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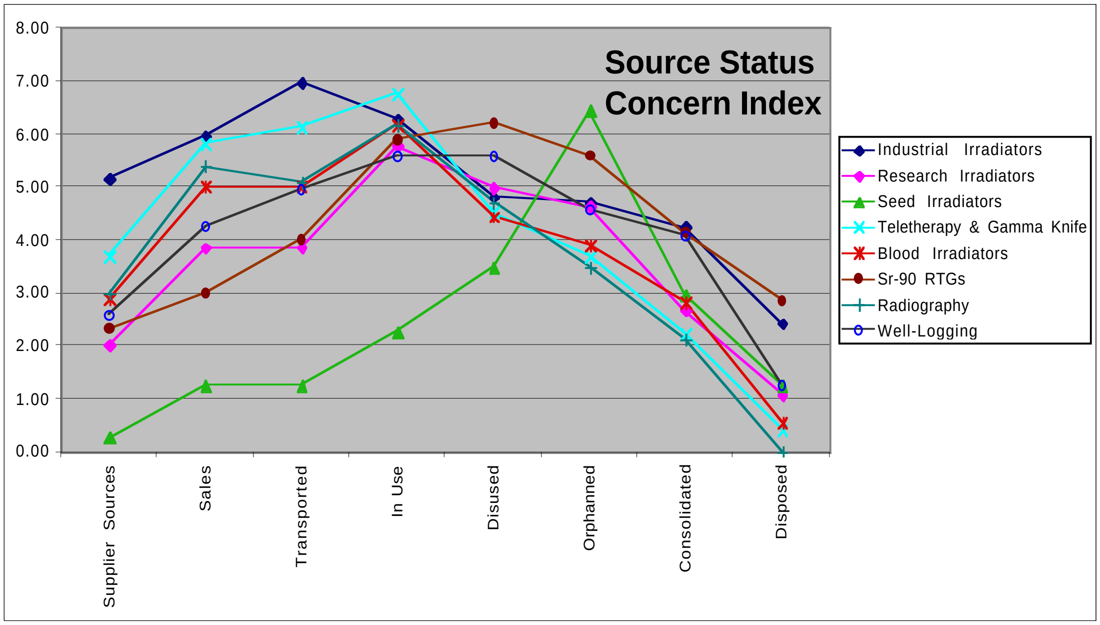
Reducing RDD Concerns Related to Large Radiological Source Applications



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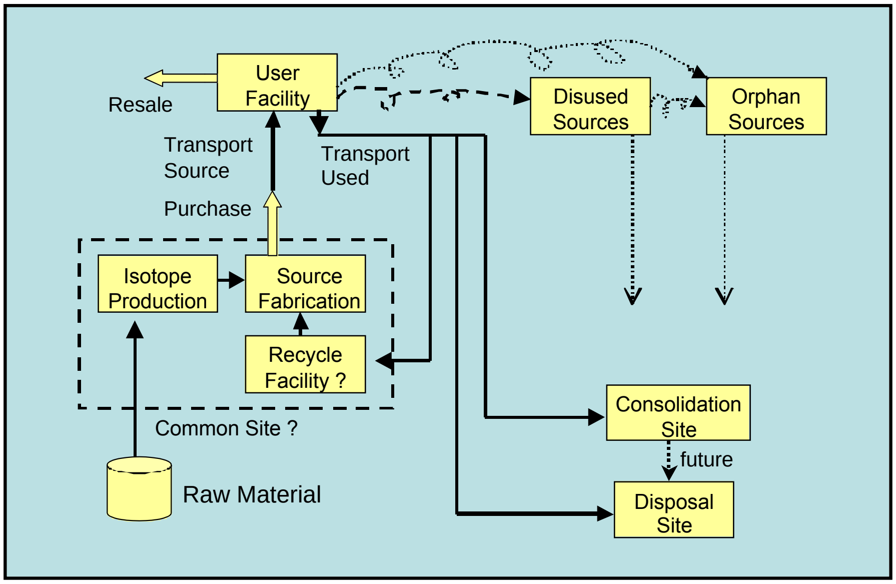
Executive Summary

Radioactive materials are used around the globe to provide benefits to mankind in many fields, including medicine, research, and numerous industrial applications. The usage has developed since the early days of nuclear energy to include numerous applications, dozens of radiological source producers and suppliers spread across six continents, and on the order of a billion sources world-wide. The growth of terrorism during the 1990s and more recently has heightened concerns about some of the same radiological sources, namely whether they could be used in radiation dispersal devices (RDDs), or “dirty bombs” so as to create both panic and potentially large economic consequences. Although there are many variables that can make an RDD attack much worse, a key factor is the quantity and type of radiological source material that is dispersed. Because there are far more relatively inconsequential radiological sources in use than there are large sources, this provides an important focusing element in reducing the RDD threat, i.e., to reduce access to large and potentially hazardous RDD source materials.

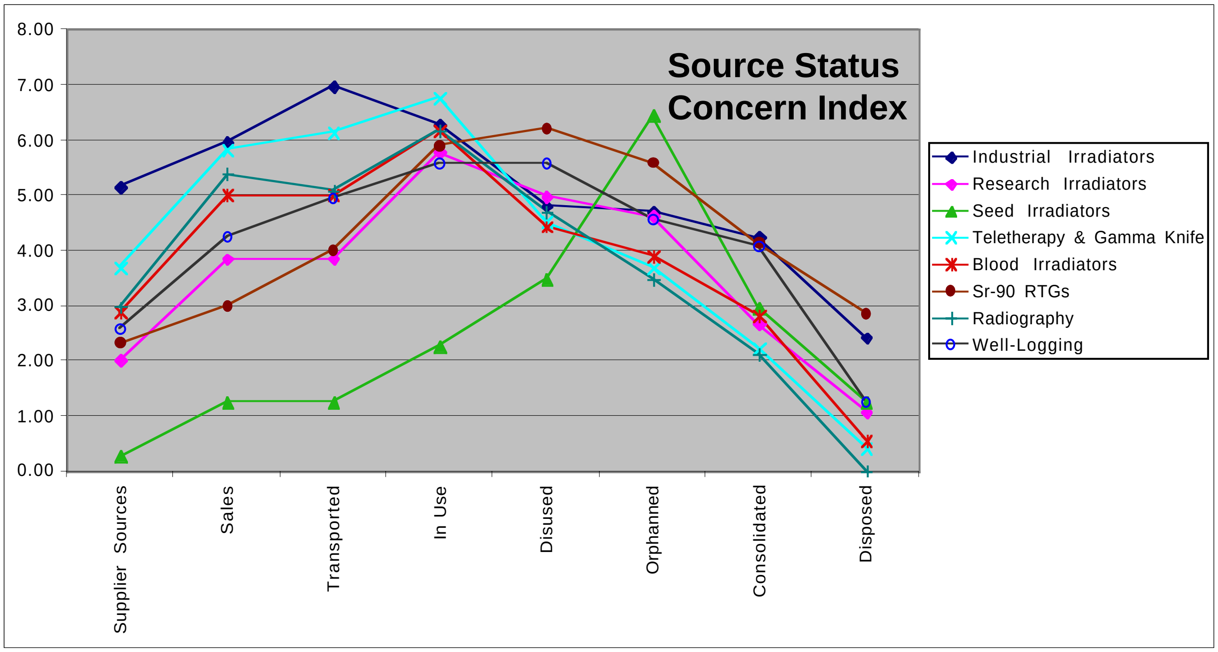
In order to assess the vulnerabilities associated with the radiological sources it was essential to examine the entire life-cycle (see Fig. E.1). This included the producer/suppliers, the sales, the transportation, the users, and the disposition possibilities that include disused sources, orphan sources (disused sources no longer under control of owner), waste consolidation sites, and waste disposal sites. The largest producers and suppliers of radiological source materials, as well as the users of some of the largest applications, were identified. Some of this information was derived from IAEA databases, but more of the data was developed independently using open source information. It is clear that the commerce in radiological source material is global, with suppliers on six continents and users in nearly every country.

Figure E.1 The Life-Cycles of Radiological Source Materials



There are many options for cross-comparing the vulnerabilities associated with the large radiological source applications at the various life-cycle stages. We chose to use a Source Status Concern Index (SSCI) that multiplies together the number of sources, the radioactivity level of the sources, and the hazard factor for the material, and then divides by the inaccessibility and the security factors (rated on scales from 1 to 100). Because the vulnerability varies by many orders of magnitude, we used the logarithm in base ten of the product for comparison. Tables were created to approximate these parameters to the best of our ability, given the available data and potential concerns about putting too many details about hazards and security into the open. The results are displayed in Figure E.2. Because of the logarithmic nature of the scale, a score of 7 is ten times greater than a score of 6, indicating ten times the level of concern.

Figure E.2 Source Status Concern Indices for Current Circumstances

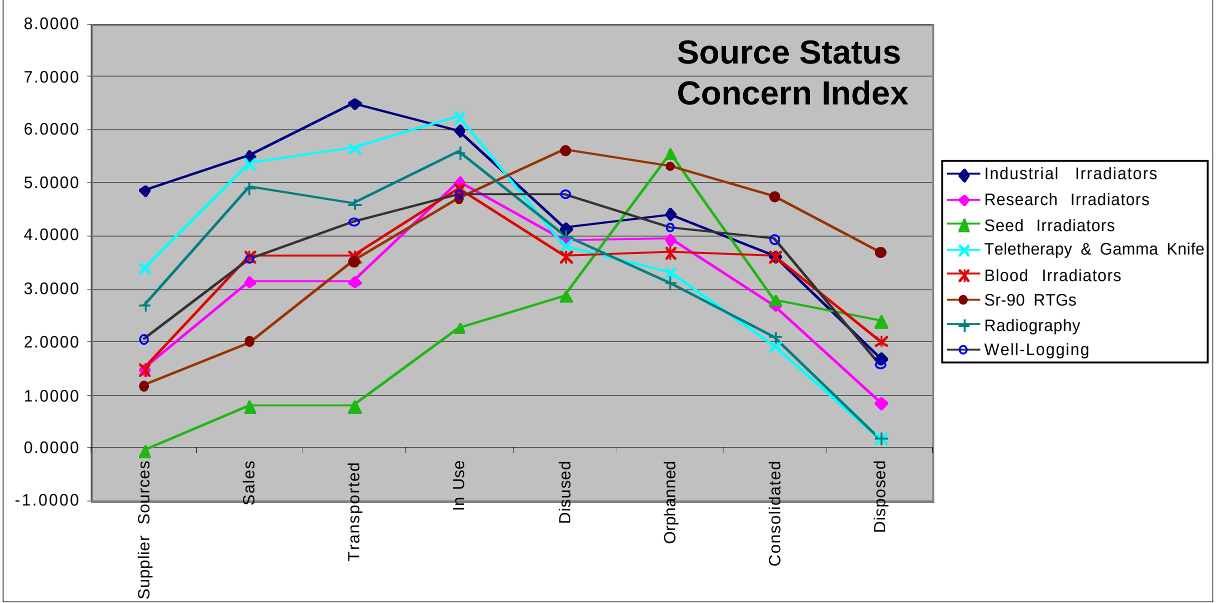


Based on this analysis, a list of the ten highest risk reduction priorities was generated:

1 Transportation of Cobalt-60 sources
2 Teletherapy Source User Facilities (Hospital Cancer Treatment Centers)
3 Disused and Orphaned RTGs (Radioisotope Thermoelectric Generators)
4 Orphaned Seed Irradiators
5 Industrial Irradiators, Blood Irradiators, and Radiography Sources in Use
6 Sales and Re-sales of cobalt-60 sources and radiography sources
7 RTG, Research Irradiator, and Well-Logging Source Users
8 Disused Well-Logging Sources
9 Sales and re-sales of radiography sources and blood irradiators
10 Transportation of radiography, well-logging, and blood irradiator sources

Three categories of source vulnerability reduction options were considered: source security actions, international agreements/regulatory environment improvements, and introduction of alternate technologies. Key options and assumptions were described and a representative set of tables was generated for use in regenerating the SSCI scores. Although each set of options resulted in some reduction in the vulnerabilities, the greatest overall risk reduction would result from an integrated strategy utilizing all three sets of options. These results are displayed in Figure E.3

Figure E.3 SSCI Values Resulting from Integrated RDD Risk Reduction Program



The analyses represented by Figures E.2 and E.3 provide several useful insights, but the interpretation must take into account two factors that will contribute to possible erroneous results. First, there exists considerable uncertainty in the number of sources no longer in use, particularly the disused and orphan sources. Second, concerns about the potential hazards associated with each type of source materials and estimates regarding the potential effectiveness of security features are represented only approximately in the analysis due to concerns of potentially providing too much information. Because the RDD risks are fundamentally an order-of-magnitude science, the results and prioritizations are somewhat forgiving of such uncertainties and the approximations.

Within the limitations of the analysis, the following recommendations are provided:

1 Repeat the SSCI analysis (or a variation) using more time and resources. Additional research many be able to reduce the uncertainties, especially regarding disused and orphan sources. A classified study using more precise analysis for the hazard and security factors could also improve the fidelity of the results.

2 Continue to aggressively develop the capability to detect and intercept attempts to transport RDDs and RDD source materials, as well as the capabilities needed to respond to RDD attacks. Although the recommended course for RDD risk reduction through denial of sources could reduce the vulnerabilities by up to an order of magnitude, the base is currently so large than the remaining 10% would be too high. The recommended efforts would require a decade of intense effort to achieve the projected risk reduction, so the other major options must be pursued aggressively.

3 Balance the three classes of options and pursue each as aggressively as is practical. The source security effort can be used to address the most urgent needs, but its effectiveness is fundamentally limited. The problems will continue to grow, and major vulnerabilities will remain un-addressed. The international agreement/ regulatory infrastructure effort will likely proceed slowly, unless an RDD attack inspires a more intense effort. However, this approach can provide some far-reaching and widespread improvements in the current handling of sources. Alternate technologies can provide permanent solutions to some of the problems caused by technology choices made prior to today's global threats. But alternate technologies will take time to develop and implement.

4 Focus the resources available for recovery of disused and orphan sources on the three sources of greatest concern, i.e, the RTGs, the seed irradiators, and the well-logging sources. These problems are concentrated in the former Soviet Union in the first two cases and in western countries for the third case. There is also the potential for far more disused and orphan sources to develop over the next ten years. The best option for addressing the broader disused and orphan source problem may be to establish consolidation sites that could be used to address the current problems and head off a much bigger problem in the future.

5 Pursue the international agreements and improved regulatory environment as aggressively as is practical. Although this will be a time-consuming and tedious process, it may provide the best opportunities for global improvements in the way large radiological sources are handled. Unless and until there are improvements in this arena, actions taken under recommendation 4 can have only a marginal impact, addressing urgent issues but unable to reverse a growing problem.

6 Develop and implement the alternate technologies that can fundamentally reduce the RDD vulnerabilities. In most cases, this involves technology development and deployment, as opposed to more basic and time-consuming R&D. There will be delays while the alternate technologies are being deployed, but the improvements will be lasting.

7 Examine more carefully some of the high vulnerabilities that appear to be difficult to reduce, as they may be largely intractable. Transportation of large cobalt sources across continents exposes the sources to theft regardless of the security provided. And the location of large teletherapy sources in hospitals around the world is very troubling, despite the best intentions of those who provided life-saving technology to third-world countries. Unless and until the vulnerabilities in these crucial areas are significantly reduced, the strategy of reducing RDD risk through denial of source materials will be fundamentally limited.

8 Develop a staged approach, where some types of actions could be developed and then queued for future implementation. With the current frequency of terrorist bombings, the publicity regarding the RDD threat, and the widespread availability of radioactive source materials, an RDD attack somewhere in the world is overdue. If the U.S. is prepared with a global strategy of RDD risk reduction, the best opportunity for global cooperation may develop right after the first significant RDD attack.

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

Am- Americium
AmBe- Americium-Beryllium
BINE- Beijing Institute of Nuclear Engineering
BRIT- Board of Radiation and Isotope Technology (India)
CDE- Committed Dose Equivalent
Cf- Californium
Ci- Curies
CNEA- National Commission of Atomic Energy (Argentina)
Co- Cobalt
Cs- Cesium
CsCl- Cesium Chloride
DIRAC- Directory of International Radiotherapy Centers
DOE- U.S. Department of Energy
D-T – Deuterium-Tritium (fusion reaction)
EU- European Union
GPS- Global Positioning System
GVHD- Graft-Versus Host Disease
IAEA- International Atomic Energy Agency
Ir-Iridium
KCi- Kilo-Curies
KeV- Kilo electron Volt
M- Meter
MeV- Mega electron Volt
Mo- Molybdynum
MPC&A- Materials Protection, Control, and Accountability
NTP- Nuclear Technology Products (South Africa)
Pu- Plutonium
Ra- Radium
R&D- Research & Development
RASL-C- RAdiological Source Life-Cycle
RDD- Radiation Dispersal Device
RED- Radiation Exposure Device
RHM- Rem per hour at 1 meter
RITEG- RadioIsotope ThermoElectric Generator (Russian)
RTG- Radioisotope Thermoelectric Generator (American)
Se- Selenium
Sr- Strontium
SSCI- Source Status Concern Index
USDA- U.S. Department of Agriculture
Yb- Ytterbium

1. Introduction

Radioactive materials are used around the globe to provide benefits to mankind in many fields, including medicine, research, and numerous industrial applications (Ref. 1). The usage has developed since the early days of nuclear energy to include numerous applications, dozens of radiological source producers and suppliers spread across six continents, and on the order of a billion sources world-wide (Ref. 2). With rapid growth anticipated in the use of new radioisotope applications in nuclear medicine diagnostics and therapeutics, the radiological source business is a healthy and expanding industry.

The growth of terrorism during the 1990s and more recently has heightened concerns about some of the same radiological sources, namely whether they could be used in radiation dispersal devices (RDDs), or *dirty bombs* so as to create both panic and potentially large economic consequences (Ref. 3). Because of widespread concerns among the general public about things radioactive, some degree of panic must be anticipated even if little of no radioactive material is used (the case where no radioactive material is utilized is sometimes called a phantom RDD, and might succeed primarily through confusion and misinformation). In contrast, a larger and much more problematic RDD could cause more significant and lasting health concerns and contamination problems. Although there are many variables that can make an RDD attack much worse, a key factor is the quantity and type of radiological source material that is dispersed. Because there are far more relatively inconsequential radiological sources in use than there are large sources, this provides an important focusing element in reducing the RDD threat, namely to reduce access to large and potentially hazardous RDD source materials.

This study was focused on the vulnerabilities associated with large radiological source materials, as these materials are widely available around the globe, and some are large enough to pose major concerns regarding potential use in RDDs. A survey of these applications revealed that there are only a handful of very large applications, utilizing only a small fraction of the radiological sources in use, which pose most of the risk. This is because the large sources are several orders of magnitude more radioactive than those in more widespread use. An assessment of various factors that determine the RDD hazards posed by sources indicates a strong correlation between radioactivity levels and hazards, so the largest and most radioactive radiological sources do pose some of the greatest RDD concerns.

The study continued with an assessment of the global commerce and use of the larger radiological source applications. Suppliers are often easy to identify and contact, whereas users of large radiological sources can be more difficult to find. The amount of information regarding the number of sources sold, utilized, re-sold, recycled, and disposed of is uneven, with IAEA data bases providing some of the more complete sources of data. The largest uncertainties are related to a problematic sub-category of sources, i.e., the disused and orphan sources.

Completion of an initial global assessment of the large radiological sources available at different stages of their life-cycles supported development of spread-sheet models of the life-cycle, as well as development of a Source Status Concern Index (SSCI). The SSCI is a measure of the vulnerabilities associated with each of the large source applications at each of the stages in their life cycle. It is a logarithmic index, similar to the Richter scale for seismic activity. As a result, an SSCI value of 7 indicates a ten times greater vulnerability than an SSCI score of 6. Assessment of the current situation regarding large radiological sources indicates many areas of high concern, especially related to user facilities, transported, and disused and orphan sources.

There are various options available to reduce the vulnerabilities associated with some large radiological source applications in various stages of the life-cycle. One DOE effort that is currently in progress involves recovering disused and orphan sources, and providing rapid security upgrades for particularly vulnerable sites and facilities overseas. Another effort, being led by the IAEA, focuses mostly on international agreements and regulations, and could result in more secure handling of large sources, as well as better practices in importing, exporting, and disposing of used sources. Yet another useful contribution could come from source manufacturers and suppliers, and perhaps from the source users, as the deployment of some alternate technologies could reduce risks significantly. All of these options were assessed using the SSCI analysis. Significant risk reduction is possible, but progress must come on several fronts in order to obtain a significant reduction in the vulnerabilities.

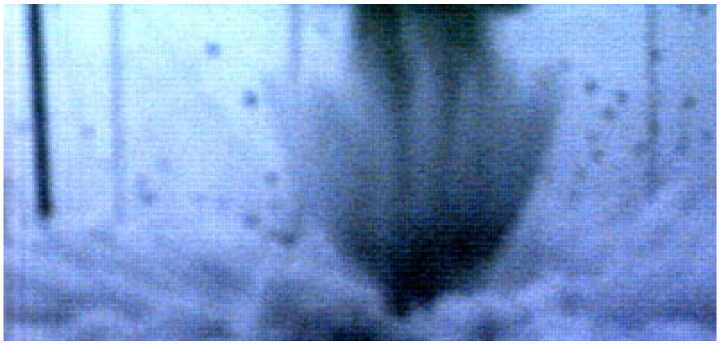
The materials included in this report were gathered from openly available sources, although some of the IAEA databases are not universally accessible. The information represents a snapshot in time, and must be updated in order to keep up with changes in the global commerce in radiological sources. As of September 2003, this report is thought to portray the global commerce in large radiological sources with reasonably good fidelity. Regarding the various ongoing efforts to improve the situation regarding RDD vulnerabilities, these efforts are unlikely to significantly alter the global risk picture for a few years, although the risks regarding certain sources and circumstances (e.g., orphans) could change more quickly.

2. RDDs and Options to Counter the Threat

2.1 Radiological Dispersal Devices

RDDs or *dirty bombs* are devices that disperse radioactive materials. They can take many forms - from containers of radioactive materials wrapped around with conventional explosives, to aerosolized materials sprayed using conventional equipment, and to manual dispersion of a fine powder into the environment (Ref. 4). (See Figure 2.1) Also of concern are radiation-exposure devices (REDs), designed by terrorists to expose people to dangerous beams or particles of radiation. An RDD attack can produce general panic, health consequences including immediate fatalities and long-term increases in cancer incidence, long-term denial of property use, disruption of

Figure 2.1. Explosives-Driven Materials Dispersal.



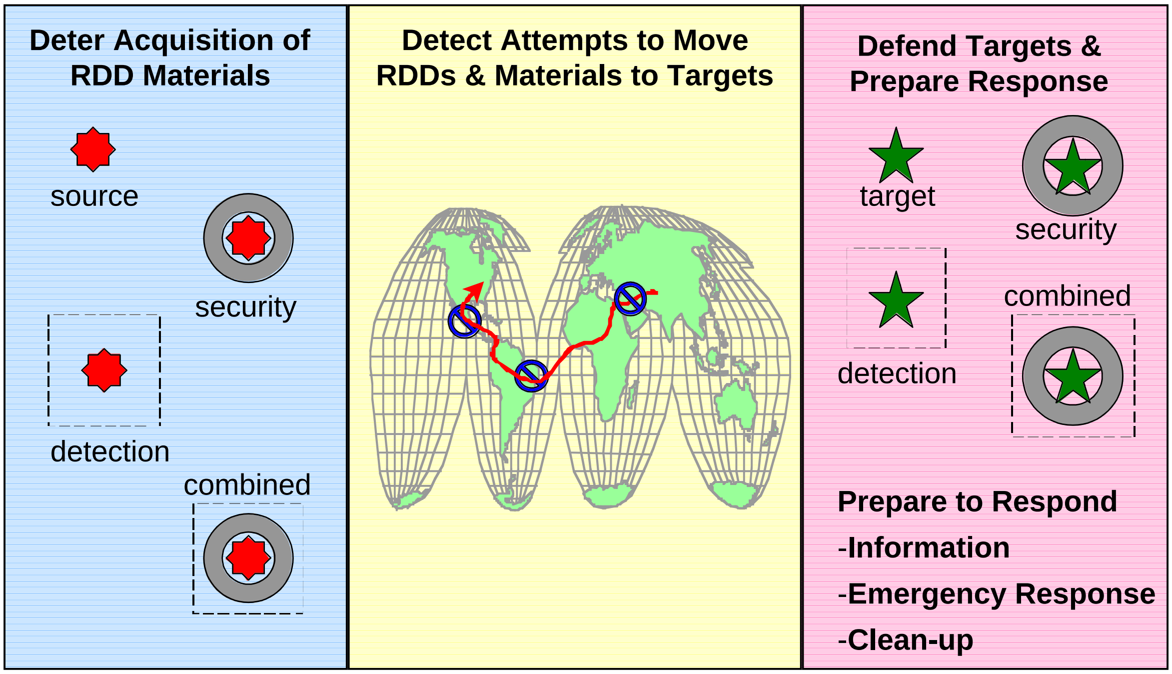
services, and property and facility decontamination needs.

In principle, any radioactive material can be used in an RDD, and the amount of material dispersed could range over many orders of magnitude. The initial public response to an RDD attack is likely to include a degree of panic and hysteria regardless of the amount and type of radioactive material dispersed. Because it is nearly impossible to prevent RDDs that use minimal amounts of radioactive materials (other than by the normal intelligence processes that uncover terrorist plots, in general), the most viable response is to fully prepare to get the word out that the radiation hazard is of no real consequence (and to counter claims by others to the contrary). In contrast, the probability of the largest and most consequential RDD attacks can be reduced by restricting the availability of large and hazardous sources materials.

2.2 Top-Level Options: Deny, Detect, Defend

The options for reducing the RDD risk, from a technical perspective, come down to three steps. First, deny access to the materials needed to create an RDD. Second, detect the radioactive materials while they are being transported from their point of acquisition to the target area. Third, prepare to respond to an attack, which involves both the emergency response and the post-event cleanup. These options are illustrated in Figure 2.2.

Fig 2.2 Three Components to RDD Risk Reduction



Due to the widespread availability of radioactive materials (in addition to explosives), it is impossible to preclude RDDs entirely. Because the number of radiological sources that are large enough to create a very damaging RDD are far fewer, it is possible to significantly reduce the likelihood of a very bad RDD. That can be achieved by reducing the use of very dangerous sources, by providing security features to protect those sources, and by providing radiation (and related) detection capabilities that will alert authorities and allow them to respond to an attempted theft. Because many sources are currently considered to be in highly vulnerable circumstances, a significant risk reduction may be possible in this area.

