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Large Radiological Source Applications: RDD Implications and Proposed Alternative Technologies

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Abstract- *Because of their widespread usage and vulnerability to theft, large radiological sources are a major concern for possible use in Radiation Dispersal Devices (RDDs), a.k.a., dirty bombs. These applications developed prior to recent concerns about terrorism and RDDs, so the source designs, uses, and handling practices are not optimized to reduce the vulnerabilities. Although there are many radiological source applications and millions of sources in use, the number of large applications and the total number of large sources is more manageable. A review of the large source applications and possible alternate technologies indicates several potential strategies for reducing the RDD vulnerabilities.*

I. INTRODUCTION

The recent growth of terrorism has increased concerns about radiological sources, namely whether they could be used in radiation dispersal devices (RDDs), or "dirty bombs" so as to create both panic and large economic consequences.[1,2] Although there are many variables that can make an RDD attack worse, a key factor is the quantity and type of radiological source material that is dispersed. Because the number of radiological sources that are large enough to create a very damaging RDD is small compared to the total number of radiological sources in use, it is possible to significantly reduce the risk of a very bad RDD. An important class of options in reducing the availability/ vulnerability of large and dangerous source materials is through the use of alternate technologies. A range of options is available, including replacing the application, using less worrisome radioisotopes and/or chemical forms, and the use of gadgetry to make the sources less vulnerable to theft (or make recovery of the source more likely). In this paper, we'll discuss several viable options and recommend some of the more attractive alternatives.

II. LARGE RADIOLOGICAL SOURCE APPLICATIONS

The focus on radiological sources was driven by the perception these sources are widely available and vulnerable. At the most fundamental level, radiological sources are used for three purposes:(1) to kill or otherwise alter organisms or tissue, (2) to generate energy on a localized and/or remote basis, or (3) to scan objects or provide other types of measurements.[3] Some of these have features that would make them desirable as RDD sources. Others materials not included in this study would also make desirable RDD materials, and there is some chance they might be acquired and so utilized.

Industrial Irradiators

Large industrial irradiators are typically regional facilities, used for sterilizing medical suppliers and irradiating food products. There exist approximately 190 such facilities world-wide.[2] The facilities typically use hundreds of Cobalt-60 *pencils* to deliver gamma radiation. Cobalt-60 is the preferred isotope in this process, however cesium-137 can also be used. The activity level generally ranges from 100,000 to 5 million curies of cobalt, though REVISS has designed an 8 million curie capacity irradiator. The largest known cesium unit contains 250,000 curies. Most, perhaps all, such industrial irradiators were developed by Western companies and are equipped significant safety and security features.

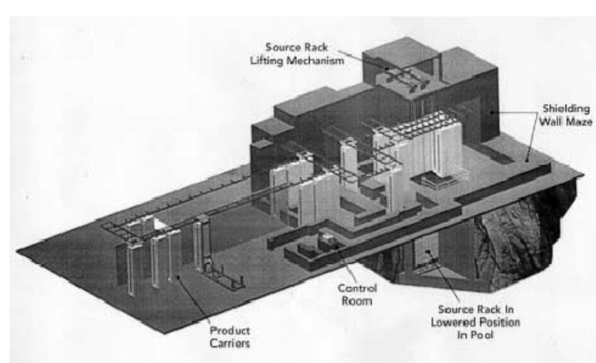


Figure 1. Large Industrial Irradiators [2]

The manufacturing industry of irradiation and sterilization facilities is rather limited due to the high entry costs of development. Many irradiators have been purchased with international assistance and the transactions have generally been documented. Since 1980, the IAEA, through its technical cooperation program, has supplied 40 cobalt-60 irradiators to developing countries.

Food irradiation is a growing industry. Irradiation reduces bacteria and other contaminants, thus extending the shelf life of the product. According to the International Consultative Group on Food Irradiation (ICGFI), more than 50 countries have approved the irradiation of various foods. In 2002, the US Department of Agriculture approved importation of irradiated produce into the United States. The implications of this decision pertain to both the large industrial irradiators and the smaller, more mobile variations covered in the sections that follow.

The large industrial irradiators are generally provided industrial security, and they are self-protecting to the extent that anyone attempting to steal the source material will need to work carefully in order to avoid lethal doses of radiation. The need for frequent replenishment of source strength implies frequent shipments of significant quantities of cobalt-60, but again, these shipments have some of the same security features- in terms of personnel and radiation hazards. Because cobalt-60 has value (currently $1.50 per curie) and is routinely recycled, problems with disused and orphaned sources are minimal.

Mobile Irradiators

A recent application of irradiation technology is the development of mobile irradiators. These machines are designed to accommodate a variety of products, most common of which is agriculture. Tens of thousands of curies of a high-energy gamma emitter are loaded into these modified trucks and driven around various countries.

