Technically Speaking

by Dr. John S. Nordin, PhD.

Detection of Radiation from Illicit Materials

The release of dangerous radioactive substances on civilian populations by a terrorist as in a dirty bomb is one of the worst-case situations short of a nuclear blast itself. AristaTek has written an earlier article on "dirty bombs" and the havoc that they may create (see March 2003 Newsletter, Technically Speaking). This newsletter article looks at the problem of locating illicit radioactive materials, of the type that might be used to make a dirty bomb. Let us first review some radiation basics.

Radiation Basics

Of the approximately 200 different radioactive isotopes listed in the PEAC tool, only a few stand out as being highly suitable for radiological terror. These are cesium 137, cobalt 60, californium 252, strontium 90 (at its short-lived daughter product yttrium 90), iridium 192, radium 226, plutonium 238, and americium 241.

Example: Cesium 137:

Let us look at cesium 137 as an example. We will set the PEAC tool to read metric units, go to "radioactive isotopes", select "cesium 137" or "Cs 137" and look at the PEAC tool display. Sometimes cesium 137 is written as ^{137}Cs. The number "137" is the sum of the number of protons (55) plus neutrons (82) in the nucleus of the cesium atom. The atomic number (55) is the number of protons. An atom must have the right number of neutrons and protons to be stable. If there are too few or too many neutrons for the number of protons, the atom will shed some of its excess mass (in the form of alpha or beta particles or even neutrons depending upon the radioactive isotope). In the process of shedding mass, a minute portion of the atom mass will be converted to energy. In the case of Cesium 137, much of this energy will be converted to gamma radiation with an energy level of 0.6616 MeV (million electron volts). A beta particle will be ejected from the nucleus, which will have a kinetic energy of up to 1.176 MeV. The beta particle has a mass (same mass and charge as an electron) and will slow down and eventually stop as it interacts with the surrounding air. The maximum travel distance of the beta particle from the Cesium 137 source can be calculated (e.g. 419 cm in air at sea level). On the other hand, gamma radiation has no mass and can travel much further. Theoretically, gamma radiation can travel an infinite distance in the vacuum of outer space. If there is some material in the way, the gamma radiation will eventually be absorbed as it penetrates the material.

Cesium 137 has a half life of 30.2 years. This means that if there is a canister containing some cesium 137, half of the cesium 137 will be gone after 30.2 years. The cesium will be converted to barium 137, which is stable, meaning that there is no further radioactive decay. A barium 137 atom contains 56 protons and 81 neutrons. One of the neutrons of the cesium 137 atom has been converted to a proton and a beta particle plus energy (kinetic energy of the expelled beta particle plus the gamma radiation) to give barium 137. When barium 137 is initially formed (designated barium 137m, with a half life of 2.55 minutes), some x-rays are given off before forming the stable isotope barium 137. We can't predict when an individual atom of cesium 137 will undergo radioactive decay, but a few milligrams of cesium 137 will contain many billions of atoms and half of these will be converted to the stable (non-radioactive) barium 137 after 30.2 years.

The PEAC tool display shows cesium 137 has a radiation activity of 86.7 curies per gram. Radiation activity can be calculated directly from the half-life, e.g.

$$\text{Radiation activity} = 1.31(10)^8 / [(\text{half-life in days})(\#\text{ of protons + neutrons})]$$

For Cesium 137,

$$\text{Radiation activity} = 1.31(10)^8 / [(30.2)(365)(137)] = 86.6912 \text{ Ci/g}$$

Sometimes radiation activity is expressed in Becquerels (Bq). To convert Curies to Becquerels, multiply by $3.7(10)^{10}$.

People have asked, what does cersium 137 look like? Is it a powder and what color is it? How can I recognize it?. Cesium 137 looks like any other chemical. It may a powder, an aqueous solution, a solid, or mixed with other chemicals. It may be in the form of cesium chloride (CsCl), cesium fluoride (CsF), cesium sulfate (Cs_2SO_4), cesium hydroxide (CsOH) or some other chemical. The only way of detecting it is by the radiation given off, in particular, gamma radiation with an energy level approximately equal to 0.66 MeV. A first responder investigating a mysterious package or canister might be tipped off if the package is unusually heavy for its size because of lead shielding, but there is no guarantee that a terrorist will adequately shield the package. The radiation given off would cause the canister to feel warm to the touch, but by that time the responder would already have been exposed to dangerous radiation.

