50,000 Curies per source. Up to 5,000,000 Curies per facility.	Most often a tube of about 0.4 inch diameter by 18 inches length. Can be as large as 1.4 inch diameter by 28 inch length	N/A
Teletherapy Machine	Teletherapy head-12-24 inches in diameter by 12-24 inches in length, in the form of a cast shell filled with lead or tungsten shielding and a central channel for the sliding source drawer. The shielding may also include depleted uranium.	^{60}Co, 10,000-15,000 Curies in a single source	Typically a cylinder of about 0.8 inch diameter by 1.2 inch length that sits in a shielded, sliding drawer. The radioactive material is normally in the form of about .04 inch metal beads but may also be a solid metal rod or in the form of powder.	Varies from about 18 x 18 x 24 inches to about 60 x 24 x 24 inches depending on source configuration and total activity. Weight varies from about 3,000 to 5,500 pounds
Multi-beam Teletherapy Machine (Gamma Knife)	About 6-6.5 ft diameter spheroid divided into multiple sectors that hold the individually shielded and collimated sources (up to	^{60}Co, 5,000-7,500 Curies total activity, when sources are freshly installed. Most common configurations use 192 or 201 individual sources	Outer stainless steel source capsule is approximately 1 inch in diameter by 1.25 inches length. Radioactive material is in inner welded stainless steel tube about 0.1 inch	The “Radiation Unit” that contains the source shielding and collimators weighs approximately 40,000 pounds. The unit will likely

Application	Typical Configuration	Isotope & Typical Activity (Curies)	Typical Dimensions for Individual Source	Approximate Shipping Configuration*
	201 total)	of up to 36 Curies each	diameter by 0.95 inch length.	be shipped as a 6-6.5 ft. spheroid containing the full source loading and packaged in some form of over-pack container.
Blood Irradiator	Consists of a shielded chamber with sources arranged in circular array. Interlocked door for sample introduction.	Up to 7,000 Curies total activity of ^{137}Cs or ^{60}Co incorporated into 1-3 source "pencils".	Source pencils ranging from about 0.5-0.7 inches in diameter up to 11 inches in length	About 24 x 28 x 65 inches high, fully assembled. 24 x 28 x 36 inches if removed from stand. Weight is approximately 2300-2600 pounds
Small-scale Sample Irradiator	Similar to blood irradiators, sources enclosed in a shielded chamber with interlocked access for sample introduction	2,000 – 25,000 Curies total activity of $^{60}C0$ or 1,000 – 3,000 Curies total activity of ^{137}Cs.	Source pencils ranging from about 0.5-0.7 inches in diameter up to 11 inches in length	Fully assembled units can be approximately 32-36 inches wide, 54-60 inches long, and about 60 inches tall. Weight ranges from about 4000-6000 pounds.
RTGs for terrestrial power generation	^{90}Sr fuel is in form of hockey puck-sized disks of strontium titanate, a solid ceramic material. U.S. RTGs made with ^{90}Sr typically have incorporated ~1.2-3.9 pounds of this material, depending on the required power levels.	Up to 330,000 Curies total activity of ^{90}Sr. The average activity appears to be about 100,000 Curies.	Source disks are typically up to a few inches in diameter	Fully assembled RTGs, made with ^{90}Sr, range from about 2000-4000 pounds in a cylindrical shape. Dimensions range from about 36 inch height by 20 inch diameter to 46 inch height by 28 inch diameter. The outer casing may be aluminum, steel, or cast iron.

Dimensions are based on average numbers for common versions of the equipment.

III. HEALTH PHYSICS CONCERNS

The IAEA describes the hazards for individual Category 1 sources that can be picked up or otherwise handled in the following manner[2]:

Personally extremely dangerous: This amount of radioactive material, if not safely managed or securely protected would be likely to cause permanent injury to a person who handled it, or were otherwise in contact with it, for more than a few minutes. It would probably be fatal to be close to this amount of unshielded material for a period of a few minutes to an hour.

Note that Category 1 sources in their normal shielding containers do not exhibit radiation fields that are immediately dangerous to life and health.

IV. DOSE RATE ESTIMATES USING COMMONLY DEPLOYED DETECTORS

The expected dose rate of a Category 1 source is affected by a number of measurement variables. The source activity, isotope, shielding, scattering of radiation in the measurement environment, and measurement distance all significantly affect the expected dose. Figure 2 depicts the expected dose rate of an unshielded teletherapy ^{60}Co source with an activity of 10,000 Ci at distances of 160 to 3300 ft and assuming no line-of-sight obstructions. At a distance of 2/3 mile the expected gamma ray dose rate is 100 µR/h and increases by a factor of 1000 to doses greater than 100 mR/h for distances less than 1/8 mile. It should be noted that at high dose rates (>100 mR/hr) associated with distances less than ~1/8 mile, the functionality of commonly used detectors is limited. Please refer to section V.A for high count rate operational details of common detector types.

