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Commercial Radioactive Sources:

Surveying the Security Risks

Charles D. Ferguson
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MONTEREY INSTITUTE OF INTERNATIONAL STUDIES

CENTER FOR NONPROLIFERATION STUDIES

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Acronyms

ACRR	Annular Core Research Reactor
AECL	Atomic Energy of Canada Ltd.
ALARA	as low as reasonably achievable
Am-241	americium-241
ANSTO	Australian Nuclear Science and Technology Organization
ARI	ANSTO Radiopharmaceuticals and Industrials
ARN	Nuclear Regulatory Authority (of Argentina)
ATR	Advanced Test Reactor
Be	beryllium
CANDU	Canadian Deuterium Uranium
Cf-252	californium-252
CFR	Code of Federal Regulations
Ci	curie
CNEA	National Atomic Energy Commission of Argentina
Co-60	cobalt-60
CPD	Commercial Products Division
CRCPD	Conference of Radiation Control Program Directors
Cs-137	cesium-137
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EC	European Commission
EPA	U.S. Environmental Protection Agency
ESC	European Economic and Social Committee
EU	European Union
FAS	Federation of American Scientists
FY	fiscal year
GAO	General Accounting Office
GTCC	Greater Than Class C
HEU	highly enriched uranium
HFIR	High Flux Isotope Reactor
HPS	Health Physics Society
HFR	High Flux Reactor
IAEA	International Atomic Energy Agency
IBA	Ion Beam Applications
ICRP	International Commission on Radiological Protection
IMPEP	Integrated Materials Performance Evaluation Process
INEEL	Idaho National Environmental and Engineering Laboratory
IPL	Isotope Products Laboratories
IPPE	Institute of Physics and Power Engineering

Ir-192	iridium-192
IRE	Belgian National Institute for Radio Elements
ITRAP	Illicit Trafficking Radiation Detection Assessment Program
KAERI	Korean Atomic Energy Research Institute
Kr-85	krypton-85
LANL	Los Alamos National Laboratory
LEU	low enriched uranium
LNT	Linear No-Threshold
MAPLE	Multipurpose Applied Physics Lattice Experiment
MINATOM	Russian Ministry for Atomic Energy
Mo-99	molybdenum-99
mSv	millisievert
MW	Megawatts
NAS	National Academy of Sciences
NECSA	South African Nuclear Energy Corporation
NEI	Nuclear Energy Institute
NRC	U.S. Nuclear Regulatory Commission
NRU	National Research Universal
NTP	Nuclear Technology Products
ORNL	Oak Ridge National Laboratory
OSR	Off-Site Source Recovery
Pd-103	palladium-103
PNNL	Pacific Northwest National Laboratory
PNPI	St. Petersburg Institute of Nuclear Physics
PO Mayak	Mayak Production Association
Pu-238	plutonium-238
Ra-226	radium-226
RDD	Radiological Dispersal Device
RERTR	Reduced Enrichment for Research and Test Reactors
RTG	radioisotope thermoelectric generator
Sr-90	strontium-90
SRIAR	Scientific and Research Institute of Atomic Reactors
Sv	sievert
Tc-99	technetium-99
TECDOC	Technical Document
Tl-204	thallium-204
TRIGA	Training, Research, Isotopes, General Atomics
UK	United Kingdom
U.S.	United States

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Executive Summary

This study examines the security risks posed by commercial radioactive sources. While these sources provide benefits to humanity through numerous applications in medicine, industry, and research, some of these same materials, if not secured, may end up in radiological dispersal devices (RDDs)—one type of which is popularly known as a "dirty bomb." Though RDD use has not occurred, the September 11, 2001 terrorist attacks, al Qaeda's expressed interest in acquiring the means to unleash radiological terror, and widespread news reporting on this topic have sparked renewed concern about the security of commercial radioactive sources.

Although radioactive materials other than commercial radioactive sources—such as radioactive waste from nuclear power plant operations—might contribute to the components of an RDD, an examination of these materials is beyond the scope of this study. The Center for Nonproliferation Studies intends to publish in the near term a systematic, comparative analysis of the major aspects of nuclear and radiological terrorism. The forthcoming report will examine the security risks posed by all relevant radioactive materials. This current report focuses on the security of commercial radioactive sources because they represent a significant category of radioactive materials that are used widely throughout the world and, until recently, have not been considered high security risks.

A major finding of this study is that only a small fraction of the millions of commercial radioactive sources used globally, perhaps several tens of thousands, pose inherently high security risks because of their portability, dispersibility, and higher levels of radioactivity. As a rule, these more dangerous commercial sources are those containing relatively large amounts of radioactivity (typically more than a few curies worth of radioactivity, or in terms of mass, roughly a gram or more of radioactive material) of seven reactor-produced radioisotopes: americium-241, californium-252, cesium-137, cobalt-60, iridium-192, plutonium-238, and strontium-90. Some of these isotopes (americium-241, californium-252, and plutonium-238) would only pose internal health hazards by means of ingestion or inhalation, while the others would present both internal and external health hazards because the emitted ionizing radiation could penetrate the dead outer layer of human skin.[1]

To maximize harm to the targeted population, radiological terrorists would tend to seek very highly radioactive sources (containing tens of thousands or more curies) that pose external and internal health hazards. However, even suicidal terrorists might not live long enough to deliver an RDD because they might receive lethal acute doses of ionizing radiation from these sources in the absence of adequate shielding surrounding the radioactive material. But adding heavy protective shielding could substantially increase the difficulty in transporting an RDD and could dissuade terrorists from employing these types of sources. In contrast, sources that only present an internal health hazard and that contain very high amounts of radioactivity could be handled safely without heavy shielding as long as precautions are taken to minimize internal exposure.

While terrorist misuse of radioactive sources with low levels of radioactivity might cause a degree of panic for a brief period, the high-security risk sources are those that present genuine dangers to the public, in terms of long-term health effects and major financial loss. For this reason, this report concludes that properly regulating and securing this smaller subset of sources could contribute significantly to reducing the

[1] Strontium-90 would primarily present an internal health hazard.

overall dangers posed by commercial radioactive sources. Public education, however, is also needed to familiarize the public with the RDD threat and, in particular, to provide, insofar as is possible, reassurance that some RDDs will have so little radioactivity as to pose little, if any, actual danger to the public.

This report finds that, unlike nuclear weapons, RDDs (including those using the seven radioactive isotopes noted above) are typically not weapons of mass destruction. Few, if any, people would die immediately or shortly after use of an RDD from exposure to the ionizing radiation from such a device, although, depending on its placement and size, many individuals might die from the conventional bomb blast, if this method were used to disperse radiological materials. Most people not directly affected by the conventional blast would receive relatively low doses of ionizing radiation, even from weapons using the seven high-security threat radioactive isotopes, and possible cancer deaths would usually require years to decades to develop.[2] Nonetheless, an RDD can be a weapon of mass disruption or dislocation. Preying on the public's fears of radioactivity, terrorists who used RDDs would try to cause panic. The possible resulting chaos during evacuation of the immediate and surrounding areas of RDD use could not only cause injury and anguish, but could hinder emergency response efforts to assist the victims of the conventional blast. Moreover, the time needed for first responders to prepare to operate safely in a radioactive environment could add to delays in tending to these casualties. Further, the decontamination costs and the rebuilding costs, if necessary, from an RDD could be immense—perhaps upwards of billions of dollars. Therefore, while not causing the immediate, large-scale loss of life and physical destruction associated with nuclear detonations, RDD effects could be substantial.

In addition, this study points out that only a few corporations, headquartered in a handful of nations produce most of the commercial radioactive sources that pose high security concerns. This small group then distributes sources to tens of thousands of radioactive source users throughout the world. The leading radioactive source producing nations are Canada, South Africa, Russia, Belgium, Argentina, and France. In addition, the United States and the European Union (EU) also play leading roles. Although the United States is not presently a major commercial radioactive source producing nation, it has the potential to reemerge as one, and it contributes to a large market share of source use. The member states of the EU also use a significant portion of the commercial radioactive sources. This source production finding is significant because it indicates that by tightening export control standards and by conditioning exports on certification that effective security measures will cover the sources in recipient countries, some half-dozen exporting nations, together with the EU, could rapidly ensure that the considerable majority of high-risk radioactive sources in use around the world are properly protected against misuse. (As explained below, in discussing a major gap in current export control rules, implementing this change regarding importer-country regulations could be made in conjunction with a restructuring of the export licensing system that is needed for other reasons.)

This finding is part of the report's broader analysis of the "cradle to grave" stages of a radioactive source's lifecycle. All of the high-risk radioisotopes that are the active components of the sources of greatest security concern are created in nuclear reac-

[2] Under certain highly specialized scenarios, it is possible to imagine many thousands of individuals receiving small ionizing radiation doses that could ultimately prove lethal over a long time period. For this reason, under some circumstances, RDDs could result in mass long-term casualties, making them weapons of mass destruction of a unique variety, but ones unlikely to be attractive to terrorists.

tors. These sources are then distributed to tens of thousands of global users. Ideally at the end of life, a source is safely and securely disposed of in a corporate or government-operated depository. Advanced industrialized countries use most of the high-risk radioactive sources, which are subject to regulation throughout their lifecycles. Traditionally, these regulations were concerned principally with protecting worker and public safety, rather than with securing high-risk sources against malevolent misuse, but these states are taking steps to address this gap. Indeed, this study finds that private industry and regulatory agencies in these industrialized countries have already taken steps to secure those commercial radioactive sources that pose the highest security risks, in particular, at reactors that produce commercial radioisotopes, in transit, and at the facilities employing the highest-risk sources. In other settings in these countries, industrial practices intended to protect sources as dangerous and valuable items provide an important measure of security against theft.

Domestic regulatory controls in the states of the former Soviet Union and in a number of developing countries are weaker, or in some cases, non-existent, and reforms (supported, as appropriate, by external assistance) are urgently needed in these places. In many of these states, however, the number of high-risk radioactive sources is more limited than in the advanced industrialized states. Therefore, intensive efforts to improve security over high-risk sources are needed for only a relatively small fraction of these sources worldwide, permitting efforts to be concentrated on this aspect of the radioactive source threat and offering the prospect of rapid improvement. By focusing its regulatory assistance programs on many of the nations in this group, the International Atomic Energy Agency (IAEA) has helped develop new regulatory agencies or improved weak regulatory infrastructures. However, further improvement requires additional funding from IAEA member states that can provide it. Moreover, time and diligence are needed to instill a safety and security culture in nations that lack it.

Irrespective of the regulatory environment, this report points out that many end-users retain disused sources because of high disposal costs or lack of adequate depositories. These barriers to proper disposal create pressures on end-users to dispose of their high-risk sources outside of regulated channels, that is, to abandon, or "orphan," them. Although major source manufacturers and many industrialized countries have programs to sweep up disused sources before they are abandoned, these programs should be expanded to mitigate this aspect of the risk posed by radioactive sources. Moreover, these efforts should concentrate on the high-risk radioisotopes. In addition, this study examines the dangers posed by previously lost or abandoned orphan sources. Although official reports and press accounts suggest that there are conceivably tens of thousands of such orphan sources worldwide, the study finds that of these, only a small fraction are in the high-risk category, with the preponderance probably to be found in the states of the former Soviet Union, as a legacy of the Cold War. By focusing resources on the high-risk sources (especially in the latter setting) significant progress can be made to reduce the worldwide dangers posed by orphan sources.

This report identifies a significant gap in U.S. export licensing rules covering high-risk radioactive sources that could facilitate illicit commerce in these materials, a gap also seen in the licensing rules of a number of other developed Western states. Specifically, current U.S. regulations permit the unlimited export of most high-risk sources under "general" licenses, to all destinations, except Cuba, Iran, Iraq, Libya, North Korea, and Sudan. Consequently, exports of these materials can be made without any governmental review of the bona fides of end-users, and exporters are not required to report on transfers of these materials. In other words, unlimited exports of cobalt-60, cesium-137, and other potentially dangerous radioisotopes incorporated in sources are permitted without any official review of end-users to many states where extensive terrorist activities are taking place—including all the states of the former Soviet Union, Afghanistan, Algeria, Columbia, India, Indonesia, Israel, the Philippines, Pakistan, Saudi Arabia—and, to at least one state deemed by the U.S. Department of State to be a state supporter of terrorism—Syria. Although the licensing authority, the U.S. Nuclear Regulatory Commission, has taken interim steps (until permanent regulations are adopted) to intensify security at domestic sites where high-risk radioactive sources are used, it has not taken parallel interim steps to tighten export controls over these materials. (Separately, the Commission needs to intensify efforts to ensure the legitimacy of U.S. end-users, when it grants domestic licenses for the possession of high-risk radioactive sources.)

Finally, this study examines a number of technical approaches, some of which are now being implemented, for reducing the dangers from radioactive sources. These measures include creating sources that are difficult to disperse, lowering the radioactivity level of radioactive sources, and developing non-radioactive alternatives for uses of radioactive sources.

Based on the above findings, this study urges high priority work in the following areas.

Protect against illicit commerce of radioactive sources by:

- Maintaining strong domestic regulatory oversight of users of highly radioactive sources through verifying the legitimacy of the user before issuing a license to possess these sources and conducting more frequent inspections once a license is granted.
- Requiring *specific* licenses for exports of the high-risk radioactive sources to permit end-user reviews, beginning with the United States implementing and leading this effort.
- Conditioning exports of high-risk sources on confirmation that the importing country has in place adequate controls and security measures; allow exceptions on humanitarian grounds, with case-specific safeguards.
- Continuing to enhance border and port security to prevent smuggling of illicitly obtained highly radioactive sources.

Dispose of the large pool of disused sources by:

- Developing, or ensuring adequate funding for, national programs aimed at recovering disused sources from the public domain and placing them in secure interim storage. For example, the Off-Site Source Recovery Project operated by the United States Department of Energy has secured more than three thousand disused sources, but the project faces a substantial funding shortage that, if not remedied, would cripple its ability to secure more than ten thousand additional disused sources that potentially pose a high security concern.
- Creating incentives for the prompt and proper disposal of disused sources, for example, by imposing a disposal fee to be paid when sources are acquired that would be partially refunded upon evidence of their proper disposition.
- Expediting creation of a permanent, secure disposal site in the United States for Greater Than Class C disused sources (which are long-lived and relatively highly radioactive sources that currently exceed regulatory standards for near surface disposal).
- Developing secure disused source depositories in countries that lack such facilities or in regional settings open to many contributing countries.

Address the outstanding problem of the thousands of radioactive sources that have been lost, abandoned, or stolen—the so-called "orphan" sources—by:

- Concentrating recovery efforts on the small fraction of orphan sources that pose a high security concern.
- Providing adequate funding for the United States Orphan Source Initiative, operated by the Environmental Protection Agency in conjunction with the Department of Energy and the Nuclear Regulatory Commission.
- Assessing whether adequate resources are being devoted to address the worldwide orphan source problem.
- Prioritizing finding and securing high security risk orphan sources in the Newly Independent States. In particular, the United States, Russia, and the International Atomic Energy Agency should ensure that their recently launched tripartite initiative to secure orphan sources in the Newly Independent States remains a top priority.

Assist the approximately 100 nations—about half the world's total number—with weak regulatory controls, starting with those having the greatest number of high-risk radioactive sources, by:

- Expanding the International Atomic Energy Agency's regulatory assistance efforts, which have been successful in building up the regulatory infrastructure in several IAEA member states. Moreover, all member states should adhere to the Code of Conduct on the Safety and Security of Radioactive Sources, which is currently being revised to focus more on security concerns.
- Offering regulatory and security assistance to the approximately 50 non-member states of the IAEA that possess radioactive sources, but lack adequate regulatory infrastructures. The leading radioactive source producing nations should consider providing this assistance.

Reduce security risks from future radioactive sources by:

- Encouraging producers to make sources that are relatively difficult to disperse. For example, reduce the production of powdered cesium-chloride.
- Continuing to reduce the radioactivity levels of sources to the minimum required to perform the necessary, beneficial task.
- Promoting the use of non-radioactive alternatives to radioactive sources (such as accelerators[3]), where those non-radioactive methods can provide the same or greater benefit as radioactive sources.

Mitigate the potential effects of RDD use by:

- Educating the public and the press about the hazards and appropriate responses to the use of an RDD.
- Preparing first responders by providing radiological training and equipment.
- Conducting regular emergency planning exercises involving coordinated efforts of local and federal officials, and applying lessons learned from these exercises to develop more effective response capabilities.

[3] Non-radioactive alternatives, such as accelerators, which generate radiation by accelerating charged particles, only produce radiation when an electrical power supply is turned on and do not pose a radiological dispersal device threat.

- Investing in research and development of effective decontamination technologies.
- Investing in research and development to enhance the protection, detection, and tracking of radioactive sources.

In addition to reducing the risks from RDDs, these recommended measures will improve radiation safety and, thereby, enhance public health. Through continued attentive effort, clear vision of priorities, and focused initiatives, governments, international organizations, and industry can meet the challenge of the potential misuse of highly radioactive sources by terrorists.

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Introduction: Setting the Security and Safety Context

Although the terrorist attacks of September 11, 2001 did not exploit radioactive materials, al Qaeda's expressed interest in acquiring the means to unleash nuclear terrorism has heightened concern about the security of commercial radioactive sources.[4] To date, terrorists have not exploded any radiological dispersal devices (RDDs)—popularly known as "dirty bombs"—which would spread radioactivity from radioactive sources to attempt to harm human health, instill panic, complicate emergency response efforts, and deny access by contaminating property.[5] Nonetheless, the wide availability of these sources and inadequate or nonexistent controls over many sources underscore the risk of potential RDD use.

This risk must be weighed against the overwhelming benefits of radioactive sources. Millions of these sources, used worldwide, provide valuable services to humanity for medical, industrial, agricultural, and research purposes. While non-radioactive alternatives can reduce some of this usage and should be pursued, many applications will continue to require radioactive sources. Moreover, development of low-cost production methods and new applications will tend to promote the increased use of these sources.

Long before concern over RDDs, numerous radiation accidents involving sources harmed human health and prompted measures to improve radiation safety. These accidents have mainly occurred because of inadequate control over radioactive sources. National and international radiation safety and regulatory authorities have, therefore, sought to prevent sources from becoming "orphaned," or lost from institutional controls. Though controls have improved, thousands of sources worldwide (hundreds in the United States) continue to be lost, abandoned, or stolen on an annual basis. In addition, tens of thousands of sources remain orphaned due to insufficient resources to find and secure them and, thereby, pose safety and security threats.[6] As noted below, only a small fraction of this total might pose significant dangers to the public if used in an RDD.

Increased efforts to enhance safety can also strengthen security.[7] In particular, both safety and security demand effective materials accounting from cradle to grave. Moreover, sound security requires strong protection methods to prevent malicious seizure of radioactive sources. In the past, safety concerns justifiably drove the formulation of regulatory controls. Today, facing the perceived increased likelihood

[4] The IAEA defines a radioactive source as "anything that may cause radiation exposure—such as by emitting ionizing radiation or by releasing radioactive substances or materials—and can be treated as a single entity for protection and safety purposes." IAEA Safety Glossary, version 1.0, January 31, 2002, <http://www.iaea.or.at/ns/CoordiNet/safetypubs/iaeaglossary/glossarypages/s.htm>.

[5] RDDs are not nuclear weapons and are generally not considered weapons of mass destruction. Although radioactive materials other than commercial radioactive sources, such as radioactive waste from nuclear power plants, might contribute to the components of an RDD, an examination of these materials is beyond the scope of this study. The Center for Nonproliferation Studies will publish in the near term a systematic, comparative analysis of the major aspects of nuclear and radiological terrorism. This forthcoming study will examine the security risks posed by various radioactive materials.

[6] In most languages, the same word represents both safety and security. Therefore, confusion can result if these terms are not precisely defined. According to the "Draft Revised Code of Conduct on the Safety and Security of Radioactive Sources," IAEA, August 2002, "'safety' means measures intended to minimize the likelihood of accidents with radiation sources and, should such an accident occur, to mitigate its consequences," and "'security' means measures to prevent unauthorized access to, and loss, theft and unauthorized transfer of, radioactive sources, and measures to protect facilities in which radioactive sources are managed."

[7] However, sometimes safety measures can work against security. For instance, labeling that spells out the safety hazards of a source can inadvertently serve to highlight the attractiveness of this material for radiological terrorists.

of radiological terrorism, regulatory authorities are planning to devote more resources toward protection. Even if a radiological terrorist attack never occurs, enhanced security over radioactive sources would be beneficial for the improvements they would provide in public health alone.

An act of radiological terrorism has two fundamental prerequisites. First, terrorist motivations matter. If terrorists do not seek to commit radiological terrorism, it will not happen. Recent analysis indicates that few terrorist groups desire or have the capability to commit radiological terrorism.[8] Nonetheless, sufficient interest in radiological terrorism by even a small number of groups would be adequate to warrant efforts to protect against this danger.[9]

Second, a terrorist must gain access to radioactive materials. To understand this dimension of the security risk, this paper surveys how radioactive sources are produced, distributed, used, regulated, and sometimes misused. The section on producers of sources highlights that only about six major corporations and nations produce most of the sources in use today. From the standpoint of enhancing security and regulatory control, this fact is encouraging because concentrated efforts on a few nations and companies can yield substantial security improvements. Many sources do not pose high security risks, as explained later; therefore, enhanced and focused control on sources that do will permit rapid strides toward improved security. In particular, ensuring adequate security for each segment of a source's lifecycle will reduce the probability that terrorists could seize the components for radiological weapons.

[8] See, for example, Jerrold M. Post, "Differentiating the Threat of Radiological/Nuclear Terrorism: Motivations and Constraints," Paper for IAEA Symposium on International Safeguards: Verification and Nuclear Material Security, November 2, 2001.

[9] Although this paper does not examine the motivational aspect in depth, it will be examined in greater detail in the forthcoming Center for Nonproliferation Studies assessing all major aspects of nuclear terrorism.

However, industry is concerned that security costs will continue to spiral upward, eroding the profit margin and, in some cases, driving companies out of business. This paper also examines the steps industry has taken post-September 11 to improve security.

Although this paper describes potential consequences of RDD use, it does not consider radiological weapons made from fissile material, spent nuclear fuel,[10] or radioactive waste.[11] Setting the context of the threat requires essential background information about radioisotope properties, human health effects from ionizing radiation, and radiological weapons. The first section begins by providing that background.

The challenge is lessening the likelihood of radiological terrorism while preserving the benefits of radioactive sources. Finding the proper balance demands constant attention to the evolving nature of the threat and an awareness of the consequences of security measures.

RADIOACTIVE SOURCES

Radioisotope Properties

About 100 elements make up all substances on Earth. Each element has unique chemical properties.

[10] Spent nuclear fuel assemblies would typically be much more difficult for a terrorist to acquire and handle without receiving a lethal dose in the process of producing a radiological weapon than the typical radioactive sources considered in this paper.

[11] Certain types of radioactive waste might appeal to terrorist groups. According to the Committee on Science and Technology for Countering Terrorism, National Research Council, "Nuclear and Radiological Threats," Chapter 2 in *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism*, National Academy Press, 2002, "Low-level waste may be a particularly attractive terrorist target: It is produced by many companies, universities, and hospitals, it is not always stored or shipped under tight security, and it is routinely shipped across the country. Although labeled 'low-level,' some of this waste has high levels of radioactivity and could potentially be used to make an effective terrorism device."

However, each element comes in different forms called isotopes that differ in their nuclear properties. In general, isotopes are either stable or unstable. Unstable isotopes are called radioisotopes because they emit radiation and decay to either other unstable or stable isotopes.[12] Radioactive sources are made from radioisotopes.

Knowing the type, energy, decay rate, and amount of radiation of particular radioisotopes helps to characterize the security risk posed by a radioactive source. Ionizing radiation, which has the ability to strip electrons from atoms and break chemical bonds, leading to possible human cell damage, comes in three types: alpha, beta, and gamma. Alpha radiation is composed of a helium nucleus (two protons and two neutrons bound together). Beta radiation consists of high-speed electrons or their positively charged counterparts (positrons). Gamma radiation, highly energetic light, differs from alpha and beta radiation because it is massless and uncharged. It often accompanies the emission of alpha or beta radiation from a particular radioisotope.[13]

The types of ionizing radiation vary in their ability to penetrate materials. A piece of paper can stop most alpha particles. For most beta particles, a thin piece of aluminum or glass suffices to halt them. Blocking gamma radiation, the most penetrating, usually requires thick concrete or lead, whereas reducing it requires less material. The discussion below concerning human health effects will further help to classify the type of radiation from the security perspective.

Predicting when an individual radioisotope decays is impossible because the decay occurs randomly. However, in a large group of identical radioisotopes, the average decay rate can be specified and is usually characterized by the concept of half-life, which is the amount of time required for half of the radioactive sample to decay. After two half-lives, one-fourth of the sample remains; three half-lives, one-eighth; and so on. After seven half-lives, the radioactive substance has decayed to less than one percent of its initial amount. The shorter the half-life, the more frequently the radioactive source emits ionizing radiation.

To visualize the radiation emission, imagine a pipe with a valve connected to a pool of water. The pool represents the source of radiation, and the half-life controls the setting of the valve. A short half-life means the valve is almost fully open; therefore, the pool drains quickly. In contrast, a long half-life means the valve is almost shut, letting out a trickle of water; thus, the pool empties slowly.

From the security viewpoint, very short and very long half-life radioisotopes present far more limited security risks compared with those having medium length half-lives on the order of months to decades. In particular, radioactive sources with very short half-lives (hours or minutes or less) do not last long enough (the pool drains rapidly) to give terrorists sufficient time to produce radiological weapons with those substances; nor do they exist long enough to contaminate places for an appreciable time period. In contrast, those sources with very long half-lives (millions or more years) release radiation at much slower rates (the pool drains slowly) and typically would not be ideal for radiological weapons devised to maximize the output of radiation during a relatively short time period—the human timescale.

[12] The cores, or nuclei, of all isotopes contain two types of particles: positively charged protons and uncharged neutrons. Unstable isotopes (radioisotopes) have either a surplus or a deficit of neutrons as compared to the stable isotopes within an element's family of isotopes.

[13] The emission of gamma radiation typically occurs after emission of alpha or beta radiation and de-excites a radioisotope from a metastable state to a stable state of the same isotope. The emission of alpha or beta radiation changes an isotope of an element to an isotope of a different element. Other types of radioactive decay, such as spontaneous fission and neutron emission, are not considered here as major types of ionizing radiation.

Determining the amount of radiation emitted by a radioactive source requires knowing its half-life and mass. In general, the shorter the half-life and the larger the mass, the more radiation will be emitted within a time period. The amount of radiation is characterized by the number of disintegrations (nuclear transformations) per time period and is measured in curies (Ci). One curie equals 3.7×10^{10} disintegrations per second.[14]

To relate this scientific measurement to a common substance, consider a banana. Bananas contain potassium, which is an essential mineral to maintain human health. A small fraction of naturally occurring potassium includes the radioisotope potassium-40, and a typical banana emits a few disintegrations per second or contains about 10^{-11} curies of radioactivity. This amount is miniscule compared to a radioactive source that could be a security concern. For instance, a capsule of the radioisotope cobalt-60 (Co-60) used in some cancer treatment applications contains about 2,000 curies. Each capsule usually holds about 1,000 pellets; therefore, a pellet of Co-60 has about 2 curies. Thus, a banana emits about 100 billion times less ionizing radiation in a given time period than a radioactive source, such as a Co-60 pellet, that could pose a security threat.

Health Effects from Ionizing Radiation

When used in a controlled fashion by medical professionals, certain radioactive sources can provide ionizing radiation that is well-suited for destroying cancerous cells in the human body. The same or similar radioactive sources can harm healthy human cells if safety precautions are violated or security of the sources is breached and they are deliberately placed to cause injury.

Ionizing radiation can affect cells through either external exposure (outside the body) or internal exposure (by inhalation or ingestion). Alpha, beta, and gamma radiation, the three types of ionizing radiation, were introduced above. Alpha emission cannot typically penetrate the outer dead layer of skin and, therefore, is not a significant external hazard. However, as mentioned above, gamma rays and high-energy beta emissions are very penetrating and thus comprise the leading factors when evaluating external exposure. Internal exposures arise when ionizing radiation is emitted from radioactive materials present within the body. For these exposures, all three forms of ionizing radiation can lead to detrimental effects.[15]

As ionizing radiation enters human tissue, or organs, the absorbed energy[16] excites atoms and

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[14] The Becquerel is the newer unit and equals one disintegration per second. It is used widely, especially by many international radiation safety agencies. One curie equals 3.7×10^{10} Bq, which is approximately equivalent to the amount of radioactivity emitted by one gram of radium-226. To mitigate the use of too many units in what is primarily a policy paper, this paper will exclusively employ the curie because scientific notation will generally not be needed to express the radioactivity levels of those sources that pose a potential security concern. For other measurements, this paper will use internationally accepted SI units.