Example Cobalt 60:
Let us look at Cobalt 60 (or Co 60) in the PEAC tool. A Cobalt 60 atom has a nucleus with 27 protons and 33 neutrons. The half life of cobalt 60 is 5.271 years. When a cobalt 60 atom undergoes radioactive decay, a neutron is converted to a proton and a beta particle and a very small amount of mass is converted to energy. The energy shows up in part as kinetic energy of the beta particle, which is ejected from the atom, and partly as gamma radiation. Each atom disintegration produces gamma radiation at two energy levels, 1.1732 MeV and 1.3325 MeV. If a responder had a gamma radiation detector capable of measuring gamma radiation at different energy levels and measured radiation at 1.1732 MeV and 1.3325 MeV, some cobalt 60 would be expected to be nearby. The cobalt 60 atom undergoing radioactive decay is converted to nickel 60, which is a stable atom and does not undergo further radioactive decay. Nickel 60 has 28 protons and 32 neutrons.

Example Californium 252:
The PEAC tool display for Californium 252 (or Cf 252) shows that a lot of things happen with this radioactive isotope as it undergoes radioactive decay. A californium 252 atom contains 98 protons and 154 neutrons. The half life of Californium 252 is 2.65 years. Most (96.9%) of the atoms undergoing radioactive decay shed a mass equal to two protons and two neutrons (called an alpha particle, or alpha radiation) from the atom nucleus forming curium 248. The curium 248 nucleus has 96 protons and 152 neutrons, and also undergoes further radioactive decay. The other (3.1%) of the atoms of Californium 248 undergo spontaneous fission, that is, the atom splits apart forming smaller fragments. There are many different ways that Californium 248 can split into smaller atoms. These fragments are also radioactive, that is, they may shed alpha and beta particles plus more gammas radiation. During the fission process itself, neutrons and beta particles will be expelled from the atoms plus accompanying gamma radiation. Neutrons can travel far from the source and can inflict severe damage to the human body. Prompt gammas refer to gamma radiation emitted at the time the atom undergoes fission; delayed gammas refer to later gamma radiation. Almost all (99+%) of the neutrons emitted at the time the atoms undergoes fission are prompt, that is, they are emitted at the time of fission. Very few (<1%) are delayed.

If cerium 248 is pulled up on the PEAC tool, the display shows a half life of 340000 years. When cerium 248 undergoes radioactive decay, 92% of the atoms shed an alpha particle producing plutonium 244 and the other 8% undergo spontaneous fission producing various smaller atom fragments, neutrons, gamma radiation, and beta particles. Plutonium 244 has a very long half life (82 million years), but eventually it too will shed an alpha particle (99.9% of the atoms) producing uranium 240; a small fraction (0.1%) will undergo spontaneous fission. Uranium 240 has a short half life (14.1 hours) shedding a beta particle producing neptunium 240, and then plutonium 240, and so on, until stable elements are eventually produced many millions of years later.

What Does Radiation Basics Tell Us?

Two things given off by radioactive materials can be measured by detection equipment located at a distance. One is gamma radiation, the other is neuron particle radiation. Gamma radiation is given off by radioactive isotopes, which can be used to make a dirty bomb. Neutron radiation is given off by

certain heavy radioactive isotopes (atomic number 92 or greater) undergoing at least some fission, and could mean the presence of ingredients to make a nuclear bomb. These heavy radioactive isotopes also give off gamma radiation.

Alpha and beta particles do not have enough kinetic energy to travel from the source. Alpha particles can travel at best only a few centimeters and beta particles only a few meters in air. Gamma radiation and neutrons do not have that restriction. Some of the natural gamma radiation reaching the earth originated from galaxies millions of light years away.