Large radiological sources materials provide clues regarding their presence. Radiation detection equipment will alarm if large radiation sources are nearby, unless they are very well shielded. Large sources also emit a lot of heat, providing a large thermal signature. Containers that provide radiation shielding are heavy, and containers that shed heat efficiently are bulky. Given the various clues available, it should be difficult to sneak a large radiological source from the acquisition to the target, if enough people are looking. There are major efforts under way to detect radioactive materials, and the infrared scanners used at some border crossing will *light-up* in response to large sources. As more and more equipment is deployed at additional locations, the risk reduction will be significant. But real-world limitations in physics and economics will eventually limit the effectiveness of the detection and interdiction option.

Because the risks of illicit source acquisition and successful evasion of detection equipment can never be driven to zero, preparation for a response to RDDs attack is vital. For various reasons, a public panic is anticipated, regardless of the true danger of the threat. This will almost certainly result in an over-taxing of the health care system, compounding the difficulties in helping people that have been injured or are truly at risk. The contamination problem may or may not be significant, and could cause problems on two levels. Even if the contamination is localized and of little concern, the public will likely be confused by conflicting opinions and statements regarding the dangers posed. But a greater problem will result in the event a *large* source is very well dispersed, creating a decontamination problem in a densely populated urban environment. The government must and is believed to be preparing to deal with all of these problems, but some of the challenges are formidable.

3. Candidate Radioactive Material

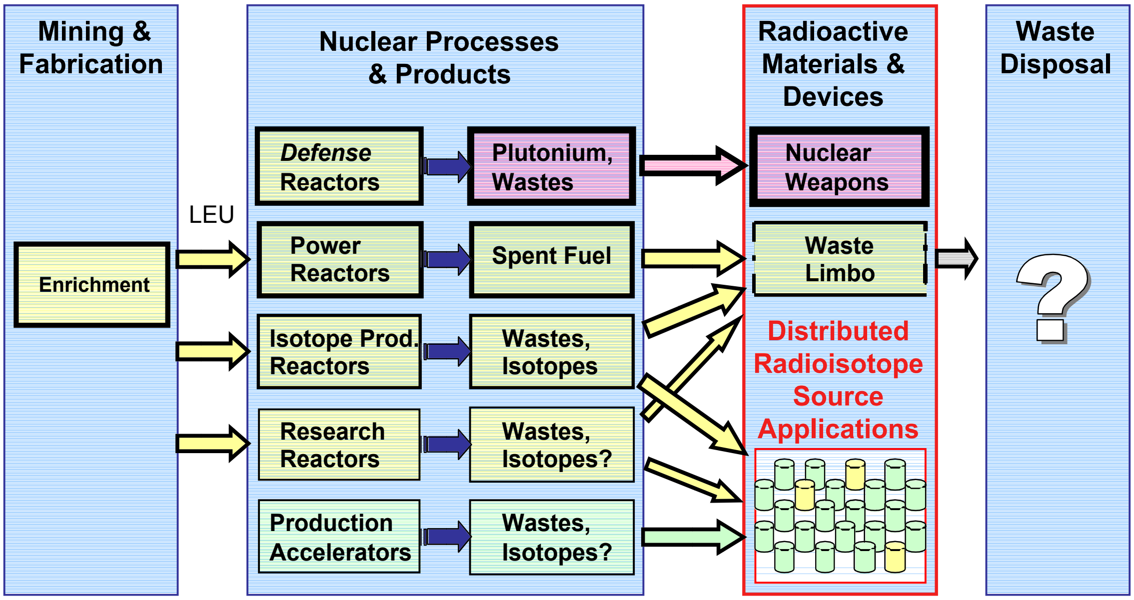
Radioactive materials are a natural part of the environment, pre-dating life on earth. However, scientific and technological developments of the twentieth century significantly increased the availability of much more concentrated and hazardous quantities and types of radioactive materials. It is impossible to preclude dispersal of radioactive materials, because something as routine as cremations or combustion will disperse radioactive materials into the atmosphere. Further, a person who is clever about staging events and manipulating information could create a significant disruption using a phantom RDD that utilizes no radioactive material whatever. As a result, any attempt to reduce the RDD risks must partition the problem and focus on the largest and most dangerous sources of radioactivity.

3.1 Overview of Nuclear and Radiological Materials

An overview of the nuclear and radiological source production, utilization, and disposal process is provided in Figure 3.1. At the initial mining and fabrication stage, radioactive materials exist in only modest concentrations, with the exception of the enrichment process, which could produce some materials of interest. Most nuclear and radiological source materials currently exist in the *nuclear processes and products* box, which include nuclear reactors, particle accelerators, chemical and mechanical processing facilities, and local holding points or facilities. The box labeled *Radioactive materials and devices* represents materials that are in some form of distributed use or possibly in a remote storage point awaiting disposal. The last box represents waste disposal sites, which are uncommon in many parts of the world. Because there has been long-standing concern about both nuclear weapons and materials that could be used in making nuclear weapons, there is generally good security in the handling of these materials (especially the weapons!). In contrast, the world of radiological sources developed prior to recent concerns about terrorism, and many of the sources are either unsecured or provided, at best, with an industrial level of security.

The focus on radiological sources was driven by the perception that these sources are widely available and vulnerable. Some of these have features that would make them desirable as RDD sources. Some of the materials shown in Figure 3.1 but not included in this study would also make desirable RDD materials, and there is some chance they might be acquired and so-utilized. But the vulnerabilities and the concerns are quite different, and these are being assessed and addressed by others. Thus, our focus on the radiological sources is not intended to dismiss the other source materials suggested by Fig 3.1, but rather to allow us to focus on a particularly worrisome part of the problem.

Figure 3.1. Overview of Available Nuclear and Radiological Source Materials

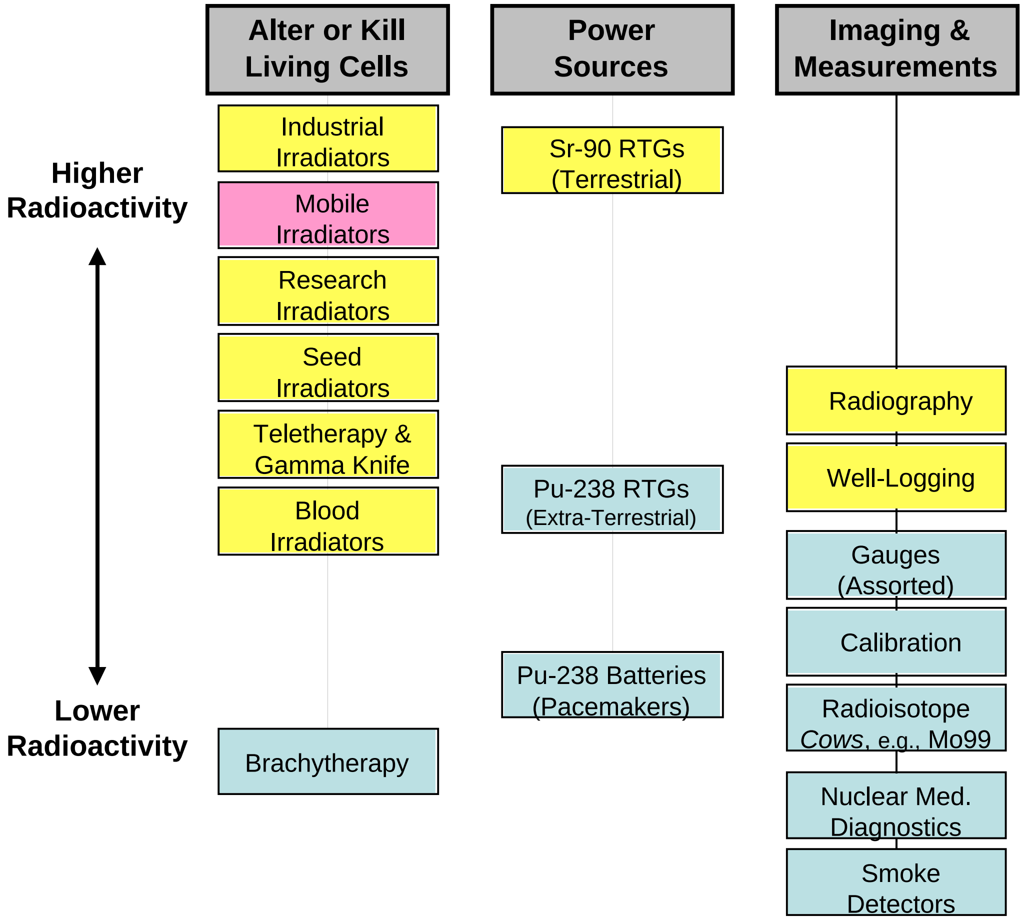


3.2 Focus on the Large Radiological Source Applications

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. A hierarchy of radiological sources, grouped in terms of these three purposes, is provided in Figure 3.2. The sources near the top of the chart can utilize thousands, and sometimes millions, of curies of radioactive materials, whereas something nearer the bottom of the chart uses a very small fraction of that amount of radioactivity. The sources highlighted in yellow are thought to be of primary concern regarding usage in a large and damaging RDD. Mobile irradiators, which are uncommon, are shown in pink because these could make large and dangerous RDD sources if they become more common. The other sources, shown in blue, are considerably smaller and/or quite difficult to obtain.

There is a time element in the first and third classes of application, as the radiation dose or the measurement accumulates over time, so a stronger source completes the job more quickly. The second class of application generally requires a consistent or static rate of energy generation. If one wished to merely reduce the radioactivity levels of the sources, the result would be lengthier procedures for the first and third classes of sources, and reduced power availability for the second class of sources.

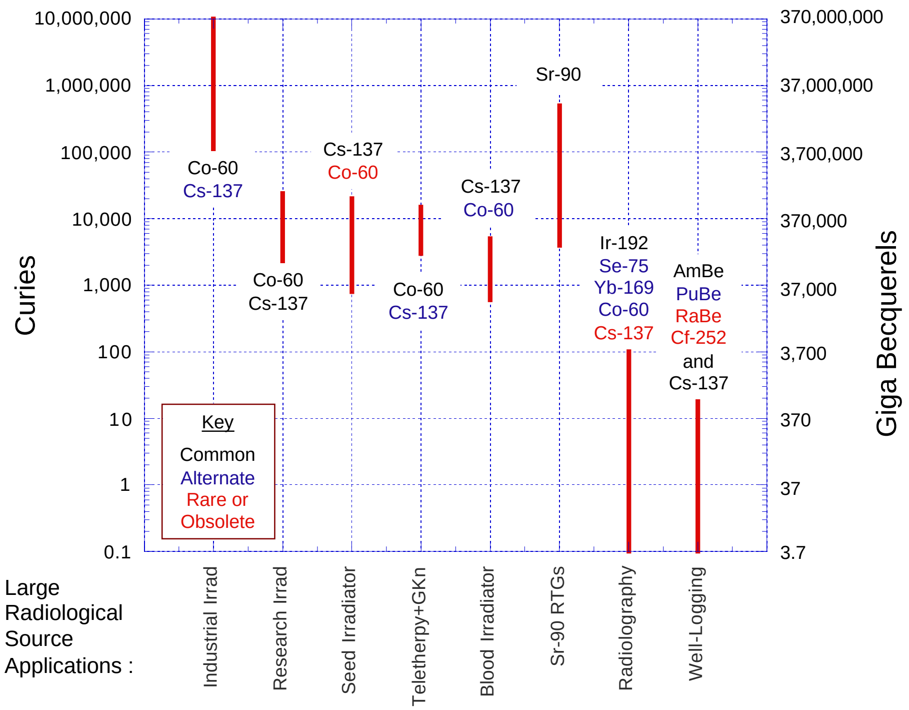
Figure 3.2 Hierarchy of Radiological Source Applications



Applications involving the largest radioactive sources are included in Figure 3.3, which also includes the typical radioisotopes and activity levels (Ref. 5). The scale spans eight orders of magnitude, so a source at the top of the scale is one hundred million times more powerful than one at the bottom of the scale. While radioactivity level is not the only factor in determining the effectiveness of an RDD, a source even one thousand times as powerful as a smaller source is almost certain to have a greater impact. Thus, the impact of a dispersed sterilization facility source would be immense in comparison to that of a low-end radiography source.

Only a few radioisotopes are utilized in the larger applications. The largest industrial sterilization units use cobalt-60 sources in facilities that number around 190 world-wide (Ref. 2). Smaller units that are sometimes mobile use cesium-137, as it is easier to shield. The smaller cesium units are more difficult to quantify. There are more than 100 research irradiators, and many of them use cesium-137. The former Soviet unit deployed many mobile seed irradiators, which are now obsolete. Teletherapy units are used to irradiate cancer tumors, and usually use cobalt-60 to produce the gamma irradiation. There are about 5300 of these, mostly outside the U.S (Ref 6, 7). Most blood irradiators are located in Western countries, and use cesium-137 to kill antibodies in blood prior to transfusions. These are thought to number between 1000 and 2000 worldwide. Radioisotopic Thermal Generators (RTGs) (Ref. 8) are based primarily on large amounts of the beta-emitting strontium-90 (about 1000 such units), although there have been a few plutonium-238 RTGs (mostly for space exploration). Radiography units are commonly used to scan industrial welds, mostly using iridium-192. Many of these are very portable, and they are toted between construction sites in pickup trucks and stored in sheds. They are far more common than the larger sources, and more likely to go missing. Well-logging sources are similar except they use neutron sources to probe the geology around oil-welling shafts (Ref. 9). Because these generally use significant amounts the alpha-particle emitting transuranics, their significance in an RDD is somewhat elevated on a per unit of radioactivity basis.

Fig 3.3 Radioactivity Ranges of Large Radiological Source Applications



Cobalt-60, cesium-137, and strontium-90 are used in the largest quantities, with iridium-192, plutonium-238, americium-241also used in fairly large source quantities. Not coincidentally, cesium-137 and strontium-90 are problematic fission products and the byproduct of spent nuclear fuel separation processes, and both are comparatively cheap. Cobalt-60 is made in nuclear reactors from Cobalt-59 and is therefore more expensive, so it is commonly recycled. There are a few other radioisotopes that appear on lists of concern, including radium-226, californium-252, plutonium-239, but these tend to be less widely available.

3.2.1 Sources Used to Alter or Kill Living Cells

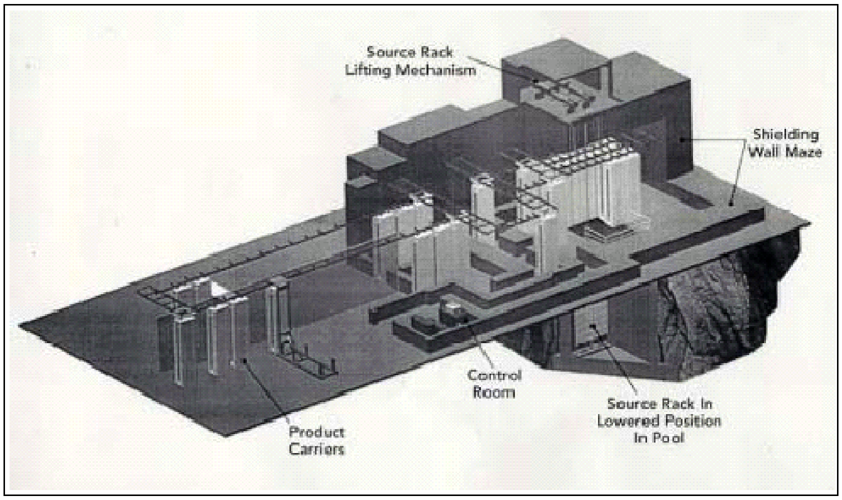
In high doses, radiation can kill living organisms, which makes it especially useful in sterilizing a range of materials ranging from medical instruments to food, including meat and produce. The large irradiators range from highly-shielded industrial units that use cobalt-60 to smaller and more mobile units that more typically use cesium-137 with its lower shielding requirements. Some of the more significant irradiators are described below.

3.2.1.1 Industrial Irradiators

Large industrial irradiators are typically regional facilities, and are most commonly used for sterilizing medical suppliers and irradiating food products. There exist approximately 190 such facilities world-wide (Ref. 2). The facilities typically use hundreds of Cobalt-60 *pencils* (small rods) to deliver gamma radiation in the 1.3 MeV range. During the irradiation process, the items to be sterilized are placed in containers and set on a conveyor system, which subsequently sends the items through a radiation beam. When the irradiation process is complete, the radioactive source is lowered into a pool for storage, since the water can absorb the emitted radiation and provide source cooling.

Figure 3.4 highlights the main components of an irradiation facility. Cobalt-60 (metal) is the preferred isotope in this process, however cesium-137 can also be used (although the solubility of cesium chloride does pose additional safety concerns). The activity level generally ranges from 100,000 to 5 million curies of cobalt, though REVISS (see section 5.1.1.2) has designed an 8 million curie capacity irradiator. The largest known cesium unit contains 250,000 curies. Most industrial irradiators were developed by Western companies (Canada and the U.K.) and are equipped with significant safety and security features.

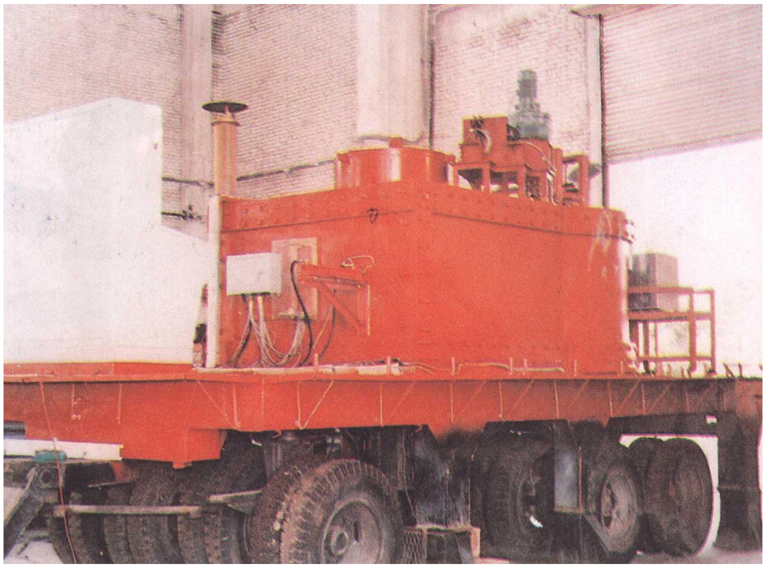
Figure 3.4. Large Industrial Irradiator (Ref. 2)



3.2.1.2 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 are agricultural. Tens of thousands of curies of a high-energy gamma emitter are loaded into these modified trucks and driven around various countries. Of particular concern are the irradiators manufactured by Argentina and China. The Beijing Institute of Nuclear Engineering (BINE) sells a 250,000-curie irradiator containing cesium-137. This mobile device weighs 67 tons and is loaded onto a large truck. The Argentinean National Commission of Atomic Energy (CNEA) makes a 40,000-curie irradiator using cobalt-60. This machine weighs 10 tons, as it requires far less shielding, and can be mounted on the flatbed of a standard truck. The BINE irradiator is shown in Figure 3.5.

Figure 3.5 A Large Mobile Irradiator (Beijing Institute of Nuclear Engineering)

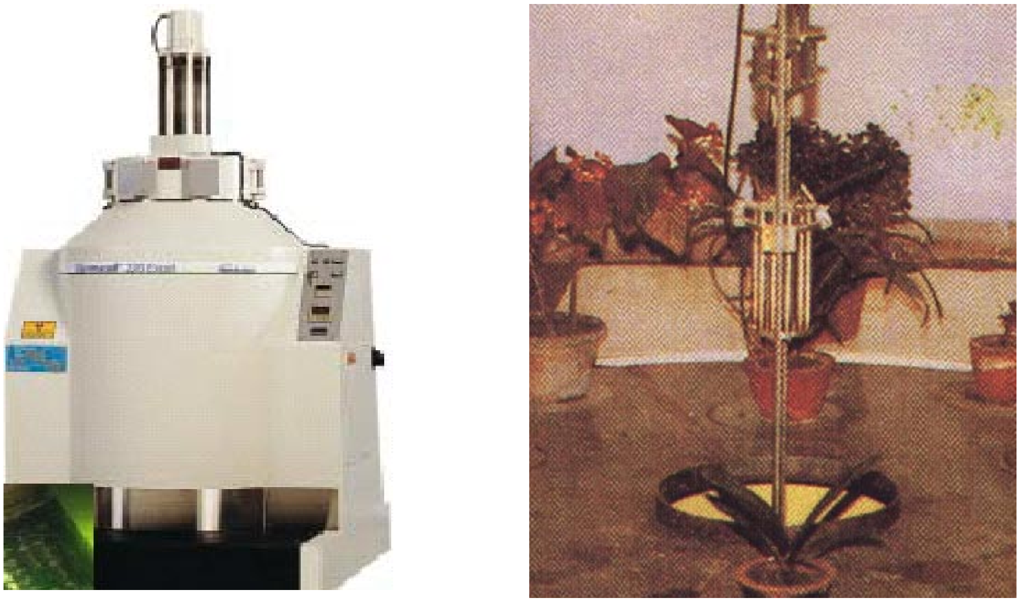


It is not clear that there is currently a market for such devices, although regulatory resistance to this application may contribute to the lack of deployment. However, during October of 2002, the USDA approved importing irradiated produce into the United States. Because food and produce irradiation can greatly extend the shelf life, there may now be greater incentives for deploying mobile irradiators in counties that export produce into the U.S.

3.2.1.3 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, shown in Figure 3.6, utilizes 100,000 curies of cobalt-60. Most manufacturers of industrial irradiators also make irradiators for research applications.

Figure 3.6. Research Irradiators

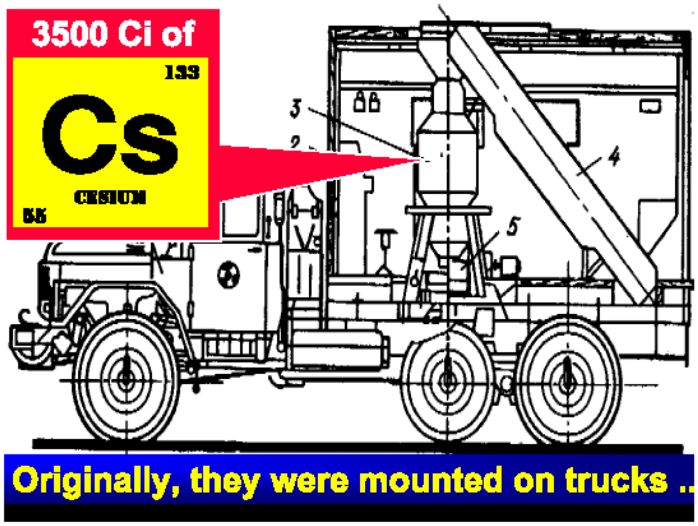

Cobalt-60 Research Irradiator from Nordion
Cobalt-60 Research Irradiator from BINE

3.2.1.4 Seed Irradiators

During the 1970s, scientists in the Soviet Union designed seed irradiators using approximately 3500 curies of cesium chloride (Ref. 10). Under the project name Gamma Kolos (kolos is Russian for an ear of corn), mobile irradiators were shipped by truck (see Fig 3.7) to parts of the Soviet Union as an agricultural research project to study the effects of radiation in plants. It appears there were multiple testing objectives. Wheat and corn were irradiated to stimulate favorable mutations in the crop. They were again irradiated after harvesting to delay germination. Irradiation performed in the spring was determined to stimulate the germination process, and there were reports of greater yield (Ref. 10). In addition, it is possible that some of the programmatic objectives may have been linked to the cold war, since the fallout from nuclear weapons could have had impacts similar to those that were evaluated using the seed irradiators.

Mobile seed irradiators disappeared after the 1970s due to their low capabilities and outdated conveyor systems. Partly as the result of the economic collapse of the former Soviet Union, 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.

Figure 3.7 Seed Irradiator



3.2.1.5 Teletherapy and Gamma Knife

Radiotherapy is the use of gamma radiation for treating cancer. This process can either be external (tele) or internal (brachy).

In teletherapy, a radioactive source is placed in the “head” of the device, and a radiation beam is focused on the cancerous portion of the patient’s body (Ref. 11). Examples of teletherapy machines are shown in Figure 3.8. 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 versus 30 years), the teletherapy equipment was redesigned to allow the radioactive sources to be easily removed and replaced roughly every five to seven years. The radioactivity level of cobalt sources for teletherapy can range from 3,000 to 15,000 curies. INVAP (Argentina), MDS Nordion (Canada), NPIC (China), Xinhua Medical (China), Skoda Ujp (Czech Republic), and BRIT (India) produce equipment for teletherapy sources.

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 United 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.

Figure 3.8. Teletherapy Units.

Cobalt-60 Teletherapy Machine from MDS Nordion

Cobalt-60 Teletherapy Machine from Xinhua Medical

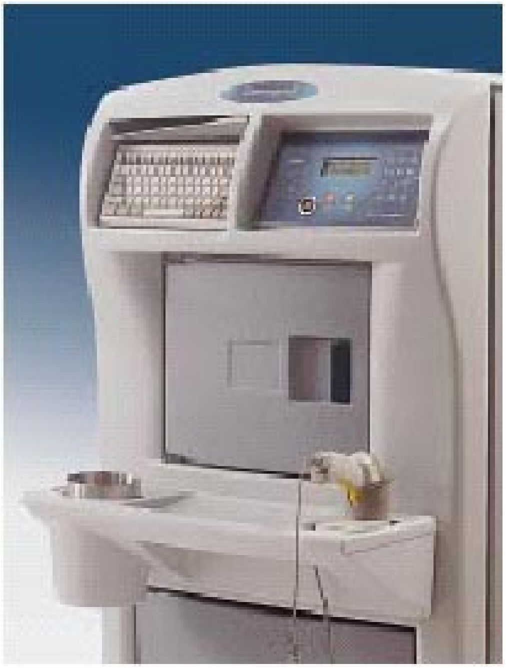
A less common variation on the teletherapy units is the so-called gamma-knife (Ref. 12). In this application, approximately two hundred cobalt-60 sources are configured so as to expose a brain tumor from many different angles. Around 10,000 curies of cobalt-60 are used in this application, so it is comparable to the basic teletherapy units in that respect. There are thought to be dozens of these devices, mostly in Western countries.

3.2.1.6 Blood Irradiators

Blood irradiators sterilize blood using cesium-137 after the blood has been placed in bags and loaded into the ionizing chamber (Ref. 13). Figure 3.9 illustrates these irradiators. 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.

There are conflicting estimates as to the number of blood irradiation machines in use. The Rad Journal states that roughly 300 irradiators exist in the US (Ref. 14), whereas the NEI claims the number to be much higher, around 1000 (Ref. 17). These blood irradiators are located mostly in western countries. 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. Gammasonics (Australia), MDS Nordion (Canada), STS Biobeam (Germany), BRIT (India), CIS-US, and JL Shepherd (US) are the main manufacturers of blood irradiators.