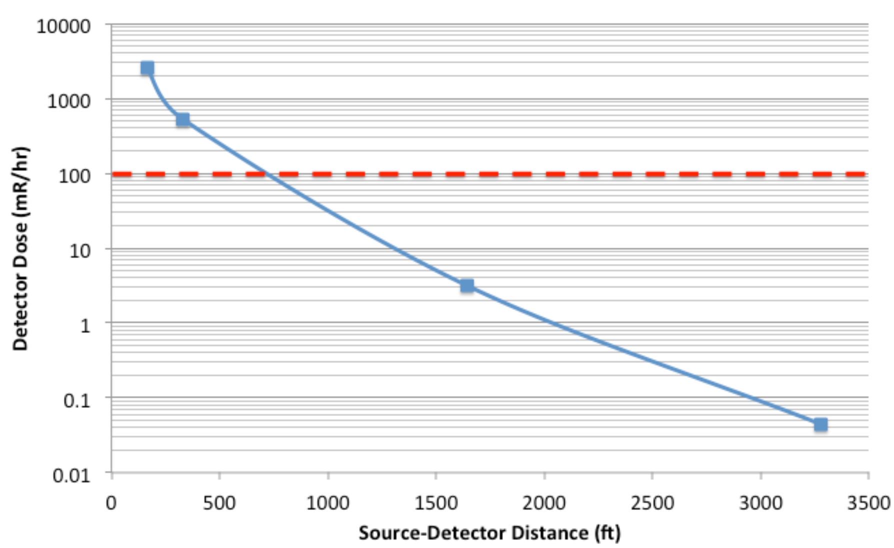


Figure 2: Detector dose rate for unshielded 10,000 Ci ^{60}Co Category 1 source. The red dotted line indicates the dose rate at which most commonly used handheld detectors reach saturation.

V. DETECTING, LOCATING, AND IDENTIFYING CATEGORY 1 SOURCES

Limited detector functionality at high count rates, scattering in the measurement environment, and source shielding are elements that make the localization and identification of a Category 1 gamma ray source difficult. The following sections detail each of these factors and their potential effect on the search for and identification of these high activity source types.

V A. DETECTOR RESPONSES TO HIGH COUNTING RATES

A variety of deleterious effects occur when operating common handheld radiation detectors in the very high count rate environments that are present in the proximity of unshielded or poorly shielded Category 1 gamma ray sources. These high count rate effects hinder both the localization and identification of a high activity source in a search scenario.

Handheld instruments commonly used in search scenarios have a range of maximum dose limits and functional behavior at or beyond these limits. The high dose rate environment in the presence of an unshielded or lightly shielded Category 1 source will require the operator to be familiar with the instrument in use and its behavior when approaching its maximum dose rate. It should be noted that individual instruments behavior in high count rate environments may change over time with software and firmware updates.

Spectrometer components of most instruments are automatically powered off or become unresponsive at excessively high gamma count rates. For many instruments, once the gamma dose rate approaches a few mR/h the job of measuring dose is often automatically switched to an integrated Geiger-Mueller (GM) tube. Most onboard GM tubes report reasonably reliable dose rates up to a few R/h. Beyond the manufacturer-specified limits, significant dose rate inaccuracies can exist and responders are cautioned that they should not be trusted to predict personal radiation doses during an event. At high dose rates a conservative approach should be considered for the sake of personal safety.

A high gamma flux can also induce false neutron counts in instruments containing ^{3}He neutron detectors, such as the Detective EX-100. This gamma ray sensitivity in neutron detectors typically manifests at dose rates of a few R/h[8]. For details regarding the behavior of commonly used instruments in high gamma count rate environments, please refer to Appendix 2.

Handheld instruments in high count rate environments will also display degraded energy resolution and high data acquisition dead times. Additionally, the gamma spectra could exhibit intense peak pile up artifacts that diminish the accuracy of isotopic identification algorithms. Figure 3 depicts a ^{137}Cs spectrum obtained with an identiFINDER at a count rate just below the maximum rate of the instrument. Most events above the 662 keV photopeak are anomalies caused by pileup events in the detector system that might be misidentified as other isotopes that are not actually present.