Gamma and neutron radiation decrease inversely approximately as the square of the distance from the source. This means for example there is a flux of a million neutrons per square centimeter (or a million gamma photons per square centimeter) at a ten meters distance from the source, there would be approximately 10,000 units per square centimeter 100 meters from the source. The word "approximately" is used rather than "exactly" because some scattering takes place as the radiation travels through the air.

Another thing radiation basics tell us that each radioactive isotope is different. The various energy levels associated with gamma radiation represent a signature for that isotope allowing it to be identified. Mixtures of several radioactive isotopes will be more difficult to identify, but even these may have recognizable signatures at distinct gamma energy levels.

Gamma and Neutron Signatures

Let us look at some gamma and neutron radiation measurements that might be recorded by a monitoring system. The detection systems for gamma radiation and neutrons are different so we will look at gamma radiation first. Gamma radiation detectors are available which simply give a total count rate, but we will look at a system that gives the total gamma-ray spectrum as a function of energy level. This will help in identifying of the radioactive isotopes and to distinguish between the target illicit material and natural radiation background.

Figure 1 shows a hypothetical tracing of what background radiation might look like for a detector allowed to record counts at different energy channels [1000 KeV = 1 MeV] for some specified period of time. The natural radiation comes from many sources, the rocks and soils of the ground, building materials, radiation from outer space, and some minute residuals from nuclear tests conducted decades ago.

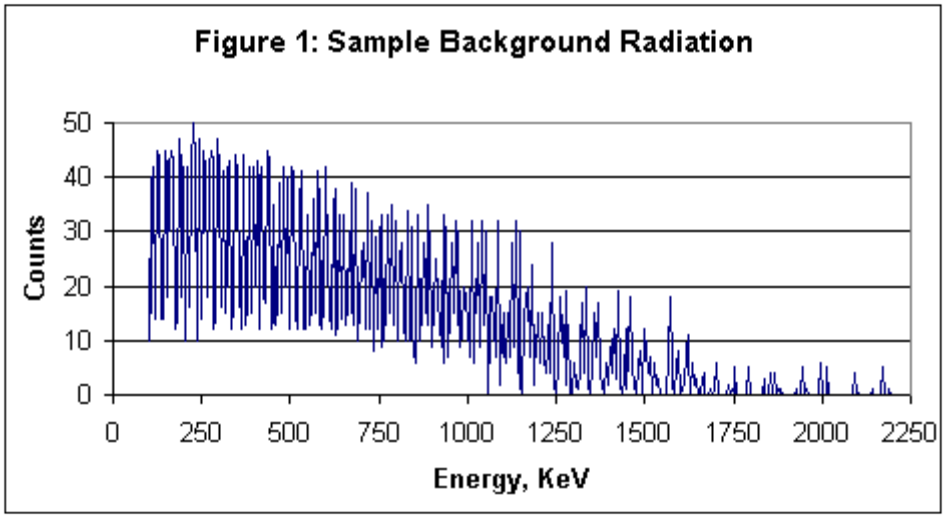
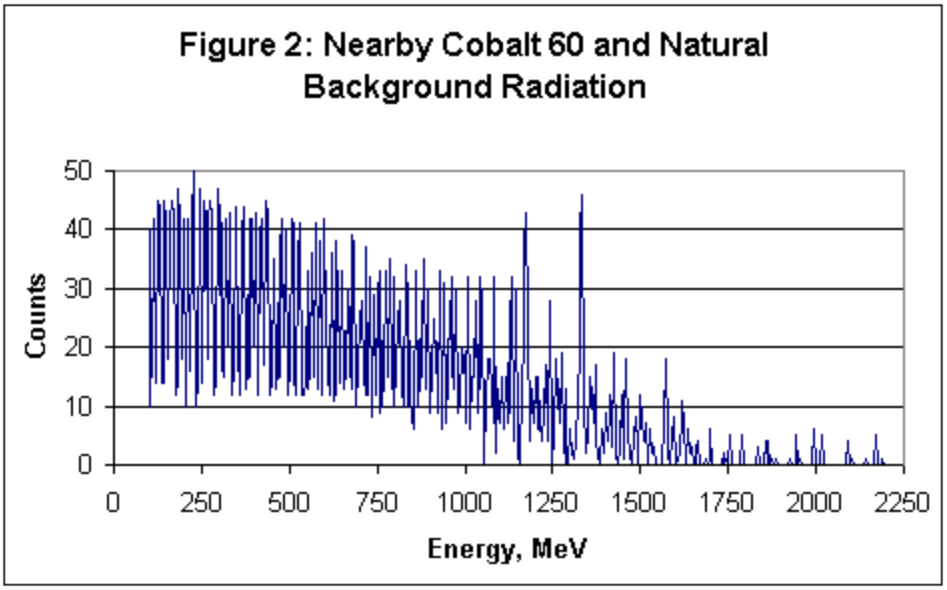