Figure 3.9. Blood Irradiator



3.2.1.7 Brachytherapy

Brachytherapy sources are typically needles or small pellets of radioactive materials that are inserted surgically into the tumors of cancer patients. In some cases, the material is later removed; in other cases it is left to decay away. There are a few radioisotopes involved, with the selection driven by the organ that has been impacted by the tumor.

3.2.2 Sources Used to Provide Power

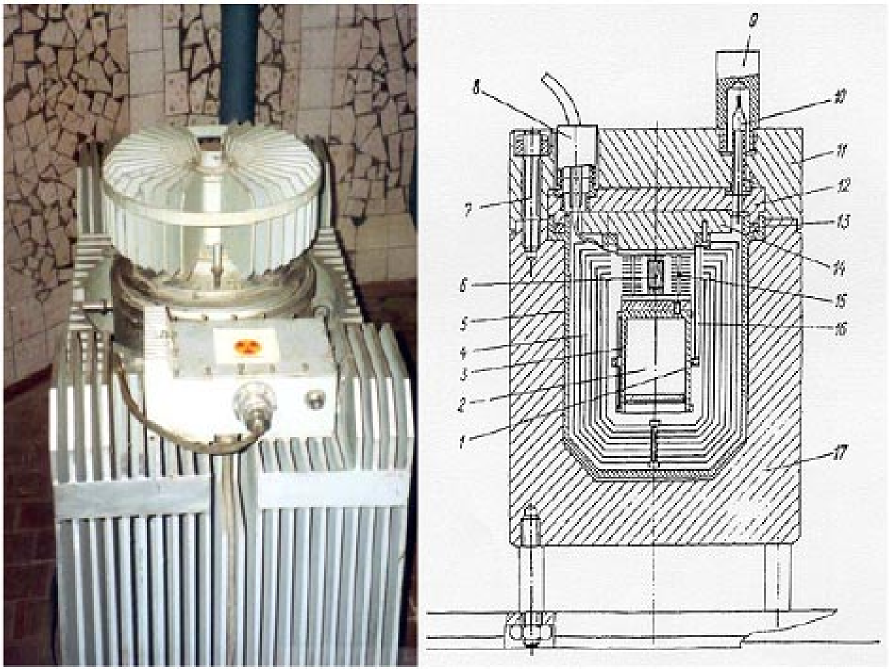
3.2.2.1 Sr-90 RTGs (Terrestrial)

Radioisotope Thermal-electric Generators (known as RTGs in the US and RITEGs in Russia) use the heat emitted from source decay to produce power (Ref. 8). They are also referred to as nuclear batteries or lighthouses. An RTG is shown in Figure 3.10.

Among the fission products in nuclear waste, strontium-90 is a dominant after-heat generator. 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 half-lives of strontium-90 (29 years) and Pu-238 (87 years) contribute to their usefulness in RTGs.

The Soviet Union began manufacturing RTGs in the 1960's as lighthouses, mostly along its northern coast. Soviet RTGs were designed to operate with very little manpower. 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. The All-Russian Scientific Research Institute of Technical Physics and Automation (VNIITFA), MAYAK, and AVANGARD (all Russian institutions) produce RTGs. Both the Soviets and the U.S. also deployed quite a few units for military purposes.

Figure 3.10. Soviet-made RTGs.



3.2.2.2 Pu-238 RTGs (Extra-Terrestrial)

In contrast to strontium-90, which is a waste product from nuclear fission, plutonium-238 must be specially produced in nuclear reactors and is quite expensive. The plutonium-238 RTGs units are typically in the tens to hundreds of curies range, and are controlled quite closely. Although 100 curies of plutonium-238 could make a nasty RDD source, the availability of such sources is so limited that such usage is quite unlikely.

3.2.2.3 Pu-238 Batteries (Pacemakers)

For a few years, some American and Soviet heart patients received a few curies of plutonium-238 to provide the power for their pacemakers (Ref. 5). Today's pacemakers are battery powered, but the old plutonium *batteries* turn up occasionally. It is thought that a few hundred of these may have been used in the U.S., and the Soviet usage may have been comparable. The plutonium might have offered the prospects of a much longer *battery* life-time, but whatever advantages existed proved insufficient to keep the technology in use. Although used Pu-238 batteries turn up occasionally, they are rare and would be difficult to acquire.

3.2.3 Sources Used for Imaging or Measurements

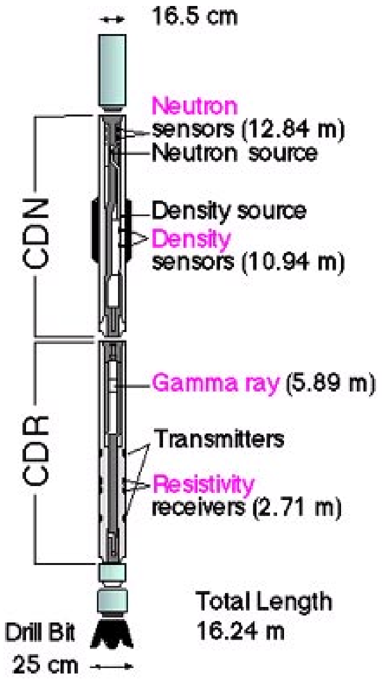
3.2.3.1 Radiography

Radiography sources are also mobile sources, although a few of them 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 (like an x-ray, but higher energy) 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 (Ref. 16), it is a good choice for such an application, as it is not uncommon for radiography sources to be lost or stolen (often in the back of a pickup truck that is stolen).

3.2.3.2 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 (Ref. 9). 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. Many are used in the oil-rich Middle East.

Figure 3.11. Well-Logging *Sonde*



3.2.3.3 Gauges

Gauges use radioactive sources to make measurements of parameters such as moisture. Typically smaller than well-logging and radiography sources, they pose a lower hazard.

3.2.3.4 Calibration

Calibration sources are used to determine the sensitivity of a radiation measurement device, as knowledge of the original radiation level of a source and the extent to which it has decayed specifies the current radioactivity level quite closely. Calibration sources are usually small.

3.2.3 5 Radioisotope Cows (Mo99)

The concept of a cow is tied to the desire to use a short-lived radioactive material that happens to be the daughter product of a radioisotope that has a more convenient half-life. The classic example is short-lived technetium-99m, used in medical procedures, which is the daughter of longer-lived molybdynum-99. Hospitals will typically utilize molybdynum-99 cows that produce technetium-99m continuously, and then *milk* the technetium-99m off on a routine basis. Like many sources, the Mo99 cows could be used as RDD source materials, but the 2.75-day half-life is much shorter than those for most materials thought likely for RDD usage.

3.2.3.6 Nuclear Medicine Diagnostics

Several radioisotopes are used in medical procedures to illuminate body organs that are thought to be likely tumor sites, or in some cases, to examine blood flow through arteries. Most of the radioisotopes are quite short-lived, and the risk from one dose of the material inside someone's body is not great. Nuclear medicine diagnostic procedures are common, and the use of such procedures is growing rapidly. Therefore, one must assume that they could be easily acquired and used in RDDs. But such sources are comparatively harmless.

3.2.3.7 Other Small Sources, eg., Smoke Detectors

There are several smaller applications of little concern, with the best known being the tiny americium-241 sources used in smoke detectors. For any of the smaller sources to be a concern someone would need to accumulate a large number of such sources. This is conceivable, but with the availability of so many large sources one would have to question why anyone would take the risk of such a path.

4. Setting the Bar in Denying Access to Sources

As was discussed in section 3, 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. For this reason, one can not simply draw a horizontal line across Figure 3.3 and declare all sources above 500 curies warrant immediate attention. But it is possible to do something almost as straightforward, as discussed in this section.

4.1 Defining the Concerns: Radiation Dose, Contamination, Detection

An important limitation in Figure 3.3 is that the comparison is made in terms of radioactivity levels, as measured in either Curies or Bequerels, whereas the potential RDD impact would be more closely related to radiation dose. This is because radioactivity is an inherent property of a given mass of a radioactive material, and dose is dependent on how humans are exposed to the material. 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. [note that doses in excess of 500 rem are often fatal] 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 4.1, which also includes normalization against the potential dose impacts from the dose from cobalt-60 (Ref 17). 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 4.1. Radiation Doses Relative to Cobalt-60 (Ref 17).

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

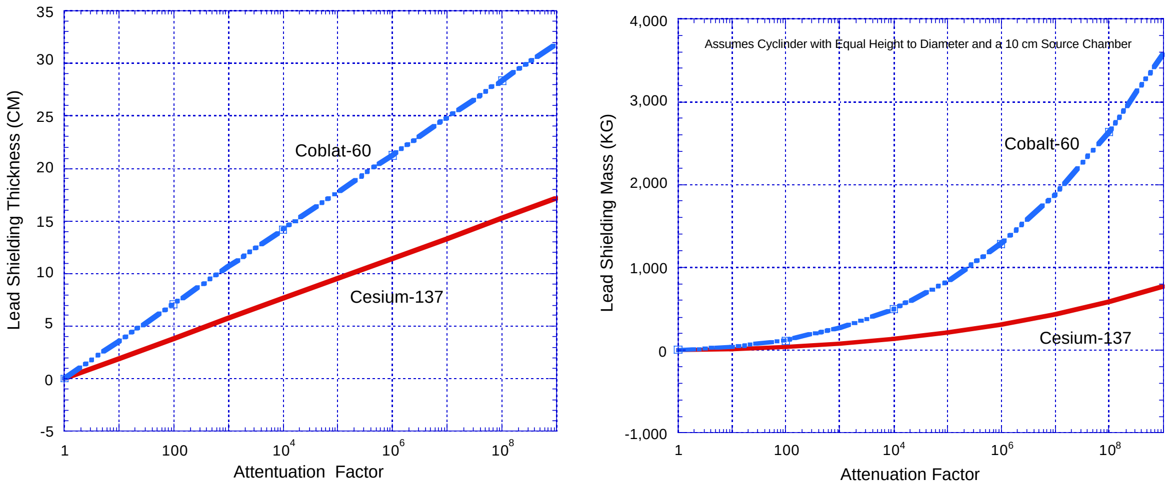
Source: Handbook of Health Physics & Radiological Health by Shleien

There are four groups of radiological source materials in Figure 4.1, specifically the gamma emitters (Co-60, Cs-137, Ir-192), the beta-emitters (Sr-90 and its daughter Y-90), the alpha-emitters (Pu-238, Ra-226, Am-241), and the neutron emitter (Cf-252). Given that RDD analysis is essentially 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.

In projecting a RDD dose from Table 4.1 there are some important factors to consider. First, a fifty-year dose may not be a good measure for cross comparison, as the human body better accommodates long-term radiation than short-term radiation. Ingestion and inhalation are further complicated by the need to get the material into someone's body, which depends greatly on how the material is dispersed and how many people absorb the dose. It is hard to adjust the ingestion and inhalation doses downward relative to the gamma emitters, as this depends strongly on the scenario. However, the relative impacts through ingestion and inhalation are probably overestimated by between one and three orders of magnitude relative to the direct radiation dose. Thus, 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. Therefore, the cross-comparison by radioactivity levels (curies) is appropriate for the eight radiological source materials in Table 4.1, as long as one remembers that the alpha and neutron emitters may be a factor of 10 to 100 more potent in terms of radiation dose, depending on the event.

In addition to dose, there are some others factors that can raise or lower the RDD risk. Some of these factors are related to ease or difficulty in acquiring, transporting, dispersing, and other complex factors such as fear and decontamination problems. Radiological sources that emit high-energy gamma radiation are more difficult to shield than those producing low-energy gamma rays, as illustrated in Figure 4.1. It is noted that this analysis is based on physics fundamentals that have been known and documented for more than 40 years (Ref. 18). Poorly shielded sources are hazardous to handlers and are easily recognized by radiation detection equipment. On the other hand, adequate shielding for cobalt-60 is quite heavy, making it difficult to transport and providing alternate means of detection. Radioactive materials with short half-lives could present difficult constraints, especially if they must be transported some distance. Heat is also a problem for the larger sources, as illustrated in figure 4.2, which shows the surface temperature elevation for a lead (shielding) container with 1000 curies of four candidate radiological source materials. Infrared detectors commonly used at border crossings will *light-up* in response to temperatures less than one degree above ambient temperatures, and will detect RTGs and other large sources easily.

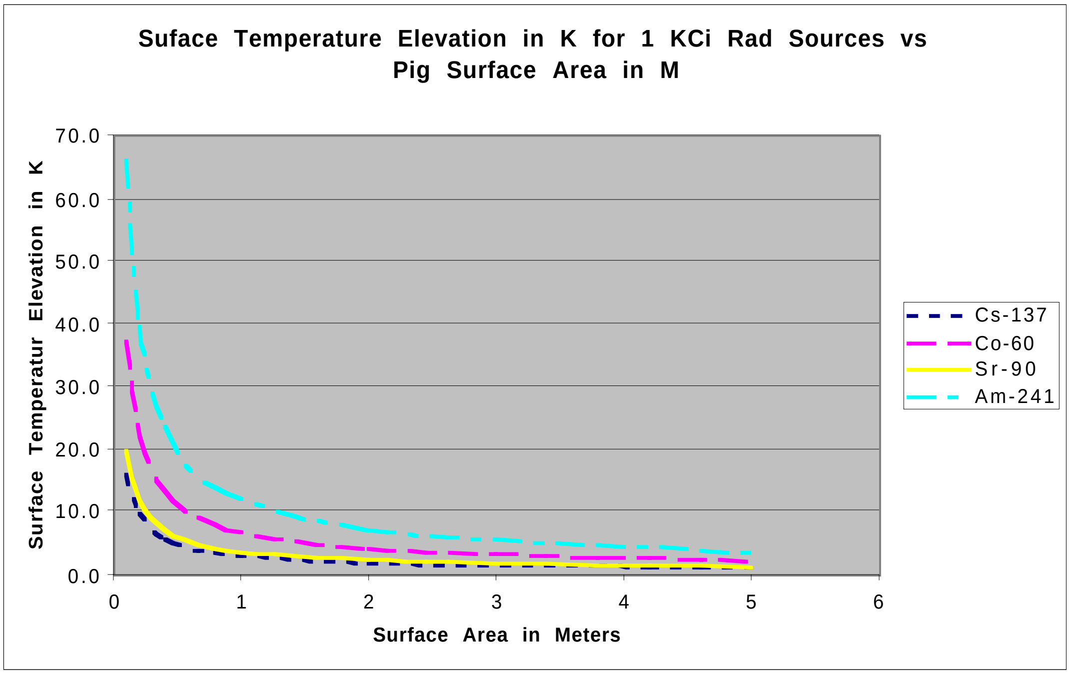
Figure 4.1 Shielding Requirements for Cesium-137 vs. Cobalt-60



Gamma Radiation Energies: Cesium-137 661 KeV

Cobalt-60 1173 KeV and 1332 KeV

Fig. 4.2 Surface Temperatures of Pigs Containing Large Radiological Sources



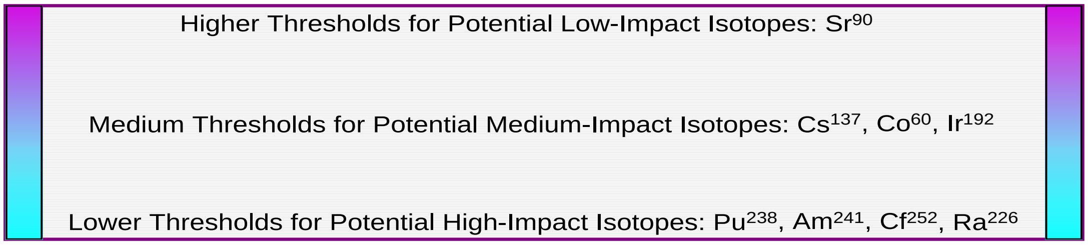
In addition to the radiation dose that could result from an RDD attack and the difficulties associated with acquiring and transporting a radiological source, there is a major concern about the potential contamination. Larger radioactive sources will generally result in higher levels of radioactive contamination, but the chemical form can also be a factor. In the extreme cases, the dispersion could either (1) propel a high-temperature material through the air or (2) create a material that attaches itself irreversibly to only high-value infrastructure. In the first hypothetical case, robotics might be required to remove the object, but the removal would be nearly 100% effective. In the second hypothetical case, effective decontamination technologies would be needed to restore an area to usefulness. Obviously, an RDD attack is likely to produce something in between the extreme cases.

There are two levels of information regarding the potential for radiological source dispersion and the effectiveness of decontamination technologies. There have been instances where sources have been accidentally dispersed, and much of that information has been published openly. Similarly, there has been some experience with decontaminating areas after accidental dispersions, and the results of these efforts have also been documented in the open literature. The discussions in this report are based entirely on this class of experience, based on the assumption that this experience will carry over, to a degree, into the RDD realm. However, a very large detonation would have the potential to disperse nearly any source material, so the potential contamination problems from an RDD attack will be highly scenario dependent.

4.2 Establishing Levels of Concern: Setting the Bar

As was stated in Section 4.1, the likely radiation dose impact from the various radioisotopes depends on the type of radiation and the extent to which it is deposited into the lungs (and digestive system). Thus, it is improper to simply draw a horizontal line across Figure 3.3, at perhaps 5000 curies, and state that is the level of concern. An alternate approach is nearly as practical and much more appropriate. This involves defining a Priority Bar of concern, as illustrated in Figure 4.3. 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 ten times the dose of the high-energy gamma emitters and one hundred times the dose of the beta emitters, we get the priority bar shown in Figure 4.3.

Fig 4.3 Defining a Priority Bar Based Only on Potential Doses.

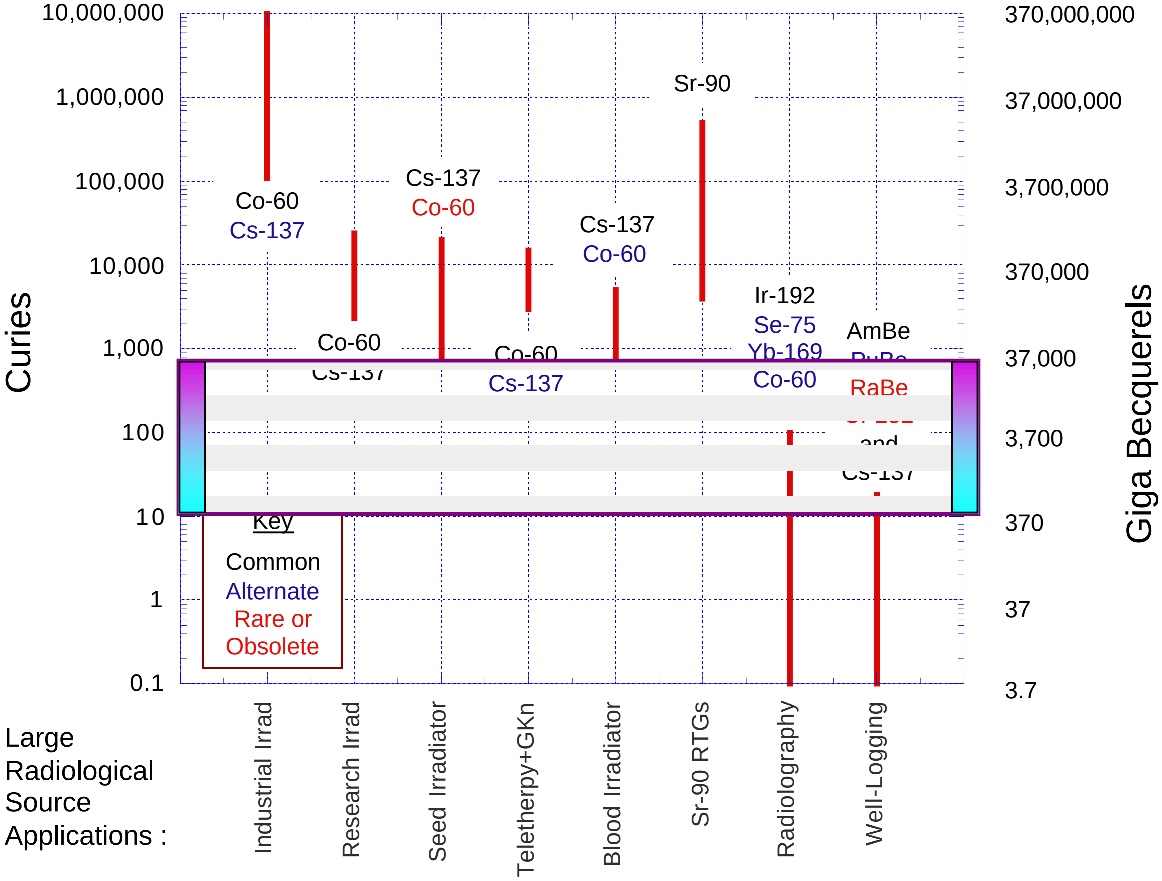


A more sophisticated priority bar would include factors other than dose. It would include the potential problems involved in acquiring and transporting the source, and it would also factor in potential concerns regarding contamination, as well as knowledge of our abilities to decontaminate infrastructure. If all factors (including any additional details about potential radiation doses) were to be factored into the priority bar shown in Figure 4.3, some of the radioisotopes might shift upwards or downwards somewhat. The provision of additional accuracy in the priority bar would not shift the results of this study significantly.

4.3 Identifying Source Applications of Concern: Using the Bar

The overlaying of the priority bar (Figure 4.3) on the Bar Chart that shows the large radiological sources of concern (Figure 3.3) is illustrated in Figure 4.4. 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. Assuming the placement of the priority bar is correct, for the time being, 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.

Fig 4.4 Overlay of Priority Bar on Radiological Source Chart



Naturally, the exact placement of the bar depends on when and where one is looking when asking the question. If one is considering a remote corner of the planet under current circumstances, one might shift the priority up by an order of magnitude. On the other hand, if one is considering sources in Central Manhattan, the bar might be shifted downwards by an order of magnitude. For the purpose of this study and the balance of this report, we'll assume the priority bar has been placed properly in Figure 4.4.

5. Large Suppliers and Users of Sources

There are few (if any) countries that do not have at least some radioactive sources in use. In contrast there are far fewer producers of radiological source materials, as the radioisotope production process requires nuclear reactors or particle accelerators, as well as sophisticated chemical separations processes. Because producers and suppliers are in the marketing business, they can be identified and their available products can often be ascertained. Even though their customer lists are often proprietary, the links between major producers/suppliers and radiological source users can sometimes be determined. In addition, entities such as the IAEA can provide supplementary data linking producers/suppliers and users, partially based on information from governmental regulatory bodies. The links between suppliers and users are often sustained for many years, whether due to the need to replace source materials frequently, the need to obtain technical advice and expertise, the need to recycle used sources, or the need by the supplier to retain a good customer. Thus, for at least the larger radiological source users, they can often be identified with one or more of the large source manufacturers/suppliers, and this is an important means of identifying them and tracking the extent of their radiological source applications.

5.1 Radiological Source Producers and Suppliers

The number of major manufacturers of radioisotopes is relatively small, due, in large part, to the need for costly nuclear reactors or particle accelerators and their appropriate safeguards. Since the quantity and the type of radiological material are the main factors in determining the impact level of an RDD, the smaller sources and their producers do not warrant the same level of attention or concern. Though some isotope production can occur in power reactors, the vast majority of the radiological sources discussed in this report are manufactured in research reactors. Therefore, by identifying the research reactors in use (greater than 1MW) and the companies/agencies that operate or have access to them, it becomes possible to determine the source producers.

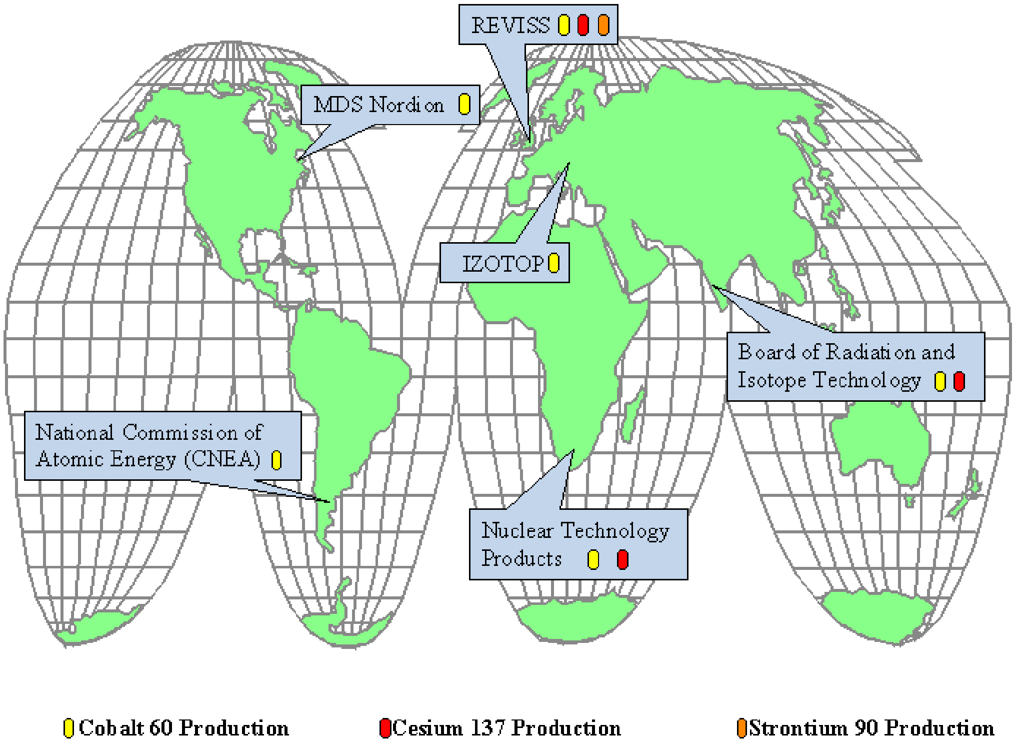
Many radiological source materials that are used in large quantities are waste products from nuclear fission, falling into two categories. Fission products result from the splitting of the uranium or plutonium fuel atoms, and include cesium-137 and strontium-90. Transuranics are produced when the fission neutrons are captured without triggering nuclear fission, and produce heavier isotopes of uranium, plutonium, americium, and californium, among others. Most spent nuclear fuel is not processed, but in cases where it has been processed to either re-use the uranium and plutonium in reactors or to use the plutonium in making weapons, the fission products and the transuranics are by-products. Although the are few facilities that perform such spent fuel separations, those that do will generate a generous supply of the fission products and the transuranics for use in radiological sources.

In contrast, the production of cobalt-60 is fairly costly and time-consuming. Stable cobalt-59 is plated with nickel and placed in a target region of a reactor. Through neutron capture, a process of a few years, the cobalt-59 captures an additional neutron that was released during fission and becomes radioactive cobalt-60. The radioactive cobalt is then encapsulated in steel and becomes ready for use. The sealing is designed to prevent isotope leakage, and does little to reduce the gamma radiation. The sealed sources are pencil-shaped, and are 12 to 18 inches in length and half an inch in diameter. A single source pencil can contain 14,000 curies of cobalt-60.