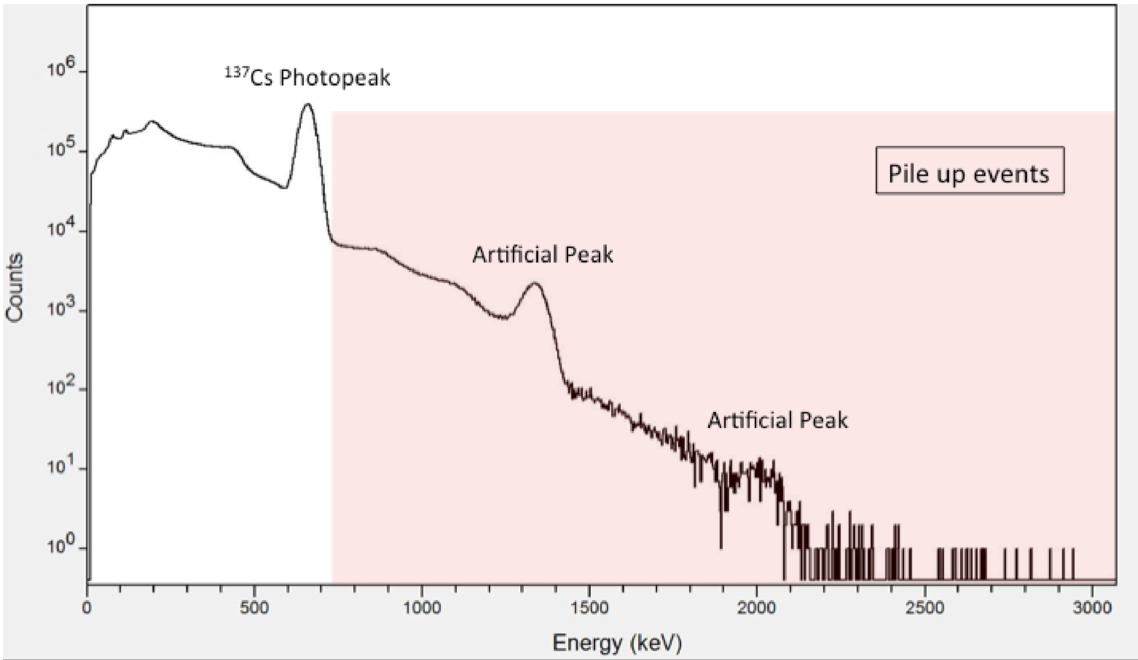


Figure 3: High count rate ^{137}Cs spectrum obtained with identiFINDER RIID (NaI).

V B. SHIELDING

Both the IAEA and NRC have established guidelines for the packaging of high activity Category 1 gamma ray sources. In the United States, The Department of Transportation utilizes the regulations set forth by the NRC[14,15]. Category 1 sources must be transported by exclusive use shipment only and radiation levels during transportation must not exceed 200 mR/h on the external surface of the package. This limit is increased to 1000 mR/h if the shipment is (i) made in a closed transport vehicle, (ii) the package is secured within the vehicle, and (iii) there are no loading or unloading operations performed during transportation.

To meet the dose rates dictated by the NRC, large amounts of lead or depleted uranium are commonly used as shielding. The dimensions of a shielded Category 1 package are typically up to 5 ft diameter, up to 8.5 ft m in height, and weighing up to 11000 lb. Loaded containers are often hot to the touch on their outer surfaces[5]. An example of a shielded Category 1 source in its transport configuration is shown in Figure 4. While significant count rates should be expected in the proximity of a shielded Category 1 source, isotopic identification is difficult due to the extreme shielding of the primary gamma rays. One should also be aware that if the shielding is depleted uranium, a low level of radiation is emitted even when no payload is present.

Figure 4: A high activity gamma ray source container in a shielded transport configuration[5].

V C. SKYSHINE

The scattering of radiation complicates the localization of a Category 1 gamma ray source in an atmosphere and building environment. The interaction of gamma rays with the atmosphere and building materials can result in radiation measurements that are difficult to interpret, as is depicted in Figure 5. In this hypothetical scenario we depict a responder traveling down a street between two buildings with the strong ^{137}Cs source on the far side of the building to their left. As they move from position 1 towards position 6 it appears as though they are moving towards the source when in fact their distance to the source decreases until position 3 and then increases as they continue towards position 6. This illusion is caused by source gammas that scatter off of the building to their right, when the source is actually behind their left shoulder. Even if the searcher eventually obtains line-of-sight with a Category 1 gamma ray source, the handheld instrument used by the responder may saturate due to excessive count rates making further search progress impossible. Please refer to section V A. for a discussion of the high count rate functionality of common handheld detectors.