[15] For book-length United States government reports on external and internal exposures from ionizing radiation, see Keith F. Eckerman and Jeffrey C. Ryman, "External Exposure to Radionuclides in Air, Water, and Soil," *Federal Guidance Report #12*, EPA-402-R-93-081, U.S. Environmental Protection Agency, September 1993; and K.F. Eckerman, A.B. Wolbarst, and A.C.B. Richardson, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," *Federal Guidance Report #11*, EPA-5201/1-88-020, U.S. Environmental Protection Agency, 1988.

[16] The amount of radiation energy absorbed by a target material per unit mass is referred to as the absorbed dose and is measured in grays, where one gray equals one joule of energy deposited per kilogram of the absorber. The older unit of absorbed dose, which is still widely used in the United States, is the rad, where 100 rad = 1 gray. The earliest unit of radiation exposure was the roentgen, which is still used somewhat today. It represents the amount of ionization in air produced by x-rays.

Table 1: Typical Radiation Doses from Common Radioactive Sources that Humans Encounter[a]

Common Radioactive Sources	Typical Dose (mSv/yr)
Natural:	
Indoor Radon	2.0
Food, drink, and body tissue	0.4
Terrestrial radiation	0.3
Cosmic rays (sea level), increases with altitude	0.3
Total (Natural Sources)	**3.0**
Manmade:	
Nuclear weapons tests fallout	0.003
Medical (X-rays)	0.39
Medical (Other treatments)	0.14
Consumer Products	0.1
Nuclear Fuel Cycle	0.0005
Total (Artificial Sources)	**0.633**
Behavioral:	
Skiing holiday	0.008 mSv per week
Air travel in jet airliner[b]	0.0015 – 0.005 mSv per hour

[a]See, for example, David Bodansky, *Nuclear Energy: Principles, Practices, and Prospects*, American Institute of Physics, 1996, for more detailed information on typical radiation doses from natural and manmade sources.

[b]To calculate the dose received from particular flights, see Wallace Friedberg, "A Computer Program for Calculating Flight Radiation Dose," *The Federal Air Surgeon's Medical Bulletin,* Spring 1999, which includes an online calculator at <http://www.cami.jccbi.gov/AAM-400A/FASMB/FAS9901/rads.htm>.

sometimes changes their structure, possibly causing living cells containing the atoms to be killed, damaged, or prevented from reproducing properly. Measuring absorbed dose of radiation requires knowing how much energy is deposited in the material of concern, such as living tissue. However, biological damage also depends on other factors. In particular, the types of ionizing radiation differ in their biological effects. For instance, an alpha particle that deposits the same amount of energy as a beta particle is more damaging because the alpha leaves its ionizing energy within a more localized space, increasing the likelihood of tissue destruction. To quantify these differences, the concept of dose equivalent[17] measures the relative biological effectiveness of different types of ionizing radiation.[18] The sievert (Sv) is the scientific unit of dose equivalent.[19] Typically, the

[17] The dose equivalent equals a quality factor times the absorbed dose. The quality factor for alpha particles is 20, and it is 1 for beta particles and gamma rays.

[18] The relative biological effectiveness also depends on the type of tissue exposed.

[19] In the United States, the rem, the older unit for equivalent dose, is still used. One sievert equals 100 rem.

normal individual, from the natural background, medical treatments, air travel, and other manmade sources, receives 3-4 mSv, or 0.003-0.004 Sv, annually. Table 1 lists the most common radioactive sources and their equivalent doses.[20] Highly radioactive sources generally result in a dose rate of greater than one mSv per hour at one meter from the unshielded source. In comparison, the common sources listed in Table 1 give typical doses much less than a highly radioactive source because their doses are on the order of mSv per year, not per hour.

Depending on the dose, health effects can appear in the near term (minutes to days) or long term (years). The larger the dose and the more rapidly it is delivered, the bigger the harm to health and the more likely effects will show up in the near term. Usually, near term effects have a direct causal link to the radiation dose. Such effects are called "deterministic" because the health effects can be directly predicted if factors, such as amount and type of radiation and organ affected, are known. Thus, the loss of organ function is a deterministic effect of ionizing radiation. Other deterministic effects include nausea, visual impairment, hair loss, and skin burns. Because deterministic effects increase with radiation dose, short-term, high-level (acute) doses of ionizing radiation largely result in deterministic human health effects. The doses listed in Table 1 are much too small to cause deterministic effects, which typically require doses on the order of sieverts' worth of exposure over a brief period. For instance, 3 to 5 Sv dose received in a short time period leads to a 50 percent chance of death within 60 days. The actual dose that can kill an individual depends on the person's state of health, his or her genetic makeup, and the availability of treatment.

Exposure to small doses, especially over a long term, can result in health effects that can take years to develop. The doses are usually small enough, such as tens to hundreds of mSv, to not lead to the loss of an organ or other clearly deterministic effects. Instead, the ionizing radiation has potentially modified, but not killed, affected cells, which still retain their capacity to make more modified cells. This modification can result in cancer or cause hereditary harm if reproductive cells are affected. Only one cell need be affected to potentially cause harm, while other modified cells may not lead to any illness. Unlike deterministic effects, these effects are inherently probabilistic, that is, it is impossible to predict the exact health effect given the dose received. However, a statistical distribution of health effects can be derived from a large enough sample size of affected individuals who have received similar radiation doses. Some will develop cancer, for example, and others will not. Using these statistics, a person can assess the likelihood of harm coming from the radiation received. Such health effects are termed "stochastic" because of the random or statistical nature.

Quantifying stochastic effects relies on epidemiological data from previous exposures, such as those from radiography, medical treatments, and Japanese atom bomb survivors. The data are as yet insufficient to determine how these effects change with radiation dose. However, the generally used, though scientifically unproven, relationship is linear no-threshold (LNT) meaning that the health effects are directly proportional to the dose and that even tiny doses can result in harm. Although there are great uncertainties in extrapolating from high to low doses,[21] the LNT model offers a convenient method of estimating cancer risk. The lack of conclusive data has led to the development of competing models. For instance, one

[20] Gamma factors can be used to calculate the external equivalent dose from gamma-emitting radioactive sources. Given the curie content and the type of source, i.e., the particular gamma-emitting radioisotope in the source, these factors specify the dose received per unit time at one meter distance from the unshielded source. For a list of the gamma factors, see, for example, Bernard Schleien, *Health Physics and Radiological Health Handbook*, Scinta Publishing Company, 1992.

model posits a hormesis effect, i.e., a beneficial effect for low doses; whereas another model asserts increased health risk for low doses. An analysis of these models is beyond the scope of this paper.[22] Appendix 1 lists the probable health effects resulting from exposure to various levels of ionizing radiation.

Because even very small doses are presumed by LNT to have potential adverse health effects, efforts to reduce the radiation dose received by the general public or workers in nuclear and radiation industries usually follow the guiding principle of reducing radiation exposures to levels that are "as low as reasonably achievable" (ALARA).[23] The U.S. Environmental Protection Agency (EPA) uses the LNT model for deriving cancer risk probabilities[24] from which U.S. national standards, such as EPA acceptable levels of radiation exposure, are established. Currently, acceptable levels of exposure for the general population are at 1 mSv per year from manmade sources. Most radiation absorbed by humans comes from natural sources, as depicted in Table 1. On average, an individual absorbs about 150 mSv in his or her lifetime from natural sources, and the increase in dosage due to manmade sources of radiation (mostly because of diagnostic techniques in medicine) has been about 20 percent since the beginning of the 20th Century. The U.S. Nuclear Regulatory Commission (NRC) has set an annual occupational (for workers in the nuclear industry) whole body dose equivalent limit of 50 mSv, which is 50 times greater than the public's level of exposure permitted under EPA regulations, but still in the low dose range.

Production Methods

Radioisotopes for medical, industrial, and scientific use are produced in either nuclear reactors or particle accelerators. In reactors, nuclear fission creates excess neutrons that can be absorbed by target nuclei to produce radioisotopes, such as the conversion of cobalt-59 to cobalt-60. Moreover, fission products, such as cesium-137 and strontium-90, can also be employed in radioactive sources. Further, radioactive decay in reactors can generate radioisotopes, such as plutonium. Reactor radioisotope production begins with neutron absorption. In contrast, accelerators bombard targets with charged particles (for example, protons and deuterons[25]).Because the radioisotopes of greatest security concern are generally produced in reactors, this paper focuses on reactor, instead of accelerator, production.

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[21] The International Commission on Radiological Protection (ICRP) concedes, "There is a wide spread in the data and the Commission recognizes that [its system of measurement] is somewhat arbitrary and may be conservative." ICRP, "1990 Recommendations of the ICRP on Radiological Protection: User's Edition," *ICRP Publication 60*, (Tarrytown, NY: Pergamon Press, 1992), p. 19. In 1990, the ICRP updated their 1977 *Publication 26*, establishing criteria for measuring radiation dosage and associated health effects (i.e., the radiotoxicity) for various radioisotopes. The publication discusses both the stochastic and deterministic biological effects that can develop from exposure to ionizing radiation, and elaborates on the difficulties related to measuring stochastic effects.

[22] Scientific debate on the LNT model—and the radiation standards that stem from it—is still ongoing. See for example, Zbigniew Jaworowski, "Radiation Risk and Ethics," *Physics Today*, September 1999, pp. 24-29 and letters-to-the-editor in response in several subsequent *Physics Today* editions, as well as LeRoy Moore, "Lowering the Bar," *Bulletin of the Atomic Scientists*, May/June 2002, pp. 28-37. This debate has persisted in the political realm. As a recent example, Senator Pete Domenici of New Mexico has suggested that current standards may be too stringent and asked the General Accounting Office (GAO) to report on the scientific basis of existing radiation standards. GAO, "Radiation Standards: Scientific Basis Inconclusive, and EPA and NRC Disagreement Continues," Report number# RCED-00-152, June 30, 2000.

[23] U.S. Code of Federal Regulations, title 10, part 20.

[24] K.F. Eckerman, R.W. Leggett, C.B. Nelson, J.S. Puskin, and A.C.B. Richardson, "Cancer Risk Coefficients for Environmental Exposure to Radionuclides," *Federal Guidance Report #13,* EPA 402-R-99-001, 1999.

[25] A deuteron is the nucleus of a heavy isotope of hydrogen and consists of a proton and a neutron.

Research Reactors Most radioisotope production occurs in research reactors, with power ranges from tens of kilowatts to several hundred Megawatts (MW), compared to 3,000 MW thermal (i.e., about 1,000 MW electric) for a typical commercial nuclear reactor.[26] However, a few commercial power reactors also function as radioisotope producers. Less than half (about 100) of the over 250 operating research reactors produce commercial radioisotopes.

Highly enriched uranium[27] (HEU) has powered much of this production at research reactors because it can readily result in a high-density flow, or flux, of neutrons, which optimizes radioisotope creation. Increasingly, reactors are shifting to low enriched uranium (LEU) power generation to guard against nuclear weapons proliferation.[28] Ongoing development of high density LEU fuel for these reactors can lead to the best overall situation that efficiently produces radioisotopes and lessens the likelihood of proliferation.

Several types of research reactors are operating and producing radioisotopes. A pool-type reactor, one of the most common, uses a large pool of water surrounding the fuel core. The water cools the core and moderates the nuclear reactions by slowing down the neutrons. As an advanced, multi-purpose pool-type reactor, the MAPLE[29] reactor incorporates two independent shutdown systems for enhanced safety and is designed for ease of operation. The tank-type reactor is a second design used in radioisotope production. Similar to a pool reactor, a tank-type reactor involves more active cooling using pumps. Heavy water and graphite moderated reactors are also used for producing radioisotopes. Generating commercial electric power and having radioisotope production capabilities, CANDU[30] reactors, for example, use heavy water to cool and moderate the reactors' cores. The TRIGA[31] research reactor, another prevalent design, is water cooled but primarily moderated by the hydrogen mixed in the fuel assembly. It differs from other research reactors most prominently in design by using a pulsed operating mode to reach high power levels. Other designs include fast flux reactors, which rapidly drive a high number of neutrons through the reactor core and require no moderator, and homogeneous type reactors, which use a core of uranium salt solution in a tank. Appendix 2 lists reactors that are known to produce commercial radioisotopes.

Because reactors are often multi-purpose facilities, scientific, defense, and energy experiments can limit the time devoted to radioisotope production, directly affecting a manufacturer's ability to compete in the radioisotope market. Other reactor characteristics, such as ability to generate a high flux of neutrons and accessibility to the reactor core, also contribute to its radioisotope production capacity. Table 2 summarizes these factors.

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[26] Reactor power is generally measured by thermal power in research reactors, and electric power in nuclear power reactors. The efficiency for conversion of thermal to electric power is usually about 33 percent. Thus, 1 Watt electric corresponds to 3 Watts thermal.

[27] Uranium enriched to 20 percent or more of the isotope uranium-235 is considered highly enriched and potentially usable for nuclear weapons. Nuclear weapons grade uranium is HEU with 90 percent or greater enrichment. Nuclear weapons cannot be made from low enriched uranium (LEU).

[28] The U.S.-sponsored conversion program is called Reduced Enrichment for Research and Test Reactors (RERTR). Russia has a similar program.

[29] MAPLE stands for Multipurpose Applied Physics Lattice Experiment technology.

[30] CANDU stands for Canadian Deuterium Uranium. Canada originally developed this type of reactor.

[31] TRIGA stands for Training, Research, Isotopes, General Atomics. Designed by General Atomics in the late 1950s, TRIGA research reactors have been operating for more than 40 years. The power levels range from 20 kW to 16 MW, and the reactor can be pulsed to power levels over 1,000 MW. The reactor design includes a large number of inherent safety features.

Table 2: Reactor Characteristics Affecting Radioisotope Manufacturing Capacity

Preferred Reactor Characteristics for Radioisotope Production
High neutron flux to increase likelihood of nuclear reactions
A broad flux profile with availability of high neutron energy regions and thermal flux traps to tailor production of different radioisotope types
Reactor availability (Percent of time in operation): >98% (excellent); 97-90% (good); 89-80% (fair); <80% (poor); <50% (marginal)
Easy access to the reactor core, including during reactor operation with a shuttle system to quickly transport newly produced radioisotopes out of the core
Source: Information derived from Final Report of The Nuclear Energy Research Advisory Committee (NERAC), Subcommittee for Isotope Research and Production Planning (within the DOE), April 2000.

From the security viewpoint, it is worth noting that both reactor and accelerator produced radioisotopes are usually processed in hot cells near the production facility. This processing involves chemical preparation after initial manufacture to produce a more pure form of the radioisotope for commercial use. It also physically shapes the product into the desired form (for example, pellets or pencils).

Sealed and Unsealed Sources

Radioactive sources can be either sealed or unsealed. Sealed sources completely enclose the radioactive material, which is also permanently bonded or fixed to a capsule or matrix designed to prevent its release under the most severe conditions of normal use and handling, short of deliberate destructive acts. Usually, radioisotopes with high radioactivity and radiotoxicity are placed in sealed sources to mitigate leakage of the isotope itself. However, sealing is not intended to provide radioactive shielding. The desired radiation emanates from a sealed source and precautions are necessary to minimize the risk to humans, such as surrounding the sealed source in shielding made of material containing lead. Thus, sealed sources stripped of their shielding could pose a security risk even when the sealing remains intact. Table 3 shows a partial list of radioisotopes embodied in sealed sources.

Table 3: Principal Radioisotopes in Sealed Sources

Isotope	**Physical Form**	**Half-life**	**Emission**
Cesium-137 (Cs-137)	Solid (powder)	30.1 years	beta gamma
Cobalt-60 (Co-60)	Solid (metal)	5.3 years	beta gamma
Iridium-192 (Ir-192)	Solid	74 days	beta gamma
Krypton-85 (Kr-85)	Gas	10.8 years	beta gamma
Radium-226 (Ra-226)	Solid	1600 years	alpha gamma
Strontium-90 (Sr-90)	Solid	28.8 years	beta

In the case of an unsealed source, the radioactive material remains accessible. It may be contained in a glass vial or other type of container with a removable stopper or lid. Unsealed sources, therefore, could easily present potential external and internal radiation hazards if mishandled.

In addition to these manmade sources of radioactivity, sources manufactured from naturally occurring radioactive material have proved useful in various applications, most notably in cancer treatment. Radium, the most prevalent natural radioisotope in use, presents a problem from the safety and security standpoints because many of the sources (in the form of radium needles) that employ it were distributed widely before regulatory infrastructures began to develop in the 1950s. Because of its 1600-year half-life, uncontrolled radium sources pose a long-term risk. The International Atomic Energy Agency (IAEA) has a program for conditioning and packaging these radium sources with the goal of global elimination of radium needles by 2005.

Applications

Radioactive sources have medical, industrial, agricultural, and research applications. They can be found in hospitals, medical and industrial irradiation facilities, large farms, universities, and even homes throughout the world (for example, a miniscule amount of americium-241 is used in many smoke detectors). Varying widely in radioactivity amounts as well as sizes and mass, radioactive sources differ significantly in their potential threats to security. In general, the sources that pose the greatest security risk have high radioactivity levels and are intended for use mainly in the industrial and medical sectors. These applications deserve a closer examination.

Medical Uses Around 100 radioisotopes are used in medical diagnosis, sterilization of medical products, radiotherapy, and research in nuclear medicine. Diagnostic uses include gamma-ray scintillation imaging, positron-emitting imaging (Positron Emission Tomography, or PET) and radioimmunoassay (the method of quantifying antibodies in a sample). Radioisotopes used for diagnosis are selected for their ability to provide useful clinical information while exposing the patient to minimal radiation. Thus, they need to have a short half-life appropriate to the investigative procedure. From a possible 2,300 radioisotopes only a few satisfy the selection criteria for diagnostic use. Of these, none present a significant security risk because these radioisotopes are too short-lived, not very abundant, or not very radioactive.

Radiotherapy, the primary therapeutic application of nuclear radiation, destroys unwanted or malfunctioning tissue, such as cancerous cells, in the body. External radiotherapy is called teletherapy. Typical teletherapy sources contain 1,350 to 27,000 Ci. Other therapeutic applications include the irradiation of blood for transfusion and the treatment of clogged blood vessels. Like diagnostics, radiotherapy employs various radioisotopes. Unlike diagnostics, which does not use high security risk sources, radiotherapy uses some radioactive sources that are worrisome from the security standpoint because of their prevalence and radioactivity levels. These sources contain Co-60 and cesium-137 (Cs-137). Radiotherapy makes extensive use of remotely controlled Co-60 sources. According to the IAEA, Co-60 is the most common radioisotope used in radiotherapy—with over 10,000 teletherapy sources in use worldwide[32]—followed by Cs-137. However, within the United States and other parts of the developed world, the trend has been to reduce the use of Co-60. Only a small number of hospitals in the United States use large Co-60 sources for cancer treatment. (At least one medical center still favors Co-60 because of the beam profile generated.[33]) Instead,

[32] A.J. Gonzalez, "Security of Radioactive Sources: The Evolving New International Dimensions," *IAEA Bulletin*, 43/4/2001, p. 41.

[33] Interview with hospital radiologist, September 23, 2002.

many U.S. hospitals have shifted to generating highly energetic beams with accelerator technology for such therapy. But much of the developing world still employs Co-60 mainly because of the capital costs associated with switching to alternative non-radioactive source technologies.

Oncology centers also provide brachytherapy, radiotherapy that involves internal radiation. Typical high-dose rate brachytherapy sources contain up to about 10 Ci, but usually fewer. Although brachytherapy units are more common than teletherapy sources, the latter usually have a much higher radioactivity.[34] However, brachytherapy sources, due to portability, could pose a potentially greater security risk than teletherapy sources.

Industrial, Scientific, and Public Uses Industrial uses of radioisotopes include instrumentation and measuring devices (both fixed and portable), smoke detectors, irradiation and sterilization processes (food and materials), non-destructive testing, and gamma radiography. Radioisotopes used in industrial irradiators emit gamma rays mainly for the sterilization of food and medical equipment, but irradiation is also used for many other materials. Typical irradiators for these purposes contain thousands to millions of curies. Treating gemstones, for example, with irradiation enhances their color. Irradiators most commonly use Co-60, but some irradiators, such as the Gray Star Irradiator produced by Gray Star, Inc., use cesium chloride in powder form (with Cs-137 serving as the radiation source). Because of its powder form, cesium chloride can be dispersed more easily in a radiological dispersal device than metallic Co-60.

Irradiators are increasingly being manufactured using energy from sources other than radioisotopes. Shifting toward these alternatives will help reduce the prevalence of and thus the security risk from these radioisotopes. Nonetheless, the sheer number of major irradiation facilities (about 300)[35] worldwide containing large quantities of highly radioactive materials calls for increased attention on ensuring adequate security at these facilities.

Industrial radiography has applications such as checking for flaws in pipeline welds, and an extension of radiography known as non-destructive testing is used on a variety of products and materials. For instance, iridium-192 (Ir-192) is used to test the structure of steel and other light alloys. Ir-192 can be found in 80 percent of all industrial radiography sources.[36] Typical industrial radiography sources contain a few up to approximately one hundred curies. Because these sources are housed in portable equipment, they can pose a high security risk.

A third key industrial application of radioisotopes is gauging, where a detector measures the reduction in radiant energy caused by a material between it and the radioactive source. In this way, the presence, quantity, and even density of material between the source and detector can be measured without direct contact. This process employs Co-60, Cs-137, or americium-241 (Am-241). Typical gauging sources contain less than one curie, although some contain up to a few tens of curies. Because industrial gauges need relatively low radioactivity, radioactive sources in this application generally pose minor security risks.

Radioisotopes have other applications, ranging from lighting airport runways and emergency exit signs, to determining the moisture content of soil and other materials, to geological well-logging for measuring subsurface characteristics. Cs-137 is used as a tracer to identify sources of soil erosion and deposition. Am-241 is used in backscatter gauges (which are convenient for measuring thickness or density

[34] One hospital in the Washington, DC metropolitan area visited by one of the authors plans to acquire Ir-192 sources containing 10 Ci for brachytherapy. This hospital may also employ Cs-137 sources for such therapy.

[35] Gonzalez, *IAEA Bulletin*, 43/4/2001, p. 42.

[36] Ibid, p. 42.

when only one side of a material is accessible), smoke detectors, and devices to measure ash content in coal. While smoke detectors[37] use extremely small amounts of Am-241, the other applications employ much larger amounts, and certain storage sites for Am-241 have huge stockpiles of this radioisotope. Thus, home smoke detectors would not pose a security risk, but smoke detector factories could.

Scientific applications include use in both biomedical and materials research. Materials research employs such techniques as radioactive dating, for which natural carbon-14 is commonly used. In agriculture, radioisotopes are useful to investigate chemical and biological processes in plants and to sterilize pests, such as med-flies.

Radioisotopes also contribute to special purpose and remote power generation. Long-lived power sources are needed for equipment that is too remote or inaccessible for replacement. Plutonium-238 (Pu-238) and curium-244 provide power for these purposes and are widely employed in unmanned space probes.[38] Within the former Soviet Union, radioisotope thermoelectric generators (RTGs) were commonly used for remote power applications, such as naval navigational systems and some other military facilities. Powered by the radioisotope strontium-90 (Sr-90), these RTGs contain 30,000 to 300,000 curies. Hundreds of these units are located along Russia's northern coastline. Although these RTGs are generally difficult to reach, the lack of adequate protective measures highlights the security risk they pose.[39]

To reduce the usage of Sr-90 in Russian lighthouses, the Norwegian government in 1997 started a project to replace Sr-90 with non-radioactive power sources, such as batteries and solar cells. So far, the project has performed this substitution in the lighthouse lanterns at Salnyj Island in Murmansk and plans to replace the radioactive sources of four additional lighthouses (Little Ainova, Little Kij, Paltsova Pero, and Petchenga) with solar cell technology. When the project is completed, all lighthouses on the Russian side of the Varanger fjord will operate with non-radioactive power sources, but these represent only a small fraction of all lighthouses using RTGs.[40] As discussed below, recently proposed legislation in the United States Congress contains a provision to replace all these radioactive sources with non-radioactive power sources.

RANKING OF RADIOACTIVE SOURCES AND RADIOISOTOPES BY SECURITY RISK

Several different methods produce dozens of different radioisotopes used in various applications. From the radiological terrorism perspective, only a few of those radioisotopes are of primary concern. Thus, the security risk assessment focuses on sources that contain those particular radioisotopes. Not all of these sources present high security risks, as discussed below.

The key properties that determine security risk are energy and type of radiation; half-life of the radioisotope; amount of material; shape, size,

[37] Millions of smoke detectors would be required to gather enough Am-241 for a radiological weapon.

[38] U.S. space program use of Pu-238 for radioisotope thermoelectric generators (RTGs) dates back to the Apollo missions in the 1960s. "Over the last 30 years, the United States has launched 25 [space] missions involving 44 RTGs."; "Nearly Half of the Pu-238 for Space is Being Removed," *Nuclear News*, September 2002, p. 92. NASA purchases much of its Pu-238 from Russia. The cost is now about $2 million per kilogram; Ibid.

[39] Leonid Bolshov, Rafael Arutyunyan, and Oleg Pavlovsky, "Radiological Terrorism," in *High Impact Terrorism: Proceedings of a Russian-American Workshop*, National Academy of Sciences, 2002, pp. 143-144.

[40] Norwegian Plan of Action for Nuclear Safety Issues, Royal Norwegian Ministry of Foreign Affairs.

Table 4: Categorization of Radiation Sources, Primarily from Radiation Safety Perspective

Practice or Application	**Radioisotope**	**Typical Radioactivity Level (curies)**
Category 1		
Radioisotope thermoelectric generators	Sr-90	30,000 – 300,000
Teletherapy	Co-60	1,350 – 27,000
	Cs-137	13,500
Blood irradiation	Cs-137	50 – 2,700
Industrial Radiography	Ir-192	3 – 250
	Co-60	3 – 250
Sterilization and food preservation (Irradiators)	Co-60	2,700 – 11,000,000
	Cs-137	2,700 – 11,000,000
Other Irradiators	Co-60	27 – 27,000
	(Cs-137 rare)	27 – 27,000
Category 2		
High Dose Rate Remote afterloading brachytherapy	Co-60	0.27
	Cs-137	$0.8 \times 10^{-6} – 2.7 \times 10^{-4}$
	Ir-192	11
Low Dose Rate brachytherapy (manual or remote)	Cs-137	0.0014 – 0.014
	Ra-226	0.0008 – 0.008
	Co-60	0.0014 – 0.014
	Sr-90	0.0014 – 0.04
	Pd-103	0.0014 – 0.04
Well logging	Cs-137	0.027 – 2.7
	Am-241/Be	0.027 – 22
	(Cf-252 rare)	1.4
Level gauge Thickness gauge Conveyor gauge	Cs-137	0.27 – 27
	Co-60	0.027 – 0.27
	Am-241	0.27 – 1.1

Table 4: Categorization of Radiation Sources, Primarily from Radiation Safety Perspective (continued)

Practice or Application	Radioisotope	Typical Radioactivity Level (curies)
Moisture/density detector (portable, mobile units)	Am-241/Be	0.0027 – 0.054
	Cs-137	Up to 0.0011
	Ra-226/Be	0.04
	(Cf-252 rare)	0.08
Category 3		
Level gauge Density gauge	Cs-137	0.0027 – 0.54
	Co-60	0.0027 – 0.027
Thickness gauge	Kr-85	0.0027 – 0.08
	Am-241	0.027 – 0.27
	Sr-90	0.0027 – 1.1
	Tl-204	11
Source: Table adapted from IAEA, "Categorization of Radiation Sources."		

shielding, and portability of the source; prevalence of use; and how dispersible is the source material. Using many of these characteristics, the IAEA has categorized radioactive sources by radiation safety hazards.[41] The IAEA study that developed this characterization also took into account end-of-life issues and exposure scenarios.[42] Table 4 lists the three IAEA categories of radioisotopes, including typical radioactivity levels and applications. Serving as a guide for establishing regulatory infrastructure, these categories rank radioactive sources from those requiring the most to the least stringent controls. In particular, Category 1 sources pose the greatest risk and typically contain several to thousands (and in some cases millions) of curies worth of radioactivity.

An assessment of safety concerns tends to parallel an evaluation of security risks. Generally, the radioactive sources that present the greatest safety hazard pose the most serious security threat. An inspection of incidents related to radiological source accidents and illicit trafficking further supports a heightened focus on certain radioisotopes, particularly Co-60, Cs-137, Ir-192, and Sr-90. The IAEA reports that sources containing Ir-192 contribute to the most accidents resulting in deterministic health effects,[43] followed by sources using Co-60 and Cs-137. Other than uranium, Cs-137 seizures are the most common, with 53 seizures occurring in 1993-1998, making up 22.6 percent of all radioactive material seizures.[44] As with uranium and Cs-137, the radioisotopes Co-60 and Sr-90 have been involved in numerous illicit trafficking incidents.[45] These events suggest that sources

[41] IAEA, "Categorization of Radiation Sources," *GOV/2000/34-GC(44)/7, Attachment 3, Annex*, July 10, 2000.

[42] As of the second half of 2002, the IAEA is in the process of revising its source categorization from the standpoint of security; Brian Dodd, "Protection against Nuclear Terrorism: The IAEA Response," Presentation at EU-High Level Scientific International Conference on Physical Protection, September 9, 2002.