Figure 2 shows a plot at the same location and for the same time period but with some cobalt 60 located perhaps 100 meters away. The increased counts at energy levels near 1.173 and 1.333 MeV represent a signature for cobalt 60.



Recall that gamma radiation decreases inversely as the square of the distance from the source. As the detector moves further from the cobalt 60 source, the cobalt 60 counts will blend into background. But if the detection system does identify peaks, the instrumentation system can be set to measure counts at these energy levels and move into the source.

If the detection system only measured the total gamma count summed over at all energy levels, it probably would not be sensitive enough to make a distinction from background unless it moved in relatively close to the source. Being able to rapidly measure gamma radiation at different energy levels allows for better distinction from background at greater distances. This is important in the detection of illicit materials which may be hidden and partially shielded.

In the case of neutron radiation, natural background neutron radiation is extremely low. Therefore the neutron detector need only measure the total neutron count rather than consider neutrons at different energy levels. For example, the total neutron count per unit time reaching a detector say 30 meters away from 0.000001 grams of Californium 252 will still be several times background, and could be picked up by an appropriate detector. As the detector moves in closer, the count rate should go up by roughly a factor of 100 as we moved in by a factor of 10. Again, the neutron flux varies approximately as $1/r^2$ where r is the distance from the source. The relationship is approximate because of neutron scatter in the air and from the ground.

A description of a vehicle-carried gamma and neutron detection system is available at http://www.ortec-online.com/papers/cartop_inmm04.pdf. The system described is the ORTEC NaI-SS Portable Search System, available at a cost of $68,600 (as of February 2005). ORTEC (Oak Ridge, TN) is a subsidiary of AMETEK, Inc. The system is designed to operate in a moving car. The paper at the website presents drive-by test results for Cesium 137 and Cobalt 60 gamma radiation sources and Californium 252 neutron sources. The system also includes a Global Positioning System (GPS) to determine its location while each spectrum and count is collected.

Shielding

- Gamma Radiation. Denser materials, especially lead, are most effective in reducing gamma radiation from the source. A lead shield does not stop the radiation but only reduces it. Higher energy gamma radiation are more likely to pass through shielding than lower energy gammas. From a practical standpoint, this means that the detection equipment must move in closer to the source to detect radiation from background.
- Neutron radiation. While more dense materials are generally more effective in reducing neutron radiation, there are also many exceptions. The neutrons interact with nuclei of any intervening material; the neutrons may either be absorbed by the nuclei or scattered by the nuclei of the material. Some of the energy produced as the result of the collisions may be emitted as gamma radiation. Certain elements, in particular boron 10, are rather effective in slowing down neutrons. The mineral colemanite, which has a high proportion of boron, may be incorporated into concrete as an effective shielding material. Gamma radiation with energy 0.48 MeV is produced as the result of interaction with boron 10. The addition of iron and/or barium to concrete also attenuates neutrons. Again, from a practical standpoint, shielding means that the detection equipment must move in closer to the source to detect neutrons.

How Safe Is It to Approach Radioactive Materials?

We will look at gamma and neutron radiation only. Alpha and beta particles carry a charge and can travel only a finite distance, which is a function of their kinetic energies only. Alpha particles will be stopped by the canister containing the radioactive material. Beta particles can easily be contained by shielding. Gamma photons and neutrons can travel much further.