It is unclear to whom these mobile irradiators have been sold. With the growth in popularity of food irradiation and the fact that it can be difficult to bring large quantities of food to an irradiation facility that often serves the entire country, mobile technology could become much more common.

The concern regarding the mobile irradiators is that having a large inventory of cesium chloride already available in mobile form is disconcerting. If these devices were to be transported around a third-world country during the harvest season, the risk of theft would increase. Even the massive shielding that is required might not be a deterrent, as a lesser shielding mass would suffice if the perpetrators chose to transfer the material into some form of shipping pig/casket (at some personal risk in the process).

Research Irradiators

Research irradiators vary from their industrial counterparts in both size and application. Research irradiators are relatively small machines used for a larger variety of purposes. They can be used in dosimetry calibration, insect control, and materials research, as well as food irradiation and medical sterilization, albeit on a much smaller scale. The cobalt and cesium sources are also smaller, ranging from 2,000 to 24,000 curies, with cesium units generally residing on the lesser end of the continuum. There is one notable exception. The BINE irradiator, utilizes 100,000 curies of cobalt-60. Most large manufacturers of industrial irradiators also make irradiators for research applications.

Fig. 2. Co-60 Research Irradiators Cobalt-60 from Nordion

Research irradiators are utilized in laboratory environments, often in connection with research institutes. Because of the potential safety hazards, procedures to protect people from the radiation hazards are the norm. However, such institutions are unlikely to place much emphasis on providing rigorous security systems and procedures. Even worse, research institutions often face difficult funding cycles, so programs that fund the research irradiators can disappear leaving the institution with an under-funded and possibly disused source.

Seed Irradiators

During the 1970s, scientists in the Soviet Union designed seed irradiators using approximately 3500 curies of cesium chloride.[4] Under the project name Gamma Kolos, mobile irradiators were shipped by truck (see Fig 3) to parts of the Soviet Union as an agricultural research project to study the effects of radiation in plants. These experiments were organized in different climatic zones, including Latvia, Moldova, Apsheronsk peninsula (Caucasus), Moscow, St. Petersburg, Nizhnii Novgorod, Kazakhstan, Kyrgyzstan, Azerbaijan, and Uzbekistan.[2] Mobile seed irradiators disappeared after the 1970s due to their low capabilities and outdated conveyor systems. Several of these units were never returned to Russia and decommissioned. As a result, orphaned seed irradiators have turned up in several countries that were formerly part of the Soviet Union.

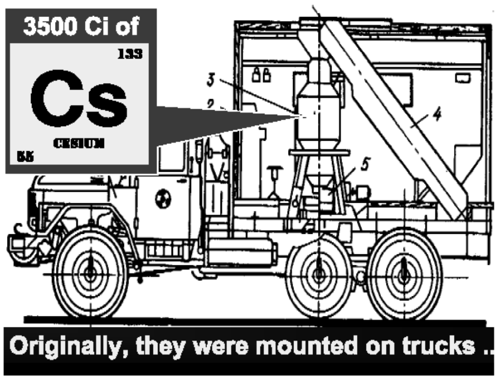


Fig. 3 Seed Irradiators were developed by Soviet Union

There is no known account of how many seed irradiators were produced or where they were sent. Estimates vary from 100 to 1,000 machines. Only nine irradiators have been found and properly stored (five in Georgia and four in Moldova). The best indication of the seed irradiator locations may be the locations of the agricultural research laboratories that participated in the test program, and the regions over which they conducted tests. Unfortunately, it appears that other agricultural laboratories also participated in the testing program, so these locations should not be considered bounding. The primary concern regarding is the orphans, which have turned up in a few locations around the former Soviet Union.

Teletherapy and Gamma Knife

In teletherapy, a radiation beam is focused on the cancerous portion of the patient's body. When teletherapy machines were first produced, they contained cesium sources. These were gradually phased out and replaced with cobalt material. Since the half-life of cobalt is much shorter than cesium (5 years vs. 30 years), the teletherapy equipment was redesigned to allow the radioactive sources to be easily removed and replaced. The radioactivity level of cobalt sources for teletherapy can range from 3,000 to 15,000 curies. In order to minimize collateral damage to surrounding tissue, the patient is exposed from several different directions over the course of treatments. Most of the 5300+ teletherapy units exist outside the Unite States, as the U.S. units were replaced by electron accelerators during the 1970s. Ironically, a major program to export the excess teletherapy units to poorer countries succeeded in proliferating the units, each containing several thousand curies of cobalt-60 or cesium-137, around the world. Any efforts to replace the teletherapy units with electron accelerators will be difficult in third world countries, as the cobalt-60 works without the reliable electric power needed by the accelerators. A less common variation on the teltherapy units is the so-called *gamma-knife*.[5] In this application, approximately two hundred cobalt-60 sources are configured so as to expose a brain tumor from many different angles. Around 10, 000 curies of cobalt-60 are used in this application, so it is comparable to the basic teletherapy units in that respect. There are thought to be dozens of these devices, mostly in Western countries.