[43] Abel Gonzalez, "Strengthening the Safety of Radiation Sources and the Security of Radioactive Materials: Timely Action", *IAEA Bulletin*, 4/13/1999.

[44] IAEA, "Categorization of Radiation Sources," p. 4.

[45] Ibid, p. 7.

containing Co-60, Cs-137, Ir-192, and Sr-90 could plausibly end up in the hands of terrorists and cause great risk to the public.

In addition to these radioisotopes, three others, Pu-238,[46] Am-241, and Cf-252, stand out because they are relatively abundant in certain applications and, as alpha-emitters, can be readily transported in sealed form without exposing those handling them to lethal radiation. Therefore, terrorists could safely handle these sources before dispersing them in populated areas. Further, detecting the radioactive signal from alpha-emitters is much more difficult than finding emissions from gamma-emitters, such as Co-60. Once released from the sealed sources and aerosolized, these alpha-emitters can, moreover, lead to internal health effects through inhalation or ingestion. Pu-238, in particular, presents a greater inhalation hazard than the more commonly known plutonium radioisotope, Pu-239, which is used in nuclear weapons.[47]

Throughout the remaining sections, this paper will focus on these seven radioisotopes, which are produced primarily in nuclear reactors[48] and pose the greatest security risk. Table 5 shows the half-life, specific activity,[49] as well as types and energies of emissions of these radioisotopes. All seven have half-lives on the order of months and years and would, therefore, require prolonged evacuation periods or extensive clean-up procedures in the event of public exposure, depending on the amount of dispersed radioactive material. Three of the radioisotopes, Co-60, Cs-137, and Ir-192, are strong beta and gamma emitters, thereby posing external health hazards, while Sr-90 only emits energetic beta particles, presenting primarily an internal health risk by means of ingestion or inhalation of the radioisotope. The specific activities listed in Table 5 indicate that even gram quantities of these radioisotopes contain more than enough radioactivity to raise a security concern.

The conditions of use of these radioactive sources further contribute to their highest priority for increased security. Such attributes include whether the source is in a fixed facility or is mobile, its type of application (e.g., industrial, medical, research, or military), the design and construction of the source and enclosing equipment, the source size, and the presence of other equipment, such as interlocks inhibiting its removal. The physical size of these materials varies, depending on the manufacturer. Often radioactive sources incorporating Co-60, for example, take the form of a pellet and are, therefore, small and light. Depending on the required radioactivity for an application, one or several pellets are loaded into stainless steel capsules and sealed by welding. Highly radioactive sources such as Co-60 rods (containing thousands of pellets and, thus, thousands of curies) used in industrial irradiation could cause immediate or near-term harm to the handler and, thus, may be an unlikely target for premeditated theft unless adequate shielding surrounds the source. Shielding, however, significantly increases the weight and the difficulty of carrying the material away from the facility. High activity sources such as teletherapy and food irradiation units are installed in specially designed facilities and are not very mobile. On the other hand, high dose brachytherapy units are designed to be portable. Other portable housing for sources can be found in well-logging and some gauging devices. In

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[46] This radioisotope should not to be confused with its fissile cousin plutonium-239, which is employed in nuclear weapons and nuclear power plant fuel.

[47] The hazard from Pu-238 is about 275 times greater than from Pu-239. That is, 14.5 g of Pu-238 poses the same health hazard as 4 kg of Pu-239; Steve Fetter and Frank von Hippel, "The Hazard from Plutonium Dispersal by Nuclear Warhead Accidents," *Science and Global Security*, Vol. 2, No. 1 (1990), p. 2, footnote 7.

[48] As mentioned in a previous section, radium-226 also would rank high in security risk; however, because it is a naturally occurring radioactive source, this paper does not focus on it. Nonetheless, in many locations, radium lacks adequate regulatory controls.

[49] Specific activity is defined as the amount of radioactivity emitted per time period divided by the mass of the radioactive material. This paper measures specific activity in curies per gram, or Ci/g.

Table 5: Reactor-Produced Radioisotopes that Pose the Greatest Security Risks

Radioisotope	**Half-Life**	**Specific Activity (Ci/g)**	**High Energy Alpha Emissions**	**High Energy Beta Emissions**	**High Energy Gamma Emissions**
Cobalt-60	5.3 years	1,100	N/A	Low Energy	Yes
Cesium-137 (Barium-137m)[a]	30 years (2.6 min)	88 (540 million)	N/A	Low Energy (Low Energy)	N/A (Yes)
Iridium-192	74 days	>450 (std) >1,000 (high)	N/A	Yes	Yes
Strontium-90 (Yttrium-90)[b]	29 years (64 hours)	140 (550,000)	N/A	Yes (Yes)	N/A (Low Energy)
Americium-241	433 years	3.4	Yes	No	Low Energy
Californium-252	2.7 years	536	Yes	No	Low Energy
Plutonium-238	88 years	17.2	Yes	No	Low Energy

Source: Information for this table comes from the Center for Risk Excellence's Technical Information Documents, "Summary Fact Sheets for Selected Environmental Contaminants to Support Health Risk Analyses," November 2001, and Oak Ridge National Laboratory's Radioisotopes Production Website, <http://www.ornl.gov/isotopes>. These references also provide detailed information about the energy of the alpha, beta, and gamma emissions for each radioisotope.

[a] When Cs-137 decays, it produces a metastable radioisotope barium-137m (Ba-137m), which has a short 2.6 min half-life. Ba-137m creates the external health hazard because of the energetic gamma ray it emits.

[b] When Sr-90 decays, it produces a daughter radioisotope yttrium-90 (Y-90), which has a 64 hour half-life and decays by beta emission, which is the main health concern. The accompanying gamma ray is not very energetic, and thus it would not pose a significant health hazard.

addition, the physical form of the source can add to or decrease the security risk. For instance, solid pellets, a common form for Co-60, would be more difficult to aerosolize and disperse than powders, a typical form for Cs-137 in the chemical compound cesium chloride.

Finally, though the factors above demonstrate why these seven reactor-produced radioactive sources pose the greatest security concern, this analysis does not imply that other sources would never present security threats. New production methods or market demand could result in other radioisotopes occupying a larger fraction of worldwide usage. Importantly, terrorists determined to employ radiological weapons would tend to seek the most accessible radioactive sources.

Orphan Sources

Radioactive sources outside of institutional controls are called orphan sources[50] because they have been lost, abandoned, or stolen. Thousands of sources have been orphaned throughout the world. While most orphan sources present a safety hazard, only a small fraction pose a potentially high security risk.

If lost from a licensed institution, the sources may or may not be in the possession of an individual or organization. Every year, many sources are abandoned or improperly disposed of and can pose a public health threat if unsuspecting people encounter them. High-activity orphan sources can also present a security threat if terrorists find them and incorporate them into RDDs. Those who steal a source for profit may or may not know that it is radioactive but will seek to sell the radioactive substance itself or the materials, such as metallic parts, surrounding the

[50] For the Nuclear Regulatory Commission's definition of orphan source, see <http://www.nrc.gov/materials/miau/miau-reg-initiatives/orphan.html>.

radioisotope. In contrast, radiological terrorists deliberately seek to acquire radioactive sources through theft, purchase, or any other means to gather the components for an RDD. Below are status reports based on recent information concerning orphan sources within the United States, the European Union, and the Newly Independent States.

Up to 500,000 of the two million sources in the United States may no longer be needed and thus could be susceptible to becoming orphaned. In the United States, as many as 375 sources have been reported as orphaned in a single year.[51] Over the latest five-year reporting period from October 1996 to September 2001, on an average annual basis, 300 sources fell into this category. Of these, 56 percent were not recovered. While the exact amount of radioactivity in each orphan source is not known, the Nuclear Regulatory Commission (NRC) has estimated the cumulative radioactivity amounts of each type of radioisotope in the unrecovered sources. Of the 21 radioisotopes in the NRC's database, four (Am-241, Cs-137, Ir-192, and Sr-90) have enough cumulative radioactivity amounts in the un-recovered sources to raise the potential for a heightened security concern. The cumulative amounts are 11.2 Ci of Am-241, 11.3 Ci of Cs-137, 7.0 Ci of Ir-192, and 1.3 Ci of Sr-90. Because the amount of radioactivity in each orphan source is unknown, determining the exact number of orphan sources that pose a potential high security concern is impossible. However, based on the fact that no more than 20 percent of the radioisotopes contained within the un-recovered orphan sources can be potentially classified as part of the potentially risky security category and the fact that the cumulative radioactivity amounts for each radioisotope are relatively small, the inference can be drawn that only a small fraction of the total number of un-recovered orphan sources belong to this category.[52] An important caveat is that this estimate only applies to sources that were reported as orphaned. Because users tend to be disinclined to report sources as orphaned, many more sources are likely to belong to this category.

Within the European Union (EU), an estimated 70 sources are lost annually from regulatory control. Moreover, some 30,000 disused sources in the EU could be in danger of becoming orphaned.[53] Because "most suppliers of sources essentially refused to provide specific details on the numbers and types of sources supplied, as this was regarded as commercially sensitive information,"[54] the actual number of disused sources that belong to the potentially high security risk category is unknown. If the pattern is similar to the situation in the United States, as described above, only a small fraction of the EU orphan or disused sources pose a heightened security concern.

Further, strewn throughout the former Soviet Union are thousands of orphan sources. During its return to Russia following the collapse of the Soviet Union, the Russian Army left behind many of these sources in the Newly Independent States.[55] Because

[51] R.A. Meserve, Chairman, Nuclear Regulatory Commission, "Effective Regulatory Control of Radioactive Sources," in *National Regulatory Authorities with Competence in the Safety of Radiation Sources and the Security of Radioactive Materials*, proceedings of IAEA International Conference held in Buenos Aires, Argentina, December 11-15, 2000, p. 11.

[52] An NRC official, interviewed on October 16, 2002, confirmed this analysis.

[53] M.J. Angus, C. Crumpton, G. McHugh, A.D. Moreton, and P.T. Roberts, "Management and Disposal of Disused Sealed Radioactive Sources in the European Union," EUR 1886, 2000, p. 3.

[54] Ibid, p. 13.

[55] See, for example, Diego Lluma, "What the Russians Left Behind," *Bulletin of the Atomic Scientists*, May/June 2000, pp. 14-17. For example, during the 1970s, Soviet scientists experimented with the effects of cesium-137 on plants. As part of this project known as Gamma Kolos, perhaps hundreds of powerful cesium sources were strewn across the former Soviet Union. One of the objectives of this project was to simulate the effects of nuclear war on agriculture. The present daunting task is to track down and secure these sources; Joby Warrick, "Hunting a Deadly Soviet Legacy: Concerns About 'Dirty Bomb' Drive Efforts to Find Radioactive Cesium," *Washington Post,* November 11, 2002, p. A1.

of the applications of the Russian Army sources, a large, but unknown, number probably belong to the high security risk category.

A later section, "Regulatory and Industry Efforts to Secure Radioactive Sources," describes what various governments and other organizations are doing to secure orphan sources.

RADIOLOGICAL WEAPONS—RADIOLOGICAL DISPERSAL DEVICES

Terrorists who seek to unleash radiological terror could obtain radioactive sources through a variety of methods. First, they could find a lost or abandoned source. Second, they could steal a source from a licensed user or a manufacturer, or while it is being transported. Third, they could try to buy a source through normal commercial channels by pretending to be a legitimate user. These methods point toward the need for greater resources to track down orphan sources, to secure sources at users' and manufacturers' facilities and during transport, and to provide more effective licensing. Later sections address these security enhancements; this section turns to what could happen if radiological terrorists acquired radioactive sources and employed them to harm the public.

Definitions

If terrorists seized radioactive sources, they would have two basic options, one passive and the other active, for instilling terror with these materials. Employing the passive option, they could place radioactive sources in high-profile areas, such as highly trafficked urban sites and government facilities. An often-cited example of the passive option is the situation in November 1995 where Shamil Basayev, a Chechen rebel leader, directed a Russian television crew to Moscow's Izmailovsky Park, where they found a container with a small quantity of Cs-137. No one reportedly suffered injury from this episode, which demonstrated the potential for inflicting harm with radioactive sources. Thus, the effect of this incident was entirely psychological.[56] Such sources would only cause harm to people who came in close contact with them but could still incite panic.

With the active option, terrorists would attempt to disperse the radioactivity over a large or confined area. Fortunately, they could not turn the radioactive sources that are the focus of this paper into nuclear weapons.[57] Depending on the motives of the terrorists, the dispersal could occur in an obvious way to draw immediate notice. This method would involve a so-called "dirty bomb." The EPA defines a "dirty bomb" as "commonly refer[ring] to a device that spreads radioactive material by exploding a conventional (non-nuclear) explosive, such as dynamite. Because they do not involve the sophisticated technology required to create a nuclear explosion, dirty bombs are much simpler to make than a true nuclear bomb."[58]

Though news media attention has focused on the possibility of explosive dispersal, terrorists could decide to employ non-explosive means of spreading radioactivity. Such methods include aerosolizing the radioactive material or dissolving it in water reservoirs. Aerosolized material could pose both internal (inhalation), depending on the size of the particles,

[56] William Potter, "Less Well-Known Cases of Nuclear Terrorism and Nuclear Diversion in the Former Soviet Union," August 1997, <http://www.nti.org/db/nisprofs/over/nuccases.htm>; and Vladimir A. Orlov, "Russian-U.S. Cooperation in Preventing Megaterrorism: Opportunities and Limits," PONARS Policy Memo No. 213, December 2001.

[57] Traditionally, HEU and weapons-grade plutonium (highly concentrated in the radioisotope plutonium-239) have been the fissile materials used in nuclear weapons. Radioactive sources that use the radioisotopes considered in this paper, such as Co-60 or Cs-137, cannot fission and are unsuitable for nuclear weapons. However, americium could, in principle, be used as the fissile material in nuclear weapons. Several tens of kilograms of americium would be required; Linda Rothstein, "Explosive Secrets," *Bulletin of the Atomic Scientists*, March/April 1999, and also see David Albright and Lauren Barbour, "Troubles Tomorrow?: Separated Neptunium 237 and Americium," in *The Challenges of Fissile Material Control*, ISIS Reports, 1999, pp. 85-96, for more technical details.

[58] EPA, "Radiation Terms," <http://www.epa.gov/radiation/terms/termdef.htm>.

and external health hazards, depending on the type of radiation. Because contaminating large water supplies to levels beyond acceptable health limits would require an enormous amount of radioactive material, this method is not likely to succeed. Moreover, certain radioisotopes, such as Pu-238, are not even water soluble and would tend to sink to the bottom of reservoirs, thereby presenting an essentially insignificant danger to human health.

In general, the active option requires construction of an RDD. According to the Department of Defense (DOD), an RDD is "any device, including any weapon or equipment, other than a nuclear explosive device, specifically designed to employ radioactive material by disseminating it to cause destruction, damage, or injury by means of the radiation produced by the decay of such material."[59]

When constructing an RDD, terrorists face constraints arising from the radioactivity of the source. To cause a large amount of radioactive contamination, they would be drawn toward very high activity sources. However, in order to prepare the source for effective dispersal by removing the shielding, terrorists would risk exposing themselves to lethal doses. Even suicidal terrorists might not live long enough to deliver a very highly radioactive RDD that uses gamma-emitting sources and is not shielded.[60] If they tried to protect themselves by shielding the source, the weight of the RDD could significantly increase, thereby increasing the difficulty of delivering the device and causing successful dispersion of the radioactive material. Thus, radiological terrorists might seek out moderately radioactive gamma and beta emitting sources (containing a few to a few hundreds of curies, for example) to be able to handle the materials safely. As explained earlier, alpha-emitters can be safely handled as long as precautions are taken to prevent internal exposures.

[59] As quoted in James L. Ford, "Radiological Dispersal Devices: Assessing the Transnational Threat," Institute for National Strategic Studies, National Defense University, Strategic Forum Number 136, March 1998.

[60] This discussion assumes very highly radioactive gamma sources containing thousands or more curies.

Consequences[61]

Unlike nuclear weapons, RDDs are generally not weapons of mass destruction.[62] Few, if any, people would die immediately or shortly after exposure to the ionizing radiation from a typical RDD. Possible cancer deaths from stochastic effects would usually require years to develop. Nonetheless, an RDD can be a weapon of mass disruption,[63] dislocation,[64] or effect.[65] Preying on the public's fears of radioactivity, terrorists who used RDDs would try to cause panic. The possible resulting chaos during evacuation of the immediate and surrounding areas could hinder emergency response efforts. Concerns over radioactive contamination could also cause long delays in first responders tending to casualties from a bomb blast, if such a method were used. Further, the decontamination costs and the rebuilding costs, if necessary, could be immense—perhaps upwards of billions of dollars.[66] These effects are classified as psychological, sociological, and economic.

[61] For a book-length exposition of this topic, see National Council on Radiation Protection and Measurements (NCRP), *Management of Terrorist Events Involving Radioactive Material*, NCRP Report No. 138, October 2001.

[62] Under certain highly specialized scenarios, it is possible to imagine many thousands of individuals receiving small ionizing radiation doses that could ultimately prove lethal over a long time period. For this reason, under some circumstances, RDDs could result in mass long-term casualties, making them weapons of mass destruction of a unique variety.

[63] Steven E. Koonin, "Radiological Terrorism," Statement delivered before the Senate Foreign Relations Committee, March 6, 2002, published in *Physics & Society*, April 2002, pp. 12-13.

[64] "Weapons of Mass Dislocation," *The Economist*, June 15, 2002.

[65] Morten Bremer Maerli, "Nuclear Terrorism: Threats, Challenges, and Responses," The Norwegian Atlantic Committee, Security Policy Library, 8-2002, has suggested the term weapons of mass effect to encompass the notion that certain weapons may not create massive destruction but could, nonetheless, result in other massive effects, such as psychological harm.

The actual health effects would depend on (1) the conventional explosive, if this method were used, (2) the type and amount of radioactive material dispersed, (3) the weather conditions, (4) the terrain, (5) population density, and (6) emergency response. If powerful conventional munitions were used as the dispersal mechanism in a densely populated location, the non-radioactive part of a dirty bomb could potentially injure or kill many. Consequently, none to thousands could die from the conventional component of an RDD.

But other factors would contribute to the health hazards from the radioactivity. An RDD would likely kill very few people with the radioactivity itself because the doses received would typically be small. As discussed in a previous section, such small doses might result in stochastic health effects and, therefore, typically take many years to develop. Nonetheless, very strong radioactive sources at close range delivering acute doses might cause deterministic effects. The most damaging exposure would typically be near the point of release or detonation in the scenario of a dirty bomb. Although the radioactivity diminishes with distance from this point, hot spots may form making careful monitoring of the surrounding area essential to identify concentrations of contamination. Variations in building height, spacing between buildings, the contours of terrain, and other obstacles, as well as prevailing weather conditions, would all influence the formation of radioactive hot spots.

The three key principles to minimizing exposure are time, distance, and shielding. Reducing the time spent in the contaminated area lessens the dose received. Moving away from the point of release and hot spots decreases exposure. Adding dense, large masses, such as buildings, between people and concentrated areas of contamination provides shielding, thus lowering exposure. Sheltering inside houses and buildings with closed doors and windows helps to minimize exposure to aerosolized clouds of contaminants. Therefore, the appropriate response for many people who are not close to the release point would not be to flee and potentially block emergency response efforts, but to remain inside buildings. However, those who are close to the point of release would need to evacuate the immediate area. Emergency response officials would cordon off that area and tend to those who are injured or contaminated.[67]

After tending to any casualties, emergency response officials would try to decontaminate affected buildings and land. However, depending on the amount of contamination, current decontamination technologies might not be adequate to meet EPA guidelines, which call for reducing the cancer risk to less than one per 10,000 people due to remaining radiation. Consequently, authorities may decide to tear down buildings because of this constraint. Moreover, large areas of cities might not be habitable based on present guidelines and would be subject to long-term monitoring.

Recent studies that have examined plausible dirty bomb scenarios confirm these analyses. Steven Koonin, a nuclear physicist and provost of the California Institute of Technology, testified before the Senate Foreign Relations Committee, "If just three curies (a fraction of a gram) of an appropriate isotope

[66] In a potential RDD scenario in Manhattan involving the dispersion of the amount of americium-241 used in well-logging equipment, which is not a very highly radioactive source, the Federation of American Scientists estimated decontamination and rebuilding costs over $50 billion. Of course, if rebuilding is not necessary, the costs would be much less. This scenario is described in more detail below; Henry Kelly, Statement delivered before the Senate Foreign Relations Committee on Radiological Terrorism, March 6, 2002. The NRC states that "contamination could be costly (conceivably running into the millions) and take weeks to months to complete"; "Dirty Bombs," U.S. Nuclear Regulatory Commission, <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/dirty-bombs.html>, July 2002.

[67] See NRC statement, "Response to a Dirty Bomb," July 2002.

were spread over a square mile, the area would be uninhabitable according to the recommended exposure limits protecting the general population. While the direct health effect would be minimal (for each 100,000 people exposed, some 4 cancer deaths would eventually be added to the 20,000 lifetime cancers that would have occurred otherwise) the psychological effects would be enormous."[68]

Michael Levi, Henry Kelly, Robert Nelson, and Jaime Yassif of the Federation of American Scientists (FAS) analyzed three case studies, involving Cs-137 (a gamma-emitter), Co-60 (a gamma-emitter), and Am-241 (an alpha-emitter).[69] The first case examined the dispersal of two curies of Cs-137 (an amount found in many medical gauges) by exploding ten pounds of TNT in Washington, DC. The predicted consequences are that people residing in "an area of about five city blocks, if they remained, would have a one-in-a-thousand chance of getting cancer. A swath about one mile long covering an area of forty city blocks would exceed EPA contamination limits."[70] Decontamination would be challenging because cesium would tend to combine chemically with building materials. The second case considered the dispersal of 10,000 Ci of Co-60 (from a food irradiation facility) starting at the lower tip of Manhattan. Among other consequences, the study predicted, "The entire borough of Manhattan would be so contaminated that anyone living there would have a one-in-a-hundred chance of dying from cancer caused by the residual radiation."[71] The third case examined the dispersal of 10 Ci of Am-241 (from a typical source used in oil well surveying) by exploding one pound of TNT in Manhattan. Because of the internal health hazard presented by an alpha-emitter, people in the immediate area of the blast would have to be evacuated. Within half an hour, the FAS study predicted that this area would cover some 20 city blocks. The radioactive materials that settled out of the radioactive cloud would pose a long-term hazard, if they were not cleaned up, because some material could easily be forced up into the air and inhaled. If decontamination was not successful, EPA safety guidelines could be interpreted to require demolition of buildings. The resulting cost to demolish and rebuild "would exceed fifty billion dollars."[72]

Though the FAS study admittedly used a simple model (which, for example, assumed flat terrain), its results are comparable[73] to a more sophisticated investigation (which included models of three-

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[68] Steven E. Koonin, "Radiological Terrorism," Statement delivered before the Senate Foreign Relations Committee, March 6, 2002, published in *Physics & Society*, April 2002, pp. 12-13. But such even dispersal would be difficult to achieve, according to Michael Levi, because the release of the radioactive material would more likely follow a Gaussian distribution, which is a bell-shaped curve.

[69] Federation of American Scientists, "Dirty Bombs: Response to a Threat," *FAS Public Interest Report*, March/April 2002, pp. 6-10, and testimony by Henry Kelly before the Senate Foreign Relations Committee, March 6, 2002, available at <http://www.fas.org>. For a more popular exposition of the FAS research on RDDs, see Michael A. Levi and Henry C. Kelly, "Weapons of Mass Disruption," *Scientific American,* November 2002, pp. 76-81.

[70] Ibid. The cancer risks cited in the FAS study assume a residence time of 40 years within the contaminated area and that no decontamination would occur. Such assumptions were based on EPA guidelines for determining cancer risk. These guidelines are the strictest in the world. The FAS study also assumes "light winds of 2 mph and complete dispersal of the materials"; Michael Levi and Henry Kelly, "Dirty Bombs Continued," *FAS Public Interest Report*, May/June 2002. The Health Physics Society (HPS), a non-profit scientific professional organization devoted to promoting the practice of radiation safety, has analyzed the EPA guidelines and concluded that HPS does "not support the use of hypothetically calculated risk coefficients at the level of environmental radiation exposures, as is done by the EPA in their conversion of a risk goal to a dose constraint value"; Health Physics Society, "Background Information on 'Ionizing Radiation-Safety Standards for the General Public,'" Adopted: March 1993; Revised: August 2000; Reaffirmed: March 2001. This position is also similar to the International Commission on Radiological Protection's position.

[71] Henry Kelly's testimony, March 6, 2002.

[72] Ibid.

[73] The FAS study's margin of error was about a factor of ten.

dimensional structures) performed by Leonid Bolshov, Rafael Arutyunyan, and Oleg Pavlovski of the Nuclear Safety Institute, Russian Academy of Sciences.[74] In that investigation, the authors calculated how much radioactive material of various radioisotopes would be required to exceed the permissible threshold doses for the general public. For example, Co-60, a gamma-emitter, would potentially pose an external hazard and have an associated 5 mSv threshold dose. Alpha-emitters would present a potential internal hazard and would have a 50 mSv threshold dose. To exceed these threshold limits in a one square kilometer urban area (about 40 city blocks), this study predicted as little as a tenth of a gram to a few grams of Co-60 (about 100 to 2,500 Ci) would be required, depending on the weather conditions. For Cs-137, a few grams to just over one hundred grams (about 500 to 10,000 Ci) would be necessary to exceed the dose limits, taking into account different weather conditions.

The NRC agreed with the FAS researchers that two of the scenarios—the Cs-137 and Am-241 examples—of the FAS study are more plausible than the scenario involving a Co-60 source stolen from an irradiation facility because of the relatively strong security systems employed at such a facility. However, the NRC took issue with the consequences to public health and the extent of the contamination predicted by the FAS study. In particular, the NRC did not believe that contaminated areas would have to be condemned, although it did not give its reasons for these conclusions.[75]

Case Study of Radiological Dispersal: Goiania, Brazil Because radiological material dispersal by terrorists has not happened, there are no actual examples to compare to these simulations. However, examining a case study of a radiological accident can give a sense of the damage that can result from an RDD. On September 13, 1987 in Goiania, Brazil, scavengers broke into an abandoned cancer clinic and took a metal canister from a radioteletherapy machine. The canister contained 1,375 curies of cesium-137. The scavengers broke off pieces of the canister, revealing the Cs-137 source, and distributed some of the material among family and friends, spreading the radioactive contamination. Less than a week later, the rest of the canister and the source became the property of a junkyard. There, a junk dealer pried the source open causing the cesium chloride powder to disperse. Wind and rainwater runoff quickly spread radioactive contamination. On September 28, 1987, a health care worker diagnosed the first case of radiation sickness. A Brazilian Nuclear Energy Commission team found more than 200 contaminated people. Four deaths and one arm amputation resulted. In addition, 28 people suffered radiation burns. Panic among the local populace sparked monitoring of more than 112,000 people, but the vast majority of which experienced no contamination. Some cite the press as inflaming this response through exaggerated reporting.[76] In addition, large land area contamination of about one square kilometer (roughly 40 city blocks) required a massive cleanup effort. Seven homes and some other buildings had to be demolished. About 3,500 cubic meters of radioactive waste were generated. Encouragingly, this cleanup recaptured most (about 1,200 curies) of the contamination.

[74] Leonid Bolshov, Rafael Arutyunyan, and Oleg Pavlovski, "Radiological Terrorism," in *High-Impact Terrorism: Proceedings of a Russian-American Workshop*, 2002, pp. 137-148, and Leonid Bolshov and Oleg Pavlovski, "Radiation Sources in Russia and Their Potential Attractiveness and Accessibility for Radiological Terrorists," Presentation given at June 2002 American Nuclear Society meeting.

[75] Interview with U.S. government official, October 8, 2002.

[76] Agency for Toxic Substances and Disease Registry, "Radiation Accidents," in *Toxicological Profiles*, <http://www.atsdr.cdc.gov/toxprofiles/tp149-c4.pdf>, pp. 197-199.

The clean-up costs of $20 million represented only a small fraction of the total financial impact. Economic losses from collapse in tourism and business regression are difficult to assess but are estimated to be up to hundreds of millions of dollars.[77] Reacting to fears of persistent contamination, many people fled the area, reversing the previous growth in population. Prices of manufactured products fell by 40 percent after the initial news reports and remained depressed for 30 to 40 days although no contamination was found on these goods.

This incident teaches several lessons applicable to RDDs. One key difference is that social contacts responsible for much of the Goiania contamination spread would be unlikely to be seen in an RDD event. Similarities would likely be the relatively few killed by the radiation, combined with the psychosomatic complaints, the costly cleanup efforts, and other financial damage. News media overreaction could also fuel much panic in an RDD event. Although challenging, improved educational efforts and emergency response planning can help reduce this overreaction. Inadequate regulatory control over the hospital source contributed to the Goiania accident. As discussed in detail later, stronger regulatory controls can help prevent sources ending up in RDDs.