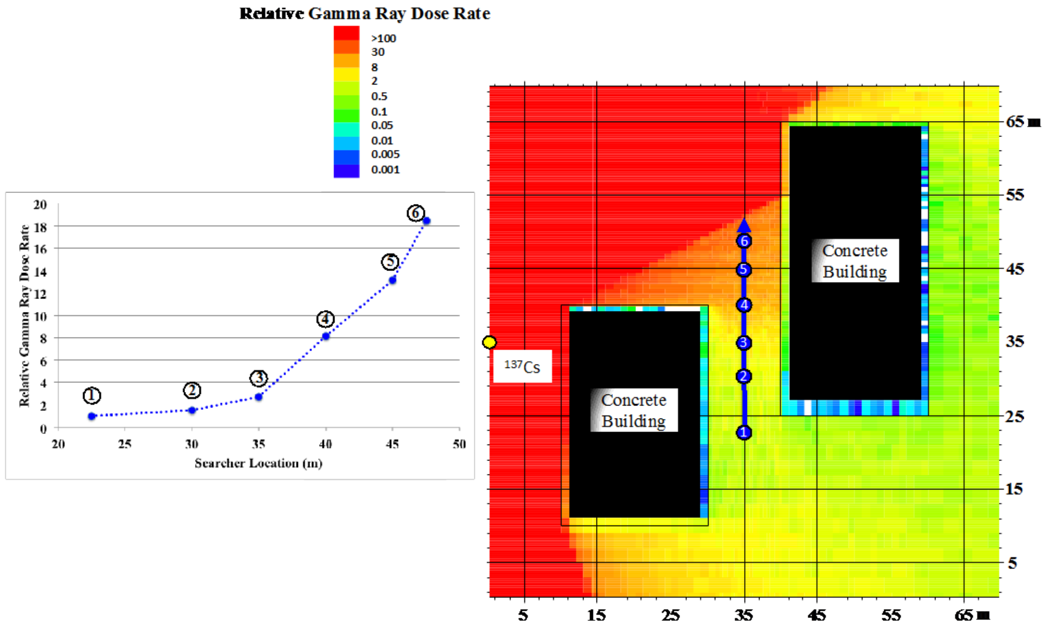


Figure 5: Gamma dose rate of a 500 Ci ^{137}Cs source in a simple building environment

Figure 6 depicts the gamma dose rate for a typical Category 1 5500 Ci ^{60}Co teletherapy source placed unshielded in the center of Times Square, New York City. The color region represents the above background dose rate expected to be encountered by a responder searching for the high activity source. Scattering through street corridors between buildings results in dose rates as high as 500 mR/h at a distance of 1/3rd of a mile from the source. Typical handheld detectors will either saturate at these high dose rates or their functionality will be reduced making the localization and identification of the source in the urban environment exceedingly difficult.

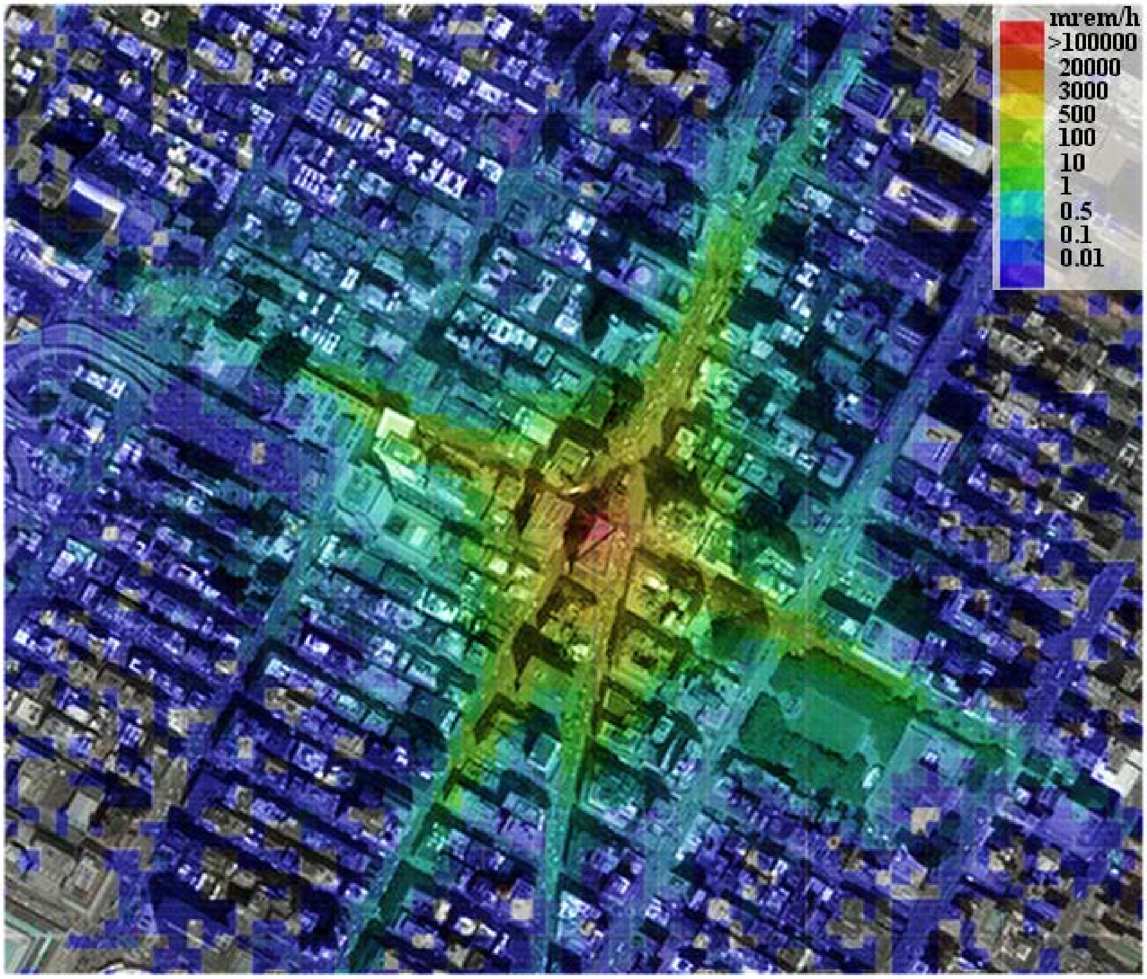


Figure 6: Gamma dose rate for an unshielded 5500 Ci ^{60}Co teletherapy Category 1 source placed in the center of Times Square, New York City. The image spans a region of 1.25 by 1.25 miles.