5.1.1 First Tier Producers and Suppliers

Companies in seven different countries currently produce large amounts of cobalt-60, cesium-137, and/or strontium-90. In addition to being producers of radioactive sources, most of the companies in this category are involved in supplying the technology to accompany their sources. The top-tier isotope producers conduct a fair amount of business among themselves. Though it is often difficult to determine specific quantities of isotopes produced, a general understanding of the production size can usually be ascertained. Figure 5.1 identifies the largest isotope producers in the world.

Figure 5.1. Large-Scale Manufacturers of Radioisotopes



5.1.1.1 Canada

MDS Nordion, a Canadian company, produces roughly 80% of the world's supply of cobalt, totaling more than 500 million curies to date (Ref. 19). Nordion is the largest supplier of reactor-produced isotopes for teletherapy, blood irradiation, and industrial irradiation. The company also manufactures and installs irradiation facilities around the world. Nordion was originally a crown-corporation owned by the AECL. In the early 1990s, MDS acquired Nordion to become its parent corporation. In addition to the AECL reactors, Nordion developed two MAPLE reactors that will be used specifically for radioisotope production.

5.1.1.2 UK/Russia

REVISS (Russian/English Venture in Isotope Supply Services) is a joint venture between Amersham of the UK, PO Mayak of Russia, and Techsnabexport (a Russian distributor). Mayak operates the Ruslan and Lyudmila reactors, and produces cobalt-60, cesium-137, and strontium-90. In 2001, Mayak announced that it planned to increase isotope production from the Lyudmila reactor in an effort to double cobalt-60 exports (Ref. 20). Mayak has also been a large producer of RTGs. Amersham is a pharmaceutical company that also sells isotopes.

5.1.1.3 Argentina

CNEA Argentina (National Commission of Atomic Energy) is poised to become a larger supplier in the isotope market. Though it began as a regional supplier to the South American market, CNEA has emerged as a large producer of cobalt-60. CNEA maintains the RA-3 reactor for radioisotope production and has supplied other countries with similar technology. In 1999, CNEA Argentina established a partnership with REVISS to secure a back-up supply of cobalt-60. The Commission claims to control approximately 10% of the cobalt market, with the US and Canada being the largest recipients of Argentinean cobalt.

5.1.1.4 South Africa

Nuclear Technology Products (NTP) is the commercial division of the South African Nuclear Energy Corporation (NECSA). NTP uses the 20 MW SAFARI-1 reactor to produce cobalt-60 and cesium-137. Nuclear Technology Products has agreements with both Amersham and IRE (see Fig 5.3) to sell radioisotopes and radiopharmaceuticals to each other. NTP also operates an in-house irradiation facility to irradiate food products.

5.1.1.5 India

India's Board of Radiation and Isotope Technology (BRIT), part of its Department of Atomic Energy, supplies all of India with cobalt and cesium. Its annual production of cobalt-60 is roughly 2-3 million curies. BRIT has four research reactors (DHRUVA, FBTR, APSARA, and CIRUS) for isotope production; however, it also produces cobalt in power reactors. BRIT was founded in 1989, and will install small radiation processing plants and operates an in-house facility for contract sterilization of medical products. BRIT also turns out teletherapy machines, and began designing blood irradiators (using cobalt-60) in 2000, both for distribution largely within India.

5.1.1.6 Hungary

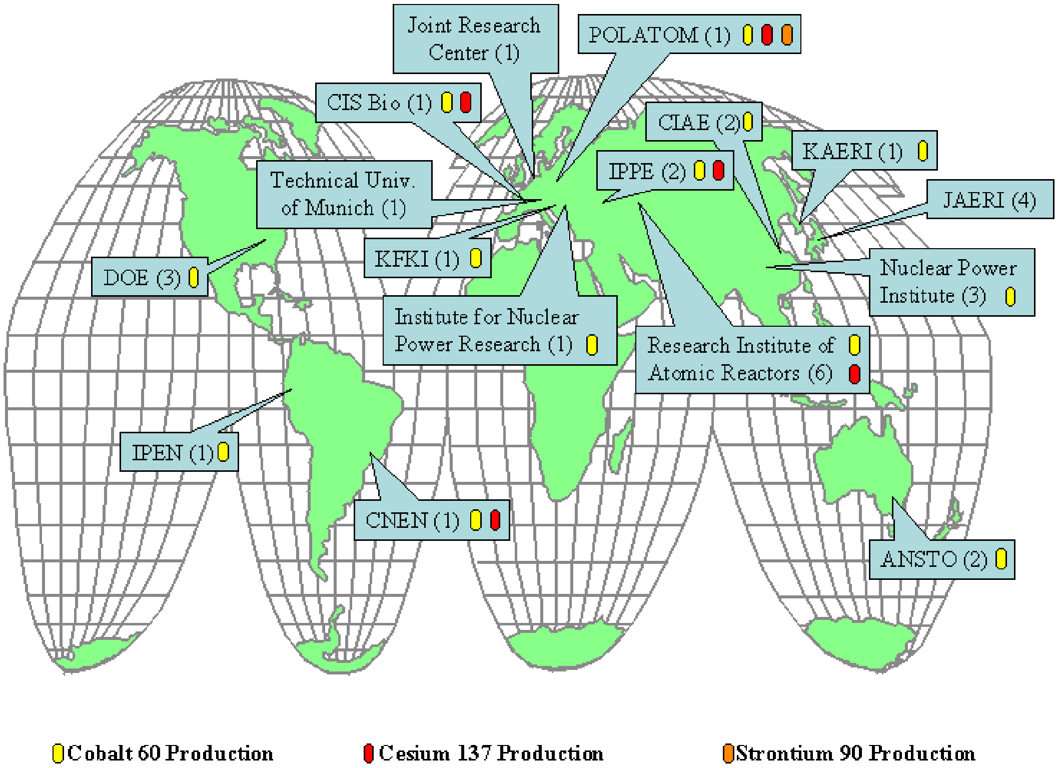
The Institute of Isotopes (IZOTOP) in Hungary, originally part of the Hungarian Academy of Sciences, has been producing isotopes since 1964. Nearly 30 years later, the radioisotope production capabilities were spun-off into a commercial business under the same name. IZOTOP focuses on manufacturing cobalt sources for teletherapy and industrial irradiation. It also supplies commercial irradiators and hot cells. Irradiation plants have been installed in Jordan, Romania, Ghana, and Cyprus, among others. Because it was part of the Hungarian

Academy of Sciences, IZOTOP has access to the 10MW Budapest research reactor owned by the Atomic Energy Research Institute (KFKI).

5.1.2 Second Tier Producers and Suppliers

The second-tier of isotope producers generate much smaller quantities of radioactive sources in comparison to the previous group. Often these companies manufacture source material strictly for personal use, or supply only their country or geographic region with smaller curie amounts, e.g. teletherapy sources as opposed to industrial irradiation sources. Additionally, these businesses and research institutes will often receive radioactive material from the first tier of producers. Shown in Figure 5.2 is a map of this second tier of source producers.

Figure 5.2. Secondary Radioisotope Suppliers and Number of Reactors

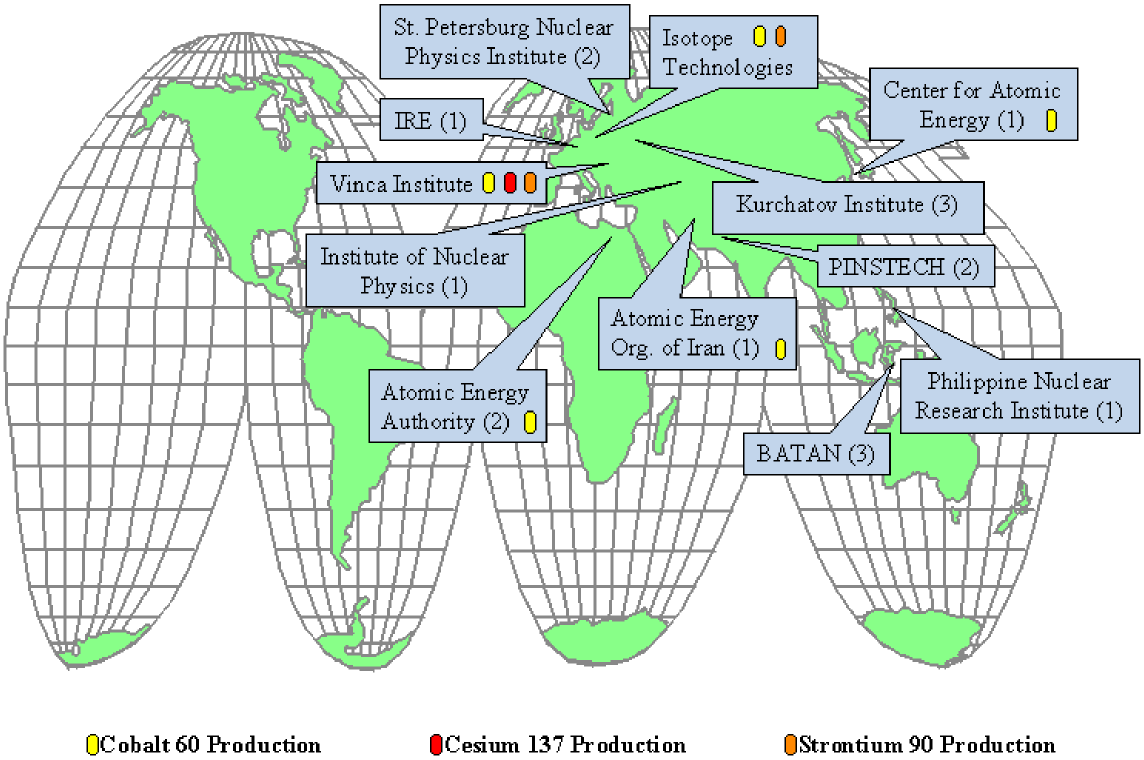


DOE-US, **IPEN**-Peru, **CNEN**-Brazil, **Joint Research Center**-Netherlands, **POLATOM**-Poland, **CIS Bio**-France, **Technical University of Munich**-Germany, **KFKI**-Hungary, **Institute for Nuclear Power Research**-Romania, **IPPE**-Russia, **Research Institute of Atomic Reactors**-Russia, **Nuclear Power Institute**-China, **CIAE**-China, **KAERI**-South Korea, **JAERI**-Japan, **ANSTO**-Australia

5.1.3 Third Tier Producers and Suppliers

The list of third tier of source producers includes considerable uncertainty. These organizations are ones that either have significant isotope-production capabilities or are known to produce isotopes, and yet the quantities of which are unknown. Most of these potential producers have nuclear reactors, however the information regarding their usage is extremely limited. The map in Figure 5.3 includes details concerning this third tier. It is labeled as possible producers and suppliers because it is unclear whether these institutions produce radioactive material, and if they do, whether they supply the sources to others. Information on the source supply-chains both to and from these organizations is absent. The institutes in Russia or Indonesia could choose to commence or increase their production of cobalt-60 in an attempt to penetrate the radioactive source market. Additionally, a few of these institutes are located in countries where the controls on radioactive material are uncertain, thus making it possible for terrorists to obtain source material for use in constructing an RDD. More information is needed to better assess these institutions.

Figure 5.3. Possible Radioisotope Producers/Suppliers



Vinca Institute-Yugoslavia, **Isotope Technologies**-Belarus, **St. Petersburg Nuclear Physics Institute**-Russia, **Kurchatov Institute**-Russia, **Institute of Nuclear Physics**-Uzbekistan, **Center for Atomic Energy**-North Korea, **Atomic Energy Authority**-Egypt, **AEOI**-Iran, **PNRI**-Philippines, **BATAN**-Indonesia, **IRE**-Belgium

5.1.4 Producers of Chloride Forms of Sources

Although most radioactive sources are manufactured in metallic form, they can also be found as a chloride powder. This is a concern because the powders are thought to be more dispersible than their metallic counterparts. Cesium chloride has been used in research irradiators, seed irradiators, teletherapy units, and blood irradiators. The seed irradiators are now obsolete, and most teletherapy units presently use cobalt-60, but the other two large applications continue to use cesium-chloride. Russian-made RTGs were often supplied with strontium chloride. Although the dangers associated with chlorides have led to its diminishing production, CIS Bio (France), Isotope Technologies (Belarus), Polatom Radioisotope Center (Poland), and Mayak (Russia) continue to produce chloride sources

5.2 Global Use of Large Radiological Sources

Although the use of radiological sources may be greater in western countries, one would be hard pressed to find countries where radiological sources are not in use. The largest sources, including the irradiator classes, tend to be concentrated in western countries or around the former Soviet Union, although they can be found elsewhere. The RTGs also tend to be mostly Western (especially the U.S) and Soviet devices. The large medical applications, especially the teletherapy units, can be found almost anywhere. Their spread was aided by the IAEA and the U.S. organizations finding new homes for units replaced by accelerators during the 1970s and 1980s. Of course, these programs pre-dated the current concerns about terrorism and RDDs, and doubtless saved many lives. Blood irradiators have not yet propagated as widely. Radiography sources are widely available, and they are commonly available at construction sites in many parts of the world. Well-logging sources are also widely used, although by a handful of multi-national corporations.

5.2.1 Sources Used to Alter or Kill Living Cells

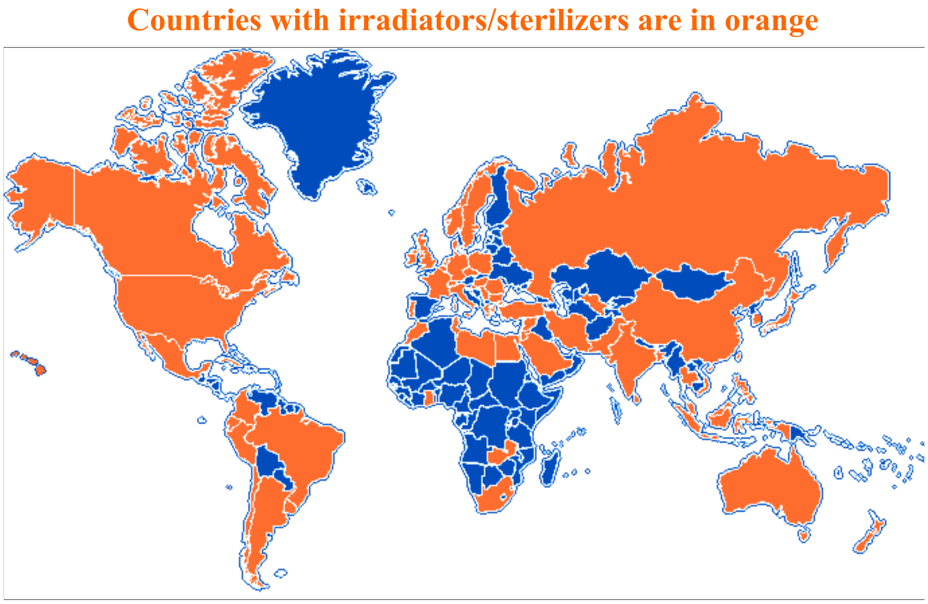
There are concentrations of the largest irradiators in western countries and countries that were formerly part of the Soviet Union, although they are sometimes found in other relatively advanced countries. Of this class of sources, the teletherapy sources have spread most widely, thanks to well-intentioned programs that brought life-saving technologies into less developed parts of the world.

5.2.1.1 Industrial Irradiators

Due to the high capital costs associated with the purchase of an irradiation facility, many companies choose to contract out their sterilization needs. Contract sterilization companies were designed for this purpose. They have a large irradiator that is used to sterilize medical equipment or irradiate food products on demand. This practice is preferable to businesses that do not regularly have a large volume of product to sterilize (for whom the investment in an industrial irradiator would be impractical), or to businesses that simply cannot afford the initial purchase price. The disadvantage of contracting sterilization services is that the businesses in need of such services must transport their product to the irradiation facility. This transportation can often be quite burdensome, as few countries have more than a couple of irradiators for public-use.

The manufacturing industry of irradiation and sterilization facilities is rather limited due to the high entry costs of development. Irradiator prices can range from $3 to $5 million. Additionally, it takes 15 months to commission a large irradiation facility. CNEA (Argentina), MDS Nordion (Canada), BINE (China), IZOTOP (Hungary), REVISS (Russia), and Gray Star (US) supply most of the world's industrial sterilization and irradiation equipment. Nordion is by far the largest and has supplied more than 120 commercial irradiators (Ref. 21). Due to the fact that there are so few suppliers, and that the level of controls and regulations for facilities with hundreds of thousands to millions of curies of radioactive material is so great, irradiators are fairly easy to track in the supply chain. Additionally, 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, along with the appropriate training and security (Ref. 22). Recipients include China, Colombia, Libya, Peru, Malaysia, Syria, Vietnam, and Zambia. Figure 5.4 provides a map of 191 identified irradiation facilities (supplied by the IAEA as well as by others).

Figure 5.4. Locations of Large Irradiators/Sterilizers Worldwide



N-AMERICA: Canada-2, US-34, Mexico-2, Cuba-1. **(39)**
S-AMERICA: Argentina-2, Brazil-6, Chile-2, Colombia-1, Ecuador-1, Peru-1, Uruguay-1. **(14)**
EUROPE: Belgium-3, Bulgaria-1, Croatia-1, Czech Rep-1, Denmark-2, France-5, Germany-4, Greece-1, Hungary-3, Ireland-1, Italy-3, Netherlands-3, Norway-1, Poland-2, Portugal-1, Romania-1, Spain-1, Sweden-1, Switzerland-1, Turkey-3, UK-6. **(46)**
MIDDLE EAST: Iran-1, Israel-1, Jordan-1, Saudi Arabia-1, Syria-1. **(5)**
AFRICA: Algeria-1, Cote d'Ivoire-1, Egypt-2, Ghana-1, Libya-1, Morocco-1, South Africa-3, Tunisia-1, Zambia-1. **(12)**
ASIA: Bangladesh-1, China-28, India-10, Japan-5, Pakistan-2, Russia-1, South Korea-1, Sri Lanka-2, Taiwan-2, Thailand-5, Uzbekistan-1, Vietnam-2. **(60)**
OCEANIA: Australia-4, Indonesia-2, Malaysia-7, New Zealand-1, Philippines-1. **(15)**
TOTAL: 191 facilities, 63 countries

Food irradiation is a growing industry. More and more countries are realizing the benefits of irradiating food. 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 (Ref. 23). Thirty-two countries have been identified that have approved the use of irradiation and who have established irradiation facilities in their respective countries. There are an additional 19 countries who have approved the technique, but who do not yet have domestic companies to carry out the task. In October of 2002, the US Department of Agriculture approved the importation of irradiated produce in to the United States. The problematic implications of this decision pertain to both the large industrial irradiators and the smaller, more mobile variations covered in the sections that follow.

5.2.1.2 Mobile Irradiators

It is unclear to whom these mobile irradiators have been sold. With the growth in popularity of food irradiation (including the recent Department of Agriculture decision to allow irradiated produce into the US) 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. To the extent mobile irradiators do become deployed, it could be assumed they would be most common in countries that export fresh fruit and vegetables into the U.S., e.g., Central and South America. No such equipment is licensed for use in the U.S., and the posture of U.S. regulators against this technology may encourage neighboring countries to take similar positions.

5.2.1.3 Research Irradiators

Research irradiators are utilized in laboratory environments, often in connection with research institutes. Although we have located about 70 such units (out of an estimated 100 to 150), the disclosure of their locations could add to concerns about the security of such facilities. A global distribution that is similar to the large industrial irradiators (see figure 5.4) would be expected.

5.2.1.4 Seed Irradiators

The first studies on seed irradiation date back to the mid 1950s. The Scientific Council on Problems of Radiobiology of the USSR Academy of Sciences supervised the study of irradiating seeds before planting in order to delay germination or produce mutations. These experiments were organized in different climatic zones, including Latvia, Moldova, Apsheronsk peninsula (Caucasus), Moscow, St. Petersburg, Nizhnii Novgorod, Kazakhstan, Kyrgyzstan, Azerbaijan, and Uzbekistan.

The "Kolos" irradiator was designed in 1966-1967 upon an order from the State Committee on the Peaceful Uses of Atomic Energy. The Special Design Bureau of the Zelinskii Institute of Organic Chemistry (part of the USSR Academy of Sciences) designed and manufactured the "Kolos" irradiators and loaded them with 3470-3500 ci of cesium-137. The irradiator was mounted onto an enclosed truck, and its total combined weight was 11.3 tons. The mobile facility was designed to adhere to weight limitations on highways and could also be used on dirt roads. Seeds of 15 different plants were irradiated from 1968-1970 in Moldova. A trial set of "Kolos" irradiators were subsequently produced in 1970 and tested more extensively in Moldova between 1971-1972. Kazakhstan began using the “Kolos” in 1970 in its Pavlodar region. By 1974, the Pavlodar Regional Agricultural Administration owned and operated eight “Kolos” units. The Kyrgyzstan Scientific Research Institute of Agriculture began irradiating corn seeds with a “Kolos” in 1972.

Although most of the mobile irradiators were designed for cesium, cobalt units were also developed. Moscow used cobalt-60 mobile irradiators for sprout inhibition in potatoes. These units contained 20,000 Ci of cobalt, and were approximately 10 x 2.5 x 3.5 meters. The

Dzerdjinsky Vegetable and Fruit Storage facility in Moscow owned such a unit. The quantity of irradiators produced is unknown, though they were most likely manufactured by Izotop. During an IAEA tour in 1972, Izotop put two seed irradiators on display, one with 12,000 ci of cesium-137 and the other with 16,500 ci of cobalt-60. Though there was no reference of mobility, it is likely that these units were portable.

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. Regardless of the quantity produced, they are most likely poorly secured, and there has been very little success in finding them. Only nine irradiators have been found and properly stored (five in Georgia and four in Moldova). Since each unit was equipped with 3500 curies of cesium-137 chloride, mobile seed irradiators pose a significant concern.

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. The locations corresponding to the major participates are included in Figure 5.5. It is likely that orphan seed irradiators remain in these regions. Unfortunately, it appears that other agricultural laboratories also participated in the testing program, so the locations shown in Figure 5.5 should not be considered bounding.

Figure 5.5. Locations of Soviet Agricultural Laboratories

5.2.1.5 Teletherapy and Gamma Knife

Teletherapy devices are somewhat obsolete in the US, however, they are abundant in many other regions of the world where medical funds and technology options are more limited. Most medical institutions in the US prefer to use particle accelerators, however these devices are much more costly to operate. 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 (Ref. 24). This database has it limitations, as all the information gathered was done via questionnaires, and no institution was obligated to respond. Since teletherapy machines often use multiple sources, a minimum of 10,000 sources are thought to exist worldwide (Ref. 25).

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 (Ref. 26). Additionally, Neutron Products, a US-based company, has shipped approximately 1600 teletherapy sources and 150 teletherapy units since the mid 1970's (Ref. 27). The records of Neutron Products regarding the teletherapy sources have been described as *poor*, and the company indicates that it would be difficult to identify the institutions that received exported and donated equipment. It is very likely that some individual hospitals may have also exported their used equipment.

The Gamma-Knife units are uncommon, and most likely found in western hospitals. Although they are doubtless more convenient for treating people with certain types of brain tumors, it would seem likely that most hospitals in poorer countries would either use a standard teletherapy unit or send a more affluent patient to a western hospital for treatment.

5.2.1.6 Blood Irradiators

Blood irradiators are more common that gamma-knifes, but they are also found primarily in western hospitals. This could change, however. An x-ray based blood irradiator is now also available, and this technology may induce users of the cesium blood irradiators to buy the new technology and export the older cesium units to poorer countries. In western hospitals, theft of a large and heavy blood irradiator would be difficult, and a successful theft would not go undetected for long.

5.2.2 Sources Used to Provide Power

5.2.2.1 Sr-90 RTGs (Terrestrial)

It is believed that there are 1000 Soviet-produced RTGs, however, there exists uncertainty regarding the exact number and locations. The most detailed figures from the Russian institute VNIITFA indicate that 929 RTGs are currently operating in Russia, with an additional 169 being stored in the state. Twenty-six RTGs are located in other former Soviet countries. With the radioactivity levels of the strontium RTGs ranging from 5,000 to 500,000 curies, the uncertainties are worrisome.

The US has also participated in the RTG business. According to the Off-Site Source Recovery Program at Los Alamos, the US has manufactured 134 strontium-90 RTGs. Of these, only 47 have been accounted for. It would be difficult to steal an RTG due to its physical properties- it can weigh between 800 and 8,000 pounds and generates a lot of heat, as well as the remote locations of the units.

5.2.3 Sources Used for Imaging or Measurements

5.2.3.1 Radiography

Radiography sources are used almost everywhere that sophisticated construction processes are utilized. This means nearly every part of the world. Although many of these sources are utilized by large multi-national-companies, it would be equally common for construction companies operating in one moderately sized country to use several sources apiece.

5.2.3.2 Well-Logging

Well-logging sources are well-traveled sources, 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 multi-national companies- Haliburton, Baker-Hughes, and Schlumberger- take their sources with them, and their unused sources accumulate at their operating bases and (reportedly) not at the drilling sites. 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.

5.3 Regulatory Environment

There is no standard procedure for regulating radioactive sources internationally. Each system of practice varies remarkably from country to country. In 2000, the IAEA issued its "Code of Conduct on the Safety and Security of Radioactive Sources" in an attempt to cultivate "a high level of safety and security of radioactive sources through the development, harmonization, and enforcement of national policies, laws, and regulations, and through the fostering of international cooperation." (Ref. 28) The IAEA realized that this Code of Conduct is inadequate in a "post 9-11" environment, and is currently in the process of revising its recommendations. The new code will continue to focus on regulatory infrastructure, source management and control, source categorization, orphan source response, information exchange, education and training, and international support. However, four of the most important issues have not been resolved. The laws regulating the import, export, and return of sources, the definitions of ownership and operational lifetime of sources, the proper design and manufacture of sources, and the registries of sources are all still being debated (Ref. 29).

Regardless of the existence of an international advisory scheme for the management of radioactive sources, each country is a sovereign state and may implement its regulatory rules as it sees fit. Consequently, a universal or even customary set of regulations simply does not exist. Since the radioisotope production and distribution business has been, and continues to be, transnational, the import/export laws (as well as other regulations) of each state play a large role in the potential threat of an RDD.

5.3.1 Import/Export Laws

Because the infrastructure necessary to dispose of high activity disused sealed sources is so complex and costly, most countries do not operate disposal sites, and if they do, it is for housing small sources of low activity. Moreover, many countries lack a nuclear infrastructure, rendering source production minimal, and thus it is not cost-effective to design and build a large disposal complex. There are three general practices for dealing with disused source material: laws requiring the return to supplier, laws stipulating the disposal route must be indicated before purchase, or no laws at all.

