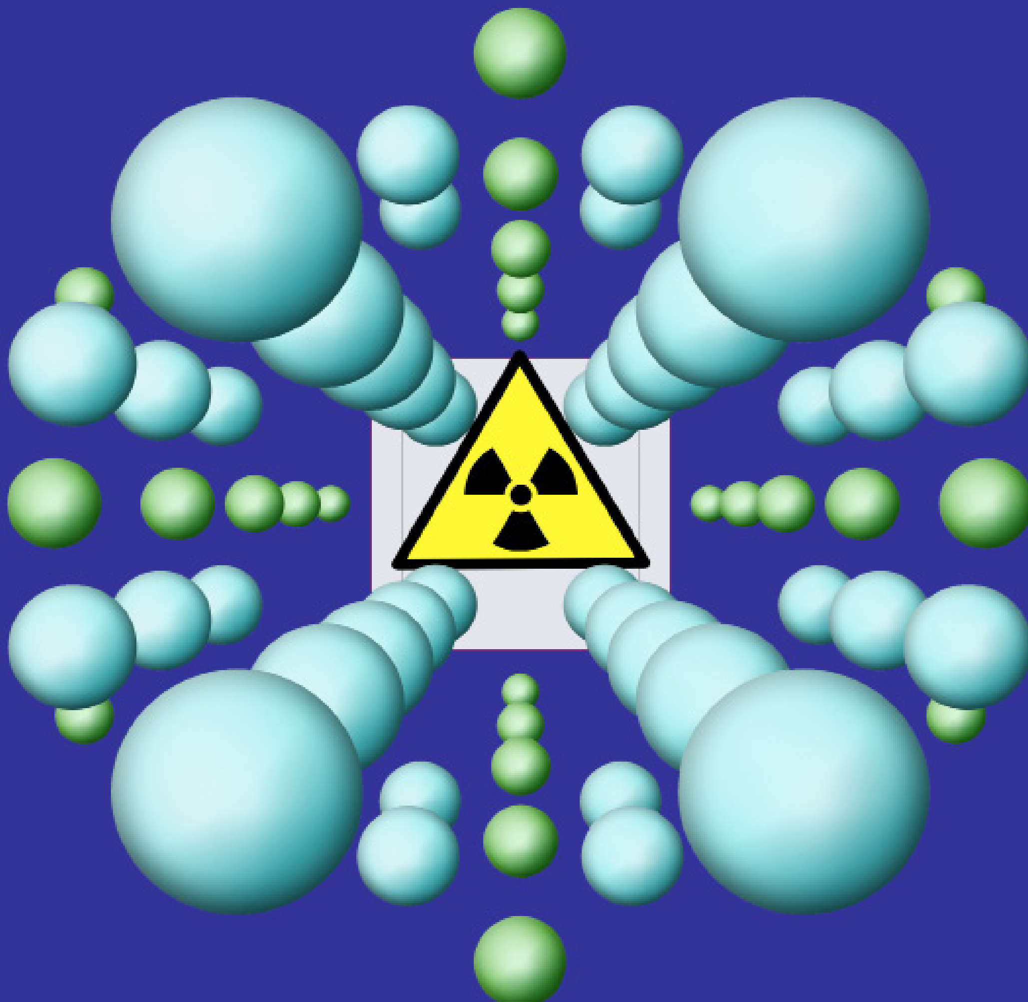
Permanent Risk Reduction:
A Roadmap for Replacing High-Risk Radioactive Sources and Materials



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Permanent Risk Reduction:

A Roadmap for Replacing High-Risk Radioactive Sources and Materials

By George M. Moore and Miles A. Pomper

Seven years ago, at the behest of Congress, the US National Academy of Sciences (NAS) published a landmark report, *Radiation Source Use and Replacement*.[1] That study examined the feasibility of replacing high-risk radioactive sources with less risky (and most likely non-isotopic) alternatives in order to forestall an act of radiological terrorism.

Since then, a quiet, behind-the-scenes battle has been waged both in the United States and overseas over how far such efforts should go. Some foreign governments, federal agencies, and US states, concerned both by the threat and the short- and long-term financial and practical difficulties of securing thousands of such high-risk sources from theft or misuse, have advocated for a more aggressive approach. On the other hand, source manufacturers, as well as some US government and international agencies, have been more cautious, given the many positive benefits these sources provide in fields as diverse as medicine, oil, gas exploration, and industry.

Within the federal government, alternatives to radioactive sources have been considered in the quadrennial report of the interagency Task Force on Radiation Source Protection and Security, which issued important reports in 2010 and 2014.[2] The 2010 report was a very cautious document, even expressing significant hesitancy on how far to proceed with replacing what the NAS report has signaled out as the biggest risk—the continued use of cesium chloride (particularly in blood irradiators), the unique characteristics of which make it especially susceptible to being used by terrorists.

By contrast, the 2014 report was considerably more aggressive in its approach to substitution and made a number of useful recommendations. It led to the government's formation of an interagency working group on alternatives coordinated by the Department of Energy (DOE) and the National Nuclear Security Administration (NNSA), acting through the Nuclear Sector Coordinating Council.