V D. DETECTION RANGES FOR CATEGORY 1 SOURCES

The distance at which a Category 1 source produces a detectable level of radiation will depend on factors such as the detection instrument, measurement environment, and background count rates. The source activity, isotopic composition, and shielding or other obstructions also significantly affect the maximum detection distance. Assuming an open measurement environment with a clear line-of-sight from the detector to an unshielded source, an approximate value of the maximum detection distance can be determined. The detectors listed in Appendix 2, with one exception, will discern a signal above background at 5500 to 6500 ft for a 10,000 Ci ^{60}Co teletherapy source. The detection range for these detectors is 2000 to 2500 ft for a 10,000 Ci ^{137}Cs blood irradiator source. The detection ranges of the Interceptor, an instrument that contains a relatively small CZT crystal, will be decreased to 2000 and 1000 ft for the ^{60}Co and ^{137}Cs sources, respectively. The higher energy gamma rays emitted from the ^{60}Co will propagate farther in the measurement environment than those emitted from ^{137}Cs, producing higher count rates at larger distances. The detection range will be slightly influenced by the elevation of the measurement environment. A Category 1 source can be detected at relatively greater distances for measurements performed at an elevation of a thousand to a few thousand feet compared to those performed at sea level. It should be noted that while detection is possible at these distances, isotopic identification will be difficult due to large number of scattered events in the spectrum compared to those corresponding to photopeaks of interest. It is also noted that detection distances will vary somewhat proportionally with the activity of the source. Therefore, higher activity sources will be detectable at greater distances, and lower activity sources will be detectable at shorter distances.

V E. FACTORS THAT AFFECT IDENTIFICATION OF CATEGORY 1 SOURCES

Isotopic identification using common detector types and their respective onboard identification algorithms is potentially problematic in a scenario involving a Category 1 gamma ray source. Shielding configurations can greatly reduce full energy gamma ray intensities and the spectrum will consist mostly of scattered lower energy gamma rays. The attenuation of gamma rays by air can also have a signficant impact with enough distance between the source and the detector. In Figure 7 we see how air alone can reduce the full energy photopeak intensities for measurements performed at sea level. With no line-of-sight-obstructions, the percent of ^{137}Cs photopeak events available for identification relative to the total counts in a spectrum decreases rapidly with increasing distance.

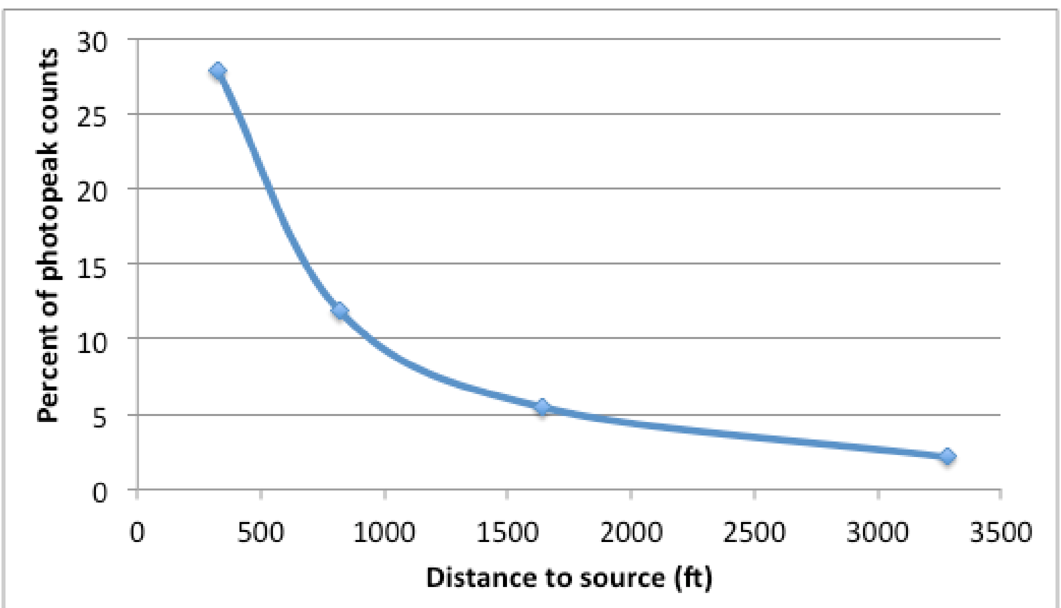


Figure 7: The percent of photopeak counts relative to total counts in a spectrum for a ^{137}Cs source with no line-of-sight obstructions.