In the first example, sources must be returned to their original supplier upon disuse. France, Greece, Ireland, Japan, Luxembourg, the Philippines, Poland, South Africa, and Thailand each have this regulation in place. With the exception of South Africa, none of these countries are major source producers. The French have the most stringent regulations, requiring that imported sources must be returned to the supplier after no more than ten years, and the disposal is included in the purchase price of the source (Ref. 30).

The second category of options is to indicate the disposal route in the user license agreement. Austria, Belgium, Denmark, and Finland apply this practice. Although evaluated on an individual case basis, sources in these countries are either returned to the supplier or removed by their national disposal organizations. A license will not be given unless a disposal route is identified. Only Finland has an operating repository; nevertheless each state does maintain interim storage sites.

The third common procedure for managing disused sources is to do nothing. In this category, regulators make no rules regarding the means of source removal and/or disposal. In essence, it is up to the user to handle its radioactive material. This category is the most worrisome and most prolific. Canada, Chile, Egypt, Germany, Hungary, India, Italy, Mexico, Singapore, Turkey, and the UK all fall into this grouping, and there are numerous others. While individual companies might take back manufactured sources as standard practice, there is no law requiring them to do so. Additionally, because cobalt-60 is expensive to produce, more manufacturers might be willing to recycle cobalt sources. Cesium-137 and strontium-90, as fission by-products, are fairly inexpensive, making voluntary source removal/recycling difficult. The unavoidable consequence of no pre-purchase disposal plans, compounded with the high costs associated with removing and disposing of radioactive sources, increases the likelihood of disused sources remaining at user institutions or becoming orphaned. Furthermore, inadequate disposal funds could make it easier for someone to illicitly acquire the disused sources, i.e., the hospitals and other businesses that are eager to get rid of their unwanted source material might not take caution to ensure that the source retriever/disposer has the proper credentials.

Of particular interest are the laws of Poland. Poland, in addition to its import regulations, states that any source produced in its country and exported cannot be returned to the supplier. Consequently, any country that buys sources from Poland will have to handle the disposal itself.

The import/export issues have yet to be solved in the new Code of Conduct, for the questions on source ownership remain. When does the manufacturer transfer ownership of its radiological material? When the source has been delivered or installed? When the source is no longer serviced? Does the manufacturer have an obligation to take back the sources that it produced? Do non-producing suppliers share any duties? Most participants in IAEA meetings on the topic felt that the importing state held the responsibility for the safe management of radioactive material. The state should allow the importation of sources only if it had the proper capabilities to safely manage them. There was no consensus as to whether the source manufacturer had any duties as well. Should the new official Code of Conduct be similar to the text just discussed, many countries will face a difficult dilemma. If a country does not have the proper resources to dispose of sealed sources, should it import the material regardless or inform its people that their cancer will not be treated and their food will not be preserved because some radioactive sources cannot be secured according to IAEA standards? It seems likely that many would choose the former option, not the latter.

5.3.2 Radioactive *Waste*

Labeling disused sources as radioactive *waste* is also problematic for it hinders the transportation of sources across international borders. Most countries have laws prohibiting (or severely restricting) radioactive waste from entering their domestic territory. Consequently, the likelihood of returning a source to its manufacturer once it is labeled as waste is greatly reduced. If a source cannot be returned to its producer, the state generally becomes the next possible handler. However, few countries have the capabilities to dispose of high activity waste. If domestic source production is minimal, states might be more inclined to require that sources be returned, since commissioning and operating a repository for minimal radioactive material is not economically viable. States with moderate to significant source production or usage are more likely to have interim waste sites (which may not be designed for sources of high activity), yet this merely postpones the disposal problem.

5.3.3 Radioactive Source Registries

There are other regulatory concerns aside from the import/export issues. According to the old Code of Conduct, each state should “maintain appropriate records of holders of authorizations in respect of radioactive sources, with a clear indication of the type(s) of the radioactive sources that they are authorized to use, and appropriate records of the transfer and disposal of the radioactive sources on termination of the authorization.” (Ref. 31) These may have been the guidelines, however they were seldom used. Additionally, under the revised plan, no recommendations have been made for general source inventories. Only the creation of an international orphan source database has been proposed and is in progress.

The domestic procedures for a national source registry are even more varied than for imports and exports. Ideally, this registry would contain data on licensees and sources in use/disuse. It would be centralized, operated by the regulator, updated frequently, and contain a provision for the timely reporting of transferred and disused sources. In practice however, there is no uniformity. Many countries do operate source registries, but they are often inadequate. In Austria, each county maintains its registry and there is no central database. The Belgian government is planning a registry, however it will only be updated every 5 years. It is understood that the level of complexity rises when operating a source database for a country with high source usage. For this reason, France, Germany, and the UK lack any sort of registry. Other countries track only disused sources, or only sources in use, or only source licenses. Italy has each institution maintain data on its sources received, disposed, and in use. As yet they do not have a national registry for radioactive sources.

5.4 Source Disposal options, including Recycle

Owners of used radiological sources have limited options for source disposal, and some of the options can be very expensive. Recycle is the most attractive option, and in the case of a valuable material such as cobalt, the owner can get money back. But most used source materials have little or no value, so the owner must pay to transfer the used source to a waste site. Waste consolidation or disposal sites are available in some countries, but the options are very limited in others. As a result, source disposal often defaults to one of three undesirable cases: re-sale to another user- often in another country, storage in a disused state, or orphaned/abandoned.

5.4.1 Recycle

The current situation regarding cobalt-60 would make an excellent model for all radiological source materials, if that was practical. Used cobalt sources are routinely recycled, which establishes a conveniently closed-loop in the life-cycle. There are some factors that make this a viable option for cobalt, including the high cost of production and the half-life of 5.5 years. This establishes a strong working relationship between cobalt-60 users and their suppliers, and makes a take-back and recycle program attractive.

The circumstances with cesium-137 and strontium-90 sources are more difficult. Cesium and strontium are unwanted by-products from spent fuel separations, so there exists some significant stockpiles of these materials in a few locations. The materials are comparatively cheap and expendable. The 30 year half-lives of these materials also tends to nudge these sources into disposable use, as the linkages between suppliers and users are weak.

Recycle of cesium-chloride sources and perhaps other problem sources is possible, even if the economic driver is not strong. Ironically, some of the sources that disperse most easily may also be among the easiest to recycle. In contrast, any steps to make radiological source materials more dispersion resistant may actually make recycling more difficult. This could pose a policy dilemma at some stage.

5.4.2 Waste Consolidation Sites

Waste consolidation sites could be critical tools in reducing RDD risks, as they are easier to establish than waste disposal sites and more responsive to current urgent needs. They can be established on an ad hoc basis at existing sites, including national laboratories. It is important that such sites be adequately secured in order to avoid creating a concentrated source of RDD materials, but this is not overly difficult in stable countries. In contrast, establishment of waste consolidation sites in political unstable areas or areas where terrorist groups are most active could be a bad idea. Under such circumstances, shipment of large sources across international boundaries to waste consolidation site in a more stable country or region may be the only viable option.

5.4.3 Waste Disposal Sites

Waste disposal sites are intended to provide permanent disposal of materials that are thought to pose some continuing hazard to people and/or the environment. As a result, most countries rely on careful processes to systematically evaluate the options and to establish facilities that provide a high-level of confidence in providing long-term isolation. In order to establish such a high-level of confidence, it is generally necessary to strictly define the types of materials that can be emplaced. Low-level waste sites are a good example, in that the license will exclude materials that are too highly radioactive.

Although there may be exceptions, waste disposal sites for large radiological sources are few and far between. Because the waste isolation requirements are less stressing than those for spent nuclear fuel, solutions will develop over the next decade or two. However, with the currently elevated concerns about terrorism and RDDs, the development of permanent waste disposal sites is less urgent than establishment of near-term waste consolidation sites.

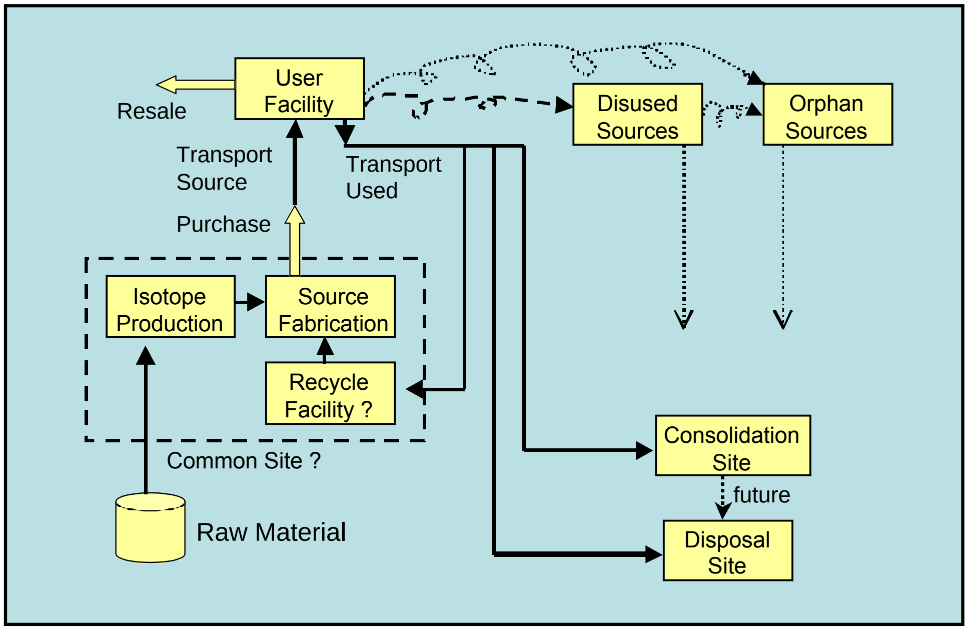
6. Life-Cycle of Radiological Sources

Although the recent media coverage regarding the RDD threats has focused primarily on the orphan sources and their obvious vulnerability, radioactive source materials pose some level of concern from the moment they are created until the time of their disposal. Indeed, the vulnerabilities are apparent throughout the life-cycles of the large radiological sources.

6.1 Defining the Life-Cycle

There exists a life-cycle in the radiological source materials / sources, although full implementation of the life-cycle has been delayed in most countries because of difficulties in establishing waste disposal options. In practice, the life-cycle resembles the illustration in Figure 6.1. Isotope production is usually in nuclear reactors, although some smaller radiological source materials are produced using particle accelerators. Some post-production processing is involved in isolating the radionuclides of interest, and this is usually associated with the isotope production facility (reactor). Source fabrication is usually a mechanical/metallurgical processing step that could be co-located with the radionuclide producers, but could be a separate business. To the extent recycling of materials such as cobalt-60 is performed, it is most likely co-located with the producer. Radiological source users are nearly always located separately from the producers, sometimes introducing some lengthy transportation routes. Ideally, when the user has finished using the source, he will return the source for recycling or will ship it to a disposal site. Difficulties in doing so, however, lead to either a disused source being retained indefinitely at the user facility, or even worse, the loss of the source rendering it into the orphan category.

Figure 6.1. The Life-Cycle for Radiological Source Materials



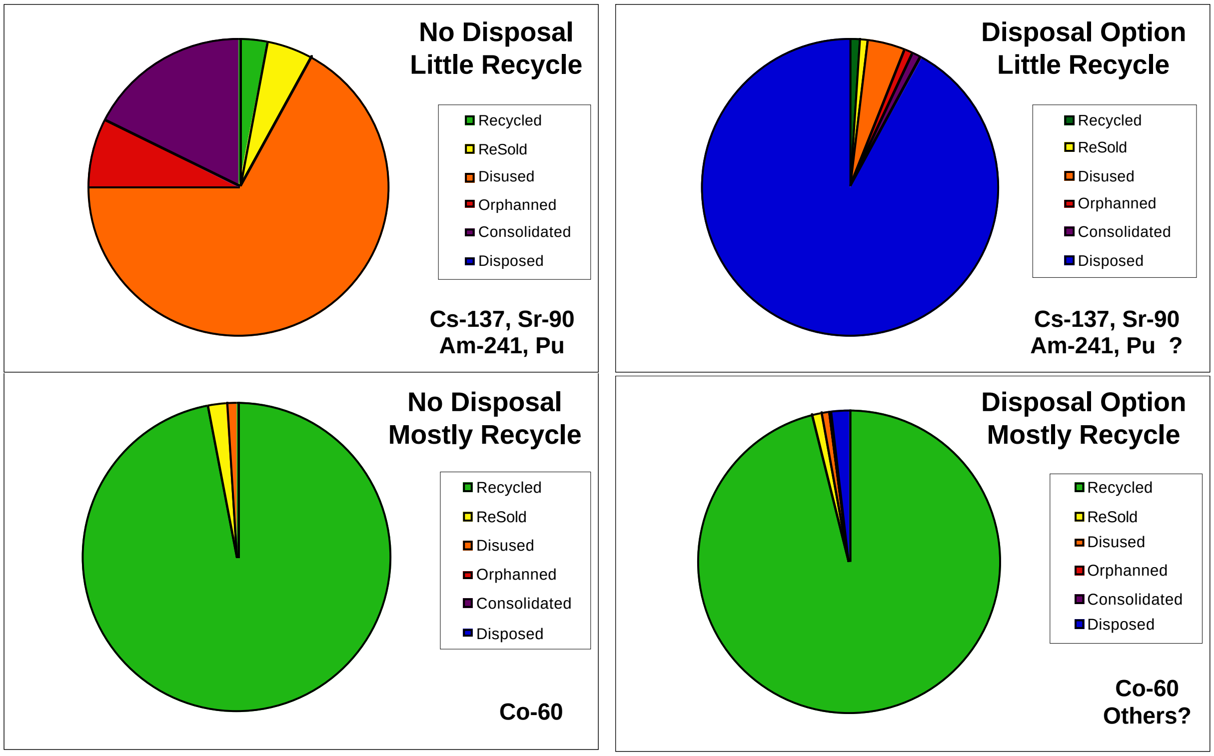
In terms of the vulnerability of sources to theft by terrorists intent on dispersing radiation in an act of terror, different points in the life-cycle present different concerns. The largest concentrations of materials are generally at production sites, but that is where the security will be greatest. User facilities can contain large amounts of dangerous radiological sources, and the security may be minimal depending on the purpose of the facility. The orphans present some well-publicized concerns, as they are very vulnerable if someone stumbles upon them. Disposal sites are uncommon in many parts of the world, and most of the sites that are open are used mostly for low-level wastes of little concern. The transportation piece could be very vulnerable, although it would be difficult to hi-jack a truck without drawing considerable attention from law-enforcement personnel.

In terms of locating these materials, the situation is also quite uneven. Manufacturers and suppliers are in the business of selling sources, so they want to be found. Large radiological source users are far more numerous and much more difficult to locate, unless they are tracked through the source suppliers. Waste sites can be found through governmental/regulatory entities, particularly if they are large enough to house radiological sources of concern. Orphan sources are the most difficult to find, although the existence of orphans can be identified/confirmed through radiological source suppliers and users, if they are still in business and have kept records. Most transportation of significant quantities of radiological source materials requires the knowledge of either suppliers or users. The common thread is that an important means of locating large radiological sources is through the source producers and suppliers and the large users.

6.2 Static Analysis of Disposition Situations

A spread-sheet model, designated RASL-C for RAdiological Source Life-Cycle, was developed in order to better understand likely trends in the system illustrated in Figure 6.1, and to predict future trends. The static (steady-state or equilibrium) version relies upon assumed fractional transitions between stages in the life-cycle. For example, for a material such as cobalt-60 it is assumed that a high fraction of the used sources are recycled, leaving small fractions to go to the re-sale, orphan, disuse, consolidation, or disposal states. In contrast, if neither recycle nor disposal options are available, the fractional flows to the problematic categories of resale, orphan, and disuse are comparatively high. If one adds waste consolidation or waste disposal options to either case the circumstances improve, although the improvement is far greater when recycle is unavailable. The results from such an analyses is shown in Figure 6.2. Note that the case with few recycle or disposal options, which corresponds to the large cesium and strontium sources, results in a high fraction of used sources sliding into the problematic categories. While this is intuitively obvious, the charts drive home the problem quite effectively.

Fig 6.2 Projected Disposition of Radiological Sources for Four Cases of Interest



Case Studies are for hypothetical sources at equilibrium

The limitation in this analysis is that no one really knows the fractional propagations of sources through the life-cycle. Information used in the RASL-C analyses is based on anecdotal information coupled with assumptions about what users are most likely doing. The trends are probably correct and useful, but the numbers have limited reliability.

6.3 Looking Ahead Ten Years for Two Sets of Assumptions

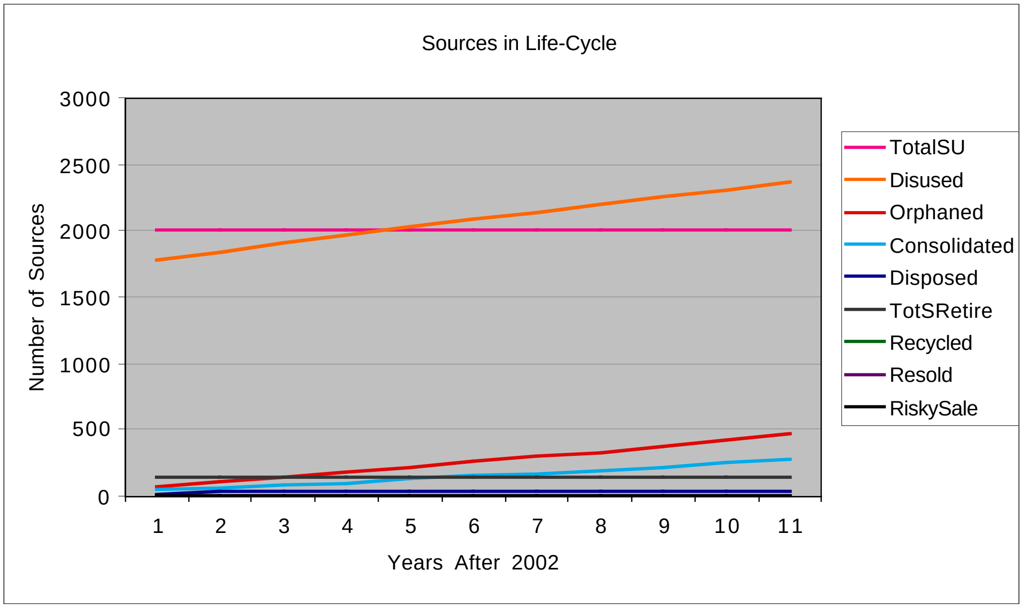
In addition to the static version of the RASL-C spread sheet model, there exists a transient version that allows one to project years into the future. This can provide an assessment of difficulties to come, as well as options that might be used to address the problem. Two cases were analyzed, one in which the status quo is maintained and used sources continue to accumulate, and one in which a major effort is made to provide waste consolidation sites.

6.3.1 Status Quo Maintained: Few Options for Disposal

Because many of the cesium and strontium radiological sources were produced during the 1970s, they have been gradually moving into disused mode over the last few years. This is driven partly by a natural loss in source strength, but also by the replacement of cesium by cobalt in some large applications. It is very likely there are quite a few disused sources being stored in facilities while the owners sort out disposal options, and it is very likely that more sources will shift into this category soon. As disused sources are candidates for possible theft, loss to orphan status, or resale to another party (often outside the U.S), this trend is worrisome.

The results from a ten-year projection are shown in Figure 6.3, corresponding to 2000 large cesium sources in use on a continuing basis (TotalSU). Most of the sources being retired from use are going into disused status. Some of the used and disused sources are assumed to be transferring to consolidation sites, but an increasing number move into the orphan and resale categories.

Fig 6.3 Predicted Changes in Large Cesium Source Status if No Changes in Disposal or Recycle Options



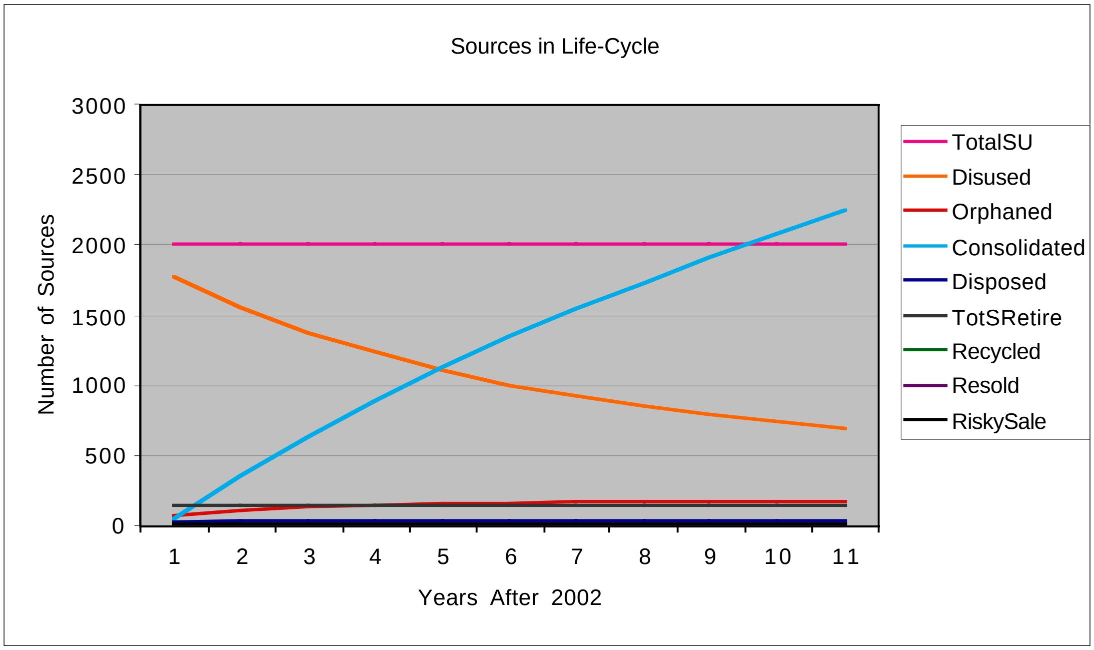
The caution from the static case regarding the uncertainties and assumptions apply to the transient case as well. While it is impossible to predict the number of sources that will be resold or become orphans over the next year, it is almost certain that the current problems will increase significantly.

6.3.2 Waste Consolidation Option Can Ease Problems

The projected increase in the problems with used radiological sources can be mitigated, to some degree, through an aggressive program of establishing secure consolidation sites and encourage countries to recover and consolidate used and disused sources. As was discussed in Section 5.4, existing facilities can often provide consolidation sites, if funds are provided to make any necessary security upgrades and assurances are provided that a consolidation sites will eventually be able to transfer the materials to permanent disposal sites.

We repeated the analysis discussed in section 6.3.1 assuming an aggressive world-wide program to establish and utilize waste consolidation sites. The assumptions that 30% of used sources would go to consolidation, 15% of disused sources would be consolidated annually, and 10% or orphan sources would be consolidated annually are ambitious, but might be achieved if any efforts were focused on western countries and the former Soviet Union. The results, shown in Figure 6.4, show major decreases in the number of disused sources and a leveling off the number of sources being resold or orphaned.

Fig 6.4 Predicted Changes in Large Cesium Source Status if Aggressive Source Consolidation



Once again, the uncertainties are such that the interpretation of Figure 6.4 should be limited to trends, rather than specifics. The primary message is that the anticipated increase in problematic used source materials that was projected in Figure 6.3 can be negated by an aggressive used source consolidation program, as indicated in Figure 6.4.

7. Quantifying the Vulnerabilities

The sheer number of large radiological sources in use around the globe, and the vulnerabilities that are apparent in each stage of the material life-cycle, makes for an overwhelming problem. In this section, we'll focus on establishing a systematic method for quantifying the vulnerabilities, specifically a Source Status Concern Index (SSCI).

7.1 Factor Contributing to Concerns

There are vulnerabilities associated with each type of large radiological source applications at each stage in the life-cycle. The concern can vary by many orders of magnitude, and depends on several factors.

7.1.1 Factors Contributing to Concern

In this section we'll focus on the factors that contribute to concern and how these vary. Five factors have been identified, namely the number of sources, the radioactivity levels of the sources, the hazard factor for a given material type, the inaccessibility of the sources, and a source security factor.

7.1.1.1 Number of Sources

The number of sources available for large source applications and at a given stage in the life-cycle is a measure to exposure to illicit acquisition. There are several times as many teletherapy units in use than blood irradiators, which tends to increase the teletherapy concern over the blood irradiator concern. Similarly, the number of disused and orphaned cobalt-60 sources is thought to be fairly limited, so the cobalt-60 sources in use at industrial irradiators or teletherapy clinics could be of greater concern than the ones in disused or orphaned status.

7.1.1.2 Radioactivity Level of Sources

Although very highly radioactive sources can pose some handling challenges, the impact of an RDD increases in proportion to the radioactivity level. Therefore, the potential concern regarding a 10,000 Curie radiological source is much greater than concerns about a 1 Curie source.

7.1.1.3 Hazard Factor

Although radioactivity level is the first measure of concern, the impact per curie can vary significantly, as was discussed in Section 4. Thus, the concern about 100 curies of plutonium is greater than the concern over 100 curies of strontium.

7.1.1.4 Inaccessibility of Sources

Some radiological sources are highly accessible, such as the americium sources used in smoke detectors. In contrast, some RTGs are used in locations that are virtually inaccessible. Most sources are at least somewhat accessible. Inaccessibility is thus defined as the difficulty one would encounter in locating and gaining access to a radiological source (irrespective of security features).

7.1.1.5 Security Factors

Security features are provided for some radiological sources, and are intended to restrict access to sources. Because many of the security features were designed prior to the recent increase in concern about RDDs, they most likely provide investment protection and safety features, but they may not be entirely effective against a determined and knowledgeable adversary. Regardless, anything that deters one from removing a source can provide a measure of protection and reduce concern.

7.1.2 Specific Concerns by Source Application Type

The circumstances regarding the large radiological source applications vary, as do concerns as they pass through the stages of the life-cycle. This section provides brief descriptions of some of the concerns.

7.1.2.1 Sources Used to Alter or Kill Living Cells

7.1.2.1.1 Industrial Irradiators

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 acquiring 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. As a result, the large industrial irradiators do not stand out as major RDD source material concerns except for two factors. First, they contain an enormous amount of radioactive material and might be intriguing for that reason alone. Second, one cannot assume that all facilities and all shipments are provided equal protection against theft, so there is always the possibility that a terrorist group could find the outliers.

7.1.2.1.2 Mobile Irradiators

The concern regarding the mobile irradiators is that having a large inventory on 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). On the positive side, there are very few mobile irradiators in existence, greatly reducing any concerns.

7.1.2.1.3 Research Irradiators

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 notoriously difficult funding cycles, so programs that fund the research irradiators can disappear leaving the institution with an under-funded facility and possibly a disused source that could be difficult to dispose of.