Incidents

No RDD explosions have yet occurred. However, a few incidents have raised concern such that the question is not if the actual use of an RDD will occur, but when. In addition to the 1995 Chechen incident described above, officials in Chechnya in 1998 reportedly defused a booby-trapped explosive connected to radioactive material.[78] In 1987, Iraq tested a radiological weapon, according to an Iraqi report obtained by the Wisconsin Project on Nuclear Arms Control. However, this weapon did not generate high radiation levels and was, therefore, considered a failure.[79] At that time, Iraq was fighting a war against Iran. Moreover, the U.S. military had a radiological weapons program during the 1940s, which was subsequently abandoned due to lack of military utility.

Of more recent concern is al Qaeda's interest in acquiring RDDs. Abu Zubaydah, a captured top al Qaeda official in U.S. custody, disclosed to U.S. interrogators that this terrorist organization was close to constructing a dirty bomb, which might be smuggled into the United States. This information helped lead U.S. authorities to arrest Jose Padilla, also known as Abdullah Al-Mujahir, in May 2002. Though Padilla apparently had not obtained radioactive materials for an RDD, law enforcement authorities uncovered evidence that he was allegedly on a reconnaissance mission to find materials and scout out potential targets. Attorney General John Ashcroft announced the arrest on June 10, 2002.[80] Padilla had allegedly met with al Qaeda operatives on several occasions. (In August 2002, CNN broadcast several of al Qaeda's training videotapes. These tapes instructed recruits on how to make conventional explosives. However, according to CNN, "Nothing in any of the 64 videos shows al Qaeda has obtained the components necessary to manufacture a dirty bomb. There are no lessons, for example, in handling radioactive material."[81])

[77] Paul Slovic, "Perception of Risk from Radiation," *Radiation Protection Dosimetry*, Vol. 68, No.3/4, 1996, p. 172.

[78] David E. Kaplan and Douglas Pasternak, "Terror's Dirty Secret," *U.S. News and World Report*, December 3, 2001.

[79] William J. Broad, "Document Reveals 1987 Bomb Test by Iraq," *The New York Times*, April 29, 2001, p. A8.

[80] Associated Press, "Text: Ashcroft on Dirty Bomb," June 10, 2002.

[81] Nic Robertson, "Bomb-making video reveals scope of al Qaeda threat," CNN.com, August 21, 2002.

The mere interest demonstrated by some terrorists in planning for radiological terrorism has spurred greater attention to the security of radioactive sources. If a dirty bomb were exploded, not only would the public and government incur potentially massive costs, but the radioactive source industry would also be adversely affected. Such an event could provoke calls for even more stringent and costly security measures. Industry would likely have to bear a substantial portion of this burden.

LIFECYCLE OF RADIOACTIVE SOURCES

Fully understanding the potential security vulnerabilities requires knowing the lifecycle of radioactive sources. Every stage in the life of a source deserves appropriate security measures.

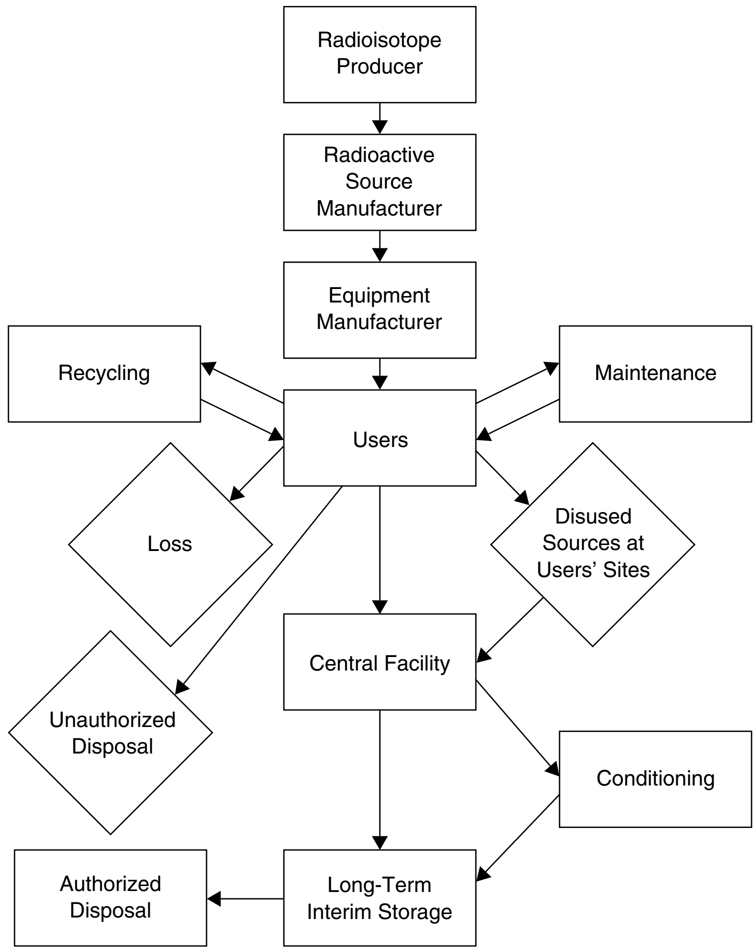
In the first stage, as noted earlier, radioisotopes, other than naturally occurring ones, are created in either nuclear reactors or particle accelerators. As discussed previously, reactor-produced radioisotopes present the greater concern from a security perspective. These radioisotopes are either processed into sources on the reactor site or transported offsite to a processing facility. From either location, sources can go directly to users or to manufacturers who incorporate the sources into specialized equipment. Either way, transportation brings the sources to the users or equipment manufacturers who will eventually sell the equipment to users. To this point, these lifecycle stages can be modeled as an inverted pyramid. In other words, a few major producers supply most of the radioisotopes to a large pool of equipment manufacturers. In turn, these manufacturers sell to an even larger group of users. Sometimes, users sell or transfer their sources to other users within or outside of the original user's country. Such transfers can at times make tracking the sources difficult, especially if the new user's country has inadequate regulatory controls. For example, some users in the developed world transfer sources to other users in the developing world, where regulatory controls may be lacking.

Depending on the requirements of the source application as determined by the user and the half-life of the radioisotope, a source will eventually no longer be able to perform its function. At that point and for some time later, a disused source can still be potent and, thus, pose a security risk. Ideally, users would then securely and safely dispose of or recycle the source. In this scenario, the flow of disused sources from users to disposal or recycling facilities resembles an upright pyramid. That is, hundreds to thousands of users would return the sources to a few recycling centers typically operated by a major manufacturer or would send the sources to a few disposal sites run by producers or governments. Unfortunately, a small portion of sources do not follow these pathways and instead become orphaned, and even for those sources that do follow these pathways, at certain points, security arrangements may be inadequate. Some of the reasons were discussed above. Other reasons stemming from inadequate regulatory control will be covered in a later section.

Figure 1 depicts the lifecycle, or flow, of radioactive sources from production to distribution to disposition. Paying attention to the arrows between the boxes is important because they represent transportation. During transport, sources are being moved from site to site and may be more or less vulnerable than on-site sources to malicious seizure, depending on the security precautions undertaken. The rectangles in Figure 1 represent places where sources would, in principle, be very secure, whereas, the diamonds mark locations where sources pose greater safety and security risks. Obviously, unauthorized disposal would fall into the latter category. Perhaps not as obviously, disused sources stored at the users' facilities present increased risks mainly because these facilities are less secure than authorized disposal or recycling centers.

The next sections track in more detail the lifecycle of those radioactive sources that pose the greatest security risk.

Figure 1: Flow of Radioactive Sources from Production to Use to Disposal or Loss



Source: This figure is based on a similar figure in M. J. Angus, C. Crumpton, A.D. Moreton, and P.T. Roberts, "Management and Disposal of Disused Sealed Radioactive Sources in the European Union," EUR 1886, 2000, p. 119.

OVERVIEW OF THE RADIOACTIVE SOURCE PRODUCTION AND DISTRIBUTION INDUSTRY

Reactor production of radioisotopes for civilian research dates back to the early 1950s when Oak Ridge National Laboratory (ORNL) first established a full-scale research reactor with applications in the biosciences. Today, the IAEA research reactor database includes about 100 reactors worldwide that are currently involved in radioisotope production.[82] (See Appendix 2 for a list of reactors that produce radioisotopes.) Worldwide, thousands of manufacturers use reactor-produced radioisotopes in their equipment. In

[82] The IAEA database of research reactors available at <http://www.iaea.org/worldatom/rrdb/fc_home.html> contains details including isotopes produced.

the United States, the NRC lists hundreds of companies as active manufacturers of equipment incorporating radioactive sources.[83] However, despite the large number of firms involved in both processing and distribution of radioactive sources, only a handful of companies contribute an overwhelming proportion of the worldwide market share and, in turn, procure raw radioisotopes from a few specific reactors. To illustrate the pathway by which commercial radioisotopes reach the end-user, a general production and distribution flowchart is shown in Figure 2.

While this section provides an overview of the production and distribution of radioactive sources, particular emphasis is placed on the production and sale of radioisotopes that have been identified earlier as posing a heightened security risk: the three beta- and gamma-emitters: Co-60, Ir-192, and Cs-137; the beta-emitter: Sr-90; and the three alpha-emitters: Pu-238, Cf-252, and Am-241.

This section begins by identifying the major commercial radioisotope-producing reactors and the organizations that run them. Profiles of key radioisotope suppliers are then given, showing the reactors they predominantly use for production, the specific radioisotopes of concern they supply, and when possible, their principal customers.

Radioactive source suppliers generally operate in two different markets. The first includes pharmaceutical or equipment manufacturers and distributors that purchase radioisotopes in bulk and then pass their products (of which the radioisotope is an integral part) along to the end-user. The second market consists of researchers who directly purchase their isotopes in small quantities. Here, the focus is on bulk radioisotope production for the commercial market, which accounts for the vast majority of radioisotopes produced.

[83] This list is available on the NRC website at <http://www.nrc.gov>.

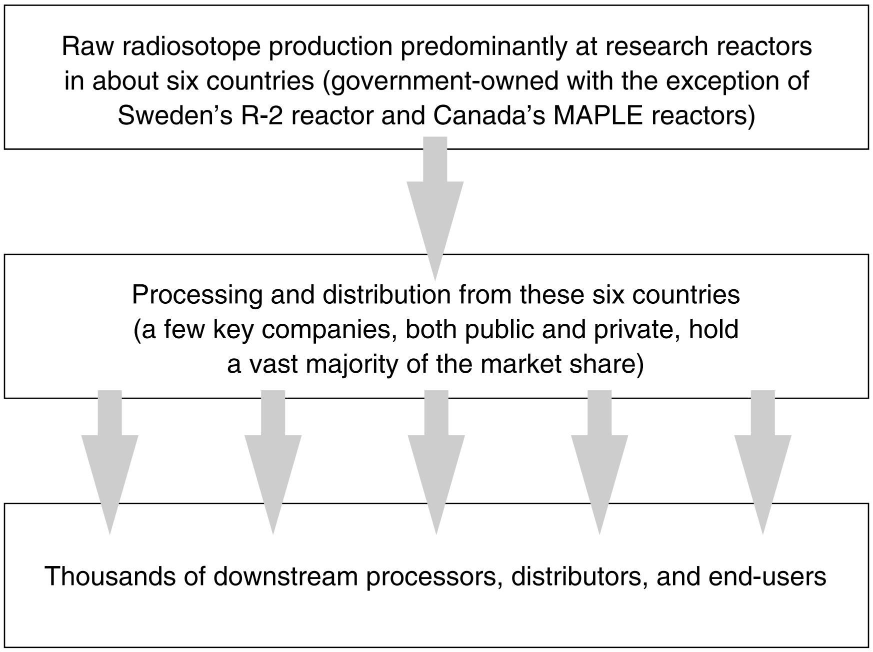
Government Reactors and Enterprises

Almost all reactor facilities used for commercial radioisotope production are government owned. Given below are descriptions of the governmental infrastructure and organizations within the nations that produce most of the radioisotopes used in medicine and industry today.

Canada's crown facilities allow this country to remain the largest exporter of radioisotopes in the global commercial market. South Africa, Russia, Belgium, Argentina, and the Netherlands (which has a reactor owned by the European Union) also have government agencies that facilitate and promote radioisotope production at their reactors, and details of these efforts follow, with each country listed roughly in order of production magnitude. The facilities of two more countries—France and the United States—are also included here. France is mentioned briefly due to the use of two French reactors by a major radioisotope producing company, and the United States, not a large producer in general, is included because it holds a substantial market share for some of the radioisotopes that pose a greater security concern. The United States also stands out because it has a significant potential for future production through ownership of various reactors and related facilities.

Finally, the efforts of several countries producing radioisotopes on a smaller scale for domestic use—as well as countries that may prove to have significant production capability in the future—are discussed.

Figure 2: Radioisotope Distribution Flowchart



Canada Canada presently leads the world in exporting radioisotopes, and MDS Nordion, a privately owned company, performs the processing and distribution of radioisotopes produced in that country's government-owned reactors. The Atomic Energy of Canada Ltd. (AECL), a federal crown corporation involved in the design and engineering of nuclear research and power reactors, owns the Chalk River facility, where the majority of radioisotope production occurs. Although the National Research Universal (NRU) Reactor at Chalk River is Canada's primary reactor for radioisotope production, it is more than fifty years old and scheduled for decommissioning by 2005.

AECL has designed and built several reactors worldwide, including the CANDU and MAPLE reactors. CANDU (CANada Deuterium Uranium) power reactors are widely used in Canada, as well as South Korea, Argentina, India, and Pakistan, with two additional reactors currently under construction in China and Romania. Some of these reactors (such as the CANDU 6 design used by Ontario Power Generation) are equipped with adjustable rods that allow for neutron irradiation for the production of radioisotopes (cobalt rods are used here for Co-60 production).

Two MAPLE (Multipurpose Applied Physics Lattice Experiment) research reactors, owned and operated by MDS Nordion, are also located at the Chalk River facility and will be used for medical radioisotope production.[84] Although construction of the reactors was recently completed,[85] the Canadian Nuclear Safety Commission is still in the process of

[84] When commissioned and operational, the MAPLE reactors will be the first privately owned research reactors with the commercial production of radioisotopes as their exclusive use.

[85] MDS Nordion has been conducting a feasibility study that is assessing the conversion of the HEU target material in the reactor to LEU, in order to comply with the RERTR program. The United States has been supplying HEU to this company.

reviewing the startup license. "As in all regulatory matters, however, it is difficult to anticipate the timeline the process will follow," according to Chris Critch, operations director at MDS Nordion.[86] When operational, the MAPLE reactors will replace—and because of their advanced design and their exclusive use for radioisotope production, will probably surpass—NRU's radioisotope production capabilities. More information about MDS Nordion and its facilities can be found in the following section on commercial distributors.

South Africa Although no other country approaches Canada in volume of radioisotopes produced, South Africa is also a significant producer. The South African Nuclear Energy Corporation (NECSA), which became a public company on February 24, 2000, after passage of the Nuclear Energy Act of 1999, owns the pool-type reactor Safari-1 in Pelindaba, where target irradiation for radioisotope production occurs.[87]

Russia Russia's involvement in the radioisotope market is growing. Several research reactors in Russia are capable of radioisotope production, attracting overseas corporations interested in forming joint ventures with Russian facilities. As part of large state-owned nuclear institutes, Russian reactors are generally administered by the Russian Ministry for Atomic Energy (MINATOM). The Institute of Physics and Power Engineering (IPPE) in Obninsk owns BR-10 (liquid-sodium) and AM-1 (graphite-water) reactors; the Scientific and Research Institute of Atomic Reactors (SRIAR) in Dimitrovgrad operates the MIR (channel) and SM-3 (tank) reactors; the Kurchatov Institute in Moscow owns the IR-8 (pool) reactor; and the St. Petersburg Institute of Nuclear Physics (PNPI) is constructing a tank reactor, PIK.[88]

The SRIAR radiochemical complex in Dimitrovgrad is the largest facility in Russia reprocessing irradiated targets in order to obtain heavy transuranic elements such as californium-252 and is, therefore, of particular interest from the perspective of radiological material security. Although further research is necessary to identify the extent of production at SRIAR, this institute reports that it manufactures, in addition to many radioisotopes of lesser security concern, Cf-252 and Am-241, as well as Ir-192 and Co-60.[89] Table 6 shows further details on the sealed sources using these radioisotopes produced by SRIAR.

Mayak Production Association (PO Mayak), another major producer of radioisotopes in Russia, is located at Chelabyinsk in the Ural Mountains. As a subsidiary of MINATOM, PO Mayak is heavily involved in the defense industry, but two of its reactors, Ludmila and Ruslan, also produce commercial radioisotopes.[90] In a 2001 interview with the local publication PrO Mayak, PO Mayak deputy director for reactor-isotope production Valery Asnovsky stated that the company is going through a conversion plan to increase isotope production in order to relieve its reliance on defense contracts.[91] Along with Techsnabexport and Amersham International, PO Mayak owns REVISS Services, a leading radioisotope distributor. Techsnabexport, a Russian joint stock company with controlling stock held by the Russian Federation, handles more than 45 percent of radioisotope exports from Russia to the world market.[92]

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[86] MDS Nordion, "MDS Nordion's MAPLE reactors to ensure security of supply: Two new reactors to be dedicated to medical isotope production," Backgrounder, June 13, 2002.

[87] Similar to MDS Nordion, NECSA is assessing the feasibility of converting from HEU to LEU in the Safari-1 reactor.

[88] Most of the reactors identified here use 90 percent enriched HEU. These reactors are BR-10, IR-8, MIR, and SM-3.

[89] See <http://www.niiar.simbirsk.su/drsp/en/sources.htm> for further details.

[90] "Mayak Production Association: Mayak PA," *Nuclear Business Directory: IBR Guide to the Russian Nuclear Industry 2000* (Moscow: International Business Relations Corporation, 2000), pp. 107-108.

[91] Rashid Alimov, "Mayak Plant to Increase Cobalt-60 Export," *The Nuclear Chronicle from Russia*, <http://www.bellona.no/>, April 30, 2001.

[92] 2000 Annual Report, Techsnabexport, p. 17.

Table 6: SRIAR Sealed Sources Containing Radioisotopes of Greatest Security Concern

Radioisotope Sealed Source	**Radioisotope Activity (Curie)**	**Application**
Americium-241		
1mm diameter Cylinders	0.00016 – 0.008	Apparatus calibration
Californium-252		
Cylinders	0.00032 – 6.5	Analysis of rocks and ore, oil-well gauging; radiography
Cylinders	0.076 – 0.37	Various
Dowels	0.00032 – 0.024	Cancer treatment; well-logging
Cylinders	0.00032 – 0.0024	Cancer treatment
Cylinders	0.0032 – 1.6	Cancer treatment
Cobalt-60		
Dowels	0.002 – 0.0031	Brachytherapy
Cylinders	0.0054 – 0.0094	Brachytherapy
Iridium-192		
Cylinders	1 – 105	Industrial flaw detectors
Cylinders	0.5 – 165	Industrial radiography

Note: The radioactivity amounts less than a curie would not present a high security concern. Source: SRIAR

Belgium The Belgian government wholly owns its radioisotope producing company, the National Institute for Radio Elements (IRE). Located in Fleures, the company produces radioisotopes from the BR-2 reactor, operated by the government-owned nuclear research organization SCK-CEN.[93] IRE also uses the Osiris and High Flux Reactor (HFR) reactors in France, and the HFR reactor in the Netherlands for radioisotope production. Further details on IRE's activities are given in the section under commercial distributors.

Argentina Argentina's most significant market contribution in radioisotopes stems from collaboration with a major Co-60 distributor, the Russian/British joint venture REVISS Services. The country's National Atomic Energy Commission (CNEA) holds a procurement contract with REVISS for the sale of Co-60 produced at the Embalse-1 CANDU heavy water power reactor and related hot cell processing facilities located in Cordoba, Argentina.[94] However, CNEA also independently sells Co-60 in sealed source form with activities between 1,000 and 14,000 Ci for use in industrial irradiation and medical radiography, as detailed in Table 7.

European Union Activity in The Netherlands The European Union Joint Research Centre's Institute for Energy owns the High Flux Reactor (HFR) in Petten, The Netherlands, from which Mallinckrodt and IRE, two key radioisotope suppliers, procure

[93] SCK-CEN is working on a new type of neutron source facility that may be able to substitute for reactor production of some radioisotopes. The project, called Myrrha, creates a neutron source with a particle accelerator and is expected to have radiation waste and safety advantages over reactors. Although SCK-CEN is still researching how Myrrha could be best used for radioisotope production (this research is being done in collaboration with the private firm Ion Beam Applications), it has already claimed that the new system would allow high quality production of radioisotopes at a reduced cost.

[94] The National Atomic Energy Commission, CNEA, <http://www.cnea.gov.ar>.

Table 7: CNEA Sealed Source Co-60 Products

Radioisotope Sealed Source	Radioisotope Activity (curie)	Application
Cobalt-60 11mm diameter cylinders (up to 450mm in length)	8,000 – 14,000	Industrial irradiation
23mm diameter cylinders (36mm in length)	~1,000	Medical radiography
Source: CNEA		

their products. According to the Energy Center of the Netherlands, more than 70 percent of medical radioisotopes used in European medical facilities are manufactured at HFR. Although HFR produces many different radioisotopes, only iridium-192 stands out as a potential, significant security risk.

United States Since the decommissioning of reactors belonging to Cintichem Inc. and General Electric by the early 1990s, the United States has not played a prominent role in bulk radioisotope production. However, several Department of Energy (DOE) facilities could be significant contributors to the radioisotope industry in the future. For instance, DOE has the capability to extract fission products, such as Sr-90 and Cs-137, from spent nuclear fuel (which originated from the U.S. nuclear weapons production program) in order to produce commercial radioisotopes.

DOE oversees the distribution of radioisotopes produced in various facilities at national laboratories, such as Brookhaven National Laboratory (accelerator), Oakridge National Laboratory (HFIR Reactor), Sandia National Laboratory (ACRR Reactor), Los Alamos National Laboratory (accelerator), Idaho National Environmental and Engineering Laboratory (INEEL) (ATR Reactor, hot cell facilities), and Pacific Northwest National Laboratory (PNNL) (hot cells for spent fuel and fission product separation). DOE offers isotope products and related services for sale through its Office of Isotope Programs and tends to specialize in radioisotopes that are not readily available but are needed by domestic and international customers. The Office adds, "Isotopes are sold by DOE only when there is no U.S. private sector capability or when other sources do not have sufficient capacity to meet U.S. needs."[95] DOE sales are generally done on the basis of full cost-recovery, where no profit is included in the selling price.[96]

Reactor radioisotope production facilities include the High Flux Isotope Reactor (HFIR) at ORNL, which produces Cf-252 and Ir-192. Additionally, INEEL's Advanced Test Reactor (ATR) produces Ir-192 and Co-60.[97] Sandia National Laboratories' Annular Core Research Reactor (ACRR), although mostly involved in defense activity, also produces radioisotopes.

Table 8 shows DOE facilities that produce the radioisotopes emphasized in this paper for their susceptibility to potential terrorist use.

Historically, national governments in most countries have heavily subsidized reactor radioisotope production. In the United States, DOE has been trying to privatize its commercial radioisotope production business for some years with limited success. It has encouraged private sector investment by

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[95] This is stated on the Office of Isotopes for Medicine and Science Programs Website, <http://nuclear.gov/isotope/pri-act.html>.

[96] Final Report of The Nuclear Energy Research Advisory Committee (NERAC), Subcommittee for Isotope Research and Production Planning (within the DOE), April 2000.

[97] Ibid.

Table 8: DOE Production of Radioisotopes Susceptible to RDD Use

Radioisotope	Radioisotope Activity (Ci/g)	Production Site	Application
Strontium-90	140	PNNL (Hanford)	Cancer therapy; Production of Yttrium-90
Cesium-137	88	PNNL	Blood irradiation
Americium-241 Double encapsulated container	3.4 (as americium dioxide powder)	ORNL	Medical radiography
Iridium-192	Up to 1000 Not available	ORNL INEEL	Brachytherapy Radiography
Cobalt-60 (High Specific Activity Co-60)	Up to 1,000	INEEL	Teletherapy
Plutonium-238	17 (in oxide powder, sold in mg)	ORNL	Used in pacemakers[a]
Californium-252	540 (in solution, sold in micro-grams)	ORNL	Radiotherapy
Source: DOE National Labs			

[a] With the advent of long-lived nickel-cadmium batteries, this use of Pu-238 has essentially been phased out.

offering to sell or lease facilities, equipment, and material for commercial purposes, or to license new patent technologies. So far, the following have been privatized: Test Reactor Area hot cells, isotope products and services at INEEL; production, packaging, sales, marketing, and distribution of yttrium-90 (Y-90) at PNNL; and fabrication of iridium targets for the HFIR at ORNL. At INEEL, International Isotopes Idaho, Inc. operates the Test Reactor Area Hot Cells for processing and sales of isotopes. At PNNL, NEN Life Science Products of Boston, Massachusetts has a five-year agreement to lease Sr-90 from DOE to extract an ultra-pure form of Y-90. Since the commercial production of radioisotopes by private enterprises has been limited, the impact of privatization on security of the facilities and sources produced is not apparent. However, clearly such issues will need to be carefully evaluated before privatizing large facilities, including research reactors.

Other Countries Given below are brief descriptions of other countries' efforts in radioisotope production. Notably, these reactors are not considered large commercial radioisotope producers today because they make up a small minority share of the market. Therefore, they pose a smaller risk from the standpoint of maintaining radioactive source security. However, marketplace changes could affect the production capacity of these reactors in the future, particularly new reactors, such as South Korea's HANARO and Germany's FRM-II.

In the Asia-Pacific region, Australia, the Republic of Korea, Japan, China, India, and Uzbekistan deserve mention. The Australian Nuclear Science and Technology Organization (ANSTO) produces radioisotopes using its HIFAR reactor at Lucas Heights and the National Medical Cyclotron in Sydney. ARI (ANSTO Radiopharmaceuticals and Industrials) markets these isotopes. Because the HIFAR reactor is scheduled for decommissioning, a new replacement reactor is currently being considered.

The (South) Korean Atomic Energy Research Institute (KAERI) owns HANARO, the first MAPLE-type reactor in operation (using LEU Fuel), with extensive radioisotope production capability, and could be a significant supplier in the future. Currently, KAERI produces Co-60 along with other radioisotopes of lesser security concern.

The Japan Atomic Energy Research Institute produces a range of radioisotopes, including Co-60, in modest quantities for domestic use. The Japanese Radioisotope Association, a professional body and research institution, makes some radioisotopes using cyclotrons, again for domestic use, but these would not pose a high security concern.

Radioisotope production is increasing in China at various centers, but there is, as yet, no significant export trade. The China Institute for Atomic Energy runs four reactors including a 15 MW heavy water reactor used for radioisotope production. The state-run China Isotope Corporation is involved with Chinese production and sales of radioisotopes and has set up joint ventures with Amersham International and Syncor (a U.S.-based pharmaceuticals distributor).

Other national agencies responsible for the production and sale of radioisotopes include India's Board of Radiation and Isotope Technology, which produces and sells a range of products within the Indian market. Most of the 170 teletherapy units in 62 Indian cities use 9,000 to 12,000 curie Co-60 sources for cancer treatment.

Near Tashkent, Uzbekistan, the Institute of Nuclear Physics, which is part of the Academy of Sciences of Uzbekistan, operates a 10 MW tank-type reactor. The Institute aims to use this reactor to become the leading nuclear research and radioisotope production facility in Central Asia.[98]

In Europe, Sweden and Germany stand out as second tier producers of radioisotopes. In Sweden, Studsvik AB owns and operates the 50 MW R-2 light-water reactor. The 20 MW high flux research reactor FRM-II in Garching, Germany, built by Technische Universität München and owned by the Bavarian government, is slotted to take over the role of several aging radioisotope producing reactors as they shut down. Considerable opposition from the federal government on licensing FRM-II has postponed its operation,[99] but this reactor should prove to be a leading medical radioisotope producer when it is fully functional.

Commercial Distributors

Radioisotope usage can be broadly divided among nuclear medicine, industrial irradiation, and measuring/gauging applications. Although radioisotopes have these diverse uses, individual manufacturers and distributors generally cater to all industries, with the nuclear medicine industry being their largest customer. Covering both therapeutic and diagnostic uses, nuclear medicine is currently a billion dollar market in the United States alone. Most sales worldwide for all radioisotopes are conducted through a few major producer/distributor companies that purchase radioisotopes from the reactors described above and then sell them usually through large networks of smaller distributors and subsidiaries, or sometimes directly to the end user. One-stop-shops, such as MDS Nordion and Amersham, have pharmaceutical divisions that sell directly to radiopharmacies.

[98] See Monterey Institute's Center for Nonproliferation Studies' database entry, "Uzbekistan: Institute of Nuclear Physics," updated June 6, 2002, <http://www.nti.org/db/nisprofs/uzbekis/inp.htm>; and references therein.

[99] At a time when other reactors are moving away from HEU to proliferation resistant high-density LEU for fuel, the FRM-II reactor is set to begin operations with weapons-grade (93 percent) HEU. A compromise agreement between the Bavarian and German governments stipulates that the enrichment will be reduced to 50 percent HEU by December 2010. However, both levels of enrichment pose a proliferation concern; Alexander Glaser, "Bavaria bucks ban," *Bulletin of the Atomic Scientists*, March/April 2002, pp. 20-22.