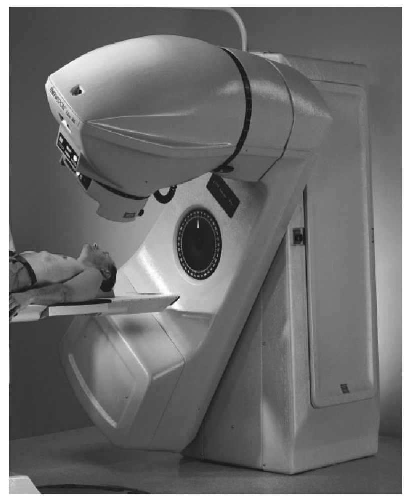


Fig. 4. Co-60 Teletherapy Machine from MDS Nordion

Identification of all teletherapy sources and devices worldwide is much more difficult than for large irradiators, since a large number of these devices were exported from the US and other developed nations for humanitarian purposes or simply to get rid of unwanted sources. The IAEA's DIRAC database (Directory of International Radiotherapy Centers) reports that there are 5,347 registered radiotherapy centers in the world housing roughly 2,350 cobalt-60 teletherapy devices and 45 cesium-137 units. [6] This database has it limitations, as all the information gathered was done via questionnaires, and no institution was obligated to respond. A few organizations may have compounded the source security problem by supplying less advantaged countries, which might lack the proper source controls, with teletherapy equipment. The IAEA has helped to establish teletherapy centers in many countries including Mongolia, Ethiopia, Nigeria, and Ghana. Additionally, Neutron Products, a US-based company, has shipped approximately 1600 teletherapy sources and 150 teletherapy units since the mid

1970's. It is very likely that some individual hospitals may have also exported their used equipment.

Fraudulent purchase of a teletherapy source is a distinct possibility, especially with credible purchases coming routinely from many countries around the globe. Although source suppliers routinely attempt to verify that source purchasers have valid licenses, this is not always practical in countries with minimal or changing governments. Because of the value of cobalt-60, problems with disused and orphaned sources should be minimal. There are teletherapy units that still use cesium-137 sources, however, and used cesium sources can be a liability, as was painfully demonstrated in Goiania, Brazil.[7] Some of the concerns regarding the vulnerability of the more common teletherapy units also apply to the gamma-knife devices, e.g., the hospital location.

Blood Irradiators

Blood irradiators sterilize blood using cesium-137 after it has been placed in blood bags and loaded into the ionizing chamber.[8] Irradiating blood reduces the risk of Graft-Versus-Host disease (GVHD), which occurs after bone marrow transplants and blood transfusions in patients with weak immune systems. Cesium-137 units contain an initial activity of 600 to 5000 curies, and are slightly bigger than a large filing cabinet. The cesium source is welded into the device, so the entire blood irradiator must be returned to the supplier for installation of a new source.

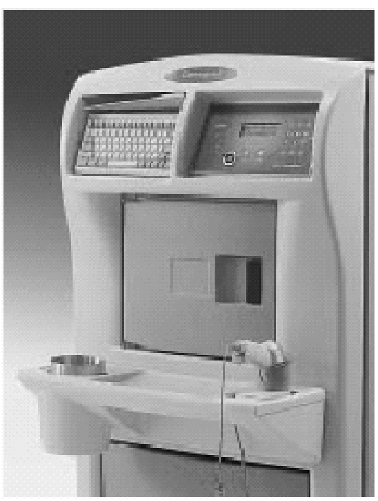


Fig. 5. Blood Irradiators Sterilize Blood

Concerns about blood irradiators are two-fold. First, as is true with the teletherapy class of devices, the use of blood irradiators in hospitals raises some security concerns. The size and weight of the device would surely discourage theft, but the theft of large objects from hospitals would not be unthinkable. Second, large inventories of cesium chloride are always a concern, especially since disposal concerns increase the likelihood of sources becoming disused. An x-ray based blood irradiator is also available, and this technology may induce users of the cesium blood irradiators to buy the new technology and export cesium units to poorer countries. In many instances, the only way for a hospital to get rid of a disused source is to purchase a new source from the manufacturer, in which case the manufacturer would likely exchange the new source for the old one. When there are disposal issues and disused sources, the likelihood of resale increases, and this could result in an unwanted blood irradiator finding its way to an illegitimate customer.

Sr-90 RTGs (Terrestrial)

Radioisotope Thermal-electric Generators (known as RTGs in the US and RITEGs in Russia) use the heat emitted from source decay to produce power.[9] Because the radiation generated by the decay of strontium-90 and its daughter yttrium-90 is via beta-particles, the energy is easily converted to heat, which is then converted an electric current. Plutonium-238 is also used in RTGs, but these units are much smaller and more expensive than the strontium-units, and reserved primarily for deep-space exploration missions (extra-terrestrial). The Soviet Union began manufacturing RTGs in the 1960's as lighthouses along its northern coast. Many RTGs have been deployed, mostly in the former Soviet Union and the United States. Some of the strontium units are as small as a few thousand curies, but some approach half a million curies. About 1000 such units were deployed in the former Soviet Union to provide power for lighthouses along the north coast. Both the Soviets and the U.S. also deployed quite a few units for military purposes.