A recent NNSA strategic plan emphasized the relevance of this effort to NNSA's threat reduction mission:

> Considering the volume of high priority sites globally, the most sustainable and resource-efficient means of addressing material vulnerabilities is to encourage reliable and efficient non-isotopic alternatives for the highest activity sources, and develop incentives for users (licensees) to replace high-activity devices with safe alternatives.[3]

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1. National Research Council, "Radiation Source Use and Replacement: Abbreviated Version," (Washington, DC: The National Academies Press, 2008), <www.nap.edu/catalog/11976/radiation-source-use-and-replacement-abbreviated-version>.
2. The task force is headed by the Nuclear Regulatory Commission and includes fourteen federal agencies and one state organization. The 2010 and 2014 task force reports and additional information on the task force and their implementation are available at <www.nrc.gov/security/byproduct/task-force.html>.
3. National Nuclear Security Administration, "Prevent, Counter, and Respond—A Strategic Plan to Reduce Global Nuclear Threats (FY 2016-FY 2020): Report to Congress March 2015, Washington, DC (2015)," pp. 2-16., <http://nnsa.energy.gov/mediaroom/pressreleases/nnsa-releases-new-nuclear-prevent-counter-and-respond-report>.

At the same time, some members of Congress have been pushing for even stronger action. Senator Dianne Feinstein (Democrat of California), then-chair of the Energy and Water Subcommittee of the Senate Appropriations Committee, pushed legislation through the appropriations panel endorsing a timetable for substituting and phasing out high-risk sources.

Nonetheless, this effort was resisted by the Nuclear Regulatory Commission (NRC), which has been among the most cautious players in interagency deliberations. In a letter dated October 8, 2014, the NRC staff provided a lengthy critique of the substantive provisions of the proposed legislation.[4] Given the NRC's opposition, as well as resistance from some in the House of Representatives, these measures did not make it into the omnibus spending bill Congress passed in the fall of 2014.

International interest in, and support for, replacing high-risk sources has also been growing.

At the national level, the status of source use and security and relevant concern varies dramatically. Nonetheless, many states have expressed the need for enhanced regulatory oversight of security issues dealing with radiological sources, education and training in developing states on radiological security, and legislative encouragement or mandate of the use of alternative sources when available. Indeed, some states have advanced well beyond US domestic positions in their advocacy for and implementation of efforts to switch to non-isotopic alternatives. Some, Norway and Japan, have taken similar steps to phase out the use of cesium chloride in blood irradiators.[5]

On the international scene, the European Union has been active in supporting the concept of alternative replacement. The 2014 EU Medical Devices Regulation states that medical devices shall be replaced with higher safety devices to reduce patient and user exposure to chemicals or radioactive material.

Multilateral instruments and international norms have also played a significant role. The Nuclear Security Summit (NSS) held in 2014 in The Hague heightened awareness of radioactive source security for both facilities and transportation. France, in its national statement to the summit, called for "minimizing the use of high activity sealed sources where it is technically and economically feasible," citing its use of x-rays rather than cesium chloride for blood irradiation as an example. And the United States, in its progress report to the 2014 NSS, said that it "intends to establish an international research effort on the feasibility of replacing high-activity radiological sources with non-isotopic replacement technologies, with the goal of producing a global alternative by 2016."

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4. Letter to the Honorable Dianne Feinstein, Chairman, Subcommittee on Energy and Water Development, Committee on Appropriations from Allison M. Macfarlane, October 9, 2014, <www.nrc.gov/reading-rm/doc-collections/congress-docs/correspondence/2014/feinstein-10-09-2014.pdf>.
5. In an off-record seminar mong industry professionals in January 2014, an NNSA official relayed that Japan, which unusually irradiates 100 percent of its donated blood supply, uses x-rays for 80 percent of such irradiations. Norway and Italy require licensees who use cesium chloride devices to justify why they have not used x-rays, and Norway anticipates phasing out cesium chloride devices over the next decade. France plans to phase out cesium chloride blood irradiation by 2016 and the Czech Republic within five years, while Denmark prohibits such irradiators already. Sweden and Finland recommend to licensees that they use x-rays rather than cesium chloride devices.

At the 2014 International Atomic Energy Agency (IAEA) General Conference, Secretary of Energy Ernie Moniz announced that the United States had committed to work jointly with France, the Netherlands, and Germany to establish a roadmap of actions over the next two years to strengthen the international framework, support alternatives for radioactive sources, and enhance efforts of source supplier states. Subsequently, other states such as the United Kingdom and the Netherlands have endorsed this effort and France has drafted—and circulated—a proposed joint statement or "gift basket" supporting alternatives to radioactive sources to governments participating in the 2016 NSS.

Given the increased interest in this subject, the James Martin Center for Nonproliferation Studies (CNS) at the Middlebury Institute of International Studies at Monterey hosted three workshops (in Washington, London, and Vienna) and completed two studies examining aspects of the alternative replacement issue with the support of the US and UK governments. Information from these workshops has been used to develop this document, a potential roadmap of actions to substitute non-isotopic alternatives for high-risk radiological sources.

High-Risk Sources: Hazards, Uses, and Feasibility of Replacements

This section addresses the radiological materials of concern and the challenges of replacing these materials with alternatives that will perform the same tasks.