Figure 3: Major Radioisotope Production and Distribution Pathways Flowchart

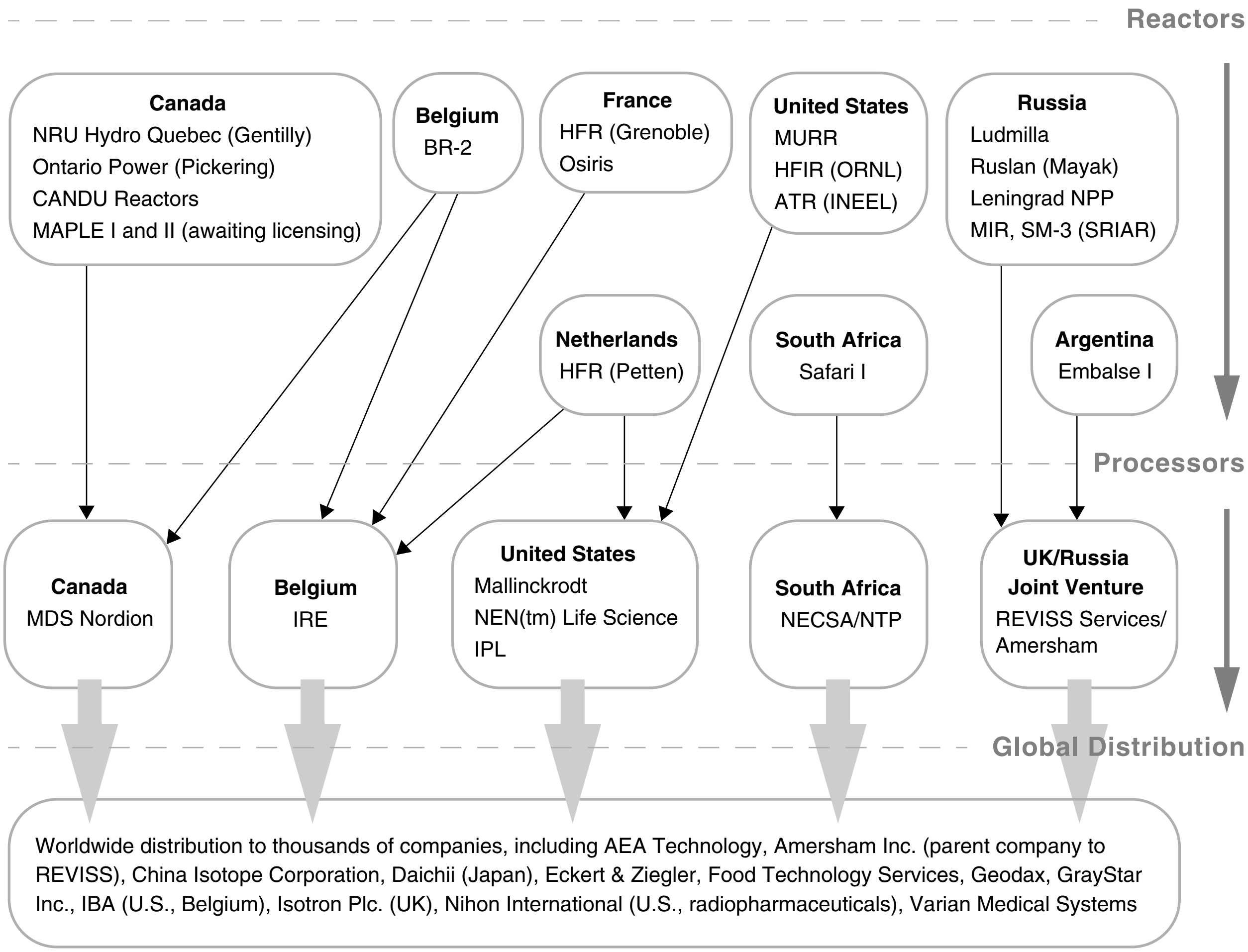

Figure 3 illustrates where the most important distributors purchase their radioisotopes and where these radioisotopes are sold. These producers/distributors, by far, cover the largest portion of the radioisotope market. MDS Nordion alone claims to provide more than half of all medical radioisotopes used worldwide[100] and is reported to supply more than 80 percent of the Co-60 in the world market.[101] Details of these key production and distribution companies follow, showing the reactors from which their radioisotopes are sourced, the products and processing methods, distribution networks and prominent customers. Again, emphasis is placed on the production, form, and sales of the seven reactor-produced radioisotopes that present the greatest security risk.

[100] G.R. Malkoske, Vice President of Engineering and Technology at MDS Nordion, "Medical Isotopes: Maintaining an Essential Source of Global Supply," Speech to the Canadian Nuclear Association's Nuclear Industry Winter Seminar, Ottawa, February 19, 2002.

[101] Roman Kupchinsky, "Dirty Bombs and Cobalt Pencils," *Crime and Corruption Watch,* Volume 2, Number 24, June 20, 2002.

Although this paper attempts to provide an estimate of the market share for each company, the dynamic nature of the industry is such that only a percentage share can be given, where that is known, and this should be regarded as no more than an approximate guide. Within these constraints, the companies are listed roughly in order of radioisotope market share, but this is based on sales of all radioisotopes, and not simply those that are the subject of this paper. It should also be noted that the most prevalent radioisotope manufactured is molybdenum-99 (Mo-99), which is mainly employed as a source for its derivative product technetium-99 (Tc-99). However, these radioisotopes do not pose a serious security concern, and Mo-99 sales are used here to indicate overall radioisotope market share.

MDS Nordion MDS Nordion, the leading radioisotope supplier in the world today, began in 1946 as the radium sales department of Eldorado Mining and Refining Ltd, an Ottawa-based crown corporation that mined uranium ore, from which radium was extracted and refined for use in cancer therapy. In 1952, the government set up the Atomic Energy of Canada Ltd. (AECL), which took over Eldorado's sales operation through its Commercial Products Division (CPD). In 1991, the private healthcare firm MDS Inc. purchased CPD, then known as Nordion International Inc.

Today, MDS Nordion supplies radiopharmaceutical companies in more than 70 countries,[102] producing a major portion of the global supply of reactor-produced bulk radioisotopes and a range of cyclotron-produced radioisotopes. By partnering with pharmaceutical manufacturers such as IDEC Corp., Human Genome Sciences Inc., Corixa Corp., and Proxima Therapeutics Inc., MDS Inc. (MDS Nordion's parent company) builds downstream capabilities with direct involvement in the market from the raw radioisotope to finished products ready for end-users. As a truly global corporation, MDS Inc. has offices in South Africa, China, Hong Kong, Israel, Japan, Singapore, Taiwan, Belgium, Denmark, France, Germany, Hungary, Italy, Norway, Poland, Romania, Spain, Sweden, Switzerland, and the United Kingdom, as well as several Canadian and U.S. locations.

Most reactor radioisotopes are produced at AECL's NRU research reactor at Chalk River. However, as discussed previously, MDS Nordion has built two new MAPLE reactors and a processing facility at the site, specifically for radioisotope production. MDS Nordion also operates out of Fleures, Belgium, after it acquired some processing facilities of the radiopharmaceutical department of the Belgian company IRE and production agreements with the BR-2 reactor, which is owned and operated by the Belgian research center SCK-CEN. While MDS Nordion markets many different reactor-produced radioisotopes, the ones that stand out from the security perspective are Co-60 and Ir-192. Table 9 provides details of the Co-60 and Ir-192 products offered by MDS Nordion.

Once purchased, the raw radioisotopes are processed and repackaged by MDS into the following products: radioactive sterilization sources (mostly Co-60); reagents and kits for clinical diagnosis; and radioisotopes in nuclear medicine. The majority of raw Co-60 processed by MDS Nordion is purchased from Ontario Power Generation (which operates the Pickering "B" CANDU reactors) and Hydro Quebec (from the Gentilly-2 CANDU reactor). In 2001, MDS Inc. reported revenues of $343 million from their radioisotope business, with Co-60 revenues accounting for 18 percent of that total.[103] MDS customers who purchase Co-60 and related equipment include sterilization contractors and large medical product manufacturers, as well as hospitals and other clinics having cancer treatment facilities. MDS also

102 MDS Inc., 2001 Annual Information Form, Isotope Sector, p. 27.

103 MDS Inc., 2001 Annual Report, Life Sciences Segment, p. 19.

Table 9: MDS Nordion Sealed Source Co-60 and Ir-90 Products

Radioisotope Sealed Source	Radioisotope Activity (curies)	Application
Cobalt-60 Capsule containing Co-60 pellets (11mm diameter × 452mm length) Capsule	Up to 14,250 0.001 – 100	Industrial and medical irradiation Level gauges and radiography
Iridium-192 Capsule with Ir-192 discs (0.5 – 4mm diameter)	1 – 200	Medical radiography
Source: MDS Nordion		

Table 10: Co-60 Based Irradiation Facilities Holding Contracts with MDS Nordion

Country	MDS Nordion Contract Irradiation Service Facility
Australia	Steritech Pty Ltd (2 facilities)
Belgium	IBA Mediris, Fleures
Brazil	Companhia Brasileira de Esterilizacao, Sao Paulo Embrarad Empresa Brasieira de Radiacoe Ltda., Sao Paulo Tech Ion Industrial Brasil S.A., Manaus
Canada	Canadian Irradiation Centre, Laval Quebec STERIS Isomedix Services, Whitby Ontario
China	Qingdao Irradiation Center, Qingdao Shandong Shenzen Irradiation Center Ltd., Shenzen
Croatia	Ruder Boskovic Institute, Zagreb
Denmark	CODAN Steritex ApS, Espergaerde NUNC A/S, Roskilde
France	Gammaster Provence S.A., Marseille Ionisos, Dagneux
Germany	Beta-Gamma-Service GmbH, Bruchsal BGS GmbH & Co. KG, Wiehl Gammaster Deutschland GmbH, Allershausen Willy Ruesch International AG, Kernan Rommelshausen
Greece	Elviony S.A., Mandra Attikis
Hungary	Agroster Irradiation Co., Budapest
India	Isomed, Mumbai Trombay
Indonesia	PT Perkasa Sterilindo, Bekasi Jawa Barat
Iran	Gamma Irradiation Centre, Tehran
Ireland	Gammaster Ireland Ltd., County Mayo
Israel	Sor-Van Radiation Ltd., Yavne
Italy	Gammarad Italia SpA, Bologna Gammatom S.r.l., Como

Table 10: Co-60 Based Irradiation Facilities Holding Contracts with MDS Nordion (continued)

Country	MDS Nordion Contract Irradiation Service Facility
Japan	Japan Irradiation Service Co. Ltd. Japan Radioisotope Association KOGA Isotope Ltd. Radia Industry Co. Ltd.
South Korea	Greenpia Technology Inc., Seoul
Malaysia	Ansell Malaysia Sdn. Bhd., Malaka Malaysian Institute for Nuclear Technology, Bangi Kajang SterilGamma (M) Sdn. Bhd., Rawang Selangor Darul Ehsan
Mexico	Instituto Nacional de Investicaciones Nucleares, Mexico City NGS Enterprises
Netherlands	Gammaster B.V. (2 facilities)
New Zealand	Schering-Plough Animal Hospital, Upper Hutt
Pakistan	Pakistan Radiation Services, Lahore
Singapore	Baxter Healthcare Pte. Ltd.
South Africa	Gammaster S.A. (Pty) Ltd., Kempton Park
Switzerland	Studer AG/Werk HARD, Daniken
Taiwan	China Biotech Corporation, Taichung Institute of Nuclear Energy Research, Taoyuan
Thailand	Gammaster Ltd., Chonburi IBA S&I Ltd. (2 facilities)
Turkey	Gamma-Pak A.S., Istanbul Gamma-Pak Sterilizasyon Sanayi ve Ticaret A.S., Cerkezkoy Tekirdag
United Kingdom	Isotron plc. (4 facilities)
United States	Abbott Laboratories, Rocky Mount, North Carolina Food Technology Service Inc., Mulberry, Florida, IBA (15 facilities) Maxxim Medical, Columbus, Mississippi Steris Isomedix Services (11 facilities)
Source: MDS Nordion	

makes the irradiators themselves, which are delivered already loaded with the gamma radiation sources included. As the radioactivity of the source within the irradiator declines, the radioisotopes have to be re-supplied separately. According to MDS Nordion, the company has installed more than 110 irradiators around the world. Table 10 provides a list of Co-60 based irradiation facilities with which MDS held contracts in 2001 and highlights the widespread distribution of these facilities.

Nuclear Technology Products (NTP) Created in the 1990s, Nuclear Technology Products (NTP), the business division of NECSA, the South African Nuclear Energy Corporation, produces a number of radioisotopes for both medical and industrial use. Target irradiation for the production of radioisotopes at NTP occurs at NECSA's 20 MW pool type Safari-1 reactor, which was commissioned in 1965. Further processing is done in 25 hot cells. Radiopharmaceutical processing facilities also exist within the Pelindaba site. The main radioisotopes produced

Table 11: NTP Sealed Source Cs-137, Co-60, and Ir-192 Products

Radioisotope Sealed Source	Radioisotope Activity (Ci)	Application
Cesium-137	Up to 1	Various Industrial
Cobalt-60	Up to 1	Various Industrial
Iridium-192 Capsule with Ir-192 discs (1– 3mm diameter)	30 – 120	Medical Radiography
Source: NTP		

by NTP that pose a potential security concern are Ir-192, Cs-137, Co-60, and Am-241. Table 11 summarizes the Cs-137, Ir-192, and Co-60 sources produced by NTP. Its products are exported to more than 30 countries in Europe, the Americas, and the Middle and Far East. NECSA has formed a joint venture with Amersham International to supply industrial radioisotopes (mainly Co-60) as well as radiopharmaceuticals produced by NTP and independently by Amersham to the southern African market. Following MDS Nordion and the Belgian company IRE, NTP is the next largest distributor of the workhorse radioisotope Mo-99, claiming its sales are approaching 15 percent of the world market.[104]

REVISS Services and Amersham International

REVISS Services is a joint venture founded in 1992 between the UK-based pharmaceutical and imaging company Amersham International, Russia's PO Mayak, and Techsnabexport (exporter of Russian products and services for the international nuclear energy industry). Based in the United Kingdom, REVISS has sales offices in the United States and China. The company has two divisions—Puridec Irradiation Technologies and REVISS Isotopes. Puridec Irradiation Technologies builds irradiation plants, processes radioisotopes, and offers related services, such as product maintenance and transportation and containers for the sources. REVISS Isotopes sells bulk radioisotopes and facilitates their transportation. Current irradiation facilities holding contracts with REVISS include Ionisos in France, IBA Mediris in Belgium, Isotron's Swindon facility, and CODAN Steritex ApS in Denmark.

As with MDS Nordion, direct access to raw radioisotopes through PO Mayak and Amersham's experience as a radiopharmaceutical manufacturer effectively allow for REVISS's parent companies to have integrated control of the radioisotope from its raw manufacture to the finished product. Amersham has been manufacturing pharmaceutical grade radioisotopes for more than 30 years and owns research, development, and manufacturing facilities in Europe, North America, China, and Japan (through Nihon Medi Physics, a joint venture with Sumitomo). In addition, Amersham has an extensive sales and distribution network in Europe, the Middle and Far East, Australasia, the Pacific Rim, and the Americas.[105]

Of the radioisotopes of greatest security concern, REVISS supplies Co-60 (mainly for industrial irradiators and exported to 30 countries), Cs-137, Sr-90, Am-241 (sold in capsules of 2.7 Ci/g), and Ir-192. They are produced in a variety of Russian manufacturing plants including Mayak (the Ludmila and Ruslan reactors), the Russian Institute of Atomic

[104] NTP Profile, available on their website, <http://www.radioisotopes.co.za>.

[105] It also possesses a total of seven cyclotrons (accelerators) for radioisotope processing in the United Kingdom and North America.

Reactors (Dimitrovgrad), and Cyclotron Co Ltd, Obninsk. Reportedly, Russian exports accounted for 25 percent of the world's Co-60 market in 2000, and the Russian Ministry for Atomic Energy (MINATOM) is trying to increase market share to 40 percent.[106] This supply comes largely from the Leningrad Nuclear Power Plant. Russia's high capacity for radioisotope production at its various reactors, including transuranic products from weapons facilities, suggests that REVISS Services could become an even greater supplier of radioisotopes of high security concern. According to REVISS, some of the Co-60 the company offers for sale also comes from Argentina, where CNEA produces the material in the power reactor Embalse 1.

National Institute for Radio Elements (IRE) IRE, a public utility company under the Belgian Ministry of Energy, operates as a commercial organization with its Board selected by ministerial appointment. IRE's plant in Fleures uses four European research reactors to obtain its raw radioisotopes. These reactors are Osiris and HFR in France, HFR in the Netherlands, and BR-2 in Belgium.[107] With the capability of supplying as much as 30 percent of worldwide Mo-99 demand,[108] IRE is MDS Nordion's largest competitor in the nuclear medicine business and is the strongest radioisotope supplier in the European therapeutic and diagnostic market.

Mallinckrodt Inc. Mallinckrodt Inc., a division of Tyco Healthcare, is a medical imaging and radiopharmaceuticals company based in St. Louis, Missouri. The company acquires its radioisotopes from the HFR reactor in Petten, the Netherlands, where Mallinckrodt also has processing facilities, including two cyclotron accelerators. Mallinckrodt uses the HFIR reactor at ORNL and the MURR reactor at Missouri University for research and development purposes. Although most of the radioisotopes that this company processes are not ones that this paper investigates, HFR Petten does produce Ir-192, so the company has the capacity to deal in radioisotopes that pose a security concern. Mallinckrodt's products are distributed through 41 radiopharmacies in the United States, as well as one in London. Additionally, Tyco Healthcare has sales units in Singapore and Japan, as well as several offices in South America and Europe.

Studsvik AB Although Swedish conglomerate Studsvik owns one of the few privately operated reactors for radioisotope production (the R-2 reactor), the company is not as large a producer as any of those previously mentioned. Its radioisotope sales amounted to about $1 million in 2001.[109] Issues relating to the transportation of radioisotopes appear to be at least one reason for Studsvik's low market share. The company was temporarily banned from transporting radioisotopes in 2002 after a package containing Ir-192 that was dispatched from Studsvik on December 27, 2001 showed increased levels of radiation when received by a customer in the United States. As a result of the incident, the Swedish authorities indicted Studsvik for breaches of transport regulations.[110]

Eckert & Ziegler and Isotope Products Laboratories Eckert & Ziegler AG of Berlin acquired California-based Isotope Products Laboratories (IPL) in 1999. Among the more than 80 radioisotopes supplied by IPL, noteworthy ones from the security perspective are Am-241, Cs-137, Co-60,

[106] Rashid Alimov, "Mayak Plant to Increase Cobalt-60 Export," Bellona Foundation Report, April 30, 2001.

[107] Mario P. Iturralde, "Molybdenum-99 Production in South Africa," *European Journal of Nuclear Medicine*, Vol. 23, Issue 12, 1996, pp. 1681-1684.

[108] Jim Green, "Reactors, Radioisotopes, and the HIFAR Controversy," Ph.D. Thesis, July 1997, University of Wollongong, NSW, Australia, Appendix 5, p. 2.

[109] Studsvik AB, 2001 Annual Report, p. 27.

[110] Studsvik AB, Interim Report, January-March, 2002.

Table 12: IPL Worldwide Distributors

Markets	Distributor
Europe, India, Israel, South Africa	Isotope Products Europe Blaseg GmbH
Australia, New Zealand	EPS Australia
Japan	Daiichi Pure Chemical Co. Ltd.
Korea	BOO KYUNG SA Co. Ltd.
Hong Kong	Patrick Trading Corporation
Central and South America	ECUACONSULT
Brazil—Nuclear Medicine	REM Industria e Comercio Ltda
Middle East, Indonesia, Malaysia, Pakistan, Thailand, Singapore, Sudan, Morocco, Tunisia, Vietnam	AMALE International Inc.

and Sr-90, but activities of these radioisotopes tend to be less than 1 curie. Thus, they would generally not present a high security concern. Table 12 shows a list of IPL's worldwide distributors. Eckert & Ziegler's holdings also include radiation source manufacturers Bebig and Eurotope; however, reactor-produced radioisotopes are acquired through IPL.

Prominent Downstream Processors and Distributors

Radioisotope applications can be found in medical devices, healthcare products and pharmaceuticals, cosmetics, food, industrial gauging, non-destructive technology, detector technology, and emergency lighting and signage. Although there are too many businesses incorporating radioisotopes into their products today to list here, given below are details of some prominent companies dealing with reactor radioisotope products.

AEA Technology AEA Technology, the privatized commercial arm of what used to be the UK Atomic Energy Authority, now operates in 31 countries in Europe, North America, the Middle East, and Asia Pacific and offers a range of products and services including the supply of radioactive sources (through AEA Technology QSA, Inc.) and equipment (through Isotrak and Sentinel). Isotrak produces instrument calibration systems and Sentinel, based at the AEAT/QSA facility in Burlington, Massachusetts, makes gamma radiography projector systems and associated accessories. AEAT/QSA, formed by acquisition of Nycomed Amersham's Quality and Safety Assurance business and based at Harwell in Oxfordshire, England, supplies products for process control, smoke detection, oil-well logging, and radiographic inspection, in addition to a wide range of reference sources for industrial, medical, environmental and research applications. Services include training in the safe use of these products, the maintenance of the products, application consultancy, as well as the recycling, conditioning, and disposal of waste residues from medical and industrial clients. This company's products contain the radioisotopes Am-241, Cs-137, Cf-252, Co-60, and Sr-90, among others of lesser security concern.

IBA (Ion Beam Applications) IBA began as a spin-off from the Cyclotron Research Center of the Catholic University of Louvain-la-Neuve. It now operates at 49 different sites in 12 countries in Asia, Europe, and America with the industrial sector accounting for two-thirds of sales and the medical sector one-third.[111] IBA also sells a range of isotopes used in Positron Emission Tomography (PET) imaging.

IBA's Sterilization and Ionization Business Unit (comprising the sterilization and laboratory service operations of SteriGenics International and Griffith Micro Science) is headquartered in Chicago, Illinois and in Herentals, Belgium. There is a network of irradiation service centers comprising 27 facilities located mainly in the United States, Canada, and Mexico (America Operations), while for the rest of the world there are eight centers based in Europe (France, Germany, Belgium, the Netherlands, and the United Kingdom) and two centers in Thailand. IBA's radiotherapy business is headquartered in Uppsala, Sweden.

In April 2000, IBA and MDS Nordion joined forces by opening an irradiation facility in Tepeji, Mexico, near Mexico City. This venture brought together MDS Nordion, the world's leading manufacturer of Co-60, with IBA, a leader in the areas of sterilization and ionization technologies.[112] In addition to using Co-60 for irradiation services, IBA also employs non-radioactive alternatives, such as ethylene oxide, electrons, and x-rays.

Other Companies International Isotopes Clearing House, Inc. (in Leawood, Kansas) distributes radioisotopes worldwide obtained from institutes and nuclear facilities in Russia and elsewhere. These include many reactor-produced isotopes of very high radiotoxicity such as americium, plutonium, uranium, and curium. Also worth mentioning is Varian Medical Systems, Inc. of California, generally recognized as the leading manufacturer of integrated cancer therapy systems, with manufacturing sites in North America and Europe, and with 34 sales and support offices around the world.

Nuclear pharmacies throughout the world offer radiopharmaceuticals to clinics and hospitals, where physicians administer the products to patients. These pharmacies carry several types of radioisotopes including Am-241, Cs-137, and Cf-252, but as local distributors, they generally stock products in small quantities. Syncor International Corp., a radiopharmaceutical firm, operates through 127 nuclear pharmacies in the United States and 19 locations worldwide. Another radiopharmaceutical supplier, Nihon Medi-Physics, a joint venture between Amersham and Sumitomo Chemical, serves the Japanese market, as well as medical facilities in Asia and Oceania.[113] Other radiopharmacies include Geodax Technology (operating within the United States), as well as prominent vertically integrated suppliers such as Amersham and Mallinckrodt.

Gamma irradiator and sterilization equipment manufacturers, and irradiation facilities—predominantly using Co-60 as their radiation source—include Food Technology Services (based in Florida), Steris Corp. (with facilities in the Americas, Asia, and Europe), and Steritech (based in Australia). The United States-based Gray Star Inc. has designed food irradiators using Cs-137 as their radiation source, however none of their products has been sold to date as the company undergoes patenting and regulatory processes. Each Gray Star irradiation unit will contain 2.8 million curies of cesium chloride in powder form, doubly encapsulated within a stainless steel container.

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[111] The invention of the Cyclone 30, the first cyclotron designed for industrial-scale production of medical radioisotopes, which now holds a large percentage of the world market share, gave IBA a financial boost.

[112] IBA, "IBA and MDS Nordion open new irradiation facility in Mexico: Innovative design treats both medical and food products," Press Release, April 2000.

[113] Nihon Medi-Physics also operates cyclotrons for medical radioisotope production.

Disposal of Disused Sources

After use, radioisotopes require safe disposal. Users can usually choose one of two authorized disposal options. They can either return the disused source to the source producer or supplier, or return it to special disposal sites that can be government or privately owned. Keeping disused sources on users' premises increases the risk of sources becoming orphaned.[114]

This section first turns to surveying disposal services within the United States and the EU nations because relatively more is known about these nations' disposal systems than other countries'. A brief discussion of Russia's system of disposal follows. Then this section discusses disposal services offered by major radioactive source producers.

United States Within the United States, three regional facilities provide disposal services for low-level waste. Such waste comprises four different categories: Class A, Class B, Class C, and Greater Than Class C (GTCC). U.S. Nuclear Regulatory Commission regulations stipulate the required physical form and characteristics of each class.[115] Due to space limitations here, tables listing the radioactivity concentration levels of various materials for each class are not reproduced but are readily accessible on the NRC website. The important point here is that the radioactivity levels increase as the classification goes up from Class A to GTCC. Thus, in general, the security risk increases from Class A to GTCC. Although Classes A through C are generally acceptable for near surface disposal, Greater Than Class C "must be disposed of in a geologic repository … unless proposals for disposal of such waste in a disposal site licensed pursuant to this part [10 CFR 61.55] are approved by the [Nuclear Regulatory] Commission."[116]

Although many of the radioactive sources addressed in this paper would be eligible, once no longer used, for near surface disposal as Class A, B, or C waste, the more highly radioactive sources with relatively long half-lives would have to be disposed of as GTCC waste. In general, radioisotopes with half-lives less than five years would not exceed the Class C standard because of their relatively rapid decay. In particular, Cf-252, Co-60, and Ir-192, the three radioisotopes having the shortest half-lives of the seven reactor-produced radioisotopes of greatest security concern, would typically not surpass Class C requirements. In contrast, depending on the radioactivity amounts, Am-241, Cs-137, Pu-238, and Sr-90 could exceed the Class C classification.

As discussed below in the regulatory controls section, most U.S. states have taken responsibility for managing their sources through the Agreement States system. These states have formed compacts, which operate low-level waste disposal facilities. The three facilities are Barnwell, located in Barnwell, South Carolina; Hanford, located in Hanford, Washington; and Envirocare, located in Clive, Utah. Though Barnwell accepts waste from all states except those in the Rocky Mountain and Northwest compacts, starting in 2008, it will only receive waste from the Atlantic Compact states of Connecticut, New Jersey, and South Carolina. Hanford can receive waste from the Northwest and Rocky Mountain Compacts. Envirocare can accept waste from all regions. Both Barnwell and Hanford can dispose of Class A through C waste, but Envirocare is currently only licensed to dispose of Class A waste.[117] Thus, in

[114] Angus et al., "Management and Disposal of Disused Sealed Radioactive Sources in the European Union," EUR 1886, 2000, p. 3.

[115] See 10 CFR 61.55 "Waste classification" and 10 CFR 61.56 "Waste characteristics."

[116] 10 CFR 61.55.

[117] U.S. Nuclear Regulatory Commission, "Low-Level Waste Disposal Regulations, Guidance, and Communications," <http://www.nrc.gov/waste/llw-disposal/regs.html>, accessed July 18, 2002.

2008, when the restrictions on Barnwell take effect, several states will not have a licensed facility available to store waste greater than Class A. Equally important, the United States faces a problem in not having a dedicated storage facility for Greater Than Class C waste. Without such available storage, users in the United States having GTCC disused sources would have to wait for the radioactivity level to decay to at least the Class C level before they can dispose of their disused sources in the three approved facilities, a period that can last for several years.[118]

In February 2001, the NRC implemented stiffer penalties for unauthorized disposal of sources.[119] In particular, the penalties are now at least three times the cost of proper disposal. The intent is to provide an incentive for authorized disposal.