In the case of an unshielded or lightly shielded Category 1 source at measurement distances where the detector is not yet saturated, pulse pileup complicates the isotopic identification. At shorter measurement distances, the use of less sensitive search instruments without isotopic identification capabilities such as Geiger-Mueller tubes are required due to the excessive count rate saturating the instrument response.

VI. SUMMARY

- Category 1 gamma ray sources are very highly radioactive materials used in a variety industrial, medical, and academic applications throughout the United States.
- Exposure to an unshielded or lightly shielded category 1 source is extremely dangerous to life and health and can be fatal in relatively short exposure times measured in seconds to minutes.
- A Category 1 source packaged according to the guidelines dictated by the NRC and U.S. Department of Transportation will typically be surrounded by a large amount of dense shielding material, but will still exhibit a significant dose rate in close proximity.
- Detection ranges for Category 1 gamma ray sources can extend beyond 5000 ft, but will depend mostly on the source isotope and activity, and the level of shielding around the source. Category 1 sources are easy to detect, but difficult to localize.
- Dose rates in proximity to an unshielded Category 1 source are extraordinarily high. At distances of a few hundred feet, the functionality of many commonly used handheld instruments will be extremely limited for both the localization and identification of the source.
- Radiation emitted from a Category 1 source will scatter off of both solid material (ground and buildings) and the atmosphere, a phenomenon known as skyshine. This scattering affects the ability to easily localize and find the source.

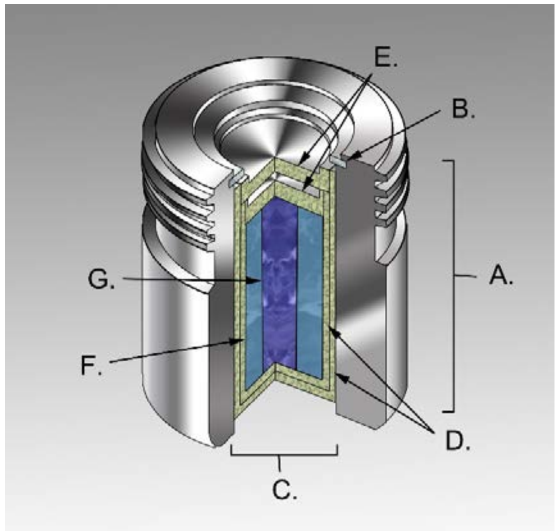
ACKNOWLEDGEMENT

This product was funded by the Department of Homeland Security's Domestic Nuclear Detection Office's Technical Reachback Program.

The Los Alamos National Laboratory's Off-Site Recovery Project team contributed the majority of the information used in this paper for Category 1 source configurations. The authors wish to acknowledge this contribution and thank the team as well as their sponsor, the NNSA Office of Radiological Security, for supporting this work.

APPENDIX 1 EXAMPLES OF CATEGORY 1 SOURCE CONFIGURATIONS

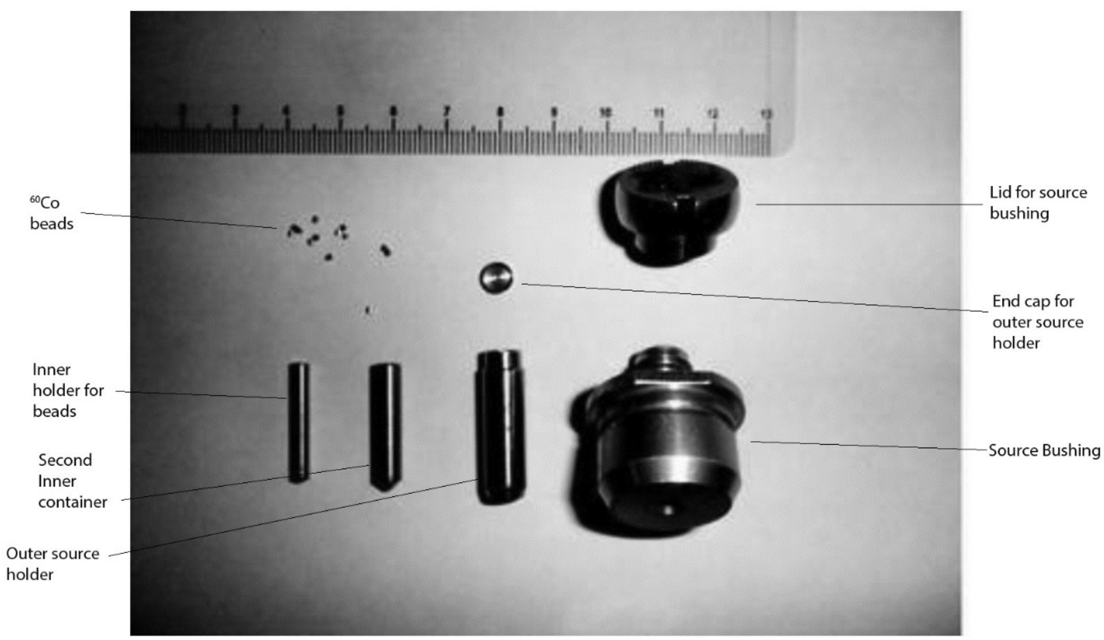
Most teletherapy sources appear to be constructed to the international teletherapy radiation capsule design[4] shown below.