Materials and Amounts of Security Concern

The US government has labeled a dozen radiological materials a security concern due to their high levels of ionizing radiation (specific activity) and significant half-lives.[6] A federal task force listed the following sixteen radionuclides as those of principal concern when considering the problems they could cause if used in a radiological dispersion device (RDD):[7]

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6. See "Table 1: Radioisotopes of Security Concern," and "Table 3: High-Risk Radioactive Sources," in Charles Ferguson, "Ensuring the Security of Radioactive Sources: National and Global Responsibilities," US-Korea Institute at SAIS, 2012, pp. 6 and 10, <http://fas.org/_docs/201203-EnsuringSecurityofRadioactiveSources-Ferguson.pdf>; Charles Ferguson, Tahseen Kazi, and Judith Perera, "Commercial Radioactive Sources: Surveying the Security Risks," James Martin Center for Nonproliferation Studies, Occasional Paper 10, January 2003, p. 16; DOE/NRC Interagency Working Group on Radiological Dispersal Devices, "Report to the Nuclear Regulatory Commission and the Secretary of Energy—Radiological Dispersal Devices: An Initial Study to Identify Radioactive Material of Greatest Concern and Approaches to Their Tracking, Tagging, and Disposition," May 2003. This US government's ranking is related but not identical to the IAEA categorization of radioactive materials. See footnote 8.
7. US Nuclear Regulatory Commission, "The 2010 Radiation Source Protection and Security Task Force Report, Report to the President and the U.S. Congress Under Public Law 109-58, The Energy Policy Act of 2005," US Nuclear Regulatory Commission, Washington, DC, August 11, 2010. See in particular Table II, which lists the lower limit for these radionuclides to be Category 2 IAEA RS-G-1.9 sources, p. 11, <www.nrc.gov/security/byproduct/2010-task-force-report.pdf>.

1. Americium-241 (Am-241)
2. Am-241/Beryllium (Be)
3. Californium-252 (Cf-252)
4. Cesium-137 (Cs-137)
5. Cobalt-60 (Co-60)
6. Curium-244 (Cm-244)
7. Gadolinium-153 (Gd-153)
8. Iridium-192 (Ir-192)
9. Promethium-147 (Pm-147)
10. Plutonium-238 (Pu-238)
11. Pu-239/Be
12. Radium-226 (Ra-226)
13. Selenium-75 (Se-75)
14. Strontium-90 (Sr-90)/Yttrium-90 (Y-90)
15. Thulium-170 (Tm-170)
16. Ytterbium-169 (Yb-169)

Five of these radionuclides are in widespread commercial use around the world—Cs-137, Co-60, Ir-192, Am-241, and Am-241/Be. Although the sixteen radionuclides above are considered the most high-risk, they are generally considered an immediate danger only when found in large enough amounts to threaten life or severe damage within short periods (categorized by the IAEA as Categories 1 and 2).[8] Some uses require large amounts of these materials, some very little. These two most hazardous categories of radiological sources, as well as some materials and amounts that fall into Category 3, are those for which replacement with feasible non-isotopic sources would appear most warranted.[9]

Challenges of Replacing High-Risk Sources with Alternatives and Suggested Next Steps by Current Use

In considering non-isotopic substitutes for high-risk sources, it is important to understand both the uses to which these materials are put and the current technological and economic feasibility of alternative technologies for achieving the same purposes.

Making these comparisons can be quite complicated. When judging economic feasibility, for example, overall costs including changes in maintenance, hiring, and training need to be considered, not just the cost of the equipment. Similarly, the more difficult disposal costs and disposal pathways that result from the use of radiological sources must be considered, even if these costs are sometimes currently picked up by national governments.[10]

Still, as a rule of thumb, before substituting an alternative non-isotopic device or material for a high-risk radionuclide, the alternative should at least be roughly equivalent in cost and utility for carrying out the intended use as the high-risk radionuclide it would replace. Where equivalence is not possible

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8. The IAEA categorization of materials describes the potential harm to human health from encountering such material, unshielded, on a descending scale from 1 to 5. RS-G-1.9 Appendix 2, Table 3- "Plain Language Descriptions of the Categories," p. 32. Categories are determined by comparing the activity in a sample to reference values for each radionuclide.
9. Some consider Category 3 also to be high-risk, and note that Categories 4 and 5, although not a significant risk to persons, could be misused to cause panic and property damage.
10. These comments on costs, training, etc., should be recognized as applicable to any alternative replacement.

with an alternative, an evaluation needs to be made as to whether the alternative's performance is acceptable or if economic or other incentives could shift relative costs and benefits to render the replacement equivalent to the original high-risk source. The following section describes the most important current uses to which the high-risk materials (and hazardous amounts thereof) are put, current challenges to substituting non-isotopic alternatives, and proposed next steps.

Medicine: Cancer Treatment and Irradiation of Blood and Equipment

High-risk radiological sources are used widely in medicine for treating cancer through radiation or surgery, irradiating blood, and sterilizing medical instruments. Alternative technologies include linear accelerators (LINACs), x-ray machines, neutron therapy, heating, and treatment with ultraviolet light using a chemical catalyst.[11]

The medical community is one of the highest users of radionuclides. Most medical uses, however, involve low-activity amounts of radionuclides used for medical diagnostics and, because they are not high-risk materials, these radionuclides are not considered in this roadmap.

Cancer Treatment: External Radiation

A common means of cancer radiation treatment, particularly in developing states, is the use of teletherapy machines that employ Co-60 and Cs-137 sources.

Existing Alternatives and Challenges

In developed states, most of these devices have been replaced with LINACs, which are small linear accelerators that produce a proton beam. While LINAC technology has been used in cancer treatment for over fifty years, and while recent advances have reduced LINAC size—making their widespread use more feasible—LINAC use is not widespread in developing states. There are a number of factors limiting the use of LINACs in developing states, beginning with the higher cost and complexity and the need for stable power sources that may not be readily available. In addition, LINAC technology requires more maintenance and a higher level of training for the operators. Some states have reported that they experience a "brain drain" once personnel have received training, and the loss of trained technicians exacerbates their problems with using alternate technologies.