7.1.2.1.4 Seed Irradiators

The primary concern regarding the seed irradiators is the orphans, which have turned up in a few locations around the former Soviet Union. Because of their large inventories of cesium chloride and their tendency to turn up in easily accessible storage locations, the seed irradiators are clearly one of the larger RDD source material concerns.

7.1.2.1.5 Teletherapy and Gamma Knife

With rare exceptions, hospitals do not usually feature much security, and there are many hospitals around the world where theft of radioactive materials would be quite feasible. In addition, the relatively short half-life of cobalt-60 implies that shipments of fresh and used (for recycling) cobalt-60 sources must be common, even in third-world countries. 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 routine 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 (Ref. 32).

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. However, there are far fewer of these and they are used mostly in Western hospitals.

7.1.2.1.6 Blood Irradiators

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 and then lingering about. Further, 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.

There are significant problems with radioactive sources in the medical industry. When a source for teletherapy or blood irradiation becomes disused, it is not uncommon for the source to remain at the user institution instead of being disposed of properly. Most companies do not make it standard practice to take back sources upon their disuse. In addition, few countries have mandated the return of sources to the original producer. Because of the high costs of removing, safely storing, and eventually disposing of high activity sealed radioactive sources, this burden usually lies with the user. There are few institutions that have the ability and/or the desire to dispose of radioactive material. As a result, the disposal costs are high, roughly $25,000 to decommission a blood irradiator. Disposal prices are similar for teletherapy machines. Because the users of medical sources tend to be hospitals with limited financial means, the disused sources remain on-site and continue to pose a security risk. 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.

7.1.2.2 Sources Used to Provide Power

7.1.2.2.1 Sr-90 RTGs (Terrestrial)

The RTGs are a worrisome source of RDD source material because of both the large inventories of radiological material and their remote utilization. Remote location of large radiological sources carries several risks, including vulnerability to theft, inability to respond to problems, and the out-of-sight-out-of-mind problem that leads to disused and orphan sources. The latter problem has become quite notorious in the former Soviet Union, where changing priorities and economic collapse has resulted in several highly-publicized orphans turning up in the wrong places. Note that a remote location could also be relatively inaccessible. In that case, the inaccessibility would reduce concerns.

7.1.2.3 Sources Used for Imaging or Measurements

7.1.2.3.1 Radiography

The risk of a radiography source being lost or stolen is quite high, and the typical usage leaves far too many opportunities for such developments. These 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. Even though the risk of radiography sources falling into the wrong hands is much higher than for the larger sources discussed previously, the potential consequences from dispersal are generally much lower.

7.1.2.3.2 Well-Logging

Well-logging sources present a unique set of concerns. One reason for their mobility is that their gamma and neutron sources are small enough to require a more manageable mass of shielding. However, if the well-logging source is dispersed in an RDD attack it is very likely the americium and beryllium would be separated, isolating the alpha emitting americium-241. Depending on the event scenario, it is possible for the alpha emitter to deliver some very large radiation doses through either the inhalation or ingestion pathways. The well-logging sources are the largest example of a radiation source that is sufficiently safe while intact for mobile handling practices, but sufficiently dangerous as a dispersed source to warrant special concern.

Well-logging sources are typically purchased by only a handful of international companies, so fraudulent purchases may not be very likely. However, their typical usage leaves many concerns about possible theft. Worse, these sources often get lost down-hole during drilling operations, which casts them in the expendable category and opens the possibility of a lost source being written off too easily. Such losses might be consistent with a short-lived source, but americium-241 has a long 433-year half-life (Ref. 16). There are also concerns about disused or orphan well-logging sources, since disposal of large transuranic sources is not always possible.

7.2 Source Status Concern Index (SSCI) Definition

There are doubtless many ways to define a Source Status Concern Index (SSCI) based on the five parameters discussed at the beginning of section 7.1. Two desirable characteristics of such an index are simplicity and that it reflects the order of magnitude nature of the problem. The best-known example of an order of magnitude scale is the Richter scale, which is a measure of the severity of earthquakes. In the case of the Richter scale, a magnitude 8 seismic event is an order of magnitude more severe than a magnitude 7 event. An equivalent measure can be derived from the five parameters:

$$\text{SSCI} : \text{Log}_{10}(\#\text{Sources x Radioactivity Level x Hazard Factor/Inaccessibility/Security}) \quad \text{(Equation 7.1)},$$

Where:
\# Sources = number of sources of a given application type at a specific stage of the life-cycle
Radioactivity Level=Typical/average radioactivity level in curies of source type at life-cycle stage
Hazard factor=On a scale of 1 to 100, how great is the concern on a per curie basis (consistent with the priority bar defined in Section 4.2 (100 is high, e.g. plutonium)
Inaccessibility=score on scale of 1 to 100, with 100 being the more inaccessible sources
Security=score on scale of 1 to 100, with 100 reflecting highest security features

As an example, if there are 1000 radiological sources in use with an average radioactivity level of 1000 curies, and the hazard, inaccessibility, and security scores are all 10, the SSCI for that type of source in the user stage would be 5 ($\text{Log}_{10}(10^5)$). If there were 10 times as many sources in use, or if each source were 10 times as radioactive, the score would increase to 6, implying the concern is ten times higher. Because these scores provide a means for cross comparison, the scores for all of the large radiological sources at each stage of the life-cycle will be needed before the significance of the scores can be placed into context.

A variation on Equation 7.1, using a fundamental law of logarithms, is also useful:

$$\text{SSCI} = \text{Log}_{10}(\#\text{Sources}) + \text{Log}_{10}(\text{Radioactivity Level}) + \text{Log}_{10}(\text{Hazard Factor}) - \text{Log}_{10}(\text{Inaccessibility}) - \text{Log}_{10}(\text{Security}) \qquad \text{(Equation 7.2)},$$

Where the parameters are all identical to those in Equation 7.1. If we plug in the numbers from the example above, we see the number and radioactivity levels each contributing 3 orders of magnitude, the hazard factor adding another, and the inaccessibility and security subtracting off one apiece. The Equation 7.2 version of the SSCI definition is most useful for quickly assessing the impact for potential changes that are being contemplated.

7.3 Assumptions and Input Tables for Large Source Applications

The example usage of the SSCI index in section 7.2 is hypothetical, but the index can be estimated for all of the large radiological sources at each stage in the life-cycle. In order to perform the analyses, we must first estimate the parameters required in the equation.

7.3.1 Numbers of Sources at Life-Cycle Stages

The number of large radiological sources in use is known to some extent, with the exception of the radiography sources. For the radiography sources, roughly 12, 000 new sources are supplied every year. Since most radiography sources are short lived, we can infer that the total number in use is probably in the range of 20, 000 to 30, 000. Based on these known or semi-known quantities and some reasonable assumptions, we developed Table 7.1.

Table 7.1 Approximate Numbers of Sources at Life-Cycle Stages

Number of Sources	Industrial Irradiators	Research Irradiator	Seed Irradiator	Teletherapy & Gamma	Blood Irradiators	Sr-90 RTGs	Radiography	Well-Logging
Supplier Sources	120	10	1	2500	150	20	12000	2000
Annual Sales	95	7	1	2000	100	10	12000	1000
Transported	190	7	1	4000	100	10	12000	1000
In Use	190	120	1	6000	1500	800	30000	10000
Disused	1	7	1	50	10	600	50000	3000
Orphanned	0.1	3	150	5	2	100	5000	200
Consolidated	1	2	15	10	5	50	20000	2000
Disposed	1	2	10	5	1	100	10000	100

Because the industrial irradiators use cobalt-60, which is commonly recycled, one can infer a re-supply chain that provides new source materials at least every couple of years (taking back used sources), and small quantities of disused, orphaned, or disposed of sources. The research irradiators use either cesium or cobalt sources, so the assumed numbers are more of a composite, with some problematic used sources. Seed irradiators are unique, in that they are nearly all believed orphaned. Most teletherapy sources and gamma-knifes use cobalt, so again the problematic used sources are not thought to be common. However, there remain a few cesium units, so there might be a few disused cesium sources in the mix. Blood irradiators are newer gadgets and their use is concentrated in western countries, so the projected problem cases are few at this time. The RTGs are nearly as unique as the seed irradiators, as many of the units are either very old or abandoned in place. One mystery is the extent to which the Russians might replace the old units, should they be recovered and dismantled. The assumptions about disused, orphaned, consolidated, and disposed radiography sources are based on extrapolations from the supply stream. However, most radiography sources decay quickly (months), so this radioactivity levels for these sources fall quickly, making the actual number of used radiography sources a less significant parameter. Finally, the well-logging sources present another special case in that the few oil exploration companies are known to possess a lot of disused sources. However, they appear to be managing these responsibly, and are known to be actively moving these sources into consolidation sites in collaboration with others.

Several of the numbers in Table 7.1 are thought to be accurate within about 20 to 30%, and few will be off by as much as a factor of two. However, the numbers towards the bottom of the table (disused, orphans, consolidated, and disposed) are less well known. For this reason, we'll examine that part of the problem in a Section 7.5 sensitivity study.

7.3.2 Radioactivity Levels of Sources at Life-Cycle Stages

The nominal radioactivity levels of large radiological sources are fairly well known, although the radioactivity level changes with time. The numbers shown in Table 7.2 and utilized in the study reflect the nominal sizes of the most typical large radiological source applications. The impact of the radioactivity decay is approximated through the life-cycle, and is most apparent with the short-lived radiography sources.

Table 7.2 Approximate Radioactivity Levels of Sources at Life-Cycle Stages

Radioactivity (Ci)	Industrial Irradiators	Research Irradiator	Seed Irradiator	Teletherapy & Gamma	Blood Irradiators	Sr-90 RTGs	Radiography	Well-Logging
Supplier Sources	1200000	10000	1800	2000	5000	100000	80	18
Sales	1000000	10000	1800	1700	5000	100000	20	18
Transported	1000000	10000	1800	1700	5000	100000	10	18
In Use	5000000	10000	1800	5000	5000	100000	5	18
Disused	500000	8000	1800	1000	4000	80000	0.3	18
Orphanned	500000	7000	1800	1000	4000	80000	0.3	18
Consolidated	500000	7000	1800	500	4000	80000	0.2	18
Disposed	250000	6000	1800	500	3500	70000	0.1	18

We have assumed that sources do not move quickly into disused condition, and that significant delays occur before disposal. We have also assumed that suppliers will typically possess up to a year's supply of sources, although perhaps less with the short-lived radiography sources.

7.3.3 Hazard Factors of Radiological Source Materials

In defining the hazard factors, we have limited ourselves to the simple dose-based model used in Section 4.1. There are two reasons for this practice. First, some applications using a few different isotopes and chemical forms, so a form of averaging was needed anyway. But more importantly, our assessment of the most hazardous RDD materials is best held closely.

Nearly anyone with access to books on health physics would be able to derive Table 7.3 within a couple of hours. More precise versions of Table 7.3 are not so easily constructed.

Despite our use of a limited version of Hazards Factors, the fidelity of Table 7.3 is believed to be accurate within a factor of three in most cases. Because our evaluations are primarily an order-of-magnitude science, the accuracy is sufficient to give meaningful results.

Table 7.3 Hazard Factors of Radiological Source Materials

Approx Impact (1-100)	Industrial Irradiators	Research Irradiator	Seed Irradiator	Teletherapy & Gamma	Blood Irradiators	Sr-90 RTGs	Radiography	Well-Logging
Supplier Sources	10	10	10	10	10	1	10	100
Sales	10	10	10	10	10	1	10	100
Transported	10	10	10	10	10	1	10	100
In Use	10	10	10	10	10	1	10	100
Disused	10	10	10	10	10	1	10	100
Orphanned	10	10	10	10	10	1	10	100
Consolidated	10	10	10	10	10	1	10	100
Disposed	10	10	10	10	10	1	10	100

The numbers in Table 7.3 are easily derived. The beta-emitting strontium-90 receives the lowest hazard score. The gamma-emitters are lumped together at 10, and the alpha emitters used in well-logging source are scored at 100.

7.3.4 Inaccessibility Factors for Sources at Life-Cycle Stages

Inaccessibility is a measure of how difficult it is to be in the proximity of a radiological source. The scores range from 1 to 100 (least accessible), as shown in Table 7.4.

Table 7.4 Inaccessibility Factors for Sources at Life-Cycle Stages

Inaccessibility (1 to 100)	Industrial Irradiators	Research Irradiator	Seed Irradiator	Teletherapy & Gamma	Blood Irradiators	Sr-90 RTGs	Radiography	Well-Logging
Supplier Sources	100	100	100	100	100	100	100	100
Sales	100	10	100	5	5	100	1	10
Transported	20	10	100	5	5	10	1	2
In Use	50	2	10	5	5	10	1	5
Disused	25	2	2	5	5	10	1	5
Orphanned	10	5	1	10	10	20	5	10
Consolidated	10	10	10	10	10	10	10	10
Disposed	100	100	100	100	100	100	100	100

Sources in the possession of suppliers or buried within a disposal site are assumed to be least accessible (100). Radiography sources and orphaned seed irradiators are notoriously accessible, and are scored at 1. Accessibility through sales (fraudulent) varies, in that certain types of sources are nearly impossible to buy (RTGs, Seed Irradiators, and industrial irradiators) unless the supplier and buyer are very well known to each other. Transportation places all sources in accessible positions (except for seed irradiators, which aren't really sold or shipped). Most sources in use are somewhat accessible, although one doesn't easily walk into an industrial irradiator or access its dangerous source. Disused and orphan sources are more vulnerable than sources in use, but their likely locations vary, as does their accessibility.

It is assumed that all waste consolidation sites have some access limitations, such as those at nuclear research facilities.

7.3.5 Security Factors for Sources and Life-Cycle Stages (Approximate)

Some radiological sources applications are provided physical security features, involving technology and/or security personnel. Others are carted about and stored as though they were chain saws or toolboxes. It is important to factor security into our analysis, but it is equally important that we not reveal some of the more subtle differences in the security of different types of radiological sources. Therefore, the values included in Table 7.5 are once again approximations to the actual situation.

Table 7.5 Approximate Security Factors for Sources at Life-Cycle Stages

Security (1-100) *Approximat*	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	100	100	100	100	100	100	100	100
Sales	10	10	10	10	10	10	10	10
Transported	10	10	10	10	10	10	10	10
In Use	100	10	10	10	10	10	1	10
Disused	3	3	3	3	3	3	3	3
Orphanned	1	1	1	1	1	1	1	1
Consolidated	30	30	30	30	30	30	30	30
Disposed	100	100	100	100	100	100	100	100

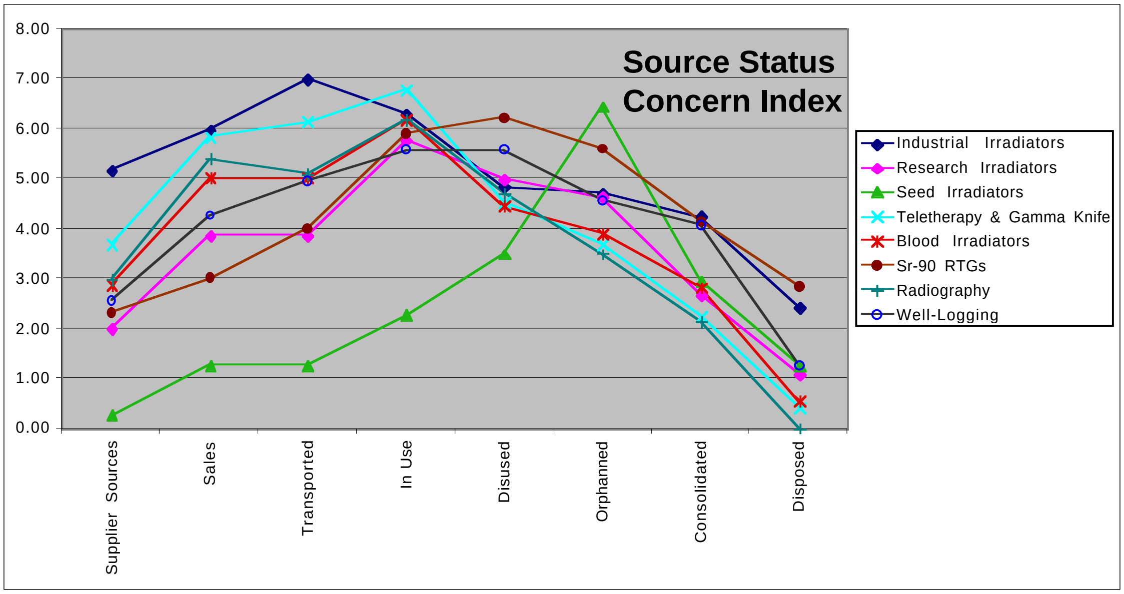
As can be seen from the numbers in Table 7.5, we have differentiated primarily between stages in the life-cycle. Suppliers and disposal sites will generally have some significant security, although some improvement may be possible. Orphans will almost never have any security, unless they happen to be lost inside a secure facility (possible, but not likely to be common). We've assumed some mid-range security features for most categories, including most applications. Regarding users, the security at industrial irradiators is quite apparent and hardly surprising, and the security of radiography sources is notoriously lacking, so we have scored those appropriately.

The extent to which subtle security features may have been designed into the various applications has been omitted even though we are aware of some differences. As was the case for Table 7.3, the accuracy of individual numbers is probably good within a factor of 3, which is sufficient for our analysis.

7.4 SSCI Values for Large Source Applications Throughout Life-Cycle

Based on Equation 7.2 (expression for the Source Status Concern Index) and the Values specified in tables 7.1 through 7.5, we generated SSCI scores for each of the eight large radiological source applications in each of the life-cycle stages. The results are displayed graphically in Figure 7.1.

Fig 7.1 SSCI Values for Large Radiological Sources at Stages in Life-Cycle-Base Case



The life-cycle stages are displayed from left to right, and the chart represents a snapshot in time, i.e., the year 2003. The eight trace lines correspond to the large source applications, as indicated in the key on the right side. Because the scale is logarithmic (base 10), a score of 7 is ten times more significant than a score of 6. As was discussed in the previous section, there are uncertainties in several of the input parameters, and the cumulative results of those uncertainties might be as high as an order of magnitude (e.g., shift a 6 to a 7). Even so, if one interprets Figure 7.1 with a little care, a very important and likely correct picture emerges.

Out of the 64 scores, 8 are between 6 and 7, and represent the greatest concern. Another 12 scores fall between 5 and 6 and must be considered very significant concerns. Scores below 5 indicate source status significantly below the top 8 and probably below the next group of 12. The uncertainties in the analyses are such that scores between 4 and 5 *could* be significant.

Starting from the left side of the graph, with the production and supplier stage, the Co-60 suppliers are the only suppliers to generate significant SSCI scores. This traces to the large quantities of radioactive cobalt they must stockpile.

Sales and re-sales (by first owners) of sources present an area of concern. The SSCI scores for both industrial irradiator sources and teletherapy sources are a little under 6, which is driven by the large commerce in these sources. Radiography sources also score as very significant concerns, because there are so many buyers in so many countries it would be hard to preclude a fraudulent purchase. Blood irradiators also score just above 5, with potential concerns about re-sale contributing to the score.

The transportation stage appears to present some major concerns, especially regarding the frequent shipments of large quantities of Cobalt-60. Even if we are underestimating the security features of such shipments, the scores for industrial irradiators and teletherapy sources constitute red flags. Three other transportation scores hover near 5, making them significant concerns. The radiography sources and the well-logging sources tend to be well-traveled, exposing the sources to theft. The blood irradiator score is in the same range, probably because there are quite a few of these large sources.

The SSCI scores for several of the users are high, probably because most of the sources are currently in the hands of the users. The teletherapy units score very high- approaching 7- and this is far from surprising. Regardless of the good intentions, the placement of several thousand teletherapy sources in third-world hospitals has resulted in a major RDD vulnerability. Three other users rate SSCI socres just above 6 for different reasons. The industrial irradiators have huge inventories of cobalt-60, so despite the challenges in stealing such sources, they remain a major concern. The radiography units are simply everywhere, and they are easily stolen. The blood irradiators are big and used in relatively open hospitals. Three additional user facilities score between 5 and 6, including the RTGs, research irradiators, and well-logging sources. Of the users, only the obsolete seed irradiators fail to score in a region of concern!

Of the disused sources, only the RTGs score above 6, mostly because there are fewer disused sources than sources in use, and because disused are often located near the sources in use. Unfortunately, RTG sources are used under somewhat vulnerable conditions, and there are a bunch of disused RTG sources. The only disused source to score between 5 and 6 is the well-logging source, largely because of the high hazard factor for the americium source material. There is a cluster of disused sources just below 5 that should serve as a warning. As long as few waste disposal or consolidation sites are available, the number of disused sources will increase greatly over the next decade or two.

Orphaned source have received great notoriety because of their vulnerability. However, there are only two that generate high SSCI scores. The seed irradiators score over 6, because they are large and often located is highly vulnerable locations around the Former Soviet Union. Orphaned RTG are less common than their disused cousins, but they have been known to turn up in very remote locations when least expected. These score between 5 and 6 on the SSCI scale. It is noteworthy that the only two orphan sources of major concern are in the Former Soviet Union, a fact that doubtless traces to the sudden economic collapse in the early 1990s.

Neither waste consolidation nor waste disposal sites generate high SSCI scores at this time, mostly because they don't yet contain that much source material. However, as more disused sources are moved to these locations, the SSCI scores will move up into regions of concern.

In summary, the RDD risk reduction priorities implied by Figure 7.1 are as follows:

1 Transportation of Cobalt-60 sources
2 Teletherapy Source User Facilities (Hospital Cancer Treatment centers)
3 Disused and Orphaned RTGs
4 Orphaned Seed Irradiators
5 Industrial Irradiators, Blood Irradiators, and Radiography Sources in Use
6 Sales and Re-sales of cobalt-60 sources and radiography sources
7 RTG, Research Irradiator, and Well-Logging Source Users
8 Disused Well-Logging Sources
9 Sales and re-sales of radiography sources and blood irradiators
10 Transportation of radiography, well-logging, and blood irradiator sources

As stated before, the uncertainties in the numbers behind Figure 7.1 suggests that items could slide up or down the priority scale a few notches. In addition, the last couple of items on the list may or may not belong. And finally, several types of disused sources will creep up in priority over the next few years if the waste disposal log-jam does not clear.

7.5 Sensitivity Study

Because there exists considerable uncertainty in some of the numbers used in the SSCI analysis discussed in the previous section, we chose to analyze a variant case and examine the impact on the results. Two areas of particular concern are the number of disused and orphan sources and the security provided for transportation modes and user facilities.

7.5.1 Alternate Set of Assumptions

No one seems to know the precise number of disused and orphan sources, and clearly the numbers would vary by radiological source applications. The fraction in this category is also likely to be much lower for the largest radiological sources, as the biggest ones are hard to overlook. Regardless, for the sensitivity study we simply double the number of sources assumed to be in these troublesome categories.

Table 7.6 Sensitivity Study- Modified Numbers of Sources at Life-Cycle Stages

Number of Sources	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	120	10	1	2500	150	20	12000	2000
Annual Sales	95	7	1	2000	100	10	12000	1000
Transported	190	7	1	4000	100	10	12000	1000
In Use	190	120	1	6000	1500	800	30000	10000
Disused	2	14	2	100	20	1200	100000	6000
Orphanned	0.2	6	300	10	4	200	10000	400
Consolidated	1	2	15	10	5	50	20000	2000
Disposed	1	2	10	5	1	100	10000	100

Because we intentionally suppressed some of the genuine variation in radiological source security, we chose to double all of those scores as part of the sensitivity study. This was done for both the transportation mode and the user mode.

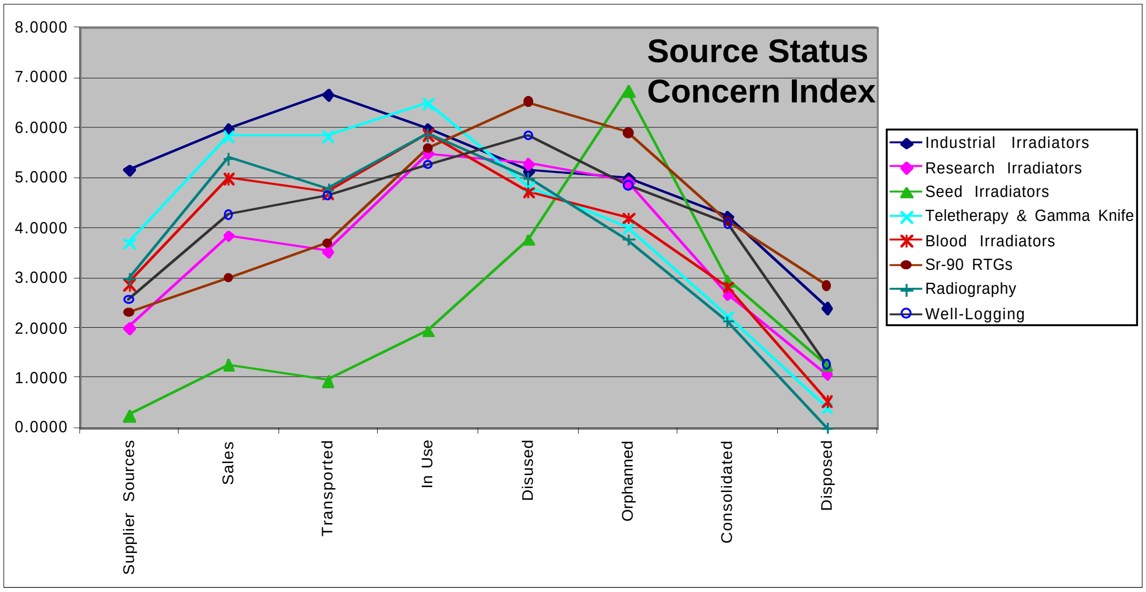
Table 7.7 Sensitivity Study- Modified Security Factors

Security (1-100) *Approximate*	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	100	100	100	100	100	100	100	100
Sales	10	10	10	10	10	10	10	10
Transported	20	20	20	20	20	20	20	20
In Use	200	20	20	20	20	20	2	20
Disused	3	3	3	3	3	3	3	3
Orphanned	1	1	1	1	1	1	1	1
Consolidated	30	30	30	30	30	30	30	30
Disposed	100	100	100	100	100	100	100	100

7.5.2 Alternate SSCI Results for Sensitivity Case

The SSCI scores for the case where there are twice as many disused and orphan sources and the security provided for transportation and user facilities is doubled are shown in Figure 7.2.

Fig 7.2 SSCI Values for Large Radiological Sources at Stages in Life Cycle



Because of the log scale, the impact of these changes is subtle, and the re-ordering of priorities would be minor. Transportation of cobalt and most of the user facilities still stand out as problems, although the two big disused/orphan problems stand out more. The biggest change is that some additional disused sources generate SSCI scores above 5. (It is noted that the current problems in disposing of sources would increase the numbers of disused and orphan sources anyway over the next several years.)