To begin to address the problem of disused or unwanted sealed sources that exceed NRC limits for low-level radioactive waste, DOE manages the Off-Site Source Recovery (OSR) Project[120] to provide safe and secure storage at its facilities. About 18,000 sources currently come under this Project's purview. The OSR Project focuses on commercially owned sources but also recovers some DOE and DOD sealed sources that are no longer used. Concerning the radioisotopes considered in this paper to be the greatest security risk, the OSR Project has mainly secured sealed radioactive sources containing Pu-238 and Am-241.[121] On an emergency basis, however, it also can collect sources containing Cs-137 and other radioisotopes that pose high security concerns, depending on the activity of the source and the availability of a disposal site. The OSR Project will not accept naturally occurring radioactive material, such as radium-226.

As a key OSR Project member, Los Alamos National Laboratory's (LANL) Off-Site Recovery Project Team recovered almost 3,000 sealed sources in 2001 and secured them in 130 storage containers at the Lab's Technical Area 54. LANL will continue to store these sources until a final disposal site is developed.[122] So far, OSR Project management has not decided when such a site will be built. However, according to a LANL report on the OSR Project, "For planning purposes, it is assumed that some form of [final] disposal option might become available in 2006."[123] Because DOE's Environmental Management (EM) division presently does not consider this disposal site construction as a priority task, it is unlikely to be completed in this timeframe.[124]

In response to the increased radiological security concern after September 11, 2001, Congress reversed the downward trend of the Project's budget and sub-

[118] According to a DOE official, DOE has estimated that of the two million sources in the United States, 20,000 to 250,000 might be considered GTCC waste, once disused. The NRC estimate is around 27,000 sources; interview on October 18, 2002.

[119] NRC, "General Statement of Policy and Procedure for NRC Enforcement Actions," NUREG-1600, February 16, 2001.

[120] Public Law 99-240, The Low-Level Radioactive Waste Policy Amendment Act of 1985, directed DOE to be the responsible federal agency for disposal of commercial low-level radioactive waste that exceeds NRC limits for low-level radioactive waste, i.e., Greater Than Class C waste. For example, radioactive material containing Cs-137 with concentration greater than 4,600 curies per cubic meter would not be acceptable for near-surface disposal.

[121] These are transuranic (elements heavier than uranium) isotopes. See U.S. DOE, "Source Acceptance Criteria," Offsite Source Recovery Project, January 19, 2001, <http://www.doeal.gov/wmd/osrp/OSRAcceptance.htm>. Some of these transuranic sources, especially those originating from or related to DOD and DOE's nuclear weapons programs, may eventually be disposed at the Waste Isolation Pilot Plant in southeastern New Mexico. It began operations on March 26, 1999.

[122] John Bass, "Los Alamos Led Project Continues to Recover Radioactive Sources," Los Alamos National Laboratory News and Public Affairs, December 20, 2001.

[123] Lee Leonard et al., "The Off-Site Source Recovery Project at Los Alamos," Los Alamos National Laboratory, 2000. This report also states, "If this assumption proves realistic, the period between 2006 and 2010 would become a transition period during which LANL would phase out of source recovery and storage operations, leaving all continued operations to be carried on directly between source owners and the disposal facility." p. 8.

[124] Interview with DOE official, October 18, 2002.

stantially increased it by a supplement of $10 million. The reorganized program[125] began in 1999 with a budget of $7 million, which was cut in fiscal year (FY) '02 to $2.5 million and was projected to experience another cut in FY '03 to $1.8 million.

Building upon the successful collection of about 3,300 sources, the OSR Project intends to use the supplemental funds to establish a comprehensive database within 18 months to help secure more than 5,000 additional sources that it has identified. It predicts that another 10,000 sources during this decade will be found eligible for collection.[126] "Based on post-9/11 analysis, the NRC has determined that all excess sources currently on the database pose a potential security risk."[127] A DOE official expressed concern that despite receiving the supplemental funds this year, the future of the project remains uncertain because EM division leadership intends to cut funding for subsequent years.

European Union Recently, a detailed examination of management of disused sources revealed that even within the European Union, a developed region, different disposal methods are employed by different member states.[128] Most EU nations (12 of 15) operate regional or central interim storage facilities that can receive most disused sources. But the three other nations do not have such stores, and thus users are forced to store disused sources onsite. Some nations are running out of storage capacity at interim facilities. Exacerbating this problem is a lack of final disposal sites in many countries. Most EU nations urge users to return disused sources to producers for proper disposal. In this respect, France maintains the strictest regulations in that users are required to return disused sources to the supplier. French regulations mandate removal of the source not more than 10 years after purchase. Further, the supplier must factor in the disposal fee with the purchase price.

Russia In Russia, disposal of disused radioactive sources is managed by Radon, the organization responsible for the localization and storage of radioactive waste. When Radon was established in 1961, it comprised 34 enterprises based regionally throughout the Soviet Union. There are now 16 enterprises in the Russian Federation, including the main center at Sergiev Posad outside Moscow. This center, together with a linked unit based in Moscow, is responsible for the city of Moscow and the 10 neighboring oblasts (districts), which includes 14 million people. Radon services a broad range of facilities, but not radiological combines, electrochemical plants, nor nuclear power plants, which are the direct responsibility of MINATOM. Although Radon is independent from MINATOM, it cooperates with the Ministry and its affiliated enterprises and institutes.

As a result of recent regulatory changes, Radon facilities are now subordinated to the Russian regional governments. For example, because it serves such a wide area, Sergiev Posad receives funding from both the Moscow city government and some federal programs, as well as earning income through its commercial activities. Its main federal function is to service some 2,000 enterprises generating radioactive waste, including disused radioactive sources. These sources are stored in underground repositories buried at a depth of six meters and are immobilized in a metal matrix, which includes lead and aluminum melts.

Russia can safely and securely manage disused sources through its many Radon facilities. However, the major problem still to be solved is identifying and collecting these sources throughout the country. Proper control was generally not exercised during the

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[125] The intent of the program reorganization was to enable the project to move aggressively to recover some 18,000 unwanted sources.

[126] Interview with DOE official, August 23, 2002.

[127] Off-Site Source Recovery Project, "Off-Site Source Recovery," Los Alamos National Laboratory, LALP 02-26, February 2002.

[128] Angus et al., (2000).

decades of Soviet rule. Moreover, the locations of many unauthorized dumps of radioactive sources remain unknown.

One radioactive source burial site location that is well known and has presented a high-security concern is the Radon Special Combine in Grozny, Chechnya. This burial site contains an estimated 1,250 curies, and three high-risk radioisotopes (cobalt-60, cesium-137, and iridium-192) account for an unknown number of these curies. Moreover, radioactive wastes are reportedly located at another 26 facilities in Chechnya. In 1995, a Russian federal government-sponsored commission launched an investigation of the security of radioactive waste at the Grozny combine and other facilities. However, because of combat operations in the area, the commission could not make a definitive determination of the security of the radioactive materials. In January 1998, Chechen officials requested help from the United Nations and the Organization for Security and Cooperation in Europe to address the issue of radioactive sources found in Chechnya. Two more years passed until the Russian federal government reported that it controlled the Radon combine. Aleksandr Koldobsky, a scientist at the Moscow Institute of Physics and Engineering (MIFI) and an expert in the field of radiological terrorism, states that there are "a considerable number of isotope sources in Chechnya unaccounted for or lost, and there is a great likelihood that they have fallen or will fall into the hands of terrorists."[129]

Industry Disposal Services Apart from nationally run disposal programs, users can often return disused sources to the original producers in exchange for purchasing replacement sources. However, the disposal fees can be substantial (hundreds to thousands of dollars for relatively highly radioactive sources)[130] and prohibitive for many smaller users. In practice, these users sometimes wait until they have accumulated a large number of sources before shipping to a disposal facility. By doing this, they can save money but may also potentially increase their security risks by keeping many unwanted sources on site. Another problem arises when users transfer sources to other users, which could result in loss of contact with the original supplier. Moreover, in these situations in which users buy from other users, the new users usually pay less than what the original user paid for the fresh source and consequently may not have adequate funds to return the disused source to the supplier for disposal. It has not been possible to determine the extent to which end-users make use of producers' or distributors' disposal services.

All major radioactive source producers and distributors surveyed in this paper offer some type of disposal service. For instance, MDS Nordion, the largest producer, operates a source disposal service. IRE runs a temporary storage site for ONDRAF (the National Body for Radioactive Waste and Fissile Materials), the Belgian government's agency responsible for radioactive waste disposal. The South African radioactive source manufacturer Nuclear Technology Products will take back any sealed radioactive source that has neared the end of its guaranteed life. The NTP facility at Pelindaba will accept these sources for checking, testing, re-encapsulation, and certification. In addition, at Pelindaba, NTP will safely dispose of spent sources supplied by the company, provided the customer pays for the transport and disposal costs. AEA Technology offers disposal and recycling services. In December 2001, Studsvik signed a disposal agreement with the Envirocare

[129] Yevgeniy Vladimirovich Antonov, "Threat of Terrorist Act Using Weapons of Mass Destruction from Chechnya," *Yaderny Kontrol,* March-April 2001, in Russian; English version: FBIS CEP20010610000001.

[130] For example, New Zealand's National Radiation Laboratory, as of June 1999, charges $500 for Co-60, Cs-137, Am-241, and other gamma sources and $300 for Sr-90 and other beta sources.

facility in Utah.[131] For its low and very low-level waste, Amersham makes use of disposal sites run by national governments. For intermediate-level waste generated only on Amersham sites, the company has built special facilities for safe and secure storage. Finally, Mallinckrodt highlights recycling and disposing of its products as integral to its "Product Stewardship" code. This company has also established a database to "better evaluate the risk characteristics of product lines."[132]

REGULATORY AND INDUSTRY EFFORTS TO SECURE RADIOACTIVE SOURCES

While regulatory authorities throughout much of the world maintain adequate control over the majority of radioactive sources,[133] more than half of the world's nations (more than 100) have inadequate regulatory systems.[134] Paucity of funds, one of the chief problems, means regulatory agencies do not have the resources to do their jobs. Other key problems include either too much interference by other government agencies or too little attention to attracting top-notch personnel to regulatory agencies. Regulators cannot achieve effective oversight if they cannot preserve their independence from corruption stemming either from government or industry. Devoting resources to recruiting, retention, and training is essential to maintain a thriving regulatory agency. A government may also fall into the trap of thinking that just because it enacts a law, radiation safety and security are assured. One high-level IAEA official has called this view "extremely dangerous."[135]

Examining how to further strengthen radioactive source security will be the top priority at the March 2003 International Conference on Security of Radioactive Sources, sponsored by the IAEA, the United States, and the Russian Federation. According to the conference announcement, "Many radioactive sources are not generally subject to tight security measures; such measures have traditionally been limited to preventing accidental access or petty theft such as the theft of shielding materials. Traditional security measures aim to prevent unauthorized access to radioactive sources; such access is facilitated when sources are misplaced, forgotten, lost or insecurely stored. Consideration must now be given to what additional security measures are required against the potential malevolent use of radioactive sources. Security measures should now also be focused on preventing the loss of control over radioactive sources."[136]

To develop a better understanding of what radioactive source regulatory and security improvements are needed, this section establishes a baseline of current practices to protect sources under regulatory controls and to detect and secure orphan sources, which, by definition, are outside of regulatory controls. Due to space and information limitations, this section discusses only four major entities, the United States, Argentina, the European Union, and the International Atomic Energy Agency, where enough is known to portray the general structure of radioactive source security and regulatory systems. This section addresses

[131] Studsvik, "Studsvik signs disposal agreement with Envirocare," Press Release, December 10, 2001.

[132] Mallinckrodt, "Code 6 Product Stewardship," <http://www.mallinckrodt.com/corpprofile/rescare/cp-rescare-6.html>; accessed October 11, 2002.

[133] In general, more sources are used in the developed world, where regulatory systems are typically more effective than many in the developing world.

[134] A.J. Gonzalez, "Strengthening the Safety of Radiation Sources & the Security of Radioactive Materials: Timely Action," *IAEA Bulletin*, 41/3/1999.

[135] A.J. Gonzalez, Department of Nuclear Safety, International Atomic Energy Agency, "Opening Address," *Proceedings of the National Regulatory Authorities with Competence in the Safety of Radiation Sources and the Security of Radioactive Materials,* International Conference, Buenos Aires, Argentina, December 11-15 2000, p. 8.

[136] International Atomic Energy Agency, "International Conference on Security of Radioactive Sources," March 10-13, 2003, Conference Announcement, IAEA-CN-113, December 2002.

each in the order presented above. Argentina and the United States are especially important examples because of their prominence as part of the select group of nations that either produce or use the majority of radioactive sources. The EU is chosen as part of this section because recent reports have illuminated current practices regarding radioactive sources, and because three nations, Belgium, the Netherlands, and France, which contribute to a significant portion of commercial radioisotope production, are EU member states. Finally, the IAEA plays a major role in working with its member states to improve safety and security of radioactive sources. Current source disposal practices are discussed in a previous section and, therefore, are not repeated here.

Radioactive Source Regulatory and Security Efforts in the United States

Overview of the U.S. Nuclear Regulatory Commission and Agreement States System Setting the context of current radioactive source security practices within the United States requires understanding the basics of the regulatory system. The Nuclear Regulatory Commission, in addition to overseeing the safety and security of nuclear reactors, licenses ownership of radioactive sources. However, this authority is limited. In particular, the NRC regulates the civilian sources that use radioisotopes produced in nuclear reactors, but it does not regulate sources that employ materials produced by other methods, such as accelerator production, or that contain certain naturally occurring radioactive materials, such as radium.[137] The individual states are responsible for regulating radioactive sources produced with accelerators and naturally occurring radioactive materials. In addition, the states regulate radiation-producing machines,[138] such as x-ray machines for both medical and industrial applications. Further, most states (32 of 50) adhere to the Agreement States system, which allows states to regulate reactor-produced sources. About three-fourths of these sources are covered under this system. In those states not under this system and in areas of exclusive federal jurisdiction, the NRC maintains complete regulatory authority. Even within the Agreement States, NRC plays an oversight role through the Integrated Materials Performance Evaluation Process (IMPEP). IMPEP ensures a common set of regulatory performance criteria are used by all states in the system. Moreover, NRC staff provides technical assistance to these states through regional offices.[139]

Two types of licenses govern the more than 2 million radioactive sources in the United States. General licenses apply to the 1.8 million less hazardous sources. These tend to be small, low radioactivity sources. About 135,000 companies are general licensees. Most of these licensees would not possess sources of potentially high security concern. Specific licenses are issued to provide stricter control over the 260,000 more hazardous sources. About 20,000 persons or companies possess specific licenses.

By conducting inspections, the NRC periodically checks on the accountability and security of sources. Specific licenses require more frequent inspections than general licenses. The inspection periodicity depends on the type of source. In particular, inspections of self-shielded irradiators, which are cabinet-sized units employing heavy shielding, occur every three to five years, while inspections of panoramic irradiators, which are specially-designed facilities with large irradiation rooms, take place every one to two years.

In his December 2000 address to the IAEA Conference on Safety and Security of Radioactive Sources, NRC Chairman Richard Meserve spelled out aspects of an effective regulatory system for

[137] Richard A. Meserve, Chairman, U.S. NRC, “Effective Regulatory Control of Radioactive Sources,” Presentation at IAEA Conference, Buenos Aires, Argentina, December 11, 2000.

[138] Such machines do not present a radiological terrorism concern.

[139] U.S. NRC, “Who Regulates Radioactive Materials and Radioactive Exposure?” September 18, 2002, <http://www.nrc.gov/what-we-do/radiation/reg-matls.html>.

sources. Primarily, he called for greater accountability. To help ensure accountability, the NRC has an enforcement program that can impose penalties, such as fines, on severe and repeated violations. It has also implemented a registration program for those generally licensed sources that could pose a significant safety hazard.[140] This program enables better tracking of these sources. He emphasized the need for greater attention to educating users about their responsibilities, especially concerning proper disposal of disused or unwanted sources. Further, he mentioned that adequate emergency response measures are required to address situations where loss of control (through theft or abandonment, for example) of sources has occurred.[141]

Radioactive Source Security Practices in the United States The Code of Federal Regulations (CFR) stipulates general security requirements for protection of radioactive sources. In particular, 10 CFR 20.1801 "Security of stored material" states in full, "The licensee shall secure from authorized removal or access licensed materials that are stored in controlled or unrestricted areas." The companion regulation 10 CFR 20.1802 "Control of material not in storage," states in full, "The licensee shall control and maintain constant surveillance of licensed material that is in a controlled or unrestricted area and that is not in storage." Determining how to implement these general requirements is the responsibility of the licensee. In practice, licensees keep sources in locked rooms when not in use and under continuous monitoring when in use. Typically, licensees employ interlock systems, such as locks-within-locks and keyed control pads, to guard against unauthorized removal although the regulations do not specifically require such practice. In many situations, such as food irradiation facilities, shielding around highly radioactive sources inhibits easy removal of sources from authorized control.

Up-to-date recordkeeping supports source security by helping ensure licensees know where the radioactive material is located. Recorded information includes the type and activity of the radioisotope, manufacturer and distributor's names and addresses, as well as model and serial numbers and location of the source. In the event of loss or theft, the serial numbers can be used to track down the source. When licensees transfer or dispose of their sources, they must keep records for three years after transfer or disposal. NRC regulations require licensees to verify that sources are not lost every time sources are accessed or moved, or at a minimum of every three years.

Prior to September 11, 2001, the NRC did not conduct or fund studies analyzing the risks of terrorist attack on irradiation facilities, which, as explained previously, are places that contain large amounts of highly radioactive materials. However, it did examine the impact on public health and safety in the event of an accident at such facilities. In the future, the NRC intends to conduct studies concerning a terrorist attack on an irradiator facility.

After September 11, 2001, the NRC acted quickly with efforts focused on improving security of radioactive sources. In October 2001, it issued a limited distribution "safeguards advisory" to organizations licensed to possess radioactive sources, broadly calling on these organizations to increase security efforts. The NRC issued a second more detailed limited distribution advisory in November 2001, specifying security measures to be used at sites holding radioactive sources and in their transportation. Although the advisories are not binding on licensees, NRC acted to monitor voluntary compliance, conducting telephone interviews with licensees holding large quantities of radioactive materials and then using its routine inspections of licensees to confirm adherence to the voluntary measures.

[140] Sources containing more than 1 mCi of Am-241, 10 mCi of Cs-137, 1 mCi of Co-60, or 0.1 mCi of Sr-90 must be registered annually.

[141] Meserve (2000).

While details of the security measures contained in the NRC advisory are not publicly available, general aspects are known. These measures differentiate among radioactive sources, requiring more stringent security measures for sources employing radioisotopes with relatively long half-lives, such as those identified in this paper as presenting a potential high security concern, although the NRC has not officially adopted this characterization. The security measures also differentiate according to the quantity of material at issue in particular settings. Irradiation facilities and large shipments of sources from producers to equipment manufacturers and end-users are among the settings where the NRC advisory calls for the highest levels of security. In most other settings (e.g., hospitals, equipment manufacturing plants, universities, and oil well-logging sites), the advisory calls for measures essentially consistent with industrial security practices for protecting high-value or potentially dangerous materials. Presumably, these practices entail, among other measures, a combination of restricted access, guards (campus police, for example, at university settings), procedures for locking away sources not in use, and procedures for identifying personnel authorized to handle the sources. Guards would probably not be authorized to use deadly force to protect the materials but would have to rely on local police to respond. The NRC has also directed licensees to report suspicious activity to the FBI and the NRC.[142] As a result of an NRC advisory issued after September 11, 2001, licensees that ship large quantities of radioactive material, such as Co-60, have taken additional security precautions, including heightened surveillance and other measures to limit the potential for sabotage or theft. Interviewed industry officials have expressed concern that security costs keep ratcheting up and would likely not go back down. Nevertheless, they emphasized that the radioactive source industry is adhering to all security requirements issued by regulatory agencies, while it is weighing how much additional security, if any, is required to meet the perceived risk.[143]

The NRC advisories were adopted by the Agreement States and sent to their respective licensees. Agreement State regulators have since followed the NRC practice of using their routine inspections to observe compliance with the new security guidelines. Moreover, the NRC is in the process of developing mandatory regulations for securing radioactive sources. As part of this process, it is conducting a joint technical study with the Department of Energy to gather information needed for establishing a permanent regulatory structure for this area. In addition, "The NRC is evaluating approaches for 'cradle-to-grave' control of radioactive sources which might be used in a radiological dispersal device."[144] However, it is unknown whether the NRC is taking, or considering taking, additional steps to ensure that users of highly radioactive sources are legitimate. Such measures could include NRC visits to users' facilities before a license is issued and more frequent inspections of these facilities once a license is granted.

Further, the NRC continues to coordinate with the Department of Transportation in determining transportation safety and security requirements. Although the NRC does not presently require individuals who transport or otherwise have access to radioactive sources to undergo criminal or security background checks, some security experts outside the NRC have suggested conducting such checks. The status of U.S. activities to regulate security over radioactive sources of high concern is summarized in Table 13.[145]

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[142] Richard A. Meserve, "Material is Tracked Closely," *USA Today*, June 24, 2002.

[143] Interviews with industry officials during August through October 2002.

[144] U.S. NRC, "Nuclear Security Enhancements Since Sept. 11, 2001," <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/security-enhancements.html>, accessed on September 20, 2002.

Table 13: U.S. Security Arrangements for Radioactive Sources of High Concern

Activity	Security Arrangements	Comments
Source Production at Reactor Sites	Government-required standard reactor security measures	Protection accorded reactor extends to production of isotopes; relatively little activity in U.S.
Source Processing and Sealing at Reactor Sites	Government-required standard reactor security measures	As above, assuming processing at reactor site or other regulated site
Source Transportation from Reactor or Processing Sites	NRC advisory/inspections; high security measures for large shipments	Not legally binding, but industry compliance confirmed through NRC inspections
Equipment Manufacture (incorporating source)	NRC advisory/inspections; security standards based on industrial security measures to protect high-value materials	Not legally binding, but industry compliance confirmed through NRC inspections
Equipment Transportation (with incorporated source)	NRC advisory/inspections security standards based on industrial security measures to protect high-value materials	Not legally binding, but industry compliance confirmed through NRC inspections; security requirements may not be as strong as those for large shipments from source manufacturers
End-user		
Food Irradiation/Medical Instrument Irradiation	NRC advisory/inspections calling for high security measures	Not legally binding, but industry compliance confirmed through NRC inspections
Radio-Pharmacy	NRC advisory/inspections; security standards based on industrial security measures to protect high-value materials	Not legally binding, but industry compliance confirmed through NRC inspections
Hospital	Same	Same
Well-Logging	Same	Same
Industrial Radiography	Same	Same
Research	Same	Same
After-use Storage by End-user	As above for various end-users	Potential risk of reduced security for disused sources and of abandonment of sources
Transportation to Longer-term Storage/Disposal	NRC advisory/inspections and/or DOE regulations (for DOE-sponsored shipments); high security measures for large shipments	Still lacking long-term disposal facility for Greater Than Class C disused sources
Longer-term Storage/Disposal	NRC regulations for state-run sites; DOE regulations for DOE sites	Level of security likely higher at DOE sites, which store more powerful disused sources

Those sources contain the seven reactor-produced radioisotopes identified by this paper in quantities greater than a few curies. Note: The NRC has not officially characterized these as being of high security concern.

Initiatives to Secure Orphan Sources in the United States Within the United States, the EPA has begun the Orphan Source Initiative, the first national program devoted to controlling orphan sources, in cooperation with the Conference of Radiation Control Program Directors (CRCPD). Because many of these sources end up in non-nuclear facilities, such as scrap yards and steel mills, this initiative concentrates its efforts on facilitating recognition of the problem at these locations and safely securing the sources. Eventually, it aims to establish a nationwide disposition program. Such a program would quickly

[145] Most of the preceding material on U.S. industry and NRC source security practices come from discussions with NRC and nuclear industry officials during the August to October 2002 timeframe.

identify, remove, and safely and securely dispose of orphan sources. To accomplish this goal, the EPA is encouraging research into improved detection methods. Quite often, radioactive sources buried in scrap, or which remain in protective housings, are difficult to detect with current methods. The EPA works closely with the NRC and the DOE in furthering this initiative.

At the state level in the United States, CRCPD, as a coalition of members of state radiation control agencies, can readily assist the states' regulatory agencies in developing effective programs for controlling orphan sources. Initially, CRCPD consulted with state radiation control boards to compile information on the numbers and types of sources. This collection led to formation of a risk-based ranking system to prioritize the disposal steps. Using this system, CRCPD initiated a pilot program in Colorado. By its completion in April 2001, this program had retrieved 30 orphan sources containing a total of 3.16 curies of Cs-137. Although the actual amount of radioactivity per source is not known, the average amount of about 0.1 Ci per source indicates that these sources, while posing potential health and safety dangers if improperly handled, do not necessarily pose a high security risk. Building on the success of the pilot program, in October 2001, the CRCPD Board of Directors started a National Orphan Radioactive Material Disposition Program. The purpose is "to financially assist, and provide technical guidance to, state radiation control programs in the disposition of discrete orphan radioactive material."[146] The NRC has provided funding for this program.

Apart from government efforts, the Health Physics Society (HPS), a leading nongovernmental professional organization devoted to radiation safety and based in the United States, but with many international members, has recently published a position paper focused on the orphan source problems faced by the United States.[147] According to the HPS study, three major factors contribute to the orphan source problem: (1) "Existing U.S. programs do not encourage and facilitate the prompt disposition of unwanted or unneeded radioactive sources for disposal or transfer to environments which provide safe and secure storage, pending final decisions on their disposition." Also, inadequate contact with regulators and ignorance about obligations can lead to improper disposal of sources. (2) "[D]isposition options are severely limited." For instance, source manufacturers may no longer be able to take back unused sources because the companies may have gone out of business or may simply be unwilling to accept these sources. Moreover, the expense of disposal may prohibit users from responsibly disposing of unneeded sources. Further, existing programs, such as the Department of Energy's OSR Project to dispose of disused sources,[148] are limited in their capacities and are restricted to collecting only certain types of sources. (3) "Some current uses of radioactive sources, as well as U.S. national radiation protection policies, do not meet the International Commission on Radiological Protection (ICRP) principle of justification." As applied to the use of radioactive sources, justification means that a particular practice should do more good than harm. In other words, if non-radioactive source alternatives can provide the same or greater benefit and decreased risk of adverse effects, those methods should be pursued and applied.[149]

As a result of this analysis, HPS made the following recommendations for the U.S. domestic regu-

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[146] Conference of Radiation Control Program Directors, Inc., "Announcement: A National Orphan Radioactive Material Disposition Program," October 2001, <http://www.crcpd.org>.

[147] Health Physics Society, "State and Federal Action is Needed for Better Control of Orphan Sources," Background Information Paper, April 2002. All quotes and paraphrased information in this paragraph come from this reference.

[148] The OSR program is discussed in more detail earlier.

lation of sources: (1) "A restructuring of the present system for the retention, transfer, and disposal of unwanted radioactive sources is needed so that it encourages prompt and proper transfer, storage, or disposal of such sources. So long as disposal options remain limited, there should be provisions for the prompt collection of unwanted sources and their storage at centralized secure facilities pending final decisions on their disposition." HPS further recommends that a "single federal agency" should be in charge of this task. In parallel, industry in cooperation with federal and state agencies should educate licensees who hold unwanted sources about proper safety and security. (2) HPS recognizes that these recommendations "will take several years to implement." However, federal and state regulatory agencies can start to take immediate actions, including:

- Developing procedures for recovery and safe transport of orphan sources;
- Creating temporary repositories where orphan sources may be stored safely and securely until disposition occurs;
- Developing national transport interception levels for these purposes;
- Developing a confidential national tracking system for licensed sources;
- Requiring financial surety for licensed sources;
- Enforcing license conditions on all licensed sources;
- Overhauling the radioactive materials licensing process for sources that could become orphaned …; and
- Working to have these measures adopted internationally.

(3) HPS recommends full implementation of the principle of justification. (4) Finally, HPS emphasizes that federal funding for these initiatives should be a high priority.[150]

U.S. Efforts to Detect Illicit Trafficking of Radioactive Sources Lacking adequate resources, the U.S. Customs Service presently does not screen all packages for radioactive material and instead relies on profiling. Last April, Customs announced steps to double its ability to conduct such monitoring. In particular, it will buy 3,400 personal radiation detectors to be in place by the end of the year. The goal is to procure enough detectors for every inspector. Moreover, Customs has also given radiation detectors to foreign customs services and trained their inspectors. Further, it will work with the NRC to develop a system to verify that importers are properly licensed.[151]

Legislative Initiatives in the U.S. Congress to Improve Radioactive Source Security Members of the U.S. Congress have launched legislative initiatives to improve source security. On June 26, 2002, Senator Hillary Rodham Clinton (Democrat, New York) introduced in the Senate the Dirty Bomb Prevention Act. On the same date, Representative Edward Markey (Democrat, Massachusetts) followed suit in the House of Representatives. This bill calls for the formation of "a task force to identify legislative and administrative actions that can be taken to

[149] The system of radiation protection stands on three legs: justification, optimization, and limitation. Optimization rests on the idea of ALARA (as discussed earlier). It also takes into account economic and social factors when weighing whether radiation sources should be employed. Limitation means that individual exposure should not exceed dose limits as determined by radiation protection authorities; Bo Lindell, H. John Dunster, and Jack Valentin, "International Commission on Radiological Protection: History, Policies, Procedures," ICRP, 1999.