Nonetheless, some states such as Peru, Zimbabwe, Malaysia, Vietnam, and Uruguay have begun using LINACs, often with equipment and training provided by the IAEA. And other states are considering

11. The Food and Drug Administration (FDA) has recently approved the Intercept Blood System for the treatment of platelets with ultraviolet light and chemical catalyst. See, "FDA approves pathogen reduction system to treat platelets," FDA News Release, December 19, 2014, <www.fda.gov/NewsEvents/Newsroom/PressAnnouncements/ucm427500.htm>.

doing so, particularly as costs between securing and maintaining today's more sophisticated cobalt teletherapy units and simpler single-energy LINACS increasingly converge.[12]

The need to find suitable non-isotopic alternatives for developing states can only be expected to become more acute. Cancer rates—and the need for radiation treatment—are growing in developing states. In 2012, cancer killed over 8 million people and figures will worsen in the future. At present, 50-60 percent of all cancer patients undergo some type of treatment involving radioactive materials (e.g. teletherapy or brachytherapy; see below). This has created a shortfall of over 5,000 radiotherapy machines in developing states. Meeting this need with Co-60 and Cs-137 units would create a serious security threat in areas where security is arguably the weakest. In addition to security concerns, this shortfall presents concerns about a limited number of suppliers and the safe management and disposal of these sources.

In sum, this is not a static issue. There is a rapidly growing need for treatment in the underserved developing states and an increasing need for treatment in aging populations in developed states. Any alternative program should address providing the alternatives for these new needs in addition to the replacement of existing devices.

Suggested Next Steps

New users should undergo continued education and training on the alternatives, and be able to take advantage of them. In order to increase LINAC reliability and lower their maintenance costs, governments can encourage research and development (R&D) through, *inter alia*, funding support and encouragement to replace original purchases of the alternative technologies. This can be encouraged at both the national and international levels. For example, "strings" should be attached to grants to states or international organizations to ensure that they use alternatives, if and when feasible.

Cancer Treatment: Internal Radiation

Brachytherapy involves placing radioactive material (typically small sources which can include small amounts of Cs-137, Co-60, Ir-192, Iodine-125, Palladium-103, and others) into the body where it may reside for protracted periods, providing localized doses in order to, for example, destroy tumors.

Existing Alternatives and Challenges

It is doubtful that the use of radionuclides for brachytherapy can be replaced in the near term by some non-radionuclide equivalent source of radiation. Doctors choose to use brachytherapy sources placed in the body because they view it as superior to external radiation in those circumstances when external

12. Massoud Samiei,"Challenges of Making Radiotherapy Accessible in Developing Countries," Cancer Control 2013, International Network for Cancer Treatment and Research, 2013, <http://cancercontrol.info/wp-content/uploads/2014/08/cc2013_83-96-Samiei-varian-tpage-incld-T-page_2012.pdf>.

radiation would result in too much damage to surrounding tissues. Brachytherapy sources placed in or near the target (for example a cancerous tumor) can deliver a very localized dose with minimal damage to surrounding tissues. Internal brachytherapy sources can also provide a localized long-term source if left in the body for extended periods. X-ray units are simply too large for internal use and there is no current adequate alternative to the use of the radionuclides in brachytherapy treatment.

Suggested Next Steps

Improvements in other treatment modalities, such as chemotherapy, may lessen the need for brachytherapy materials.

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Cancer Treatment: Radiosurgery

Radiosurgery (surgery that destroys cells using radiation) treats cancers and tumors that are otherwise not treatable with conventional surgery. It typically uses multiple collimated Co-60 sources (the so-called "Gamma Knife") to deliver a dose from a number of directions, allowing a high dose to be delivered where the beams converge on the target with only a minimal dose to the surrounding healthy tissue. Currently, the Gamma Knife is primarily used in developed countries.

Existing Alternatives and Challenges

While the Gamma Knife is well established in the medical community, some other alternative technologies have emerged. CyberKnife technology, which uses a LINAC, is the most accepted of these, while the NanoKnife, which uses short bursts of electricity to destroy hard-to-reach tissues, is undergoing clinical trials at a number of major cancer institutions.

Suggested Next Steps

Additional clinical experience and trials will be needed to determine the degree to which alternatives can be substituted for the Gamma Knife. In the meantime, additional research and development and adequate security are needed.

Blood Irradiation

Cs-137 in the form of cesium chloride (CsCl) is commonly used for blood irradiation prior to blood transfusions to prevent Graft-Versus-Host-Disease (GVHD), an immunorelated complication caused by white blood cells in donor blood that attacks tissue in the body of the recipient, which almost always proves fatal. GVHD poses a risk for recipients whose immune system is weakened, suppressed, or defective, including neonatal patients. In addition, there is a heightened risk of GVHD in blood transfusions where donor and recipient share close genetic ties (i.e. family members or members of a particularly homogenous population).

Existing Alternatives and Challenges

The replacement of Cs-137 (particularly when it is in the form of CsCl) is one of the highest priorities for implementing the use of alternative technologies.[13]

Currently, x-ray units and LINACs provide viable replacement options for blood irradiators, small sterilization devices, and for cancer treatment teletherapy units. Still, governments and users note the difficulties of x-ray tube maintenance, heat generation during radiation, and budgetary concerns due to the costs of training staff. In developing a source replacement plan, it is important that these additional, or "hidden," costs be taken into account when determining cost comparison, but more importantly in funding programs. If they are not, particularly in developing states, the alternative replacement could become a failed project over the long term.