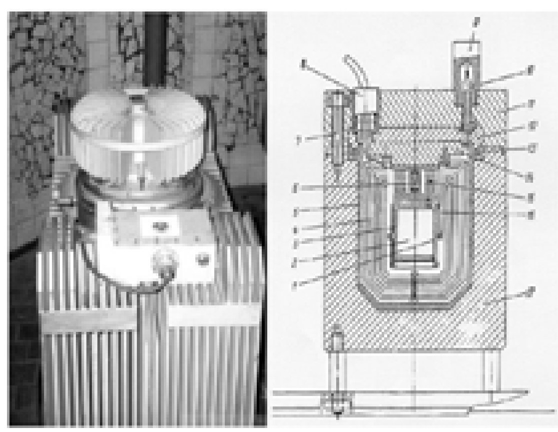


Figure 6. Soviet-made RTGs Power Russian Lighthouses

It would be difficult to steal an RTG due to its physical properties—it can weigh 800 - 8,000 pounds and generates a lot of heat, as well as the remote locations of the units.

Radiography

Radiography sources are mobile sources, although some are large enough to require heavy shielding and are thus mounted on carts. There are many radiography sources, with over ten thousand new sources sold every year. They are typically used to produce a gamma scan of welds, and are quite commonly found at construction sites. Although cobalt-60 and cesium-137 have been used in radiography sources, most of the new ones use iridium-192, or sometimes selenium-75 or ytterbium-169. Because iridium-192 has a half-life of 74 days, it is a good choice for such an application, as it is not uncommon for radiography sources to be lost or stolen. Radiography sources are purchased by numerous parties globally, and the chances for fraudulent purchases are relatively high. It would not be unusual for a radiography source to become disused or orphaned, although the short half-life of iridium clearly reduces the concern about this possibility.

Well-Logging

Well-logging sources are used in the oil well drilling business, as well as some other drilling and mining operations, in order to better assess the geology surrounding exploratory bore-holes. Most well-logging sources are used by large international oil-exploration companies, such as Schlumberger, Haliburton, and Baker-Hughes.[10] There may be five to ten thousand sources in use, with many containing a neutron source in the 15-20 Curie range to perform neutron activation analysis and other diagnostics. Well-logging sources also typically use a cesium source in the tens of curies to provide a simultaneous density scan. Well-logging units are highly mobile, are typically carted about on trucks, and are sometimes shipped from country-to-country.

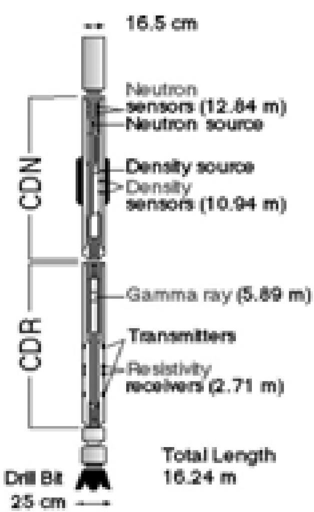


Fig. 7. A Well-Longing *Sonde* [10]

Well-logging sources are well-traveled, raising concerns about theft during transport and use. These are utilized by multi-national companies to search for oil in many parts of the world. But the oil exploration companies generally take their sources with them. The extent to which other companies, or perhaps even governmental entities in some countries, might be attempting to use well-logging sources on their own is not known. But the interpretation of the data from well-logging measurements is very difficult, so attempts by less sophisticated entities to use well-logging sources in oil exploration may not yield great success.

III. SETTING PRIORITIES IN DENYING ACCESS TO SOURCES

One can rank the larger radiological sources by radioactivity level, and clear patterns and priorities begin to emerge. But with 5 to 10 radioisotopes used in the biggest radiological sources, one must then differentiate between these materials. For example, 100 curies of cobalt-60 and 100 curies of plutonium-238 pose very different types of concern. If a one-curie radiation source is one meter from a person, it is not difficult to estimate the direct radiation dose to that human in rems per hour at one meter. In addition, if a human ingests or inhales one curie of a radioactive material the cumulative dose to that person over the next fifty years can also be estimated. These numbers form the basis for Table 1, which also includes normalization against the potential dose impacts from the dose from cobalt-60.[11] The challenge is to anticipate the cumulative dose that results when a source is dispersed in a way that could expose many people to radiation in all three manners (direct exposure, ingestion, and inhalation).