(A) International standard source holder (usually Lead), (B) a retaining ring, and (C) Teletherapy source composed of (D) Two nested stainless steel canisters welded to two (E) stainless steel lids surrounding an (F) internal shield (usually uranium metal or a tungsten alloy) that protects a (G) cylinder of radioactive source material (normally ^{60}Co).

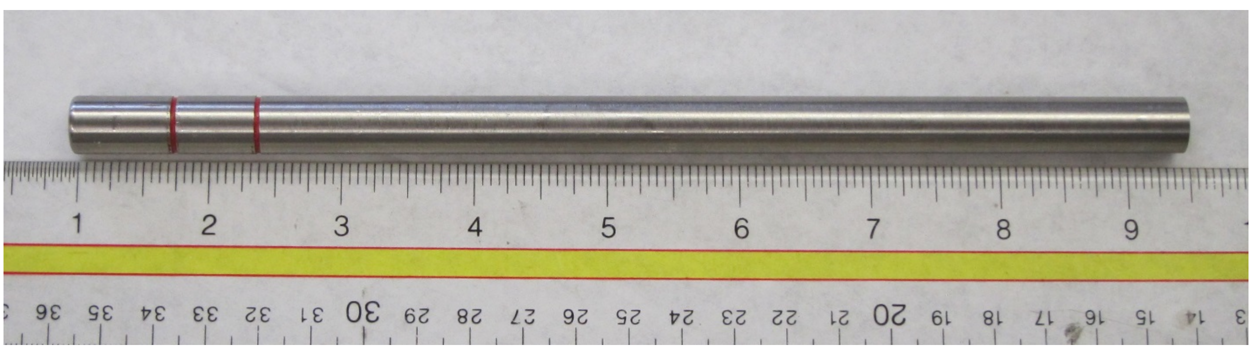
Below is a photograph of replicas of the holder, without the retaining ring. Two outer casings are shown in the figure below. The fully sealed source (components C-G above) is represented by the silver canister that is inserted into the replica of component A (casing on the right) from the drawing above. The scale in the picture is in inches. The dimensions of the components in the photograph are typical of those for real teletherapy sources.

The picture below[5] shows all of the components, including, ^{60}Co metal beads, that are used to fabricate a single source for a Gamma Knife. The scale in the picture is in centimeters. The radioactive beads are inserted into the inner holder which is sealed and inserted into the second container and sealed. This package is sealed into the outer source holder then inserted into the source bushing and capped with a lid that is engraved with a unique serial number. This number is also engraved on the source bushing.



A photograph of a fully assembled source holder/bushing is shown below, to the left. The dimensions (scale in inches) are typical of an actual Gamma Knife source. The image to the right shows the source bushing opened with the engraved serial number visible.

Industrial irradiation facilities, blood irradiators, and research irradiators typically use sources that are configured in a shape that is generically referred to as a source "pencil". The picture below is a replica of a source pencil that might be found in a blood irradiator or research irradiator. The scale in the picture is in inches. Pencils found in an industrial irradiation facility would typically be approximately twice the length of this example but could be as large as about 1.4 inches in diameter and 28 inches long.



Radioisotope Thermoelectric Generators (RTGs) with ^{90}Sr as the radioactive source are typically used as terrestrial power sources in remote locations in Arctic regions. In the U.S. most of these locations are, or have been, in Alaska. The picture below shows a schematic[6] of a typical ^{90}Sr-based RTG on the left and a photograph of a Russian RTG[7] on the right.

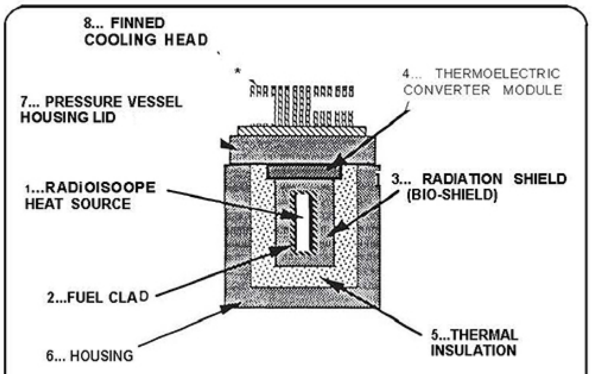


FIGURE 2. Schematic Diagram of a Typical RTG Used for Terrestrial Applications. The diagram illustrates the major features of an RTG.