LINACs can be used for blood sterilization with only minor modifications.[14] However, simultaneous use for radiotherapy and blood irradiation is not an option, and LINAC use for blood irradiation is a high-cost and low-capacity alternative to either dedicated x-ray or radionuclide blood irradiators.[15]

Another technology that involves a photochemical process with ultraviolet light has been employed in Europe and elsewhere with significant success, but is only just now beginning to be licensed in the United States for preventing GVHD.[16]

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13. Miles Pomper, Egle Murauskaite, and Tom Coppen, "Promoting Alternatives to High-Risk Radiological Sources: The Case of Cesium Chloride in Blood Irradiation," Occasional Paper 19, James Martin Center for Nonproliferation Studies, March2014, <www.nonproliferation.org/alternatives-to-high-risk-radiological-sources/>.
14. Ibid., p. 17.
15. Thus, LINACs can be used for blood irradiation as an alternative to Cs-137 or Co-60 blood irradiators in some situations where the demand for blood irradiation is not high and a LINAC is available. LINACs have a significantly lower throughput, and using a LINAC for blood irradiation means it is not available for its primary use. On the plus side, LINACS provide the most uniform dose of radiation to a blood bag. In cases where demand for blood irradiation is increasing or an emergency exists, LINACs can be used for blood irradiation as a stopgap measure and have been in some US regions and in developing states. Ibid.
16. Laurence Corash, "Intercept Photochemical Technology for Prevention of Transfusion Associated Graft-Versus-Host Disease," and Richard Gonzales, "The Mirasol System for the Prevention of Transfusion Associated Graft Versus-Host Disease" presentations delivered at the webinar "Alternate Technologies for Radioactive Sources Working Group," organized by the Department of Homeland Security, April 7, 2015. See also Pomper, Murauskaite, and Coppen, "Promoting Alternatives to High Risk Radiological Sources," p. 18.

Suggested Next Steps

Next steps include continued education and training to ensure that potential users are aware of the alternatives for blood irradiators, research and development of improved x-rays or alternative technologies, and expedited medical approval of technologies approved elsewhere in order to provide additional alternatives to end users. Similar to teletherapy devices, funding support to encourage replacement or original purchases of the alternative technologies should be done at both national and international levels. For example, "strings" should be attached to grants to countries or international organizations to ensure that they use alternatives if feasible.

Irradiation: Medical Research

There are a number of medical research uses of radioactive sources and materials. Many of these uses involve small amounts of radioactive materials for tagging and tracing biological activities. However, cell and animal research may use significant amounts of radioactive materials, particularly when animal trials are conducted in areas of cancer treatment research, prior to use of the treatment on humans.

Existing Alternatives and Challenges

The use of high-risk sources in medical research is similar to the use in cancer treatment. Often, cancers are induced in animals and alternate treatment trials conducted, some of which use the same type of radionuclide equipment used for treating human cancers. Like the medical cancer treatment systems, there are alternative possibilities of using x-ray machines or small accelerators to replace the radionuclide systems.

Suggested Next Steps

The next steps would depend on the uses already outlined. For example, the suggested next steps for a medical research use of a teletherapy unit would be the same as those listed above for cancer treatment. To the extent that researchers may be concerned about equating previously collected data with data collected using alternative technology, dose equivalents can be established, but this may require a program of assistance, since it may be beyond the ability of individual research teams to make such measurements.

Irradiation: Medical Equipment (Sterilization)

At present, approximately 80 percent of the 420 million curies (MCI) of Co-60 in use worldwide is used for sterilizing medical devices.[17]

Most of this type of sterilization is done in large facilities where the medical goods and equipment

17. 10 percent is used for food sterilization and 10 percent for other uses including cancer treatment and industrial radiography. 75 curies of Co-60 are shipped to users every year and 40 reactors worldwide are producing Co-60.

are manufactured, and the sterilization process typically takes place after packaging. This type of sterilization has many common characteristics with food sterilization. In addition to sterilization by the manufacturer, some larger hospitals—using smaller units—also sterilize by radiation.

Existing Alternatives and Challenges

The advantage of replacing Co-60 in medical device sterilization with x-ray units is that the latter offer better penetration of the products and less overdosing potential, allowing the sterilization user to work with larger volumes and larger packaging. However, while there is significant use of x-ray units as alternatives in the smaller-scale blood and instrument irradiators, approximately 40 percent of sterilization is still done with Co-60 and 10 percent with electron beam technology.[18] Although progress is being made in alternative replacement, cost factors and the long life of the current radionuclide systems make non-mandatory replacement slow, absent an incentive system for the users.

As in blood irradiation, LINACs could be used for sterilization, but the throughput would be so low with a LINAC that the older traditional means of sterilization, such as autoclave, would be the best alternative.

Suggested Next Steps

The suggested next steps are the same as for blood irradiators described above.

Food Industry: Irradiation

Sterilization can improve both food safety and shelf life. Massive amounts of high-activity radioactive material, typically Cs-137 and Co-60, are used in large facilities for food sterilization and preservation. To some extent, this material has heretofore been thought of as self-protecting, since the tens of thousands of curies in typical facilities would provide a disabling or lethal dose in minutes, a sort of built-in deterrent against theft. However, this assumption may require rethinking in light of terrorists' suicidal willingness, which, coupled with their knowledge of explosives, might result not only in theft of these materials but also their dispersal by explosive means in an onsite sabotage scenario.

Existing Alternatives and Challenges

Because food irradiators require massively large dose rates to handle economically viable throughput rates, replacing the use of radioactive material for food sterilization is generally considered impractical in current facilities. Facility redesign to allow irradiation of smaller amounts in parallel processing

18. Electronic beam technology is cheaper than x-ray or Co-60 but does not penetrate as deeply, while ethetyl oxide technology is used for some functions which cannot be carried out using either x-rays or Co-60 devices. Unless otherwise noted, statistics and comments in this section are taken from presentations made at "Building an International Coalition on Alternative Technology," organized by James Martin Center for Nonproliferation Studies, Vienna Center for Disarmament and Non-Proliferation, October 17, 2014. Chatham House rules restrict attribution.

lines while maintaining overall throughput could make x-ray machines a viable—albeit expensive—alternative. Absent incentives, replacement by alternatives will probably not be considered until the current radioactive material requires replacement, or the operator becomes convinced that security and liability issues would make continued use a bad option.