Table 1. Radiation doses relative to Cobalt-60 for radioisotopes used in large source.[11]

Isotope	Half-life	RHM Note 1	CDE Ingest Note 2	CDE Inhale Note 2	RHM/ RHM,Co	Ingest/ Ingest,Co	Inhale/ Inhale,Co
Co-60	5.3 yr	1.37	26900	219000	1.0	1.0	1.0
Cs-137	30.1 yr	0.38	50000	31900	0.3	1.9	0.1
Ir-192	74 d	0.59	5740	28100	0.5	0.2	0.1
Sr-90	29.1 yr	0.00	142000	1300000	0.0	5.3	5.9
Pu-238	88 yr	0.08	3200000	392000000	0.1	119.0	1790.0
Ra-226	1600 yr	0.01	1320000	8580000	0.0	49.1	39.2
Am-241	433 yr	0.31	3640800	444000000	0.2	135.3	2027.4
Cf-252	2.6 yr	0.04	1084100	136900000	0.0	40.3	625.1

Note 1: Rem per hour at 1 meter per curie   Note 2: 50 year cumulative dose, per curie

Source: Handbook of Health Physics & Radiological Health by Shleien

There are four groups of radiological source materials in Figure 1, specifically the gamma emitters, the beta-emitters (Sr-90 and its daughter Y-90), the alpha-emitters, and the neutron emitter (Cf-252). Given that RDD analysis is effectively an order of magnitude science, the three gamma emitters would likely give similar doses during an RDD event (although there may be post-event differences, due to different contamination problems). The beta-emitting strontium-90 is far less effective in delivering a direct radiation dose, but it can deliver a bigger ingestion or inhalation dose than the gamma emitters on a per curie basis. The alpha and neutron emitters are also less effective than the gamma emitters in delivering external doses, but they can deliver much greater ingestion and inhalation doses.

It is difficult to estimate radiological doses from RDDs using Table 1, and the impact will be highly scenario dependent. In practice, it will be very difficult to deposit large fractions of the dispersed materials into the respiratory or digestive systems of people in the area, so a significant reduction in impact via these pathways is necessary. When one adjusts the non-gamma emitters accordingly, the threshold levels of concern for the radiological sources of concern tend to even out, i.e., if the level of concern for gamma emitters were determined to be 1, 000 curies, the level for the beta emitters might be a little higher, and the level for the alpha and neutron emitters might be a little lower.

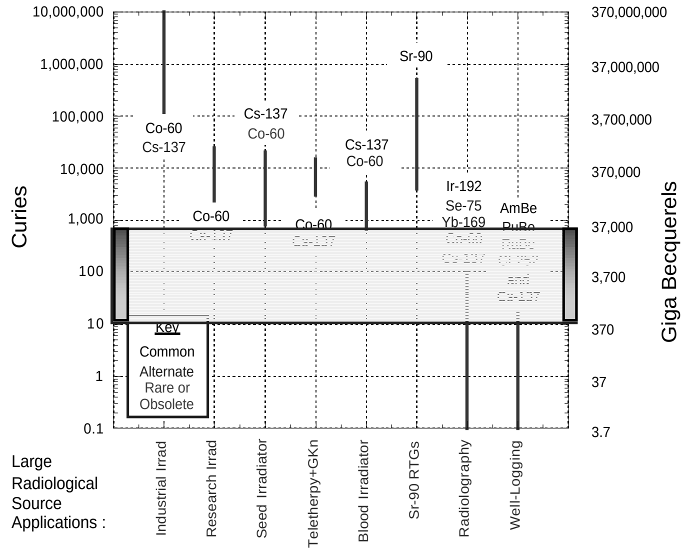
Although one could use this argument to establish priorities on a per curie basis, an alternate approach is nearly as practical and much more appropriate. This involves defining a Priority Bar of concern, as illustrated in Figure 8. A Priority Bar can be used to compensate for differing levels of concern regarding radioactivity levels of the different radioisotopes. If we make the assumption that our priorities are defined solely by dose, and that alpha emitters will deliver perhaps ten times the dose of the high-energy gamma emitters and possibly one hundred times the dose of the beta emitters, we get the priority bar shown in Figure 8.

Fig 8 Defining a Priority Bar Based on Dose.

A more sophisticated priority bar could include factors other than dose, including the potential problems involved in acquiring and transporting the source and potential concerns regarding contamination.

An overlay of the priority bar on a bar chart showing the radioactivity levels for the large radiological sources of concern is provided in Figure 9. The exact position of the priority bar is somewhat arbitrary. As shown, it suggests that strontium-90 sources above 1000 curies, cesium and cobalt sources above 100 curies, and plutonium and americium sources above 10 curies are all of concern.