The main message from this sensitivity study and others that could be performed, is that when evaluating results that vary by orders of magnitude, errors of 50 to 100% in the input parameters do not have a huge impact. Therefore, as long as we use the SSCI scores as an order of magnitude measure and unless the input errors are orders of magnitude, the SSCI scores can provide a useful measure of relative vulnerabilities.

8. Options for Reducing SSCI- Describe the Options

The RDD risks associated with the large radiological sources exist in large part because the recognition of the problem has come only recently. There is great room for improvement, and several options are available for reducing the vulnerabilities. The challenge is to properly assess the options for reducing the vulnerabilities.

The groupings of options discussed in the sections that follow are according to which types of groups can take the actions. The options described in Section 8.1 could be completed by security specialists, if they are provided sufficient technical support. Similarly, the options described in Section 8.2 are properly the domain of governmental and regulatory bodies, again with appropriate technical advice. Finally, the options described in Section 8.3 can only be implemented by the radiological source producers, suppliers, and users, again with some support from technical experts.

As was discussed in Section 7.4, the RDD risk reduction priorities implied by Figure 7.1 are as follows:

1. Transportation of Cobalt-60 sources
2. Teletherapy Source User Facilities (Hospital Cancer Treatment centers)
3. Disused and Orphaned RTGs
4. Orphaned Seed Irradiators
5. Industrial Irradiators, Blood Irradiators, and Radiography Sources in Use
6. Sales and Re-sales of cobalt-60 sources and radiography sources
7. RTG, Research Irradiator, and Well-Logging Source Users
8. Disused Well-Logging Sources
9. Sales and re-sales of radiography sources and blood irradiators
10. Transportation of radiography, well-logging, and blood irradiator sources

To some extent, each of the three set of options could reduce the risks associated with each of these ten priority items. Some of the potential actions could reduce the risk sooner, and other potential actions could result in greater risk reduction but over a longer period of time. The challenge is to sort out the various options and develop the best overall course of action.

8.1 Recovery and Consolidation of Disused & Orphan Sources and physical security upgrades

In the current environment, there exist an almost unlimited number of disused and orphan sources, and the number of radiological source locations where security upgrades would be beneficial is daunting, as well. The disused and orphan sources on the priority list include RTGs, seed irradiators, and well-logging sources. Physical security improvements could reduce the risk associated with items 2, 5, and 7 on the priority list.

8.1.1 Recovery and Consolidation of Disused & Orphan Sources

Disused sources are generally in the possession of the original users, or sometimes a party that has inherited a legacy source. In some parts of the world, the high costs associated with getting rid of the sources exceeds the available budget, so people simply leave the source in a corner. In other parts of the world, there is no option available short of shipping the source out of the country. The international regulatory environment can make this very difficult.

Orphan sources are sometimes created when a source used in the field is lost. But a more natural evolution is for a disused source to become forgotten and then somehow migrate out of the users possession. Some sources outlive people, several survive companies, and many outlast management regimes, so it not surprising that some become *homeless*. The other major difference between disused sources and orphans is that disused sources can usually be found, whereas orphans can turn up in very unexpected places.

If one could move freely about the world it would be no great challenge to acquire an enormous number of disused sources, and with a little more effort one could find many of the orphan sources. The challenge is to consolidate these sources until they can either be recycled or disposed of permanently. Such source consolidation efforts have been ongoing in the United States for several years, and many disused and orphan sources have already reach holding points around the DOE complex. The IAEA has also been working to recover sources, sometimes in cooperation with the U.S. DOE. A recent and expanding effort involving the DOE NA-25 is beginning to work the problem globally as an outgrowth of nuclear materials controls efforts in Russia.

The third and fourth items on the priority list, RTGs and seed irradiators, point to the former Soviet Union, and, to a lesser degree, the U.S. (RTGs). Most of the RTGs and all of the seed irradiators are localized to that region, and most of those countries are ill-equipped technically and financially to deal with the legacy. The eighth item on the priority list must be focused on the locations where the three major oil exploration companies accumulate their disused sources. Some, perhaps all, of these locations are in the U.S. and other western countries.

Regarding the set of disused and orphan sources that fell just below the priority line, this group of disused sources merits consideration within the U.S. and its neighbors.

8.1.2 Physical Security Upgrades

Unless focused carefully, any effort to upgrade radiological sources on global basis will lose ground every year, simply because the needs will outpace the response. But the SSCI analysis summarized in figure 7.1 can be used to focus the efforts on maximizing the risk reduction. Two needs jump off the chart and are believed to be genuine and not merely numerical oddities. The notion that large shipments of cobalt traveling across continents to a 190 huge irradiators and 6000 radiotherapy sites need a lot of security should come as no surprise. And the idea that 6000 radiotherapy centers scattered in hospitals around the world present security concerns is hardly a breakthrough, either. Unfortunately, the analysis also shows there are several other user facilities that pose concerns, so the problem is very large.

The dilemma is how to proceed. One possible solution is to work with governmental and regulatory bodies to build a better framework- mandating improved transportation security and better security for hospital cancer treatment centers and other users of large radiological sources. Such a framework will directly impact countries that can help themselves, and will strongly impact companies that transport sources. This could reduce the scope of the physical security upgrades efforts to poorer parts of the world. An enormous effort would remain, but if worked with allies at the IAEA, in Russia, and in Europe, such a mission might be feasible. Within the proposed framework, an effort should move forward to establish and secure waste consolidation sites in as many parts of the world as is feasible. Such action could help prevent the impending bow wave of disused sources from making the current situation any worse.

8.2 Improved Legal Framework and Infrastructure: including regulatory, recycling, and waste disposal provisions

International agreements and regulatory frameworks are difficult to change and enforcement borders on being impossible. However, in order to address several of the priority items, international cooperation is imperative. There are four major areas where action is needed:

disposition of used sources, transportation security, user facility security, and regulation of the commerce in sources (sales). All ten of the priority items can be impacted by changes in the four areas.

Disposition of used sources can include recycling, waste consolidation, and waste disposal. Laws that require used sources be returned to the source suppliers would be very helpful in the disposition of used sources, as suppliers are more capable of recycling sources or managing the consolidation of used sources. International agreements can also help with the development of regional consolidation sites and possibly waste disposal facilities.

Radiological sources are transported all over the world, but transportation security requirements vary. The IAEA is working to try to improve and standardize the transportation security requirements, but agreements take time, and implementation is likely to drag on and lack uniformity.

User facility security improvements will come slowly on a global basis. The teletherapy facilities alone would require a massive undertaking, and beg the question as to whether radiological source security might be a *mission impossible*. The best hope regarding source security is to forge international agreements regarding the necessary security at the various radiological source facilities and provide funding and perhaps technical assistance to foreign countries needing assistance.

Source suppliers do attempt to verify the purchaser before completing sales and shipping sources. However, sources must be provided in countries where political stability is dubious and regulatory authorities are almost nonexistent. The IAEA can help by managing international registries of legitimate radiological source users, and it appears to be moving in that direction. The re-sale of sources is a worrisome gap in the system. It is not unusual to hear of source owners attempting to market a somewhat disused source into the international market as a convenient means of off-loading a headache. International laws must be tightened to ensure that sources are not sold or re-sold to unknown parties.

In addition to the IAEA initiatives to improve source handling and international agreements, there are several other initiatives being pursued by individual countries and regional groups. The U.S is actively working with the IAEA, with Russia, and with others to try to improve upon the current international framework. In addition, there are a couple of noteworthy regional efforts within the European Union and Africa, as described below.

European Union Proposal

The EU has taken steps to adopt legislation to improve the control of sealed sources. A Council Directive was proposed in 2003 to harmonize the regulatory procedures of the 15 member states and of future members after enlargement. Under the proposal, regulatory authorities would have to make certain that preparations have been made for both the safe use of the source and the proper disposal after disuse before a source license is issued (including financial provisions). (Ref. 33) When the EU removed its border controls in the 1990s, it became more difficult to track the flow of source material between members. Currently there is a loophole in EU law that allows EU members to import radioactive sealed sources produced in non-EU countries without notifying their regulatory authorities. Although the controls on radioactive sources are to become stricter after the implementation of this proposal, there is no reference to ending the aforementioned loophole. No timeframe has been disclosed for the voting and passage of this directive.

African Proposal

The First Africa Workshop on the Establishment of a Legal Framework Governing Radiation Protection, the Safety of Radiation Sources, and the Safe Management of Radioactive Waste was held in 2001. During this workshop, the 14 present states asked the IAEA to hold a forum for African countries to consider making the Code of Conduct legally binding (Ref. 34). Though the IAEA claims that full adoption and implementation of the Code of Conduct, both by Africa and the rest of the world, would significantly reduce many of the problems associated with radiological sources (including RDD threats), the limitations of the IAEA are revealed once again. "Legally binding" might not carry the same weight in each country. Some might only obey the rules as long as it was convenient and then quickly and easily withdraw from the agreement.

8.3 Alternate Technology Options

Although improvements physical security, used source disposition, and the international regulatory environment can reduce the RDD risks associated with the ten priority items listed in Section 7.4, the root cause of the problem is the widespread use of large and dangerous radiological source materials. Each large application needs to be re-evaluated to determine whether there are better options available. Because the RDD threat is relatively new, there is likely to be significant room for improvement in many areas.

There are four classes of options of available, namely: replace the application with something that presents fewer concerns regarding RDD materials, replace the radioisotope utilized with something that presents a reduced concern, 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. The natural boundaries between the public and private sectors must be considered when considering such steps, but there are indications that both source producers and users are aware of some of the liabilities associated with hazardous source materials. Because governmental bodies are already involved in regulating the materials and in the disposal (or failure thereof) of used sources, increased government interest in the largest and most dangerous sources would come as no surprise to the industry groups and some degree of cooperation appears to be likely.

8.3.1 Replacing Large and Dangerous Applications

As the largest radiological source applications, the large industrial sterilization units require consideration. Accelerator technology is a viable competitor within the U.S. and parts of the world where electricity is available and 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 vulnerability is associated with the shipments of new Co-60 sources, which must occur frequently given the 5.27 year half-life. But one huge disadvantage of attacking an industrial source or even a shipment of radioactive cobalt would be the involvement of law enforcement personnel, which would make movement of highly-shielded Co-60 difficult. As a result, this very large application may be more a candidate for improved security features rather than an alternate technology, as such.

The research irradiator user facilities present 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, so one should assume these research irradiators are utilized to support a range of research programs. Thus, it is a little risky to offer blanket endorsements for alternative technologies. However, particle accelerators, including electron accelerators and cyclotrons, can produce a range of secondary particles. 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 present an interesting dilemma. They 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 skilled technical staff. As a result, the alternate technology may not be viable in parts of the world. 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. It appears likely that normal teletherapy units could deliver an equivalent treatment, although the time and effort involved in bringing the beam in from 200 directions would likely force some compromises

The X-ray based blood irradiators (Ref 14) appear likely to replace the cesium-based blood irradiators, if the hospitals currently using the cesium units could dispose of the unwanted cesium. But the prospect of those hospitals trying to export the cesium sources or relegating them to disused status is not attractive. 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.

Alternate technologies for RTGs are limited to devices that require special circumstances to succeed. Because of the often-remote location, regular refueling or maintenance is impractical. Power devices based on solar or wind can work in some location, but hostile climatic conditions could 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 seems a quaint anachronism. The cost of equipping the ships that pass through such remote waters would not be insignificant, 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 (Ref. 9). 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 Figure 3.11). 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 to ban the use of AmBe sources and force the drilling companies to use D-T sources, but some resistance from the industry would be likely.

Because they are used so extensively at construction sites (mobility), alternates to radiography sources may not be practical.

8.3.2 Using Alternate Radioisotopes

As was indicated in the comparisons summarized in Figure 4, the impact of radioisotope substitution on dose is not large, barring a completely different class of isotopes, e.g., beta emitters vs. an alpha emitter. There are three types of substitutions that may be useful. First, if the only chemical form assorted 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 maximum 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. Second, cobalt-60 has a market value that generates widespread recycling of the material, whereas cesium-137 is almost worthless and 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 (Ref. 32). 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. Strontium is not the worst of possible RDD materials, although it is available in very large quantities. It is not clear that a search for an alternate material would be worthwhile.

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. Were that substitution viable, the potential RDD dose impact would drop by around two orders of magnitude. 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 is not a particularly worrisome RDD source on a per-curie basis. 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 does not appear to be a high priority.

8.3.3 Deploying Alternate Chemical Forms

The discussion in this section is based on the experience with accidental dispersion of radiological source materials, as there have been cases where radiological sources have caused contamination problems (Ref. 32). The dispersion that could result 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 therefore 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 cesium-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 tetrafluoroborate (Ref. 35) but more technical work is needed before we can determine that these forms are good alternatives.

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.

8.3.4 Modifying Current Radiological Source Applications

For the large applications of radiological sources that involve sources and vulnerabilities that are worrisome, it would be better to eliminate the application or replace the problematic radioisotope or chemical form. However, there are a few cases where this may not be practical. In these cases, a combination of security gadgetry and materials tracking may provide the next best option.

For the large industrial sterilization units, an attack on the facility and an attempt to steal the source material would be very difficult. But with 190 such facilities in the world (Ref. 2), there is some chance of a poorly secured facility within a country where the law enforcement response would be minimal. 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 national authorities and possibly international responders 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.

Whenever 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 to result in recovery of the vehicle and (hopefully) the source.

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 on 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, combined with the bulk and mass of the units, 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 that is moved around on trucks might be suitable for alert and track gadgetry, depending on the potential hazard posed by the source.

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

8.3.5 Prioritizing Alternate Technology Options

The various alternate technology options discussed in Section 8.3.4 are rolled up by application type in Table 8.1. Preferred alternates are indicated using ***bold italics***.

Table 8.1. Roll-up of Alternate Technology Options (Highest Priorities in ***Bold Italics)***

Class of Radiological Source Application:	**Application**	**Competing Technology**	**Alternate Radioisotopes**	**Alternate Chemical Form**	**Modify Application**
Industrial Irradiators	**Industrial Cobalt Units**	***Particle Accelerators*** x-rays (future)	-	-	***Alarm on low source strength, MPC&A***
Research Irradiators	**Research, Smaller Scale Irradiator**	***Accelerators,*** Industrial units x-rays (future)	If Cesium, replace with Co-60 or other	***Replace CsCl (Ref. 35)***	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***			Alert & track if stolen
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

Although the **large industrial sterilization facilities** utilize large amounts of radioactive cobalt-60, most of these facilities do not appear to be very vulnerable to theft. The primary concern is for facilities in countries of concern or cases where a facility is not properly secured, and these circumstances are not believed to be common. 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. On 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. A team of experts could conceivably steal the cobalt-60 source material, given enough time and some laxity of security, so provision of systems that would deny them the time they need could be a worthwhile investment.

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. The additional costs could be a concern, however. If research irradiators are used, security features should be built in to compensate for the concerns.

The **RTGs** present some special problems, as there are few viable alternatives. The greatest weakness and the greatest advantage about these devices is their remote location. It would be hard to monitor these devices, and hard to respond even if someone is tampering with an RTG. But it is also difficult for someone to travel to a remote location and transport these devices to a different location. 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, for the reasons listed previously. 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.

The **blood irradiators** pose an interesting dilemma. The x-ray units appear to provide a viable and even attractive alternative, except for one big problem. If an x-ray blood irradiator is used to replace a cesium-based unit, the disposal of the cesium source becomes a major liability for the hospital. Thus, while the deployment of x-ray blood irradiators into facilities first acquiring the capability is helpful, the replacement of existing cesium-based units could create a new problem of disused sources, orphan sources, or sources being re-sold outside the U.S. The two options for dealing with this problem involve either providing disposal facilities for large cesium-chloride sources (easier said than done) or possibly recycling the cesium sources into a better chemical and/or mechanical source form.

The situation regarding **well-logging sources** is complex and requires interactions with representatives of the oil-exploration industry. There are several options available, and much room for improvement. It is apparent that the D-T sources can provide superior analysis of the geology around the bore-hole, if only 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* (their jargon for AmBe sources and the equivalent), 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, although much less significantly. If these alternatives do not prove to be viable, the AmBe sources are candidates for re-engineering. The notion of using powdered americium oxide and beryllium (compacted within a sealed source) to improve the fraction of alpha particle producing neutrons is a good one until one becomes concerned about the source materials being dispersed. 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, as currently postulated in Section 7.4. The practicality of the various alternate technology options must be evaluated, and some of the alternatives appear to be strong candidates for implementation.

9. Potential for Reducing SSCI- Impacts

This section provides the numerical (SSCI) analysis of the three groups of actions postulated in Section 8, followed by the analysis of an integrated strategy using all three sets of options. The options analyzed in Section 9.1 are associated with security specialists. Similarly, the options described in Section 9.2 are the domain of governmental and regulatory bodies. And, the options described in Section 9.3 are those associated with radiological source producers, suppliers, and users. The case analyzed in section 9.4 is the postulated combination.

9.1 Recovery and Consolidation of Disused & Orphan Sources in addition to Physical Security Upgrades

This section is intended to assess the potential impact of a very large scale global effort to recover and consolidate disused and orphan sources and to provide rapid security upgrades for some source users and waste consolidation sites. Because of logistical challenges, the postulated impact most likely reflects an effort extending five to tens years at a cost of perhaps $500 million. Partners in such an effort would likely include Russia and the IAEA.

9.1.1 Modified Assumptions Regarding Source Numbers and Security

In this case, we assume that, in most cases, half of the disused and orphan sources are transferred to waste consolidation sites, and that security at most user facilities is improved by a factor of 2 and at the average waste consolidation site improved by 67% (not all sites improved). It is noted that the reasons for crediting only a factor of 2 improvement in security are two-fold: first we assume rapid security upgrades that would deter theft but not stop a determined foe, and second, we assume that the intended global effort would face some practical limitations and not reach all sites in all countries. Regarding the orphan sources, it is assumed the seed irradiators receive special attention, so closer to 87% are recovered and secured. With respect to user facilities, no credit was assumed for improvements in security for industrial irradiators, seed irradiators, and RTGs. Modified sections of the tables used in generating the SSCI scores are provided as Tables 9.1 and 9.2

Table 9.1 Modified Assumptions Regarding Numbers of Sources

Number of Sources	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	120	10	1	2500	150	20	12000	2000
Annual Sales	95	7	1	2000	100	10	12000	1000
Transported	190	7	1	4000	100	10	12000	1000
In Use	190	120	1	6000	1500	800	30000	10000
Disused	0.5	3.5	0.5	25	5	300	25000	1500
Orphanned	0.05	1.5	20	2.5	1	50	2500	100
Consolidated	1.55	7	135.5	37.5	11	400	47500	3650
Disposed	1	2	10	5	1	100	10000	100

Table 9.2 Modified Assumptions Regarding Security

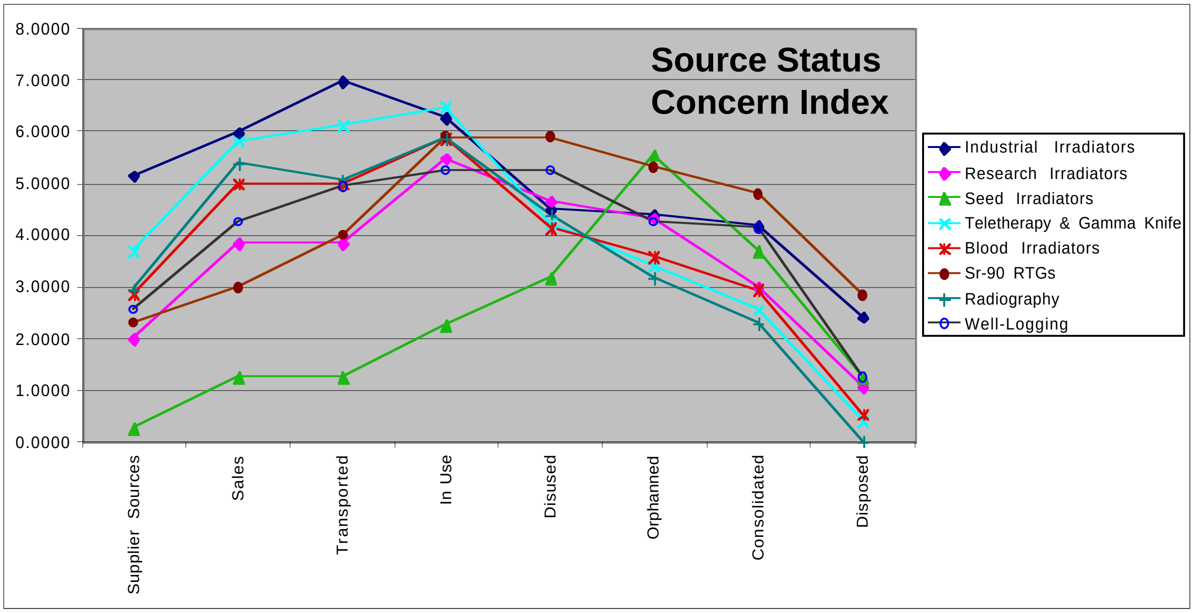
Security (1-100) *Approximate*	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	100	100	100	100	100	100	100	100
Sales	10	10	10	10	10	10	10	10
Transported	10	10	10	10	10	10	10	10
In Use	100	20	10	20	20	10	2	20
Disused	3	3	3	3	3	3	3	3
Orphanned	1	1	1	1	1	1	1	1
Consolidated	50	50	50	50	50	50	50	50
Disposed	100	100	100	100	100	100	100	100

Efforts required to achieve the indicated improvements indicated would be major and require cooperation from friends and allies. The results would also be less uniform than suggested by the tables. Finally, the potential growth in disused and orphan sources projected in Section 6.3 was not included, despite the likely time period of this effort, because establishment/ enhancement of waste consolidation sites may reduce this potential problem.

9.1.2 SSCI Adjusted for Impact of Large, Multi-Year Effort

If we use the value in Tables 9.1 and 9.2 to re-compute the SSCI scores, the result is as shown in Figure 9.1. There are some notable risk reductions projected.

Figure 9.1 SSCI Chart for Aggressive Disused & Orphan Source Recovery and Consolidation, as well as 2x Upgrades in Physical Security for Highly Vulnerable Sources



We can use the RDD risk reduction priorities implied by Figure 7.1 to focus on impact in the key areas:

1 Transportation of Cobalt-60 sources
2 Teletherapy Source User Facilities (Hospital Cancer Treatment centers)
3 Disused and Orphaned RTGs
4 Orphaned Seed Irradiators
5 Industrial Irradiators, Blood Irradiators, and Radiography Sources in Use
6 Sales and Re-sales of cobalt-60 sources and radiography sources
7 RTG, Research Irradiator, and Well-Logging Source Users
8 Disused Well-Logging Sources
9 Sales and re-sales of radiography sources and blood irradiators
10 Transportation of radiography, well-logging, and blood irradiator sources

The impact on priority number 4, the orphan seed irradiators, is very large- falling by nearly 90% (1 order of magnitude on the log, base 10 scale). Priorities 3 and 8 have also been addressed to a degree, with 50% vulnerability reductions projected. The risks associated with priority 2, two of the three sources in priority 5, and two of the three sources in Priority 7 have dropped by 40%. No impact is seen on priorities 1, 6, 9, and 10, and two of the source users in priorities 5 and 7 are not impacted.

9.2 Improved Legal Framework and Infrastructure: including regulatory, recycling, and waste disposal provisions

In this section, we evaluate the potential impact of a global effort to vastly improve the international legal and regulatory framework pertaining to the commerce in radiological sources, along with unprecedented cooperation in recycling, consolidating, and disposing of used radiological sources. Motivation for such a massively cooperative effort may already exist, or it may depend upon a future successful terrorist attack using a large and damaging RDD. Either way, the projected impacts would likely require about a decade to develop, and could require a significantly longer period.

9.2.1 Modified Assumptions Regarding Source Numbers and Security

In this case, we assume that half of the disused and about 30% of the orphan sources are transferred to waste consolidation sites, that some sources are recycled or transferred to waste disposal sites, and that some sources at consolidation sites move to waste disposal sites. We also assume several improvements in source security, including a doubling of security at industrial irradiators, an improvement by a factor of 3 in sales security (prevent fraudulent purchases) and transportation security, a tripling in security at several types of user facilities, which also benefits the security of disused sources that are co-located, and a 67% improvement in security at waste consolidation sites. Modified sections of the tables used in generating the SSCI scores are provided as Tables 9.3 and 9.4

Table 9.3 Modified Assumptions Regarding Source Numbers

Number of Sources	Industrial Irradiators	Research Irradiators	Seed Irradiators	Teletherapy & Gamma Knife	Blood Irradiators	Sr-90 RTGs	Radiography	Well-Logging
Supplier Sources	120	10	1	2500	150	20	12000	2000
Annual Sales	95	7	1	2000	100	10	12000	1000
Transported	190	7	1	4000	100	10	12000	1000
In Use	190	120	1	6000	1500	800	30000	10000
Disused	0.5	3.5	0.5	25	5	600	25000	1500
Orphanned	0.1	2	100	3	1.3	100	3500	130
Consolidated	0.5	3.5	25	10	8	30	40000	3000
Disposed	0.2	3	15	3	2	120	15000	250

Table 9.4 Modified Assumptions Regarding Security

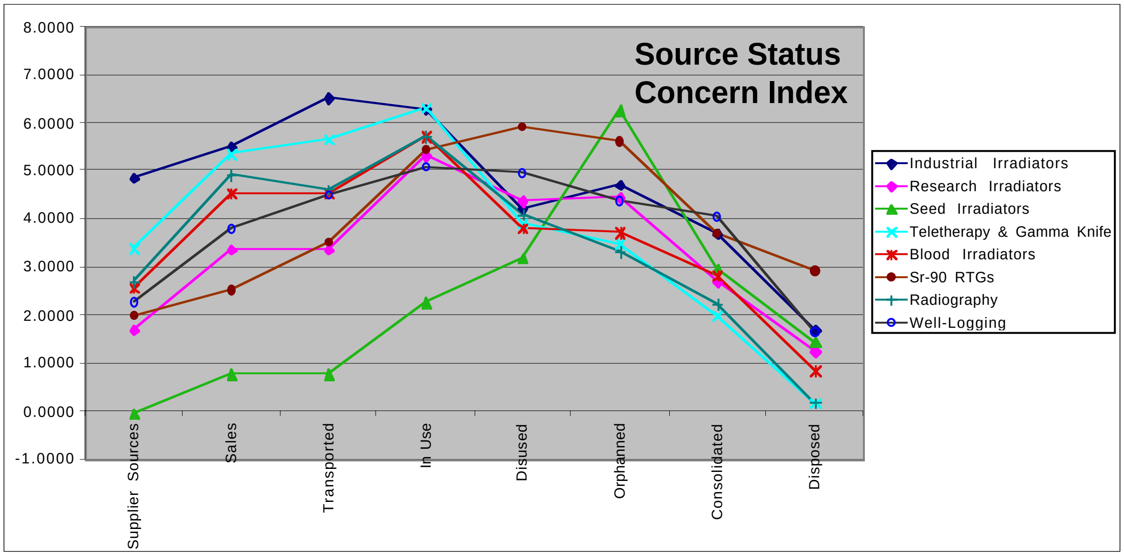
Security (1-100) *Approximate*	Industrial Irradiators	Research Irradiators	Seed Irradiators	Teletherapy & Gamma Knife	Blood Irradiators	Sr-90 RTGs	Radiography	Well-Logging
Supplier Sources	200	200	200	200	200	200	200	200
Sales	30	30	30	30	30	30	30	30
Transported	30	30	30	30	30	30	30	30
In Use	100	30	10	30	30	30	3	30
Disused	6	6	3	6	6	6	6	6
Orphanned	1	1	1	1	1	1	1	1
Consolidated	50	50	50	50	50	50	50	50
Disposed	100	100	100	100	100	100	100	100

Such major improvements could only result by an effort where the majority of the countries actively using radiological sources contributed to the global risk reduction effort. Even so, the effort would likely be uneven, leaving pockets of vulnerabilities. Again, the potential growth in disused and orphan sources projected in Section 6.3 was not included, despite the likely time period of this effort (5 to 10 years), because establishment/ enhancement of better waste recycling, consolidation, and disposal sites may reduce this potential problem.