However, while most western food sterilization is done in large facilities to which food and food products are shipped to be sterilized, not all food sterilization is done in this manner, providing some additional opportunities for alternative replacement. A particularly dangerous program of performing food sterilization at the farm or orchard was used in the former Soviet Union and China. Large, truck-mounted, Cs-137 sources were taken on-site to irradiate freshly picked items. These units posed (and those still in existence may still pose) serious security issues. However, given their smaller size and throughput, units of this size appear to be replaceable with portable x-ray units, assuming that the advantages of doing on-site irradiation are justified.

Suggested Next Steps

Suggested next steps would be to identify those situations where in-field sterilization is used and encourage the development of alternative technologies. For large, fixed facilities, the difficulty of alternative replacement should be addressed and replaced with x-ray, supplemented with education, training, and incentives. However, this will be a high-cost, long replacement effort, and in the short term, increased security measures at these sites should be the focus.

Of note is the IAEA's recent proposal for a coordinated research project entitled "Development of New Applications of Machine Generated Food Irradiation Technologies." According to the IAEA, the project aims to accelerate research, development, and implementation of practical, non-radioactive methods for treating food.

Oil and Gas Industry: Downhole and Radiography

This section addresses the use of radioactive materials in the oil and gas industry and the potential for alternative replacements.

Oil and Gas Industry: Downhole Applications

The oil and gas industry uses basically two types of radioactive sources downhole: neutron sources and gamma ray sources. For gamma sources, the industry uses Am-241 (typically 8 to 23 curies), an element used by itself for mineralogy. Am-241 is chosen for its monoenergetic, low-energy gamma, which is useful in analyzing downhole mineralogical mapping. Cs-137 (typically 1.5-2 curies) sources are used for measuring density and porosity downhole. Radioactive Krypton-85 gas is used for making inter-well measurements.

Am-241 is also combined with beryllium and used as a downhole neutron source. When the alpha particles emitted from Am-241 strike beryllium, they produce neutrons, which are particularly effective in downhole monitoring for hydrocarbons.

Although radioactive materials used in the oil and gas industry are typically double-encapsulated and are afforded security in transport and storage, security is often breached due to negligence; moreover, they are often used in politically unstable areas and have been the subject of thefts.

Existing Alternatives and Challenges

The sunk cost issue will be a factor in determining whether alternatives will be viable.

It is possible to replace the current americium-beryllium neutron sources by the use of small deuterium-tritium (D-T) generators or by using Cf-252, which is a radioactive neutron emitter. However, such alternatives have thus far not proven effective. There are significant cost and compatibility issues involved. The oil and gas industry has significant sunk (unrecoverable) costs in data already obtained by the current Am-Be sources, and it is not clear how that data could be compared, if at all, with data obtained from alternative neutron sources, since the neutron spectrum from Am-Be differs significantly from the neutron spectrum of D-T generators and Cf-252. If the use of non-nuclear alternatives were mandated, the inability to compare new data with historic data could result in large reserves uncertainty, potential well placement uncertainty, completion errors, and enormous costs for the oil and gas industry, costs that would be well in excess of the price of the replacement technology.

Thus, the challenge in using alternatives in the oil and gas industry is not just to find alternatives, but to find assured means of comparing data obtained from the alternatives with historic data.

Replacing gamma sources Am-241 and Cs-137 in downhole use by small x-ray units has also been investigated, but it is not yet as mature as neutron source replacement. Here again, the sunk cost issue will be a factor in determining whether alternatives will be viable.

DOE/NNSA's Defense Nuclear Nonproliferation's Office of Research and Development has an active program investigating a number of alternative replacement sources for use in well logging. One proposal that may have promise is using a downhole accelerator to accelerate alpha particles into a beryllium target, thereby closely matching the neutron spectrum from the Am-Be sources already in use and preserving the utility of historic data.

Suggested Next Steps

Next steps in assisting the oil and gas industry are to find ways to make accurate comparisons between older data and data taken with the proposed alternative technologies. This is a key next step in gaining acceptance of alternatives by the oil and gas industry. Funding R&D on this issue and continued and/or increased funding of a downhole alpha-Be accelerator are also important next steps.

Oil and Gas Industry: Radiography

In addition to the downhole usage, the oil and gas industry uses Cs-137, Ir-192, Se-75 and Co-60 for nondestructive testing industrial radiography on pipeline welds, welds on rigs, and other general radiography uses.

Existing Alternatives and Challenges

See the following section on *Nondestructive Testing: Radiography*.

Suggested Next Steps

See the following section on *Nondestructive Testing: Radiography*.

Nondestructive Testing: General and Radiography

Nondestructive testing (NDT) employs a number of radioactive sources, particularly in fieldwork where normal x-ray units cannot be used.

Nondestructive Testing: General

Modern construction methods employ a number of smaller sources for NDT. Moisture-density gauges are NDT devices that contain a small Cs-137 source for measuring density and an Am-Be source to produce neutrons to measure moisture content. These are high-end, Category 4 sources, and are becoming increasingly prevalent as better methods of NDT are becoming more widely used on a global basis. However, they are often left untended in vehicles and are subject to theft. Sometimes the vehicle is stolen along with the device or sometimes the gauge is stolen out of the vehicle. The gauges are typically kept in what resembles an expensive toolbox, and as such are often stolen because the thief believes that he or she is stealing valuable tools.