[150] This paragraph has been quoted and paraphrased from Health Physics Society, "State and Federal Action is Needed for Better Control of Orphan Sources," Position Statement, April 2002.

[151] Global Security Newswire, "U.S. Response I: Customs to Increase Radiation Screening," May 1, 2002.

ensure the security of sealed sources of radioactive material."[152] The task force would consist of the Chairman of the Nuclear Regulatory System (who would chair the task force), the Secretary of Energy, the Secretary of Transportation, the Attorney General, the Secretary of State, the Secretary of Homeland Security, the Director of the Central Intelligence Agency, the Director of the Federal Emergency Management Agency, and the Director of the Federal Bureau of Investigation. It would be directed to consider establishing a classification system based on source security characteristics, forming a national system to recover orphan sources, providing for safe and secure storage of disused sources, establishing a national tracking system for sealed sources, and creating a national fee-based and fee-refundable system to ensure proper disposal of sources. Moreover, the bill identifies several additional measures for the task force to consider, including periodic audits, NRC evaluation of security measures undertaken by those who own sources, increased fines for regulatory violations, background checks for those who have access to sources, physical security enhancements at facilities, and screening of source shipments for explosives.

The NRC reviewed the bill and created its own proposed version. Although the general thrust of the bill remained essentially unchanged, several differences in the NRC revision are worth noting. The NRC version broadened the scope from sealed sources to sensitive radioactive material, which would include sealed and unsealed sources and all other nuclear material, except nuclear fuel or spent nuclear fuel. Deleting reference to a task force, this version placed responsibility for the evaluation of the original bill's security considerations in the hands of the NRC itself with assistance from the federal agencies listed in the Clinton-Markey version and the U.S. Customs Service. The NRC also recommended developing a "program of life cycle management." It added the requirement to direct DOE to establish a national system for storage and disposal of disused sensitive radioactive material. Faced with the time constraints of the original bill, the NRC suggested lengthening all time requirements. The tension here was between moving quickly to address an urgent security need and giving the Commission sufficient time to manage the bureaucratic process. Finally, the NRC version did not contain the provision in the original bill calling for a National Academy of Sciences (NAS) study to investigate "means of developing alternatives to the use of sealed sources" and to "identify industrial processes and other process that use sealed sources that could be replaced with economically and technically equivalent, or improved, processes that do not require the use of sealed sources."[153]

The bill and the NRC version arrived in committee in July 2002. During the committee deliberations, the modified bill, which included portions of the NRC version, became incorporated as an amendment to the Nuclear Security Act. The version that left committee kept the requirement for a task force and maintained the original tighter time requirements for completion of the tasks. Significantly, this version dropped the NAS study to examine alternatives to radioactive sources. The radioactive source industry disfavored the NAS study recommendation.[154] In contrast, the Health Physics Society has championed this position.

On October 16, 2002, Senator Joseph Biden (Democrat, Delaware) submitted related legislation in the Senate. This legislation[155] is known as the

[152] S. 2684, 107th Congress, 2nd Session, June 26, 2002.

[153] NRC version of S. 2684.

[154] Interview with industry official, August 27, 2002.

[155] S. 3121. The paraphrases and quotes in this section come from Senator Biden's speech about the legislation and the legislation itself, October 16, 2002.

Nuclear and Radiological Terrorism Threat Reduction Act of 2002 and has two principal co-sponsors, Senator Richard Lugar (Republican, Indiana) and Senator Pete Domenici (Republican, New Mexico). In addition, Senators Clinton, Schumer, and Gregg have, to date, signed on as co-sponsors.

Concerning radioactive source security, the Biden legislation addresses seven items. First, it would "establish a network of five regional shelters around the globe to provide secure, temporary storage of unwanted, unused, obsolete and orphaned radioactive sources. The bill authorizes $5 million to get started in Fiscal Year 2003, and up to $20 million a year for construction and operation of the facilities in the future." To accomplish this mission, Senator Biden envisions the United States working bilaterally with host nations and multilaterally with the IAEA.

Second, patterned after the DOE's OSR Project, the bill would "propose an accelerated program—in cooperation with the IAEA—to discover, inventory, and recover unwanted radioactive material from around the world." The bill would authorize "$5 million a year in special voluntary contributions to the IAEA."

Third, the bill would authorize funding to replace the highly radioactive sources in "lighthouses, weather stations, communications nets, and other measuring equipment" throughout the former Soviet Union. Senator Biden believes that "$10 million a year over the next three years should not merely make a dent in this problem; it should largely solve it."

Fourth, the bill would authorize "$5 million a year for the next three years to train [emergency] responders abroad." These responders would receive training in how to manage radiological events, such as use of an RDD. This provision will serve to protect "diplomatic missions at risk around the world." It will also act hand-in-hand with the provision to fund regional depositories of unwanted radioactive sources.

Fifth, the bill would require "the Secretary of State to conduct a global assessment of the radiological threat to U.S. missions overseas and to provide the results to the appropriate committees of Congress." A primary objective of this proposed analysis would be to determine where to situate the interim regional storage facilities for disused and orphan sources. The State Department analysis would also support the program to train first responders abroad.

Sixth, the bill would establish "a special representative with the rank of ambassador with the State Department for negotiation of international agreements that ensure inspection of cargoes of nuclear material at ports of embarkation." This representative would be charged to coordinate his activities with the United States Customs Service.

Finally, the bill would encourage the development of non-radioactive alternative methods to replace radioactive sources in many applications. To facilitate this development, the bill would mandate a study by the NAS to investigate how to effectively promote the substitution of non-radioactive methods for radioactive sources. As discussed in other parts of this paper, some of these methods are already being pursued. For example, linear accelerators are replacing radioactive sources, such as Co-60 and Cs-137, in cancer treatment.

The Nuclear Energy Institute's Views on Radioactive Source Security In parallel to the Clinton-Markey legislative effort, the major lobbying organization for the U.S. nuclear industry, the Nuclear Energy Institute (NEI), offered advice about industry's and NRC's roles by publishing a policy statement concerning the safety and security of radioactive sources.[156] The guiding principle of this statement is the view that "safety is the key measure that should govern all radioactive materials regulation." Security risks would play an important but secondary factor in regulatory decisions.

[156] Nuclear Energy Institute, "Ensuring the Safety and Security of Radioactive Sources," Policy Brief, August 2002. All quotes in this subsection are taken from this document.

Amplifying this point, NEI stated that the industry "supports the development of a classification system for radiation sources based on safety considerations. Such a classification system would establish proper levels of control, monitoring, and registration fees, based on each material's health and security risks." Three other points stand out in the NEI policy statement. First, it backs the establishment of a "national registry system with a fee structure that would assure the proper storage and disposal of radioactive materials." It does not specify, however, how the fees would be collected. Second, it supports the EPA-DOE orphan source program that works in conjunction with the NRC and the states to recover, store, and dispose of "radioactive materials that have no identifiable owner" and recommends giving this program more resources. Third, NEI strongly recommends that "the NRC should remain the single agency responsible for regulating all radioactive materials" while acknowledging the important role played by the interagency in coordinating with the NRC.

The Radioactive Source Regulatory and Security System in Argentina

Argentina has developed a comprehensive regulatory system designed to ensure the safety and security of radioactive sources. This system is comprehensive because it integrates enforceable laws, regulations, an independent regulatory authority, adequate resources (well-trained personnel and funding), and interagency support. Formed in 1997 from the Nuclear Regulatory Board (ENREN) to be an independent government agency, the Nuclear Regulatory Authority (ARN) is tasked with leading this system. It licenses any person or organization in Argentina using radioactive sources.

Similar to the IAEA's "Categorization of Sources," the ARN ranks sources primarily based on safety hazards but with consideration of security risks. For instance, ARN classifies sources used in cobalt therapy units and irradiators as higher risk than sources in brachytherapy and oil-logging.[157] The ARN randomly inspects facilities containing all of these types of sources, but the frequency of inspections depends on the level of risk. In particular, annual inspections occur for industrial gamma services and radiotherapy centers, while biannual inspections are implemented for nuclear medicine centers and well-logging applications. In addition to checking on safety practices, inspections examine security features, including inventories, log books noting when sources were used, interlocks (especially in radiotherapy storage areas), and other measures to prevent theft. Those seeking a license to possess sources must demonstrate the effectiveness of security methods at their facilities.

Working closely with the Customs Service and the Federal Police helps ARN prevent sources from becoming orphaned and speeds up recovery of those that are orphaned. In particular, the agreement with the Customs Service ensures that radioactive materials will not be imported or exported without an authorization. Importers have to declare if any imported equipment contains radioactive materials. Any radioactive material left with Customs for more than 30 days is removed to the national disposal site.

Ensuring proper disposal of disused and recovered orphan sources is an essential aspect of ARN's regulatory program. An August 1998 statute specifies that producers are "responsible for the conditioning and safe storage" of disused sources.[158] The Atomic Energy Commission operates a disposal site for these materials. The ARN also requires registrants or licensees either to dispose of or deposit in a safe location any disused radioactive source, to reduce the likelihood of sources

[157] However, because the latter two examples are highly portable, they can pose a significant security risk depending on the amount of radioactive material specific sources contain.

[158] "Control of the Safety of Radiation Sources and the Security of Radioactive Materials," Paper on Argentina's radioactive source regulatory system, obtained from IAEA official in July 2002.

becoming orphaned.[159] In addition, the ARN advocates "automatic radioactive material detection systems"[160] to help identify orphan sources at sensitive and high-trafficked locations, such as steel mills and border crossings.

Radioactive Source Regulatory and Security Efforts in the European Union

A recent study[161] of radioactive source management in the European Union identified the elements of best regulatory, industry, and user practice performed by various member states. According to the EU study, best practice includes:

- Operation of central database to keep an accurate inventory of sources;
- Annual license fees that increase with number of sources owned so that users have a disincentive to hold on to disused sources and accumulate more sources than they actually need;
- Fixed-period licenses that are not too long to ensure that users take stock at frequent intervals to meet license renewal requirements;
- Leasing of sources so that disposing of the sources is the responsibility of the supplier, but users still must take responsibility for daily tracking and security;
- Import and export controls that ensure proper regulations and security are operating at both the sending and receiving ends;
- Two-way flow of frequent communications between regulators and users to facilitate a proactive approach to regulation;
- Frequent and random inspections, especially of sources in the high safety and security risk categories; and
- Detailed accounting of disused sources and operation of sufficient safe and secure disposal sites.

The European Commission (EC) has stepped up efforts to control orphan sources. On March 18, 2002, the EC adopted a proposed directive on the "control of high activity sealed radioactive sources."[162] Though this proposal urges necessary measures to protect public health from orphan source exposure, it does not specifically address malevolent or terrorist exploitation of radioactive sources. On July 18, 2002, the European Economic and Social Committee (ESC) issued an opinion on this proposal.[163] While the ESC supported the improvements, it identified a number of key issues for further consideration. Concerning the potential for malevolence, the ESC "urged that this issue be considered."[164] It also suggested that users of radioactive sources be charged a refundable deposit before acquisi-

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159 Ibid.

160 Ibid.

161 M.J. Angus, C. Crumpton, G. McHugh, A.D. Moreton, and P.T. Roberts, "Management and Disposal of Disused Sealed Radioactive Sources in the European Union," EUR 1886, 2000, pp. 29-30. Readers who want to learn more about the European Union's regulatory systems are advised to turn to this comprehensive report. However, this report does not focus on security. A more recent EU report [Commission of the European Communities, "Proposal for a Council Directive on the Control of High Activity Sealed Radioactive Sources," Brussels, 18.3.2002] covers some security aspects as well as safety concerns. Although detailed research material on many countries regulatory agencies, especially those in the developing world, is not readily accessible, a recent compilation of such material is *Proceedings of the National Regulatory Authorities with Competence in the Safety of Radiation Sources and the Security of Radioactive Materials*, International Conference, Buenos Aires, Argentina, December 11-15, 2000.

162 Commission of the European Communities, "Proposal for a Council Directive on the Control of High Activity Sealed Radioactive Sources," COM(2002) 130 final, March 18, 2002.

163 Economic and Social Committee, "Opinion of the Economic and Social Committee on the Proposal for a Council Directive on the Control of High Activity Sealed Radioactive Sources," CES 843/2002, July 17, 2002.

164 Hughes Belin, "EU Panel Wants More Work Done," *Nucleonics Week*, August 8, 2002.

tion. Serving as an incentive for proper disposal, this fee would be refunded once the source were no longer needed and were disposed of safely and securely.[165]

International Atomic Energy Agency Efforts to Enhance Source Security

For decades, the International Atomic Energy Agency (IAEA) has striven to improve radiation safety to protect public health. While source security has also been important to the IAEA's mission,[166] starting in 1998,[167] the IAEA broadened its focus to bolster security of radioactive sources in Member States. After September 11, 2001, the IAEA stepped up its security efforts further. That month, the IAEA General Conference requested review of this area. In response, the IAEA Director General's December 2001 report listed security of radioactive sources as a high priority. In January 2002, Director General Mohammed ElBaradei formed the Advisory Group on Nuclear Security (AdSec). It has the mission to advise him "on the Agency's activities related to preventing, detecting, and responding to terrorist or other malicious acts involving nuclear and other radioactive materials and nuclear facilities."[168] Because this work cuts across numerous IAEA offices, the Director General appointed a Coordinator for Nuclear Security to ensure more effective management. Recent Agency meetings addressing nuclear terrorism, including concerns over RDD use, took place in November 2001 and March 2002. Recently, ElBaradei summed up the comprehensive approach when he stated, "What is needed is cradle-to-grave control of powerful radioactive sources to protect them against terrorism or theft."[169] He emphasized IAEA's role as "assist[ing] States in creating and strengthening national regulatory infrastructures to ensure that these radioactive sources are appropriately regulated and adequately secured at all times."[170]

The Agency has crafted a multi-pronged strategy to address radioactive source safety and security. In general, the strategy entails evaluation of likely threats; postulation of threat scenarios; determination of terrorist "needs"; assessment of most desirable radioactive materials from the terrorist perspective; identification of locations of these sources; examination of how desirable sources can be acquired (e.g., bought legally, stolen, obtained through black markets); and prevention of acquisition.[171] The IAEA advocates greater

[165] Separately, the Austrian Seibersdorf Research Centers, in cooperation with an IAEA team, carried out a pilot program from September 1997 to September 2000 to determine the requirements for a useful radiation monitoring system at border crossings. Such a system can detect radioactive sources in transit. This Illicit Trafficking Radiation Detection Assessment Program (ITRAP) operated at the Austrian-Hungarian border and the Vienna Airport. The program showed that training of border guards and regular equipment testing are essential for an effective monitoring system. Moreover, some of the hand-held equipment was not sufficiently user-friendly. Connecting border monitoring personnel to experts helped keep the equipment operating on a continuous basis. The final ITRAP report also recommended that, "at least one or two border officers trained in radiation basics should be continuously available"; Peter Beck, "Final Report: ITRAP—Illicit Trafficking Radiation Detection Assessment Program," Austrian Research Centers Siebersdorf.

[166] In 1992, the *International Basic Safety Standards for Protection Against Ionizing Radiation and the Safety of Radiation Sources*, published by the IAEA, notes that radioactive sources shall "be kept secure so as to prevent theft or damage … by ensuring that … control of a source not be relinquished."

[167] As discussed below, the 1998 Dijon conference promoted increased security efforts.

[168] IAEA Board of Governors General Conference, "Nuclear Security—Progress on Measures to Protect Against Nuclear Terrorism," Report by the Director General, August 12, 2002.

[169] IAEA, "Inadequate Control of World's Radioactive Sources," Press Release, June 24, 2002.

[170] Ibid.

[171] Brian Dodd, IAEA Radiation Source Safety and Security Unit, "Radiological Threats to Man and Environment from Theft and Sabotage," Presentation at EU-High Level Scientific International Conference, Strengthening Practices for Protecting Nuclear Material (NUMAT), Salzburg, Austria, September 9, 2002.

attention both on the national (domestic regulatory oversight) and international (export controls) to the outstanding issue of terrorists posing as legitimate users of highly radioactive sources.

Enhancing safety tends to support most security objectives and protects the public from hazardous exposures. Therefore, the IAEA still devotes most of its resources dealing with radioactive sources toward improving safety. One of the most important ways to achieve this objective is for the IAEA to work closely with Member States to improve their regulatory infrastructure. To date, the Agency has helped improve regulatory control in over 80 Member States. Such activity involves "the establishment of a regulatory authority, legislation/regulations, and education and training program plus a comprehensive inventory of sources."[172] More details on the IAEA's Model Project, which is an integral part of this program, are provided below.

The IAEA Safety Guide series educates Member States about proper safety practices. In October 2002, a Technical Committee will likely review a companion Safety Report covering security recommendations for sources. In December 2002, the IAEA's Radiation Safety Standards Committee anticipates reviewing a new Safety Guide on the safety and security of radioactive sources for publication consideration. The Agency will build upon these documents to craft training modules and appraisal procedures for training missions to Member States.

If an RDD were used, Member States could conceivably ask for assistance from the Agency and other Member States through the Convention on Assistance in the Case of Nuclear Accident or Radiological Emergency if they are parties to the convention. The 1986 Chernobyl accident sparked the establishment of this mechanism to render aid during a nuclear emergency. To initiate assistance, a party to the convention must make a formal request to the IAEA. Other parties can then provide the services of their experts, equipment, and other means of assistance. In other words, this convention links parties that need assistance but cannot afford it to those who are willing to provide it and can pay for it. While, as of August 12, 2002, there were 84 parties to the convention, several dozen IAEA Member States were not parties. Further, the Agency has developed an Emergency Response Network to bring together teams of experts with equipment to provide assistance.

Action Plan and Code of Conduct The latest IAEA activities to improve source security involve revision of the Categorization of Radioactive Sources, as mentioned earlier, and revision of the Code of Conduct on the Safety and Security of Radioactive Sources. Hereafter it is specified as the Code of Conduct for short.

Renewed Agency efforts to address both safety and security of sources began in September 1998 when the International Conference on the Safety of Radiation Sources and the Security of Radioactive Materials took place in Dijon, France. This conference eventually led to the creation of the aforementioned Code of Conduct. In addition, the Agency drafted an Action Plan to detail how to implement the findings of the conference and the subsequent Board of Governors meeting in March 1999. At this meeting, key recommendations were for Member States to:

- establish or strengthen national systems of control for ensuring safety and security of radiation sources, particularly legislation and regulations and regulatory authorities empowered to authorize and inspect regulated activities and to enforce the legislation and regulations;
- provide their regulatory authorities with sufficient resources, including trained personnel, for the enforcement of compliance with relevant requirements; and

[172] IAEA, "Nuclear Security—Progress on Measures to Protect Against Nuclear Terrorism," p. 3.

- consider installing radiation monitoring systems at airports and seaports, at border crossings and at other locations where radiation sources might appear (such as metal scrap yards and recycling plants), develop adequate search and response strategies, arrange for the training of staff and the provision of equipment to be used in the event that radiation sources were detected, and take similar urgent actions.[173]

At its September 1999 meeting, the Board approved the Action Plan, which applied to the areas of regulatory infrastructures, management of disused sources, categorization of sources, response to abnormal events, information exchange, education and training, and international undertakings.[174] In December 2000, a major international conference including representatives from 75 nations under IAEA auspices, which took place in Buenos Aires, Argentina, addressed these issues and encouraged Member States to follow the Code of Conduct. Complementing the Action Plan, the Code of Conduct, a non-binding document, is intended as a guide for Member States to strengthen the safety and security of radioactive sources. The Code of Conduct urges States to give the highest priority to sources that pose the greatest risks. However, this prioritization is geared toward safety rather than security. After September 11, 2001, pressure mounted to revise the Code of Conduct to focus more on security. In August 2002, an intergovernmental working group with representatives of 17 Member States met in Vienna to develop such a revision.

The new security emphasis led to several proposed changes to the Code of Conduct.[175] First, the working group advised amending the code to establish national registries of sources, especially those that pose the greatest risk, i.e., belonging to Category 1 of the "Categorization of Radiation Sources." The group was opposed to an international registry, however, because of concerns over confidentiality and ability to protect that information against cyber attacks. Second, exports of sources "should, other than in exceptional circumstances, only take place where the exporting State is satisfied that the recipient is authorized to receive the source." Concerning export controls, the group, in general, backed stronger controls, but details, such as validating and translating authorizations, need to be further ironed out. Other parts of the draft revised Code worth highlighting are recommendations to:

- require those who intend to manage radioactive sources to seek an authorization, and to submit an assessment of the security of the source and/or the facility in which it is to be managed, when one is deemed necessary in the light of the risks posed;
- ensure the safe and secure management of disused sources, including, where applicable, agreements regarding the return of disused sources to a supplier; measures to determine, as appropriate, the trustworthiness of individuals involved in the management of radioactive sources; and the confidentiality of information relating to the security of sources;
- guarantee that financial provision has been made for its [a source's] safe management and secure protection once it has become a disused source;
- ensure inventory controls are conducted on a regular basis by the holders of authorizations;
- carry out both announced and unannounced inspections at a frequency determined by past performance and the risks presented by the radioactive source; and

[173] IAEA Board of Governors General Conference, "Measures to Strengthen International Cooperation in Nuclear, Radiation, and Waste Safety" and "The Action Plan for the Safety of Radiation Sources and the Security of Radioactive Materials," GOV/2000/34-GC(44)/7, August 7, 2000.

[174] Ibid, p. 5.

[175] Report of the Chairman, "Technical Meeting to Consider the Effectiveness of the Code of Conduct on the Safety and Security of Radioactive Sources," IAEA, August 23, 2002.

- allow for re-entry into [a State's] territory of disused radioactive sources if, in the framework of [the State's] national law, [the State] has accepted that they be returned to a manufacturer qualified to receive and possess the disused radioactive sources.[176]

The group identified other issues as needing further work, for instance, finding ways to obtain broader adherence to the Code of Conduct and to improve the security of facilities that manufacture and use sources. Some members of the group recommended encouraging regulators and manufacturers to conduct more detailed discussions on "the reuse, recycling, and standardization of sources."[177] The group also wrestled over whether to advocate making the Code of Conduct binding but did not reach consensus. Instead, this issue was left for consideration in Member States' capitals and in future Agency meetings.

Model Project to Upgrade Radiation Protection Infrastructure In 1995, the IAEA launched the Model Project to help Member States that need assistance in developing their regulatory infrastructure. As of September 2001, when the IAEA had compiled an evaluation report of this project, some 52 nations had participated and another 29 have requested to take part. The IAEA assigned the "highest priority" to "the establishment of a system for the notification, authorization, and control of radiation sources and of a national inventory of radiation sources."[178] Although safety was the primary focus, improved security tends to track effective safety, and "the infrastructure established also addresses the root cause of illicit trafficking."[179]

The IAEA assistance teams employed various tools, such as experts, radiation detection equipment, and documents[180] describing how to set up legislation and regulations. About $7.4 million was spent on radiation monitoring equipment.[181] Complementing this work, peer review groups visited 32 nations to evaluate progress toward achieving regulatory goals. These evaluations and other assessments found that as of September 2001 "about 77 percent of the participating countries had promulgated laws, about 77 percent had established a regulatory authority, more than 42 percent had adopted regulations, about 80 percent had an inventory system in place and operational, and about 50 percent had a system for the notification, authorization, and control of radiation sources in place and operational."[182] For those nations that were not able to develop an effective regulatory system during this time period, some identified roadblocks were lengthy legislative procedures, dysfunctional governmental institutions, funding shortfalls, overlapping responsibilities within the government, inadequate technical resources, and insufficient staff. Many nations would, therefore, require several more years to create functioning regulatory infrastructures.

IAEA Activity to Secure Orphan Sources Even before September 11, 2001, the IAEA had been engaged in safely securing orphan sources. For instance, it worked closely with Republic of Georgia officials to find and secure discarded sources. Since the demise of the Soviet Union, some 300 abandoned

[176] "Draft Revised Code of Conduct on the Safety and Security of Radioactive Sources," IAEA, August 2002.

[177] Report of the Chairman, August 23, 2002, p. 2.

[178] IAEA Board of Governors, "Report on the Implementation of Model Projects for Upgrading Radiation Protection Infrastructure," GOV/2001/48, November 8, 2001.

[179] Ibid, p. 7.

[180] One of the key documents is IAEA, "Organization and Implementation of a National Regulatory Infrastructure Governing Protection Against Ionizing Radiation and the Safety of Radiation Sources," Interim Report for Comment, jointly sponsored by FAO, IAEA, OECD/NEA, PAHO, and WHO, IAEA-TECDOC-1067, February 1999.

[181] IAEA, November 8, 2001, p. 4.

[182] Ibid, p. 4.

sources have been discovered in Georgia.[183] Most of these sources clearly presented a potential high security risk. After September 11, the IAEA stepped up its source recovery work. In February 2002, it helped secure two unshielded Sr-90 sources in Georgia. In March 2002, the IAEA assisted Afghan authorities to safely and securely store radioactive sources found during a UN environmental monitoring mission. The source of greatest concern contained Co-60 and was part of a radiotherapy machine housed in a former hospital in Kabul. Launching a major international response to the radioactive source security threat within the former Soviet Union, on June 12, 2002, DOE, the Russian Ministry of Atomic Energy (MINATOM), and the IAEA signed a tripartite agreement to locate, recover, and secure those sources that pose the greatest security risk.

In addition to the above activities, a technical document (TECDOC) on National Strategies for Detection and Location of Orphan Sources and their Subsequent Management is nearing publication. The next step is to have Member States volunteer to try out use of the TECDOC, leading to revisions of the document. To promote full implementation, the Agency then will hold regional workshops and work with Member States to create national action plans.

Gaps and Next Steps Seeing that dozens of Member States need substantial regulatory assistance demonstrates some of the increased demands on the IAEA. Sparked by the concerns from September 11, many Member States, especially the United States, contributed millions of dollars to help the IAEA combat nuclear terrorism. In addition to some of the upcoming activities mentioned above, the IAEA has identified other steps, including forming a peer review service to assess regulatory systems with a focus on security, doing more to locate large orphan sources, updating safety standards series of publications to give more detailed information on security, and creating an international marking system for sources that pose a high security risk. Moreover, about 50 non-Member States have radioactive sources but cannot receive IAEA assistance.[184]

As discussed above, interest exists among some Member States for making the Code of Conduct a legally binding document. Others, such as the United States, envision complications revolving around the view that the Code of Conduct should remain a living document. Nonetheless, some have raised the issue of initiating a global convention to control radioactive sources.[185]

In March 2003, the IAEA, the United States, and Russia plan to hold a conference devoted to tightening the security of radioactive sources, preventing illicit trafficking of these materials, strengthening border controls, and mitigating the effects of RDDs. The conference will be open to all IAEA Member States. In addition, the International Criminal Police Organization, the World Customs Organization, the European Commission, and the European Police Office may participate in this event.

Export Controls[186]

With the exception of plutonium-238, as discussed below, the radioactive sources of high security concern[187] are not categorized as "special nuclear

[183] IAEA Press Centre, "IAEA Searches for Discarded Radioactive Sources in Republic of Georgia," Press Release, May 19, 2000.

[184] A.J. Gonzalez, *IAEA Bulletin*, 43/4/2001, p. 46. In a September 9, 2002 interview with Brian Dodd of the IAEA's Radiation Source Safety and Security Unit, one of the authors found out that his unit hired someone to write a report on this topic but unfortunately this consultant died before completing the report.

[185] In 2002, two recent known suggestions are a senior U.S. government official raising this issue in a preparatory paper for the G8 and George Bunn, a Stanford University professor who has worked closely with the IAEA for decades, opening up this approach to questioning during the NUMAT conference in Salzburg, Austria, held during September 9-13, 2002.

[186] Leonard Spector researched and wrote this section.

material" or "special fissionable material" under national and international regulatory systems, but are placed in a category that subjects them to a lesser degree of regulatory oversight. As such, they are subject to only nominal export controls. The usual practice is to permit exports of radioactive sources under "general licenses," that is, specific licenses for individual exports are not required and no license review by governmental officials takes place. Indeed, except as noted below, exporters are not required even to report the export to licensing authorities.

Exports are prohibited to countries subject to national or multilateral embargoes, but in the absence of a process for licensing individual exports, governmental authorities have no means to confirm compliance with this rule. Similarly, developed countries limit the quantity of several byproduct materials with potential relevance to nuclear weapons (including americium, neptunium, polonium, and tritium) that can be exported annually to any individual country. In the United States, exporters must report annually on total exports of americium and neptunium to individual states. Again, the absence of a process for licensing individual exports prevents confirmation of exporters' compliance with these rules and precludes governmental checks on the legitimacy of individual end-users in the importing state.

Plutonium-238 is generally classified as "special nuclear material" and is usually subject to separate regulations. However, common practice has permitted exports of small quantities of Pu-238 to non-restricted countries under general license.