APPENDIX 2 INSTRUMENT RESPONSE TO HIGH GAMMA COUNT RATE ENVIRONMENT

Detector	Detector Type	Maximum Dose Rate	Functionality Notes
Radiation Pager™	Personal radiation detector	Radiation Pager-S: 12 mR/h Radiation Pager: 4 mR/h	Beyond the maximum dose rate, a “9” reading will persist despite decreasing the sensitivity via the update function. Near saturation, reading will not smoothly increase to max value of “9”.
Interceptor	Personal radiation detector	100 mR/h (1 mSv/h)	The instrument will power off at 100 mR/h.
IdentiFinder	Handheld	> 50 R/h. Dose reading accuracy diminishes above 1 R/h (GM)[9].	Neutron detection and spectrometer shut down and GM tube enabled at 50 mR/h. Up to a 50% decrease in reported dose rate is observed when this occurs. For older models, operator is not alerted that the spectrometer is deactivated at high dose rate. At very high count rates will display warning “False neutron alarms

			possible" Overload alarm beyond 10 R/h but will display values beyond 50 R/h.
RadSeeker	Handheld	20 mR/h	Susceptible to pile up peaks. Dose rate will saturate at 20 mR/h and operator alerted via gamma saturation alarm. Mulitple detector saturation alarms and detectors powered off at very high gamma count rates.
GR-135	Handheld	10 R/h. Dose reading accuracy diminishes above 1 R/h (GM)[10].	GM tube enabled at 2 mR/h. "Search+Dose" mode: Count rate limited to 65535 cps. Dose rate display limited to 10 R/h. Overload warning triggered at 10 R/h. "Identify "mode: Very slow display updates and excessive dead times in very high gamma count rate environment.
Micro Detective	Handheld	>5 R/h. Dose reading accuracy diminishes above 1 R/h (GM)[11].	Susceptible to pile up peaks and degraded energy resolution. Above ~250,000 cps, gamma rate drops to zero and then will be reported as 1000-10,000 cps. GM tube enabled at 2 mR/h. Dose readings displayed beyond 5 R/h. "Identify" mode: Detector will display "Elevated radiation field" warning but no indication that count rate is too high for identification.
Inspector (2x2 in. NaI probe)	Handheld	>25 R/h. Dose reading accuracy diminish above 10 R/h (GM) [12].	Voltage to PMT turned off if the dose rate from the GM tube exceeds 1 R/h. "Dose" mode: Display will read up to 25 R/h. Beyond this, reading rapidly drops to ~ 6 R/h with no displayed warning.

			Spectrum mode: "High dose field" and "Probe Stabilizing" warning displayed and no data acquired at excessive gamma count rates.
Detective EX-100	Handheld	>5 R/h. Dose reading accuracy diminishes above 1 R/h (GM)[13].	Very susceptible to pile up peaks and degraded energy resolution. GM tube enabled at 2 mR/h. In addition to the behavior of the Micro Detective, false neutron count rates observed above 1 R/h, exceeding 100 cps for gamma dose rates above 2 R/h.
RadPack	Backpack	12 mR/h per module	Acquisition pauses for a few seconds as the detector changes its sensitivity range. A "9" reading will persist despite decreasing the sensitivity via the update function when the dose at any individual module reaches 12 mR/h. Very slow detector display response above 50,000 cps. Due to this behavior, detector becomes nearly inoperable at count rates beyond 75,000 cps. Beyond 50,000 cps, false neutron count rates above 100 cps are observed.

VII. REFERENCES

1. Code of Conduct on the Safety and Security of Radioactive Sources, IAEA, Vienna, 2004.
2. IAEA-TECDOC-1344 Categorization of Radioactive Sources: Revision of IAEA-TECDOC-1191, Categorization of Radioactive Sources, IAEA, Vienna, 2003.
3. IAEA Nuclear Security Series No. 5 Technical Guidance, Identification of Radioactive Sources and Devices, Reference Manual, International Atomic Energy Agency Vienna, 2007.
4. https://en.wikipedia.org/wiki/File:Teletherapy_Capsule_3.svg
5. http://www.researchgate.net/figure/278698840_fig27_Figure-9-A-Gamma-Knife-source-and-bushing-assembly

6. U.S. Congress, Office of Technology Assessment, *Power Sources for Remote Arctic Applications, OTA-BP-ETI 129* (Washington, DC: June 1994).
7. https://en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator
8. D. Reilly, N. Enselin, H. Smith, and S. Kreiner, eds., *Passive Nondestructive Assay of Nuclear Materials* (United States NRC, 1991).
9. Identifinder R400, User manual, Flir.
10. GR-135 The Identifier System Manual, Rev 3.4, Exploranium Radiation Detection Systems, July 2004.
11. Micro-Detective Ultra-Light, High-Fidelity Hand-Held Radioisotope Identifier, User manual, Ortec.
12. Inpector™ 1000 Digital Hand-Held MCA User's Manual, Ver 1.1, Canberra, 2004.
13. Detective-EX-100T and Detective-DX-100T, HPGe-based Hand-Held Radioisotope Identifiers, User manual, Ortec.
14. NRC Regulations, Title 10, Part 71.
15. U.S. Department of Transportation Regulations review, Radioactive Material, 2008.