Existing Alternatives and Challenges

Although alternatives could be developed, the Category 4 rating of the typical devices (e.g. a Troxler moisture-density gauge) and the high cost of feasible alternatives make their replacement unnecessary.

Suggested Next Steps

Since these devices are often stolen, public education and increased emphasis on security are the suggested next steps.

Nondestructive Testing: Radiography

One of the most prevalent nondestructive testing procedures is radiography using a portable radiographic camera. The camera houses a Category 2 or 3 amount of a radionuclide, typically Ir-192, Cs-137, Se-75, or Co-60.

These camera systems are high-risk, not only because of the amount of radioactive material they contain, but because they are frequently either in transport or at field sites where security is often lower than at a fixed facility.[19]

Existing Alternatives and Challenges

Radiographic cameras were developed because alternatives such as x-ray units were far too bulky and required power sources that were not available in the field. However, this is changing. Modeling and experiments have shown that available alternatives (portable x-ray units and small accelerators) can outperform Ir-192, Cs-137, Se-75, and Co-60 in many field radiography applications. Nevertheless, there are serious cost issues, as well as training considerations, which will need to be overcome before there is widespread replacement of the current set of radiographic cameras. In addition, while alternatives may work well for most applications (such as pipeline welding inspection in the oil and gas industry), there may be applications in which small size or access constraints rule out the alternatives, including the newer, smaller, systems.

Suggested Next Steps

Education and training on the newer alternatives should be the next step. The industry has shown its receptiveness to lower-risk options. For example, the radiography industry shifted to the use of Ir-192, replacing Cs-137 and Co-60 sources in many applications, even though its shorter half-life requires much more frequent reloading of the cameras. Industry needs to be shown that the new portable x-ray units can provide the same quality of image and are rugged enough for field use.

Strategy for Replacing High Activity Sources

This section considers the elements of a strategy to replace high activity sources. Beginning with a reflection on the potential consequences of a criminal use of a high activity source, the factors that go into determining a strategy are considered, including how to prioritize replacements.

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19. Note that the IAEA's categorization guide, No. RS-G-1.9, suggests contains a table of suggested categories based on riskiness of use. Radiographic cameras are rated as Category 2 if this subjective rating scheme is used. International Atomic Energy Agency, "Categorization of Radioactive Sources: Safety Guide No. RS-G-1.9," 2005, <www-pub.iaea.org/MTCD/publications/PDF/Pub1227_web.pdf>.

Risk Mitigation Strategies

As the 1987 Goiânia incident points out, there can be extremely serious consequences to society from a dispersal of radioactive material.[20] The direct consequences (i.e. acute medical injuries) to people may be only a fraction of the problem. The short- and long-term economic consequences can be enormous. The direct cleanup costs, property loss, crop loss, and other losses may be measurable, albeit sometimes difficult to precisely measure, but the long-term psychological consequences may be much harder to identify. These psychological consequences from a Goiânia-like event could potentially include not only the initial panic and ensuing injuries, but also post-traumatic stress and ongoing effects, such as the shunning of people and produce from the affected area, consequences that are often ignored in the discussions of damages. Even today, residents of Hiroshima and Nagasaki and their descendants will often not volunteer the fact that they are survivors or descendants of survivors for fear that it will have negative consequences for them.

Public awareness of the risks and consequences of an incident or accident with a radioactive source is low and governments need to be proactive in raising awareness. The March 2011 accident at Fukushima and offsite release/contamination provides a recent example of the public's lack of knowledge and hints at the social and psychological effects that could be associated with an RDD.[21]

Replacing radionuclides in high-activity devices and processes should be driven by the need to mitigate the risk that these materials will become available for criminal or intentional unauthorized acts. For each type of use, and for each situation, consideration needs to be given to the risk of use versus the benefit from the use. In addition, a number of factors must be considered that affect replacement. For some potential replacements, the current state of alternative technologies may not be at a level where replacement is the best option. Government can both mandate replacement and encourage replacement. Decisions on replacement may arise directly from government sources or market forces or indirectly from concerns over insurance and liability issues associated with continued use of radioactive materials.[22]

Developing a roadmap needs to consider all these factors. They are discussed in the following sections, based on input from the workshops conducted and research done by CNS on the alternatives issue.

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20. On September 13, 1987, the head of a Cs-137 teletherapy unit was stolen from an abandoned hospital site in Goiânia, Brazil, by scavengers who took it for the potential scrap value, not recognizing that it contained radioactive material. The thieves sold the device to a nearby scrapyard—which sold it on to a second scrapyard that cut it open and caused the material to be dispersed—constituting a major radioactive incident that resulted in significant property damage and physical injuries, including fatalities. Over 100,000 people were screened for contamination, about 250 of which were found to be contaminated, of which twenty people required treatment for radiation sickness. Four people died, including the six-year-old niece of the scrapyard's owner. The economic loss was over $30 million.
21. See, for example, Igor Kripunov, Leonid Bolshov, and Dmitriy Nikonov, *Social and Psychological Effects of Radiological Terrorism* (Amsterdam: IOS Press, 2006), <http://bit.ly/1NusFnz>.
22. Miles A. Pomper, "Mind the Gap: The Role of Liability and Insurance Regimes in Strengthening Radiological Security," James Martin Center for Nonproliferation Studies, August 2014, <www.nonproliferation.org/mind-the-gap/>.