Fig 9 Overlay of Priority Bar on Radiological Source Chart



Assuming the placement of the priority bar is approximately correct, the interpretation would be as follows. First, all industrial and research irradiators are of concern, as are all teletherapy units and blood irradiators. Second, all of the RTGs and seed irradiators are of concern, and many of these are unfortunately in disused or orphan status. Only the very largest radiography sources are of concern, particularly if they are cesium units (many new radiography sources use radioisotopes with short half-lives). Although only the high-end well-logging sources exceed 10 curies of plutonium of americium, the standard for new well-logging sources is a problematic 18 curies.

IV. ALTERNATE TECHNOLOGY OPTIONS

There are four classes of options of available, namely: replace the application with something that presents fewer concerns, substitute a different radioisotope, alter the chemical and/or mechanical form to be more dispersion resistant, and modify the equipment to better resist theft of the device and/or the radiological source material.

Replacing Large and Dangerous Applications

Accelerator technology is a viable competitor to the industrial irradiators within the U.S. and parts of the world where electricity is available and sufficiently reliable. But it is not clear that the industrial irradiators present much of a risk in those parts of the world, since the facility already has security, and it takes many hours for skilled personnel to unload/reload source materials. Perhaps the greater risk is associated with the shipments of new cobalt-60 sources, which must occur frequently given the 5.5 year half-life and around 200 irradiators world-wide.

The research irradiator user facilities presents greater concerns regarding vulnerability due to their typical locations and the fact they use quantities of materials that are not so immediately life-threatening. Usually research facilities are most valued when they provide a range of research opportunities. Particle accelerators, including electron accelerators and cyclotrons, can produce a range of secondary particles off beam target windows. Accelerators are more costly and complex than research irradiators, but the added versatility and improved safety and security may justify the large investment.

Teletherapy units have been largely replaced in the U.S. by electron accelerators, which are believed to deliver a more precise dose of radiation to the tumor site. But in less developed parts of the world, the low-tech teletherapy unit is more practical than the electron accelerators-which require both electricity and maintenance. The gamma-knife is a niche application, as it is a special-purpose teletherapy device. They are not currently in widespread use, and it is not obvious that hospitals in less developed countries will pursue this special purpose technology.

The X-ray based blood irradiators appear likely to replace the cesium-based blood irradiators, if the hospitals currently using the cesium units could dispose of the unwanted cesium.[12] It may be practical to discourage or possibly ban the sale of new cesium-based blood irradiators and begin a program to recover the partially utilized cesium sources currently in use or disuse.

In terms of replacing RTGs as remote power sources, alternate power devices based on solar or wind could work in some locations, but hostile climatic conditions may limit the viability of the alternatives. However, if one considers the power requirement is often derived from the desire to run lighthouses along the North Coast of Russia, then the range of options improves. During a period when computer technologies are widely used and cheap, and when GPS can pinpoint one's location within a few meters, the use of lighthouses is an anachronism. The cost of equipping the ships that pass through remote waters would be significant, but it might be the best option.

An attractive alternative to well-logging source was already being deployed when the industry changed their drilling practices and reinvigorated the use of the AmBe sources.[10] The alternative is D-T (deuterium-tritium) sources, which employs a small accelerator to drive the well-known fusion reaction to generate neutrons. The change in practice is called "logging-while-drilling" and involves attaching the neutron source to the drill bit and making measurements while drilling (see Fig. 7). Such a process is too stressful for the D-T source, but the AmBe sources work well if they are big enough. It may be possible (but difficult) to ban the use of AmBe sources and force the drilling companies to use D-T sources.

Using Alternate Radioisotopes

There are three types of substitutions that may be useful. First, if the only chemical form associated with a radioisotope is very bad and no substitute form is workable, it may be best to switch isotopes. Second, if an alpha-emitter could be replaced by either a gamma- or a beta-emitter, the potential inhalation or ingestion doses would decrease significantly. Third, a radioisotope with a long half-life could be a liability for centuries, long after the useful lifetime of the application. In some cases, an alternate radioisotope could reduce the risk from sources that have fallen into disuse or disappeared.

In the case of the irradiators, the cobalt-60 offers three advantages compared to cesium-137. First, the higher energy radiation from cobalt-60 requires about four times as much shielding mass, making is much harder to truck around. Second, cobalt-60 has a market value that supports recycling of the material, whereas cesium-137 is difficult to dispose of. Third, most large cesium sources are currently cesium-chloride, which is known to have dispersed very badly in an accident in Goiania, Brazil. The problems with cesium are counterbalanced somewhat by the need for frequent re-supply of cobalt sources.

The choice of strontium-90 for use in RTGs was driven by several positive features, including its large heat generation, long half-life, low cost, and decay by beta-emission. Per unit of radioactivity, strontium is not the worst of possible RDD materials, even though it is available in very large quantities. There may be preferred radioisotopes, but it is not clear that a search for an alternate material is advisable.

For the teletherapy applications, the cobalt-60 is preferred over cesium-137 for the same reasons cited for the irradiators (above). The same is true for the blood irradiators, if one could replace the cesium-137 without generating a lot of disused cesium sources.