There are a couple of ways of estimating of how safe it is to approach a canister containing a radioactive material.

- If the radioactive material is identified and the quantity is known (e.g. 100 microcuries of Californium 252; 10 grams of Cesium 137, etc.), the gamma and neutron radiation flux can be calculated as a function of distance from the source. The flux is calculated at each energy level. Once the fluxes are known, the fluxes are converted to dose (in units of rems or sieverts).
- If the radioactive material has not been identified and the quantity is not known, detection equipment capable of measuring neutron radiation and gamma radiation is necessary. The gamma radiation detector should be capable of measuring the gamma radiation at different energy levels. The gamma radiation signature may allow identification of the radioactive material at a distance without going near the source. Once the radiation count at various energy levels is measured at a at least a couple of locations plus background, the fluxes are calculated, and the fluxes converted to dose.

As a rough rule of thumb, the dose due to normal background radiation at an uncontaminated site is about 150 mrems per year [1000 mrem = 1 rem]. Special circumstances such as use of some granites in building materials, a high elevation site, or radon gas exposure in some buildings could boost background radiation dose another 50 to 400 mrems per year. The U.S. National Council on Radiation Protection (NCRP) recommends the an annual whole body exposure limit of 5 rem in one year for workers in the nuclear industry, or an accumulated whole body exposure for adults of [(age in years – 18) x 5] rems above normal background. Dose is accumulative, meaning, if a person receives an 1 rem dose from a radioactive source in one incident plus another 1 rem dose from another incident one year later, the total dose is 2 rem.

The PEAC tool contains information relating dose to adverse effects such as increased risk of cancer, radiation sickness, and probable death.

The calculations for computing radiation fluxes and dose are very complex. We can give only a rough outline of the steps involved and present some answers for a couple of radioactive isotopes. A

basic starting step is the equation relating flux (number of gamma photons or neutrons per square meter per second) at distance d from the source to the number released per second, e.g.

$$\text{Flux} = S/(4\pi d^2)$$

where S = source strength (number of neutrons or gamma ray photons per second)
d = distance from the source, meters

The above equation is true for a vacuum. In an actual situation there will be air and other materials between the source and location at distance d. Various factors must be added to the equation to account for this.

$$\text{Flux} = B\ S\ e^{-\mu d}/(4\pi d^2)$$

B = buildup factor, dimensionless
μd = number of mean free paths, dimensionless

The flux must be computed separately for each gamma photon energy level. A similar expression is used for neutrons at each energy level. Values for B and μd are calculated from other mathematical expressions and lookup tables [such as in Appendix D and E of N. Tsoulfanidis, 1983, Measurement and Detection of Radiation, McGraw Hill]. When we get done, we get a table of fluxes of gamma radiation and neutrons at various energy levels at distance d from the source. The fluxes are then converted to rems (or sieverts) using tables in
"Neutron and Gamma-ray Flux-to-Dose Rate", American National Standard, ANSI/ANS-6.11-1977. The rems (or sieverts) are summed for each energy level to get a total dose.

If the amount of radioactive material is known, the source strength can be calculated. Conversely, if the fluxes can be measured at several locations using detection equipment, the source location can be pinpointed, the radioactive isotope identified from its energy signature, and the source strength estimated. This will help in providing an estimate of safe approach. The PEAC tool gives the number of curies per gram of material from which the number of disintegrations can be calculated [1 disintegration per second = 1 Bq = 2.703×10^{-11} curies]. The intensities in the PEAC tool give the percent of disintegrations that result in gamma radiation of that energy level.

For example, the flux of gamma photons from 1 gram of Cesium 137 at a distance of 10 meters in air is $2.7543\ (10)^9$ photons/m^2-s. This converts to a dose of 0.402 rem/hr. There is only one gamma energy level to consider (0.66 MeV) and no neutron emissions.

The calculations for 1 gram of Californium 252 are much more complex. Gamma radiation at various energy levels plus neutron radiation also at various energy levels (up to about 13 MeV) are emitted. Each energy level must be separately calculated. When we are done, the dose received by a person located 10 meters away is calculated to be roughly 30 rem/hour (roughly, because neutron scatter from surrounding materials and the ground results in some uncertainty in the calculations).