In the United States, exports of radioactive sources of high security concern are licensed by the Nuclear Regulatory Commission. The Commission's rules follow the pattern described above.[188] The Commission has granted a general license for the export of byproduct materials to all countries except Cuba, Iran, Iraq, Libya, North Korea, and Sudan. In other words, unlimited exports of cobalt-60, cesium-137, and other potentially dangerous sources are permitted without any official review of end-users to many states where extensive terrorist activities are taking place—including all the states of the former Soviet Union, Afghanistan, Algeria, Columbia, India, Indonesia, Israel, the Philippines, Pakistan, Saudi Arabia—and to at least one state deemed by the U.S. Department of State to be a state supporter of terrorism—Syria.

For Pu-238 a similar general license is granted for individual exports of very small quantities of the material to all countries except Cuba, Iran, Iraq, Libya, North Korea, and Sudan. The states noted in the preceding paragraph, where terrorist activities are occurring or in which terrorist groups are supported, are eligible for the small shipments. Because individual licenses are not required and no review of exports is undertaken, a U.S. seller could legally export multiple permissible shipments to a single end-user. Twenty such permitted shipments would enable the end-user to accumulate two curies of Pu-238, sufficient to permit the manufacture of a dangerous RDD.

Although the NRC is considering new export control regulations that would increase oversight of exports of more dangerous radioactive sources, the initiative has been moving slowly. One reason is that the Commission is attempting to coordinate any new U.S. regulations with the guidelines provided in the IAEA's Code of Conduct, which has not yet been finalized.

[187] As described above, for the purposes of this paper, sources of high security concern are those containing the beta- and gamma-emitters, cesium-137, cobalt-60, irridium-192, the beta-emitter, strontium-90, and the alpha-emitters, americium-241, californium-252, and plutnium-238.

[188] See Chapter 10 of the Code of Federal Regulation, Part 110, reproduced on the NRC website, <http://www.nrc.gov/reading-rm/doc-collections/cfr/part110/>.

As noted above, the Commission is also considering new regulations to increase security over radioactive sources used in the United States. In that area, however, the Commission, as an interim measure, has issued advisories to domestic U.S. licensees possessing radioactive sources urging them to implement added security precautions on a voluntary basis. The Commission has not issued a comparable advisory to exporters of radioactive sources urging them to take added care in transferring these materials abroad. (Canada, in contrast, has contacted major source exporters to review their export practices, including mechanisms for determining the legitimacy of end-users.)[189]

CONCLUSIONS AND RECOMMENDATIONS

This study finds that reducing the security risks posed by commercial radioactive sources should be thought of as a manageable challenge, not an unattainable goal, and that significant progress can be made if adequate resources are concentrated on the most dangerous aspects of the problem.

High-risk sources pose the principal danger. Only a small fraction of the millions of commercial-radioactive sources used globally, perhaps several tens of thousands, pose inherently high security risks because of their higher levels of radioactivity, portability, and dispersibility. As a rule, these more dangerous commercial sources are those containing relatively large amounts of radioactivity (typically more than a few curies worth of radioactivity, or in terms of mass, roughly a gram or more of radioactive material) of seven reactor-produced radioisotopes: americium-241, californium-252, cesium-137, cobalt-60, iridium-192, plutonium-238, and strontium-90. Some of these isotopes (americium-241, californium-252, and plutonium-238) would only pose internal health hazards by means of ingestion or inhalation, while the others would present both internal and external health hazards because the emitted ionizing radiation could penetrate the dead outer layer of human skin.[190]

To maximize harm to the targeted population, radiological terrorists would tend to seek very highly radioactive sources (containing tens of thousands or more curies) that pose external and internal health hazards. However, even suicidal terrorists might not live long enough to deliver an RDD because they might receive lethal acute doses of ionizing radiation from these sources in the absence of adequate shielding surrounding the radioactive material. But adding heavy protective shielding could substantially increase the difficulty in transporting an RDD and could dissuade terrorists from employing these types of sources. In contrast, sources that only present an internal health hazard and that contain very high amounts of radioactivity could be handled safely without heavy shielding as long as precautions are taken to minimize internal exposure.

While terrorist misuse of radioactive sources with low levels of radioactivity might cause a degree of panic for a brief period, the high-security risk sources are the ones that present genuine dangers to the public, in terms of long-term health effects and major financial loss. For this reason, properly regulating and securing this smaller subset of sources could contribute significantly to reducing the overall dangers posed by commercial radioactive sources. Public education, however, is also needed to familiarize the public with the radiological dispersal device (RDD) threat and, in particular, to provide, insofar as is possible, reassurance that some RDDs will have so little radioactivity as to pose little if any, actual danger to the public.

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[189] Interview with Canadian government official, October 28, 2002.

[190] Strontium-90 would primarily pose an internal health hazard.

Unlike nuclear weapons, RDDs (including those using the seven radioactive isotopes noted above) are typically not weapons of mass destruction. Few, if any, people would die immediately or shortly after use of an RDD from exposure to the ionizing radiation from such a device, although, depending on its placement and size, many individuals might die from the conventional bomb blast, if this method were used to disperse radiological materials. Most people not directly affected by the conventional blast would receive relatively low doses of ionizing radiation, even from weapons using the seven high-security threat radioactive isotopes, and possible cancer deaths would usually require years to decades to develop.[191] Nonetheless, an RDD can be a weapon of mass disruption or dislocation. Preying on the public's fears of radioactivity, terrorists who used RDDs would try to cause panic. The possible resulting chaos during evacuation of the immediate and surrounding areas of RDD use could not only cause injury and anguish, but could hinder emergency response efforts to assist the victims of the conventional blast. Moreover, the time needed for first responders to prepare to operate safely in a radioactive environment could add to delays in tending to these casualties. Further, the decontamination costs and the rebuilding costs, if necessary, from an RDD could be immense—perhaps upwards of billions of dollars. Therefore, while not causing the immediate, large-scale loss of life and physical destruction associate with nuclear detonations, RDD effects could be substantial.

Production of high-risk sources is concentrated in a few nations, thereby facilitating enhanced regulation. Only a few corporations, headquartered in a handful of nations produce most of the commercial radioactive sources that pose high security concerns. This small group then distributes sources to tens of thousands of radioactive source users throughout the world. The leading radioactive source producing nations are Canada, South Africa, Russia, Belgium, Argentina, and France. In addition, the United States and the European Union also play leading roles. Although the United States is not presently a major commercial radioactive source producing nation, it has the potential to reemerge as one, and it contributes to a large market share of source use. The member states of the European Union also use a significant portion of the commercial radioactive sources. This relatively small group of major source producers and users is significant because by tightening export control standards and by conditioning exports on certification that effective security measures will cover the sources in recipient countries, some half-dozen exporting nations, together with the EU, could rapidly ensure that the considerable majority of high-risk radioactive sources in use around the world are properly protected against misuse. (As explained below, in discussing a major gap in current export control rules, implementing this change regarding importer-country regulations could be made in conjunction with a restructuring of the export licensing system that is needed for other reasons.)

High-risk sources are relatively secure in advanced industrialized countries. All of the high-risk radioisotopes that are the active components of the sources are created in nuclear reactors. These sources are then distributed to tens of thousands of global users. Ideally at the end of life, a source is

[191] Although RDDs are usually not weapons of mass destruction, there might be some highly specialized situations in which many thousands of people receiving small ionizing radiation doses could die over an extended period of time. Thus, under these scenarios, RDDs could cause many long-term casualties, making them weapons of mass destruction of a unique variety. Because terrorists who are inclined toward weapons of mass destruction would be unlikely to want to wait several years for deaths to occur, they would probably not use RDDs.

safely and securely disposed of in a corporate or government-operated depository. The considerable majority of high-risk radioactive sources are found in advanced industrialized countries and are subject to regulation throughout their lifecycles. Traditionally, these regulations were concerned principally with protecting worker and public safety, rather than with securing high-risk sources against malevolent misuse, but these states are taking steps to address this gap. Indeed, private industry and regulatory agencies in these countries have already taken steps to secure those commercial radioactive sources that pose the highest security risks, in particular, at reactors that produce commercial radioisotopes, in transit, and at the facilities employing the highest-risk sources. In other settings in these countries, industrial practices intended to protect sources as dangerous and valuable items provide an important measure of security against theft.

Radioactive source security elsewhere is weaker. Domestic regulatory controls in the states of the former Soviet Union and in a number of developing countries are weaker, or in some cases, nonexistent, and reforms (supported, as appropriate, by external assistance) are urgently needed in these settings. In many of these states, however, the number of high-risk radioactive sources is more limited than in the advanced industrial states. Thus, intensive efforts to improve security over high-risk sources are needed for only a small fraction of these sources worldwide, permitting efforts to be concentrated on this aspect of the radioactive source threat and offering the prospect of rapid improvement. By focusing its regulatory assistance programs on many of the nations in this group, the International Atomic Energy Agency (IAEA) has helped develop new regulatory agencies or improved weak regulatory infrastructures. However, further improvement requires additional funding from IAEA member states that can provide it. Moreover, time and diligence are needed to instill a safety and security culture in nations that lack it.

Barriers to proper disposal of disused sources intensify risks of additional sources becoming "orphaned." Many end-users retain disused sources because of high disposal costs or lack of adequate depositories. These barriers create pressures on end-users to dispose of their high-risk sources outside of regulated channels, that is, to abandon, or "orphan," them. Source manufacturers and many advanced countries have programs to sweep up disused sources before they are abandoned. In a number of cases, including in the United States, these programs should be expanded to mitigate this aspect of the risk posed by radioactive sources. These efforts should concentrate on the high-risk elements. In addition, existing orphan sources pose dangers. Although official reports and press accounts suggest that there are conceivably tens of thousands of such orphan sources worldwide, only a small fraction are in the high-risk category, with the preponderance probably to be found in the states of the former Soviet Union, as a legacy of the Cold War. By concentrating resources on the high-risk sources (especially in the latter setting) significant progress can be made to reduce the worldwide dangers posed by orphan sources.

Practice of exporting sources under general licenses precludes end-user review. A significant gap in U.S. export licensing rules covering high-risk radioactive sources could facilitate illicit commerce in these materials, a gap also seen in the licensing rules of a number of other developed Western states. Specifically, current U.S. regulations permit the unlimited export of most high-risk sources under "general" licenses, to all destinations, except Cuba, Iran, Iraq, Libya, North Korea, and Sudan. Consequently, exports of these materials can be made without any governmental review of the bona fides of end-users, and exporters are not required to report on transfers of these materials. In other words, unlimited exports of cobalt-60, cesium-137, and other potentially dangerous radioisotopes contained in sources are permitted without any official review of end-users to many states where extensive terrorist activities are taking place—including all the states of the former Soviet Union, Afghanistan, Algeria, Columbia, India, Indonesia, Israel, the Philippines, Pakistan, Saudi Arabia—and, to at least one state deemed by the U.S. Department of State to be a state supporter of terrorism—Syria. Although the licensing authority, the U.S. Nuclear Regulatory Commission, has taken interim steps (until permanent regulations are adopted) to intensify security at domestic sites where high-risk radioactive sources are used, it has not taken parallel interim steps to tighten export controls over these materials. (Separately, the Commission needs to intensify efforts to ensure the legitimacy of U.S. end-users, when it grants domestic licenses for the possession of high-risk radioactive sources.)

New technical approaches could reduce inherent dangers of high-risk sources. Some of these measures are now being implemented. These techniques include creating sources that are difficult to disperse, lowering the radioactivity level of radioactive sources, and developing non-radioactive alternatives for uses of radioactive sources.

Based on the foregoing, high priority work is needed in the following areas:

Protect against illicit commerce of radioactive sources by:

- Maintaining strong domestic regulatory oversight of users of highly radioactive sources through verifying the legitimacy of the user before issuing a license to possess these sources and conducting more frequent inspections once a license is granted.
- Requiring specific licenses for exports of the high-risk radioactive sources to permit end-user reviews. The United States should take the lead in implementing this measure.
- Conditioning exports of high-risk sources on confirmation that the importing country has in place adequate controls and security measures; allow exceptions on humanitarian grounds, with case-specific safeguards.
- Continuing to enhance border and port security to prevent smuggling of illicitly obtained highly radioactive sources.

Dispose of the large pool of disused sources by:

- Developing, or ensuring adequate funding for, national programs aimed at recovering disused sources from the public domain and placing them in secure interim storage. For example, the Off-Site Source Recovery Project operated by the United States Department of Energy has secured more than three thousand disused sources, but the project faces a substantial funding shortage that, if not remedied, would cripple its ability to secure more than ten thousand additional disused sources that potentially pose a high security concern.
- Creating incentives for the prompt and proper disposal of disused sources, for example, by imposing a disposal fee to be paid when sources are acquired that would be partially refunded upon evidence of their proper disposition.
- Expediting creation of a permanent, secure disposal site in the United States for Greater Than Class C disused sources (which are long-lived and relatively highly radioactive sources that currently exceed regulatory standards for near surface disposal).
- Developing secure disused source depositories in countries that lack such facilities or in regional settings open to many contributing countries.

Address the outstanding problem of the thousands of radioactive sources that have been lost, abandoned, or stolen—the so-called "orphan" sources—by:

- Concentrating recovery efforts on the small fraction of orphan sources that pose a high security concern.
- Providing adequate funding for the United States Orphan Source Initiative, operated by the Environmental Protection Agency in conjunction with the Department of Energy and the Nuclear Regulatory Commission.
- Assessing whether adequate resources are being devoted to address the worldwide orphan source problem.
- Prioritizing finding and securing high security risk orphan sources in the Newly Independent States. In particular, the United States, Russia, and the International Atomic Energy Agency should ensure that their recently launched tripartite initiative to secure orphan sources in the Newly Independent States remains a top priority.

Assist the approximately 100 nations—about half the world's total number —with weak regulatory controls, starting with those having the greatest number of high-risk radioactive sources, by:

- Expanding the International Atomic Energy Agency's regulatory assistance efforts, which have been successful in building up the regulatory infrastructure in several IAEA member states. Moreover, all member states should adhere to the Code of Conduct on the Safety and Security of Radioactive Sources, which is currently being revised to focus more on security concerns.
- Offering regulatory and security assistance to the approximately 50 non-member states of the IAEA that possess radioactive sources, but lack adequate regulatory infrastructures. The leading radioactive source producing nations should consider providing this assistance.

Reduce security risks from future radioactive sources by:

- Encouraging producers to make sources that are relatively difficult to disperse. For example, reduce the production of powdered cesium-chloride.
- Continuing to reduce the radioactivity levels of sources to the minimum required to perform the necessary, beneficial task.
- Promoting the use of alternatives to radioactive sources (such as accelerators), where those non-radioactive methods can provide the same or greater benefit as radioactive sources.

Mitigate the potential effects of RDD use by:

- Educating the public and the press about the hazards and appropriate responses to the use of an RDD.
- Preparing first responders by providing radiological training and equipment.
- Conducting regular emergency planning exercises involving coordinated efforts of local and federal officials, and applying lessons learned from these exercises to develop more effective response capabilities.
- Investing in research and development of effective decontamination technologies.
- Investing in research and development to enhance the protection, detection, and tracking of radioactive sources.

In addition to reducing the risks from RDDs, these recommended measures will improve radiation safety and, thereby, enhance public health. Through continued attentive effort, clear vision of priorities, and focused initiatives, governments, international organizations, and industry can meet the challenge of the potential misuse of highly radioactive sources by terrorists.

Appendix 1: Probable Health Effects from Exposure to Ionizing Radiation

Equivalent Dose in sieverts (for whole body)	Immediate Health Effects	Delayed Health Effects
0-0.1	None	Premature aging, possibility of mild mutations in off-spring, some risk of excess tumors.
0.1-0.5 (e.g., dose from 100 Ci Ir-192 radiography source within an hour at 1 m away)	Most persons experience little or no immediate reaction. Sensitive individuals may experience radiation sickness.	Premature aging, genetic effects and some risk of tumors.
0.5-1.5 (e.g., dose from 100 Ci Co-60 radiography source within an hour at 1 m away)	Nausea and vomiting—radiation sickness. Spontaneous abortion or stillbirth.	Some tissue damage. Reduction in lymphocytes leaves the individual temporarily very vulnerable to infection. There may be genetic damage after conception to off-spring, benign or malignant tumors, premature aging and shortened lifespan.
1.5-2.5	Nausea and vomiting on the first day. Diarrhea and probable skin burns. Apparent improvement for about two weeks thereafter. Fetal or embryonic death if pregnant.	Radiation-induced atrophy of the endocrine glands including the pituitary, thyroid and adrenal glands. Persons in poor health prior to exposure, or those who develop a serious infection, may not survive. The healthy adult recovers to somewhat normal health in about three months, but may have permanent health damage, develop cancer or benign tumors, and will probably have a shortened lifespan.
2.5-6.0 (e.g., dose from an unshielded 1,000 Ci Cs-137 blood irradiation source, within one hour and one meter away)	Nausea, vomiting, diarrhea, epilation (loss of hair), weakness, malaise, vomiting of blood, bloody discharge from the bowels or kidneys, nose bleeding, bleeding from gums and genitals, subcutaneous bleeding, fever, inflammation of the pharynx and stomach, and menstrual abnormalities. Marked destruction of bone marrow, lymph nodes and spleen causes decrease in blood cells.	Radiation-induced atrophy of the endocrine glands including the pituitary, thyroid and adrenal glands. Within 60 days after exposure, death is closely correlated with the degree of leukocytopenia (decrease in the number of white blood cells). Around 50 percent die in this time period. Survivors experience keloids, ophthalmologic disorders, malignant tumors, and psychoneurological disturbances.
6.0-10.0	Weakness, nausea, vomiting and diarrhea followed by apparent improvement. After several days: fever, diarrhea, blood discharge from the bowels, hemorrhage of the larynx, trachea, bronchi or lungs, vomiting of blood and blood in the urine.	Death in about 10 days. Autopsy shows destruction of tissue, including bone marrow, lymph nodes and spleen; swelling and degeneration of the intestines, genital organs and endocrine glands.
10.0 or more (e.g., an unshielded 100,000 Ci Co-60 irradiation unit at 1 m away could result in >1,000 Sv within an hour.)	Immediate death—"Frying of the brain"	None

Note: Health effects shown assume a linear, no-threshold model for stochastic effects.

Appendix 2: Reactors Known to Produce Radioisotopes

Country	Reactor	Owner	Operator (if not same as owner)	Thermal Power (kW)[a]	Reactor type	Location	Isotopes
Argentina	Atucha 1	CNEA		335,000 (kWe dual use)	Pressurized Heavy Water	Cordoba	Co-60
	Embalse 1	CNEA		600,000 (kWe dual use)	Pressurized Heavy Water	Lima	Co-60
Australia	HIFAR	Australian Nuclear Science & Technology Organisation	Lucas Heights Science and Technology Centre	10,000	Heavy Water	Sydney	Mo-99, Ir-192, I-131, Sm-153
Belgium	BR-2	SCK/CEN		100,000	Tank	Mol	Mo-99, Ir-192
Brazil	IEA-R1	IPEN-CNEN/ Sao Paulo	IPEN	5,000	Pool	Sao Paulo	I-131, Sm-153, Mo-99, Ir-192, Au-198, Br-82
Bulgaria	IRT Sofia (closed for refurbishment)	INRNE		2,000	Pool	Sofia	Au-198, Ta-182, Br-82, Co-60
Canada	NRU	Atomic Energy of Canada Ltd.	Chalk River Laboratories	135,000	Heavy Water	Chalk River	Mo-99, I-125, Co-60, C-14
	Slowpoke	Saskatchewan Research Council		20	Slow-poke	Edmonton	Na-24, K-42, Br-82, I-128, Ce-141, Nd-147, Yb-169, Yb-175
	MAPLE 1 & 2 (waiting licensing)	MDS Nordion		10,000 each	Tank in pool	Chalk River	Mo-99, I-125, I-131, Xe-133
	Bruce B	AECL		769,000 (kWe dual use)	CANDU (commercial power reactor)	Bruce	Co-60
Chile	La Reina (RECH-1)	Comision Chilena De Energia Nuclear	La Reina Nuclear Centre-CChen	5,000	Pool	Santiago	TC-99m, I-131

Country	Reactor	Owner	Operator (if not same as owner)	Thermal Power (kW)[a]	Reactor type	Location	Isotopes
China	HFETR	Nuclear Power Institute of China		125,000	Tank	Chengdu (Sichuan)	Co-60, Tc-99m, Ir-192
	MJTR	Nuclear Power Institute of China		5,000	Pool	Chengdu (Sichuan)	Tc-99m, Sm-153, I-131
Czech Republic	LWR-15 Rez	Nuclear Research Institute REZ PLC		10,000	Tank	Rez (Prague)	Sm-152, Ho-166, Re-186, Ir-192, Hg-203
Denmark	DR-3	Risoe National Laboratory		10,000	Heavy Water	Riso	Na-24, Cu-64, Br-82
Finland	FIR-1	Technical Research Centre of Finland	VTT-Chemical Technology	250	TRIGA II	Otaniemi	Br-82, La-140
France	Orphee	CEN-SACLAY	Orphee Reactor Service	14,000	Pool	Saclay	Various
	Osiris	CEA/CEN-SACLAY	DENIS/ DRSN, Service d' Exploitation Du Reacteur Osiris	70,000	Pool	Saclay	Mo-99
Germany	FRMZ	Johannes Gutenberg – Universiteat Mainz	Institut Fuer Kernchemie	100	TRIGA II	Mainz	Various 50+ isotopes
	FRJ-2 Dido	Forschungs-zentrum Juelich GMBH		23,000	DIDO	Julich	Co-60, Zr-95, Ir-192, Ir-194
Hungary	Budapest Research Reactor	Atomic Energy Research Institute		10,000	Tank	Budapest	I-131, I-125, Sm-153, P-32

Country	Reactor	Owner	Operator (if not same as owner)	Thermal Power (kW)[a]	Reactor type	Location	Isotopes
India	Cirus	Bhabha Atomic Research Centre (BARC)	BARC, Reactor Operations Division	40,000	Heavy Water	Trombay	Mo-99, Cr-51, S-35, Hg-203, I-131, Co-60, Ir-192, Hg-197, Sr-85, Tl-204, P-32, Ca-45
	Dhruva	BARC	BARC, Reactor Operations Division	100,000	Heavy Water	Trombay	I-131, Cr-51, Mo-99, I-125, Ir-192, I-125 H-3, C-14,
Indonesia	GA Siwabessy MPR	National Nuclear Energy Agency	Pusat Pengembangan Teknologi Reaktor Riset	30,000	Pool	Jakarta	Mo-99, I-131, Ir-192, P-32
Italy	Triga RC-1	ENEA, Ente per le Nuove Techologie L'energia E L'Ambiente	A.N.P.A., Agenzia Nazionale Protezione Ambiente	1,000	TRIGA II	Rome	Medical, Ho-166
	Lena Triga II	Laboratorio Energia Nucleare Applicata		250	TRIGA II	Pavia	Tracers, Cu-64
Japan	JRR-4	Japan Atomic Energy Research Institute	Tokai Research Establishment	3,500	Pool	Tokai-mura	Au-198, I-192, Lu-177, As-76
	Triga II Rikkyo	Institute for Atomic Energy Rikkyo University		100	TRIGA II	Rikkyo	Na-24, Fe-55, Fe-59
	JMTR	Japan Atomic Energy Research Institute	Oarai Research Establishment	50,000	Tank	Oarai	Ir-192, Yb-69, Re-188, Lu-171m
	JRR 3M	Japan Atomic Energy Research Institute	Tokai Research Establishment	20,000	Pool	Tokai	Ir-192, Au-198, Yb-196, Co-60

Country	Reactor	Owner	Operator (if not same as owner)	Thermal Power (kW)[a]	Reactor type	Location	Isotopes
Korea (South)	HANARO	Korea Atomic Energy Research Institute		30,000	Pool	Yuseong (Daejeon)	Co-60, Ir-192, Tc-99m, Mo-99, An-198, P-32, Fe-59,
	Wolsong 1 & 2	KAERI		629-650,000 (kWe dual use)	CANDU (power)	Wolsong	Co-60
Malaysia	MINT Triga Puspati RTP	Malaysian Inst. For Nuc. Tech. Research (MINT)	Atomic Energy Licensing Board	1,000	TRIGA II	Bangi	Sm-153, Ho-166, Tc-99m, I-131
Nether-lands	HFR	European Commission	Joint Research Centre	45,000	Tank in pool	Petten	Mo-99, Tc-99m, Ir-192, Sr-89, others
Norway	Jeep II	Institutt for Energiteknikk		2,000	Tank	Kjeller	Sm-153, Br-82, Co-60
Pakistan	Parr-1	Pakistan Atomic Energy Commission	Pakistan Inst. of Nuclear Science & Technology	10,000	Pool	Islamabad	I-131
Peru	RP-10	Institute Peruano de Energia Nuclear		10,000	Pool	Lima	I-131. Mo-99, P-32
Poland	Maria	Institute of Atomic Energy		30,000	Pool	Swierk	I-1312, P-32, S-35
Portugal	RPI	Institute Tech-nologico E Nuclear (ITN)		1,000	Pool	Lisbon	Short-lived, Au-198, radioactive sources
Romania	TRIGA II Pitesti	Institute for Nuclear Power Research, Pitesti		14,000	TRIGA II	Pitesti	Ir-192, I-131

Country	Reactor	Owner	Operator (if not same as owner)	Thermal Power (kW)[a]	Reactor type	Location	Isotopes
Russia	SM3	Scientific & Research Inst. of Atomic Reactors (SRIAR)		100,000	Tank	Dimitro-vgrad (SRIAR)	P-33, Gd-153, W-188, Ni-63, Fe-55, Fe-59, Sn-113/117m/119m, Sr-89, others
	IR-8	Russian Research Centre, Kurchatov Institute		8,000	Pool	Moscow (Kurchatov)	Hg-197, Au-198, I-131, Tc-99m, others
	WWR-M	Russian Academy of Sciences	Petersburg Nuclear Physics Institute	18,000	Tank	Gatchina (PNPI)	P-33, Ta-182, Ir-192, Mo-99
South Africa	Safari-1	South African Nuclear Energy Corporation		20,000	Tank in pool	Pelindaba	Mo-99, I-131
Sweden	R2	Studsvik AB		50,000	Tank	Nykoping	I-125, Sr-89, Na-24, Ir-192, P-32, S-35, Gd-159, Co-60
Switzerland	AGN 211P	Universitaet Basel	Institut Feur Physik Universitaet Basel	2	Homogenous	Basel	Na-24, Co-60, Al-28
Taiwan	Thor	National Tsing Hua University	Nuclear Sci. & Tech. Development Centre	2,000	TRIGA	Tsing Hua	I-131
Thailand	TRR-1/M1	Office of Atomic Energy for Peace		2,000	TRIGA III	Ongkharak	I-131
UK	Imperial College	Imperial College of Science, Tech & Medicine	Reactor Centre	100	Pool	Ascot	Cr-51, Br-82, Co-60, Na-24, Sc-46, Ag-110m, Sb-122, Mn-56

Country	Reactor	Owner	Operator (if not same as owner)	Thermal Power (kW)[a]	Reactor type	Location	Isotopes
USA	HFIR	USDOE	ORNL-Research Reactors Division	85,000	Tank	ORNL	Cf-252, Ir-192, various medical
	McClellan	University of California at Davis	McClellan Nuclear Radiation Center	2,000 (up to 1,000 MW in pulsed mode)	TRIGA II	Sacramento, CA	Iodine isotopes plus several others for nuclear medicine
	MURR	University of Missouri	Research Reactor Center	10,000	Tank in pool	Missouri Univ.	Sm-153, Ho-166, Lu-177, Re-186, Re-188, Au-198
	NSCR	Texas A&M University System		1,000	TRIGA	Texas A&M Univ.	Na-24, Ar-41, Sc-46, Sb-194, Ir-192, I-125, Au-198
	OSTR	Oregon State University	Radiation Center, Oregon State University	1,100	TRIGA II	Oregon State University	Ar-41
	OSURR Ohio State Univ.	The Ohio State University	Nuclear Reactor Laboratory	500	Pool	Columbus, OH	Na-24, Au-198
	RRF Reed College	Reed College		250	TRIGA I	Portland, OR	Na-24, Sm-153, P-32
	Univ. Arizona TRIGA	University of Arizona		1,000	TRIGA I	Tucson, AZ	Short-lived
	WSUR	Washington State University		1,000	TRIGA	Washington State Univ.	Ir-192
Uzbekistan	WWR-CM	Institute of Nuclear Physics	Uzbek Academy of Sciences	10,000	Tank	Tashkent	P-33, P-32, TC-99m, I-131, I-125, Au-198
Vietnam	Dalat RR	Dalat Nuclear Research Institute		500	Pool	Dalat	Tc-99m, P-32, I-131, RIA Kits

a. Dual-use in this context means the reactor is used for both commercial electric power generation and radioisotope production.

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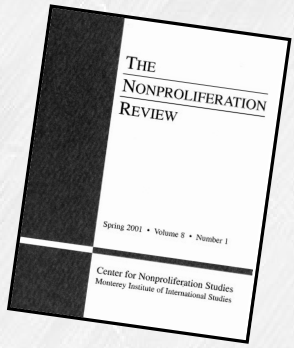

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