Well-logging sources present a unique set of problems, and the use of several curies of any transuranic alpha emitter in a source that is transported and utilized around the world raises major concerns. Should it be impractical to substitute D-T sources for the large AmBe sources, an alternate to Americium-241 should be considered. If the oil exploration industry could work with a 1 MeV monoenergetic neutron source, there exist a couple of viable gamma emitters that could be used. If the higher energy neutrons that result from the alpha, n reaction are necessary, there are a couple of shorter-lived alpha-emitters (isotopes of polonium and curium) that could be substituted for the americium. The primary improvement would be a source that decays to insignificance in a decade or two, as opposed to many centuries.

Most of the newer radiography sources use irradium-192, which has a short half-life. When cesium-137 is utilized, it is usually in the form of a sealed ceramic source. There may be room for improvement in radiography sources, but this is not a high priority.

Deploying Alternate Chemical Forms

The discussion in this section is based on the experience with accidental dispersion of source materials, as there have been cases where radiological sources have caused contamination problems.[7] The dispersion from an RDD event would be highly scenario dependent, so it is not clear that the experience from accidental dispersions is a good indicator of what should be anticipated. It is only *assumed* that sources that have behaved badly when accidentally dispersed would also behave badly for some fraction of the RDD attack scenarios, and therefore constitute a concern. The experiences/ expectations regarding two of the radiological source materials have not been/are not encouraging. Cesium-chloride is a water-soluble powder that has been spread easily by accident and has caused significant clean-up problems. The AmBe sources are a fine mixture of americium-oxide powder and beryllium powder that is blended together and compacted to optimize neutron production.

When Cs-137 is used for smaller sources, the most common form is a ceramic. Larger sources are not usually ceramic, perhaps because of poor heat conduction and other engineering factors. There exist some candidate alternate chemical forms, including cesium tetrafluoro-borate but more technical work is needed before we can determine that these forms are good alternatives.[13]

The mixture of powdered americium-oxide and beryllium maximizes the probably that the alpha particle coming from the americium-241 would strike the beryllium and trigger the release of a neutron. The mixed powder is compacted and sealed within a capsule, but in the event the capsule should be ruptured the potential for dispersion is evident. Because this source design was engineered before concerns about intentional dispersion developed, some re-engineering may be appropriate. This may increase the cost and the amount of alpha-emitting material utilized so some trade studies would be advisable.

Modifying Current Radiological Source Applications

For the large industrial sterilization units, an attack on the facility and an attempt to steal the source material would be very difficult. But, because these facilities have such massive quantities of dangerous materials, some additional security gadgetry would be a wise investment. For example, radiation detection equipment could track the strength of the radioactive source and alert authorities if the source strength mysteriously drops by a significant fraction. The system could be designed to generate a periodic *all-is-well* signal, which then generates a red flag through either an alarm signal or a lack of any signal. Authorities could then contact the facility looking for an *all-is-well* password and an explanation, and send a response team if the answers an unsatisfactory.

When a large radiological source is being transported, including any mobile irradiator units, alert and track hardware should be built into the vehicle. If the vehicle departs from its planned itinerary, a timely response from law enforcement personnel could be expected.

Any new RTGs being deployed should also be designed to use part of the power supply to generate a couple of redundant *all-is-well* signals on a regular basis. If the power supply is removed, the signals would stop. If the entire RTG were to be moved with the power supply in place, the signals would register a changing global position report, alerting the problem and providing a track beacon.

The large hospitals devices, particularly the teletherapy and blood irradiator units, should be provided better protection regardless of the radioisotope in use. For teletherapy units, access to the source itself should require special tools and procedures. Attempts at unauthorized access should trigger alarms inside and outside the hospital. For blood irradiators, the fact the sources are welded in will deter theft to some degree. It also provides an opportunity to encase some alert and track devices so authorities can quickly find a stolen blood irradiator.

The mobility of well-logging sources and the dangers they pose are such that each unit should be rigged with alarm and tracking equipment, hidden deep within the *sonde*. The process of removing the AmBe source from the *sonde* should be difficult so entire unit is more likely to be, transported rather than just the source.

Most radiography sources sources are not large enough to require special gadgetry for tracking source materials, and are not well suited for such an approach anyway. It is possible that a very large radiography source might be suitable for alert and track gadgetry.

Materials tracking technology could be adopted from the Materials, Control, Protection, and Accountability (MPC&A) programs used for special nuclear materials. Such technology should be applied selectively to high priority items, such as large cesium and cobalt sources. Regarding the cesium sources, MPC&A programs could help reduce the problems with disused and orphan sources.

V. PRIORITIZING ALTERNATE TECHNOLOGY OPTIONS

The various alternate technology options are rolled up by application type in Table 2. Preferred alternates are indicated using ***bold italics***.