At 100 meters away, the rem dose for the cesium 137 example would probably be on the order of 0.004 rem/hour. For the californium 252 example, the dose at 100 meters might be on the order of 0.3 rem/hour. With a background dose of say 0.3 rem/year [= 0.0000342 rem/hour], detection equipment located 100 meters away should be able to measure these materials remotely, assuming that the source has minimal shielding.

Example Radiation Detectors (assembled February 2005)

RAE Systems. AreaRAE Gamma. Multi-gas and Radiation Monitor. Total gamma radiation count between 0.06 MeV and 3 MeV. Scintillation crystal detector. Approximate cost $3500. Specifications at http://www.raesystems.com/~raedocs/Data_Sheets/AreaRAE_Gamma.pdf
GammaRAE II. Total Gamma radiation count. Cesium iodide scintillator. Cost $1000. See http://www.energyvortex.com/pages/headlinedetails.cfm?id=1616.
NeutronRAE Pager. Total gamma or neutron counts. Gamma count between 0.033 and 3 MeV, neutron count between thermal and 14 MeV. Cesium Iodide and lithium iodide scintillators. Cost about $3300. Details at http://www.calcert.com/pdf/NeutronRAE_pager.pdf.
http://www.mlu.at/en/instruments/neutronrae_pager_e.html.
SAIC (Canada) GR-110G Handheld Survey Gamma Radiation Detector. Total gamma radiation count between 0.045 MeV and 3 MeV. Sodium iodide detector. Specifications at http://www.saic.com/products/security/gr-110/gr-110-tech.html.

POLISMART Instruments. Several personal gamma radiation monitors. PM1801 model allows accumulation of gamma MeV spectra for isotope identification. Cesium iodide detector. Looks like an oversized cell phone. Details at http://www.energyvortex.com/pages/headlinedetails.cfm?id=1616.
Gamma-neutron PRD & RIID PM1802 detector for gamma and neutron radiation at http://www.polismart.com/model2.htm.
Technical details for PM1402 monitor at http://polimaster.com/download/pm1402mom.pdf.

Polimaster, Inc.. Alexandria VA. Various gamma and neutron radiation detectors. Details at http://www.polimaster.com/ENGL/tech_dev/1402_E.htm. General website http://www.polimaster.com/index.html. Some also available through RAE Systems, Inc.

D-tect Systems., Division of Mission Research Corporation. Gamma radiation detector useful for detection of gamma radiation in luggage, packages, or setup at doorways. Sodium iodide detector with Thallium scintillator. Cost about $10000. Details at http://www.usascan.com/pdf/rad-d.pdf. Detector measuring gamma energy spectra for remote identification of isotopes:
http://www.dtectsystems.com/dtectdocs/rad-ID%20specs.pdf .

StarDot Technologies (California). Remote gamma radiation detection equipment. http://www.stardot-tech.com/media/stardot_pr_radnetcam.pdf. Information and images from stationary detectors sent via Internet to authorized users.

Aspect Scientific Production Center (Russia). Gamma radiation and neutron detectors. http://aspect.dubna.ru/english/page.php?page=342.

Sensor Technology Engineering. Small hand-held gamma ray and thermal neutron monitor mentioned by DOD (TSWG) for use by first responders. http://www.tswg.gov/tswg/tos/tos_currpr.htm.

Inovative MicroSensors, Inc. Gamma and neutron radiation detector chips and detectors. Various costs up to about $11,000.
Details at http://www.ia-tec.com/Security/BSU3.pdf.

Synodys (MGP Instruments Inc., Smyma Georgia) PDS100GN pocket sized personal gamma and neutron radiation detector.
http://www.army-technology.com/contractors/nbc/synodys/synodys4.html.

ORTEC, Oak Ridge, TN. Gamma and neutron radiation source detector. Idendifies radioactive isotope by energy spectra. http://www.ortec-online.com/pdf/detex.pdf.