9.2.2 SSCI Adjusted for Impact of Sustained Efforts

If we use the value in Tables 9.3 and 9.4 to re-compute the SSCI scores, the result is as shown in Figure 9.2. Again, there is some very significant vulnerability reduction projected.

Figure 9.2 SSCI Chart for Tighter Regulations on Source sales, Handling, and Disposal, as well as Provision of Viable Recycle and Waste Disposal Options



We can again use the RDD risk reduction priorities implied by Figure 7.1 to focus on impact in the key areas:

1 Transportation of Cobalt-60 sources
2 Teletherapy Source User Facilities (Hospital Cancer Treatment centers)
3 Disused and Orphaned RTGs
4 Orphaned Seed Irradiators
5 Industrial Irradiators, Blood Irradiators, and Radiography Sources in Use
6 Sales and Re-sales of cobalt-60 sources and radiography sources
7 RTG, Research Irradiator, and Well-Logging Source Users
8 Disused Well-Logging Sources
9 Sales and re-sales of radiography sources and blood irradiators
10 Transportation of radiography, well-logging, and blood irradiator sources

In this case, there is significant risk reduction in each of the ten high priority items, often by a factor of 3 (consistent with the assumptions). Tighter security requirements are projected to improve the transportation scores, addressing items 1 and 10. Of the user facilities, only the industrial irradiator score was not projected to improve (part of priority 5). Priorities 6 and 9 were addressed as tighter restrictions on sales reduced the likelihood of fraudulent sales. Lastly, the risks associated with disused and orphan RTGs, seed irradiators, and well-logging sources (priorities 3,4, and 8) were reduced.

Obviously, the risk reduction projected would take a broadly-based international effort. Although the current circumstances might not trigger cooperation on a global scale, the effort should be initiated now in order to build some momentum. An RDD attack and the resulting impact could trigger the necessary cooperation and provide a more timely response once the urgency is more widely rcognized.

9.3 Alternate Technology Options

This section assesses the potential impact of an effort to implement some of the more important alternate technology options discussed in Section 8.3. It is assumed that the introduction of alternate technologies will take a few years, and that the impact will be partial after a decade. However, these are the types of changes that can have the most lasting impact, and could be very cost effective if worked on a deliberate (as opposed to urgent) basis.

9.3.1 Modified Assumptions Regarding Source Numbers, Hazard Factors, and Security

We have assumed a partial set of alternate technologies have been implemented to the extent that may be possible in about a decade. In terms of replacing large applications, we've assumed that 67% of the blood irradiators will have been replaced by x-ray units (with the waste cesium sources either recycled or consolidated) and 75% of the RTGs will have been retired from active use and disposed of. In terms of dangerous source materials and their hazards, we assumed that alternate forms of the cesium chloride sources and the americium-beryllium sources have been introduced through the source manufacturers and suppliers. The hazard reduction in both cases is assumed to be 40%, although this is pretty arbitrary. It was derived from an assumption that the alternate material would need to reduce the risk by at least half for implementation to proceed, but that replace of the original materials would be work-in progress. In terms of source security, it is assumed that enhanced gadgetry (e.g., alert and track equipment) would be added to industrial irradiators (source strength alarm), blood irradiators, RTGs, and well-logging source *sondes*. Because it would take some time for full implementation, we've assumed the improvement to be a factor of two within a decade or so. The impacts of the changes are reflected in Tables 9.5 through 9.7.

Table 9.5 Modified Assumptions Regarding Numbers of Sources

Number of Sources	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	120	10	1	2500	20	3	12000	2000
Annual Sales	95	7	1	2000	20	3	12000	1000
Transported	190	7	1	4000	20	10	12000	1000
In Use	190	120	1	6000	500	200	30000	10000
Disused	1	7	1	50	5	600	50000	3000
Orphanned	0.1	3	150	5	2	150	5000	200
Consolidated	1	2	15	10	505	100	20000	2000
Disposed	1	2	10	5	1	400	10000	100

Table 9.6 Modified Assumptions Regarding Source Hazard Factors

Approx Impact (1-100)	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	10	6	10	10	6	1	10	60
Sales	10	6	10	10	6	1	10	60
Transported	10	6	10	10	6	1	10	60
In Use	10	6	10	10	6	1	10	60
Disused	10	6	10	10	6	1	10	80
Orphanned	10	6	10	10	6	1	10	80
Consolidated	10	6	10	10	6	1	10	80
Disposed	10	6	10	10	6	1	10	80

Table 9.7 Modified Assumptions Regarding Source Security

Security (1-100) *Approximate*	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	100	100	100	100	100	100	100	100
Sales	10	10	10	10	10	10	10	10
Transported	10	10	10	10	10	10	10	10
In Use	200	10	10	10	20	20	1	20
Disused	3	3	3	3	3	3	3	3
Orphanned	1	1	1	1	1	1	1	1
Consolidated	30	30	30	30	30	30	30	30
Disposed	100	100	100	100	100	100	100	100

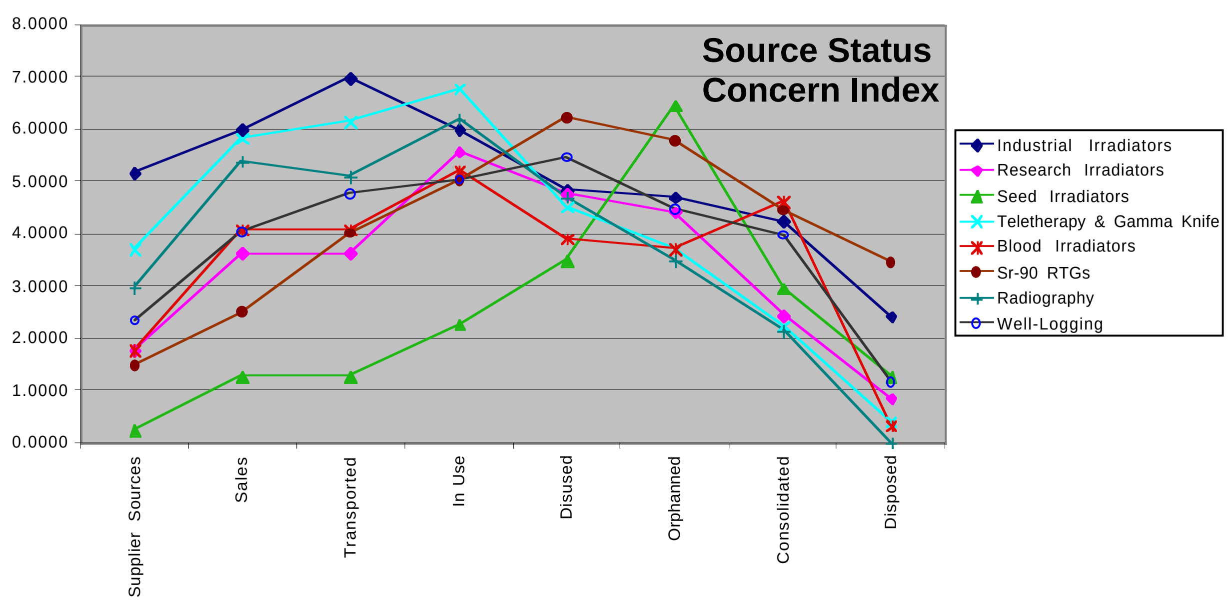
The postulated improvements would require cooperation from source producers and suppliers, as well as source users. Preliminary discussions suggest that these groups are interested in risk reduction, and the potential liabilities associated with someone's source in an RDD attack could weigh heavily on their thinking. The technical capabilities of the producers/suppliers to develop and implement alternate technologies may need to be augmented, although the DOE laboratories could likely provide sufficient facilities and personnel to close any gaps.

As was the case in section 9.1, the potential growth in disused and orphan sources that was projected in Section 6.3 was not included, despite the likely time period of this effort (10 years). This is because the alternate technologies approach would most likely be pursued in combination with one of the other two major initiatives, which in turn would take steps to reduce problems with disused and orphan sources.

9.3.2 SSCI Adjusted for Impact After Changes Implemented

If we use the value in Tables 9.5 through 9.7 to re-compute the SSCI scores, the result is as shown in Figure 9.3.

Figure 9.3 SSCI Chart for Extensive Use of Alternate Technologies



We can again use the RDD risk reduction priorities implied by Figure 7.1 to focus on impact in the key areas:

1 Transportation of Cobalt-60 sources
2 Teletherapy Source User Facilities (Hospital Cancer Treatment centers)
3 Disused and Orphaned RTGs
4 Orphaned Seed Irradiators
5 Industrial Irradiators, Blood Irradiators, and Radiography Sources in Use
6 Sales and Re-sales of cobalt-60 sources and radiography sources
7 RTG, Research Irradiator, and Well-Logging Source Users
8 Disused Well-Logging Sources
9 Sales and re-sales of radiography sources and blood irradiators
10 Transportation of radiography, well-logging, and blood irradiator sources

In this case, the impacts are primarily in priorities 5 and 7 through 9, especially the sources in use. By focusing on the source material, the risk reduction propagates throughout the life-cycles for research irradiators, blood irradiators, and well-logging sources. The reduction in the use of blood irradiators and RTGs similarly impacts the entire life-cycle. Security gadgetry brings down the vulnerabilities to theft for four of the sources, as pointed out previously.

The potential impact of alternate technologies is much greater, as the are several places where better ideas could be applied, including security gadgetry (e.g.GPS tracking) for transportation and materials protection control and accountability (MPC&A) for the cobalt sources. This is clearly a case where the expertise of the producers/suppliers needs to be tapped in order to reach the full potential of this class of improvements.

9.4 Integrated Strategy to Reduce Risk

Thus far, we have analyzed three potential sets of RDD risk reduction initiatives as though they were three sets of options. In fact, all three must be pursued in order to achieve a significant RDD risk reduction. The used source recovery and physical security efforts would provide some early benefits and could be targeted on source materials that are most worrisome- especially the RTGs and seed irradiators. However, the problem is too vast and growing too quickly for such an approach to succeed by itself. The realm of international agreements and regulations is notoriously inertial, but the opportunities for instituting improvements on a global scale will require wide-spread cooperation. Alternate technologies can make lasting changes, and profoundly change the risks, but don't do much about the most immediate threats. Each of the potential risk reduction initiatives has advantages and disadvantages, and they work best if implemented in an integrated strategy.

9.4.1 Modified Assumptions Regarding Source Numbers, Hazard Factors, and Security

In this case, we combine the revised assumptions used in the three previous cases. The results are shown in Tables 9.8 through 9.10, which are derived from Tables 9.1 through 9.7.

Table 9.8 Modified Assumptions Regarding Source Numbers

Number of Sources	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	120	10	1	2500	20	3	12000	2000
Annual Sales	95	7	1	2000	20	3	12000	1000
Transported	190	7	1	4000	20	10	12000	1000
In Use	190	120	1	6000	500	200	30000	10000
Disused	0.4	2	0.5	20	5	300	20000	1300
Orphanned	0.05	1	20	2	2	50	2200	100
Consolidated	0.5	7	20	10	100	400	38000	3700
Disposed	0.2	2	136	3	50	700	15000	250

Table 9.9 Modified Assumptions Regarding Source Hazard Factors

Approx Impact (1-100)	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	10	6	10	10	6	1	10	60
Sales	10	6	10	10	6	1	10	60
Transported	10	6	10	10	6	1	10	60
In Use	10	6	10	10	6	1	10	60
Disused	10	6	10	10	6	1	10	80
Orphanned	10	6	10	10	6	1	10	80
Consolidated	10	6	10	10	6	1	10	80
Disposed	10	6	10	10	6	1	10	80

Table 9.10 Modified Assumptions Regarding Source Security

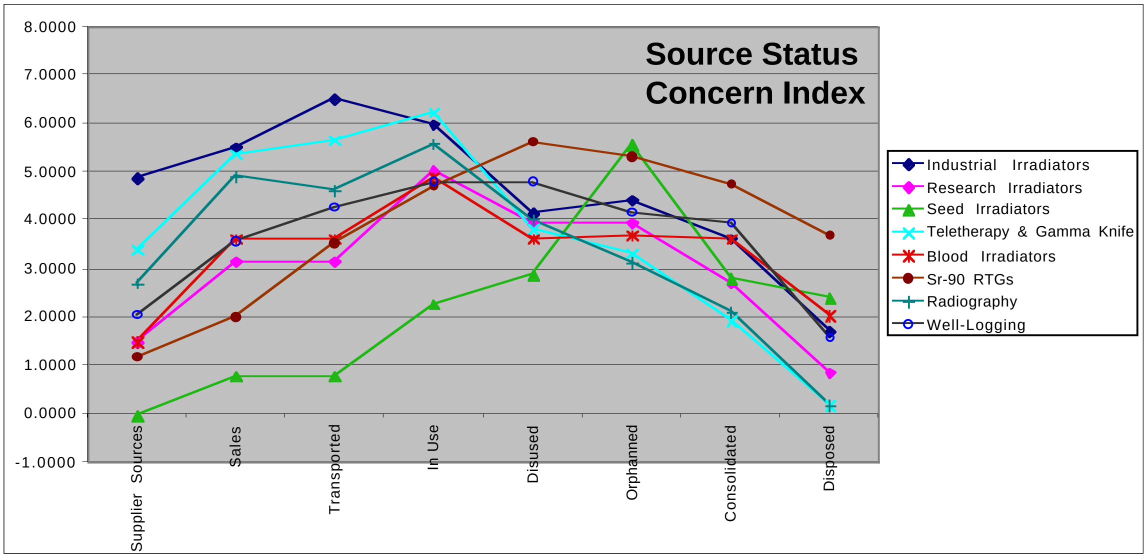
Security (1-100) *Approximate*	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	200	200	200	200	200	200	200	200
Sales	30	30	30	30	30	30	30	30
Transported	30	30	30	30	30	30	30	30
In Use	200	35	10	35	40	40	4	35
Disused	6	6	6	6	6	6	6	6
Orphanned	1	1	1	1	1	1	1	1
Consolidated	60	60	60	60	60	60	60	60
Disposed	100	100	100	100	100	100	100	100

In some cases, overlapping impacts in the tables required some interpolations. For example, if international agreements and regulations are in parts governing the recycle or disposal of used sources, then replacement of problematic sources by alternate technologies is less likely to result in a bunch of disused and orphan sources. Similarly, upgrades in security due to some combination of rapid security upgrades, security upgrades mandated by international agreements, and the introduction of innovative security gadgetry would be complementary but not simply additive.

9.4.2 SSCI Adjusted for Integrated Strategy of Risk Reduction

The impact of the integrated strategy, as captured by Tables 9.8 through 9.10, is shown in Figure 9.4. Although the trends appear similar for all cases, a careful comparison against figure 7.1 reveals a significant risk reduction in nearly all areas that are priroties.

Figure 9.4 SSCI Chart for Integrated Strategy of Risk Reduction



Because point-by-point comparison can be tedious, we provide in Table 9.11 the per cent changes (usually reduction, as shown by a negative entry) from the value in Figure 7.1 Note that the risk may actually increase in a few cases, but these all correspond to SSCI scores that are currently very low, e.g, waste disposal sites.

Table 9.11 Relative change (per cent) in SSCI resulting from Integrated Strategy

Per Cent Change	**Industrial Irradiators**	**Research Irradiators**	**Seed Irradiators**	**Teletherapy & Gamma Knife**	**Blood Irradiators**	**Sr-90 RTGs**	**Radiography**	**Well-Logging**
Supplier Sources	-50	-70	-51	-50	-96	-92	-50	-70
Sales	-67	-80	-67	-66	-96	-90	-67	-80
Transported	-67	-80	-67	-66	-96	-67	-67	-80
In Use	-50	-83	-1	-72	-95	-94	-75	-83
Disused	-80	-91	-75	-80	-85	-75	-80	-83
Orphanned	-50	-80	-87	-60	-40	-50	-56	-60
Consolidated	-75	5	-33	-50	505	305	-4	-26
Disposed	-80	-40	1245	-40	2928	592	50	98

The changes in the eight SSCI scores that were originally between 6 and 7 are highlighted in orange. These include the SSCI scores for transportation and use of cobalt sources in industrial irradiators and teletherapy devices, the orphaned seed irradiators, the blood irradiators and radiography units in use, and the disused RTGs. The projected reductions in vulnerabilities range from 50% for the industrial irradiators to 95% for the blood irradiators. Only two SSCI scores remain above 6: the transportation of cobalt for the industrial irradiators and the teletherapy devices used in hospitals around the world. Given the fundamental nature of both concerns, the difficulty in driving down the risk is not surprising.

The changes in the twelve SSCI scores that were originally between 5 and 6 are highlighted in yellow. These include the suppliers of the industrial irradiator sources, the sales of industrial irradiators, teletherapy units (and gamma-knifes), blood irradiators, and radiography sources, the transportation of blood irradiators and radiography units, the users of research irradiators, RTGs, and well-logging sources, disused well-logging sources, and orphaned RTGs. In this case, the improvements range from 50% for the suppliers of industrial irradiators to 96% for the sales and transportation of blood irradiators. Of the 12 SSCI scores originally between 5 and 6, two-thirds of those scores were reduced to below 5.

Of the SSCI scores projected to increase, only one is projected to increase above a score of 4 (consolidated RTG sources could reach 4.7). Success in reducing overall vulnerability is likely to move sources into consolidation and waste sites, so those parameters bear watching.

The picture portrayed in Figure 9.4 and Table 9.11 is encouraging, as a large multi-year effort aimed at RDD risk reduction is likely to improve the situation significantly. However, there are two disconcerting trends. First, the projected vulnerability reductions are in the range of one order of magnitude (90%), implying that 10% of a very large problem will likely remain. Second, the two vulnerabilities that remain quite high appear to be largely intractable problems. First, the shipment of large quantities of cobalt will almost certainly continue, and a review of the locations of the source suppliers and the users suggest some lengthy and vulnerable routing. Second, the teletherapy sources have been provided to hostpitals around the world and there does not appear to be any easy way to get that genie back into the bottle. In section 2.2, the top-level options for reducing the RDD risk were discussed, and we've determined that the option of denying source materials can be partially successful. But clearly there is a near to also pursue the other two options, specifically trying to detect attempt to transport RDDs and RDD source materials and preparing an appropriate response to an RDD attack.

10. Summary and Recommendations

The RDD threat appears to be very significant, and there is no shortage of radioactive materials that could be used. Among the materials most readily available are the radiological sources in widespread usage around the world. Most of these sources are comparatively small, and their usage in an RDD attack would generate fear and economic displacements, but little more. In contrast, some of the larger radiological sources could be used to create significant acute and chronic health impacts, as well as contamination problems that could be highly disruptive. A partitioning of the problem is recommended, focusing on trying to minimize terrorist access to larger sources and preparing to deal with the potential public response to the more likely smaller RDDs.

An assessment of the large radiological source applications shows that only a few radioisotopes are used in the very large applications. The hazards posed by these radioisotopes in their common chemical forms can be evaluated and ranked. The potential dose to the general population can be anticipated and used for a first order ranking of the hazards. Such a ranking tends to place alpha emitters at the high end of the hazard scale and beta emitters on the low end, on a per-unit of radioactivity basis. More sophisticated assessments of the hazards and risks can be performed, taking into account the likely contamination problems and potential problems in transporting the material. However, such a ranking is fundamentally more difficult and should not be shared. Regardless of the factors involved in establishing the hazards for each source material, a priority bar can be established and overlaid on a bar chart showing the radioactivity levels for the large radiological source applications. Such a process allows a more accurate assessment regarding sources of different radioactive materials.

We were able to identify the largest producers and suppliers of radiological source materials, as well as the users of some of the largest applications. Some of this information was derived from IAEA databases, but more of the data was developed independently using open source information. It is clear that the commerce in radiological source material is global, with suppliers on six continents and users in nearly every country. The international regulatory environment varies from country to country, and problems in disposing of used sources are nearly universal.

In order to assess the vulnerabilities associated with the radiological sources it is essential to examine the entire life-cycle. This includes the producer/suppliers, the sales, the transportation, the users, and the disposition possibilities that include disused sources, orphan sources, waste consolidation sites, and waste disposal sites. Life-cycle analyses were completed for both a static equilibrium case (2003) and for two transient cases that project forward one decade with and without waste consolidation efforts. For cases where there is little recycling (other than cobalt) and few disposal option, the current situation regarding disused and orphaned sources is troubling. But the projected situation is much worse, unless aggressive waste consolidation is implemented.

There are presumably numerous options for cross-comparing the risks associated with the large radiological source applications at the various life-cycle stages. We chose to use a Source Status Concern Index that multiplies together the number of sources, the radioactivity level of the sources, and the hazard factor for the material, and then divides by the inaccessibility and the security factors (rated on a scale from 1 to 100). Because the vulnerabilities vary by many orders of magnitude, we used the logarithm in base ten of the product for comparison. Table were created to approximate these parameters to the best of our ability, given the available data and potential concerns about putting too many details about hazards and security into the open. The resulting scores ranged from just over 0 to 7, with scores of 7 signifying a ten times greater concern than a score of 6. Of the 64 individual SSCI scores, 12.5% fell in the range of 6 to 7 and represent the greatest risk, and just under 19% fell in the 5 to 6 range, signifying the next greatest risks. A list of the ten highest risk reduction priorities was generated based on the life-cycle stages and sources scoring at the high end of the range.

Options for reducing the vulnerabilities were considered next, and grouped into three categories: source security actions, international agreements/regulatory environment, and alternate technologies. Key options and assumptions were described and a representative set of tables were generated for use in regenerating the SSCI scores. Although each set of options resulted in some reduction in risk, the greatest overall risk reduction would result from an integrated strategy utilizing all three sets of options.

Before proceeding with specific recommendations it is imperative that the limitations of the analyses be reviewed. Although the current usage of the large radiological sources is fairly well known, it was necessary to extrapolate the front-end supply chain and the disposition of used sources. The guesswork on the front-end is not too difficult, and depends on the half-life of the materials in use. There is very little information available on disused and orphan sources, so knowledge of the history of the application was used to estimate the number of source sources. The same if true for sources at waste consolidation or disposal sites. For some types of applications, the estimates are likely to be good. In other areas, the estimates could be off significantly. Regarding the intentional use of approximate values for the hazard and security factors, this might distort a few of the number by half an order of magnitude, or so, but should not significantly alter the priority list.

Within the limitations of the analysis, the following recommendations are provided:

1 Repeat the SSCI analysis (or a variation) using more time and resources. Additional research many be able to reduce the uncertainties, especially regarding disused and orphan sources. A classified study using more precise analysis for the hazard and security factors could also improve the fidelity of the results.

2 Continue to aggressively develop the capability to detect and intercept attempts to transport RDDs and RDD source materials, as well as the capabilities needed to respond to RDD attacks. Although the recommended course for RDD risk detection through denial of sources could reduce the vulnerabilities by up to an order of magnitude, the base is currently so large than the remaining 10% would be too high. The recommended efforts would require a decade of intense effort to achieve the projected risk reduction, so the other major options must be pursued aggressively.

3 Balance the three classes of options and pursue each as aggressively as is practical. The source security effort can be used to address the most urgent needs, but its effectiveness is fundamentally limited. The problems will continue to grow, and major risks will remain un-addressed. The international agreement/ regulatory infrastructure effort will likely proceed slowly, unless an RDD attack inspires a more intense effort. However, this approach can provide some far-reaching and widespread improvements in the current handling of sources. Alternate technologies can provide permanent solutions to some of the problems caused by technology choices made prior to today’s global threats. But alternate technologies will take time to develop and implement.

4 Focus the resources available for recovery of disused and orphan sources on the three sources of greatest concern, i.e, the RTGs, the seed irradiators, and the well-logging sources. These problems are concentrated in the former Soviet Union in the first two cases and in western countries for the third case. There is also the potential for far more disused and orphan sources to develop over the next ten years. The best option for addressing the broader disused and orphan source problem may be to establish consolidation sites that could be used to address the current problems and head off a much bigger problem in the future.

5 Pursue the international agreements and improved regulatory environment as aggressively as is practical. Although this will be a time-consuming and tedious process, it may provide the best opportunities for global improvements in the way large radiological sources are handled. Unless and until there are improvements in this arena, actions taken under recommendation 4 can have only a marginal impact, addressing urgent issues but unable to reverse a growing problem.

6 Develop and implement the alternate technologies that can fundamentally reduce the RDD risks. In most cases, this involves technology development and deployment, as opposed to more basic and time-consuming R&D. There will be delays while the alternate technologies are being deployed, but the improvements will be lasting.

7 Examine more carefully some of the high vulnerabilities that appear to be difficult to reduce, as they may be largely intractable. Transportation of large cobalt sources across continents exposes the sources to theft regardless of the security provided. And the location of large teletherapy sources in hospitals around the world is very troubling, despite the best intentions of those who provided life-saving technology to third-world countries. Unless and until the vulnerabilities in these crucial areas are significantly reduced, the strategy of reducing RDD risk through denial of source materials will be fundamentally limited.

8 Develop a staged approach, where some types of actions could be developed and then queued for future implementation. With the current frequency of terrorist bombings, the publicity regarding the RDD threat, and the widespread availability of radioactive source materials, an RDD attack somewhere in the world is overdue. If the U.S. is prepared with a global strategy of RDD risk reduction, the best opportunity for global cooperation may develop right after the first significant RDD attack.

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