Although the large industrial sterilization facilities do not appear to be very vulnerable, a team of experts could conceivably steal the cobalt-60 source material, given enough time and some laxity of security. The alternate technology, based on particle accelerators, requires an infrastructure of expertise and electric power that may be unavailable in countries of concern. It is very possible that the accelerators will gain a competitive edge from the RDD concerns, so the number of cobalt-60 irradiators may be on a slow growth pattern anyway. Other the other hand, the step of wiring the sterilization facilities so that an ongoing attempt to steal a source becomes obvious to law enforcement would be prudent.

Research irradiators are a concern because of the most common research environment, which is low security. Particle accelerators could provide the same capabilities but with much greater flexibility. At a minimum, the cesium chloride sources should be replaced using more dispersion resistant materials.

The RTGs present some special problems, as there are few viable alternatives. The RTGs can and should be redesigned to make source removal very difficult, to make it obvious when the device is being tampered with, and to facilitate tracking and recovery of stolen units. A much more sweeping change may be the best approach. Ships equipped with GPS technology should not require lighthouses, and without lighthouses, the need for most RTGs would be eliminated.

The first priority on teletherapy units is to get rid of any remaining cesium units. With respect to the cobalt units, the need to replenish the source strength frequently raises a concern about potential source theft. When a source supplier visits the hospital to replace the cobalt source(s), special tools are required to access the chamber, which provides a measure of theft resistance. While this is a good start, this system would have been developed prior to the days of RDD threats and needs to be re-evaluated and probably upgraded

Table 2. Roll-up of Alternate Technology Options, with Highest Prioritizing Indicated with ***Bold Italics***

Class of Source Application:	Application	Competing Technology	Alternate Radioisotopes	Alternate Chemical Form	Modify Application
Industrial Irradiators	Industrial Cobalt Units	***Particle Accelerators***	-	-	***Alarm on low source strength, MPC&A***
Research Irradiators	Research, Smaller Scale Irradiator	***Accelerators, Industrial Scale Units***	If Cesium, replace with Co-60 or other	***Replace CsCl*** [13]	Secure and Alarm Facility, MPC&A
Large Medical	Teletherapy	Particle Accelerators	***If Cesium, replace with Cobalt***	***If CsCl, replace***	***Secure source in unit, MPC&A***
Large Medical	Blood Irradiators	***x-ray units***	Replace Cesium	***If CsCl, replace***	Alarm & track if stolen, MPC&A
Power Source	SR-90 RTGs	***Solar, Wind; GPS Systems***			
Mobile Scanning	Well-Logging: Neutrons	***D-T neutron generators***	Replace Am-241 with Po or Cm isotopes	***Modify AmBe Form***	Rig for Alert & track if lost or stolen
Mobile Scanning	Well-logging: gammas	-	Replace cesium?	***If cesium, use ceramic***	Rig for Alert & Track if Lost or stolen…
Mobile Scanning	Radiography	-	Iridium preferred	***If cesium, use ceramic form***	Rig larger units for alert & track

The x-ray blood irradiators appear to provide a viable alternative to the cesium units, except for one big problem, i.e., the disposal of the cesium source. The two options for dealing with this problem involve either providing disposal facilities for large cesium-chloride sources or possibly recycling the cesium sources into a better chemical and/or mechanical source forms.

The situation regarding **well-logging sources** is complex and requires interactions with representatives of the oil-exploration industry. It is apparent that the D-T sources can provide superior analysis of the geology around the bore-hole, if they could withstand the hostile drilling conditions. The logging-while-drilling approach is relatively new, and was developed to save time and money. If large AmBe sources were unavailable, the industry may well go back to using the D-T sources. If the industry insists upon using so-called *chemical sources* (jargon for AmBe sources), development of sources based on polonium or curium isotopes could greatly reduce the source lifetime, and there may even be the option of using a gamma-driven neutron source (if 1 MeV neutrons would suffice). It is clear that gamma driven sources would reduce the RDD concerns, but the use of shorter-lived isotopes would reduce the liability much less significantly. If these alternatives do not prove to be viable, the AmBe sources are candidates for re-engineering. Many alternate design options will likely work, although most will be a bit less efficient and require somewhat more americium. Lastly, the well-logging source *sondes* could be fitted with alert and track hardware as something of a last resort. The gamma source in **well-logging** *sondes* are generally cesium-137, although a number of other radioisotopes could do the job, as well. Most of these cesium sources are ceramic, so the value of deploying alternate source materials may not be very high in this case.

Many **radiography** units use short-lived iridium-192 in quantities that are insufficient to qualify for urgent attention in RDD space. Where cesium sources are used, they are usually ceramic sources. If there are known instances where cesium-chloride is used, these should be considered candidates for replacement.

The ***prioritization*** of the alternate technology options needs to be worked in terms of the overall RDD risk reduction priorities. The practicality of the various alternate technology options must be evaluated, and some of the alternatives appear to be strong candidates for implementation and RDD risk reduction.

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