Since the risk mitigation strategy roadmap is being developed for DOE/NNSA, it will be useful to consider how the elements of the roadmap can be carried out through the NNSA's ability to directly or indirectly affect US governmental policy, commercial and market approaches, sponsor research and development efforts, and its engagement in and support for education and outreach efforts.

It is also important to understand that this roadmap is initially set up to consider both US domestic operations of DOE/NNSA as well as international efforts and operations. At some junctures, there will obviously be differences in how various suggestions would be implemented in an international versus a domestic, setting. It must also be realized that, in the domestic arena, DOE/NNSA must work, in conjunction with, and sometimes in a subordinate role to, the US Nuclear Regulatory Commission.

Government can both mandate and encourage replacement.

On the international scene, the implementation of alternatives replacement may need to be considered—and variations of the general roadmap developed—on a regional or even subregional basis. A roadmap for African states may be significantly different from one for states in South America. Although some of these differences will be mentioned in this report, no attempt will be made to spin out all the possible variations that would ultimately be necessary for DOE/NNSA to implement comprehensive domestic and international programs.

Replacement Priority

In a prior section, the IAEA's categorization using RS-G-1.9 scheme was discussed (see footnote 7) and reference was made to the sixteen radionuclides typically considered to pose the highest risk.

While it might be tempting to say that a replacement program should begin with Category 1 sources and work its way down through Category 3, this may not be the best approach. The RS-G-1.9 categorization scheme is based on what is often referred to as "pocket dose" and reflects primarily the danger of the radionuclide for external exposure to a person in close proximity. Although some deference is given in RS-G-1.9 to the use of the radionuclide, the principal consideration is external dose.[23] Certainly consideration should be given to category rating of the radioactive material in a device or process in determining replacement priority, but devices and processes themselves may determine the risk of theft or misuse, and should therefore receive the highest attention. Determining the level of risk on a case-by-case basis (or perhaps state-by-state basis) may be necessary to determine the order of priority for replacement.

23. This factor has led to some criticism that the hazard of some radionuclides, such as Po-210, are underestimated by RS-G-1.9.

When considering the replacement priority for radionuclides by alternatives, a number of factors should be considered, including:

- How dangerous is the radionuclide (i.e. what is its IAEA categorization)?

- How much of the radionuclide is needed for the specific task or device?

- Will the physical characteristics of the radioactive material have a significant impact on how easily the material might be used for criminal and/or intentional unauthorized activities?

- How essential is the use of the radioactive material? Can the same task be accomplished as effectively or better with a non-isotopic alternative material or device? If not, can it be carried out with 1) less material of the same type; 2) another physical form of the radioactive material, which is potentially less hazardous; 3) another, less hazardous radioactive material? Or, ultimately, can the use be eliminated altogether if the current risk of radioactive use is deemed to be too hazardous and there are no viable alternative replacement options?

The IAEA's Safety Fundamental (NSF-1), which sets forth a basic standard for justifying the use of radioactive materials and devices, is also relevant to alternative technology replacement of radioactive materials. It states that: "for facilities and activities to be considered justified, the benefits that they yield must outweigh the radiation risks to which they give rise."

Developing a list of replacement priorities should consider both the present risk and anticipation of future risks from the device or process. It should also be noted that the results of this risk assessment might vary depending on the location of the device or process. For example, the assessment of the risk associated with a Co-60 cancer therapy unit may result in very different conclusions if the device is in a US hospital, as opposed to a clinic in an underdeveloped country.

Though replacement evaluation should be done on a case-by-case basis, there appears to be certain fundamental replacement targeting priorities. Cs-37, particularly in the form of CsCl, should probably be at or near the top of the list for any replacement program. Cs-137's approximately thirty-year half-life, its relatively penetrating gamma decay, and its general, bad materials properties (it behaves like table salt, NaCl, including being completely soluble in water) make it a high priority for replacement.[24] Some progress has already has been made toward replacing Cs-137 in blood irradiators and other activities, but more can be done.[25]

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24. One potential alternative is the replacement of CsCl in devices with an alternative physical form of cesium. However, a different physical form only adds one step (the extraction of the radioactive Cs-137) to a potential terrorist's task. Some believe that the additional step is significant while others point out that only simple chemistry tasks are required to extract the cesium.
25. See, for example, Pomper et. al., "Promoting Alternatives to High-Risk Radiological Sources."

Although this roadmap, in its focus on alternative replacements and their prioritization, takes into account the current and future security situation, it does not directly address security issues. It should be noted, however, that some regulators see alternatives and security enhancements as competing options.[26]

Implementation Challenges: Information Gaps

Carrying out such a case-by-case program will require good data on all available sources, devices, and processes. In some cases, the data already exists, but in other cases it must be developed. However, even where such information exists, there are information-gap challenges between governments and users, users and manufacturers of devices and radionuclides, and government-to-government and even intra-governmental information gaps. In fact, in the areas of radioactive sources and materials, it might be said that information gaps are a dominant feature.

As a result, a feature of any roadmap will involve both developing information and bridging information gaps. In many states, the status of the security of radioactive materials is difficult to determine. Some undeveloped states do not even have a regulatory body that deals with these materials, despite the presence of them in their country. Sometimes foreign companies import the materials to support exploration or exploitation of natural resources without notification of the host states. Even in states with a regulatory body, the historical focus may have been on nuclear materials and they may not have a viable registry of radioactive sources or materials. Experience has shown that often states do not know what radioactive materials and sources are in the country. However, although specific knowledge about states' radioactive materials security regimes may be difficult to obtain, such knowledge is essential to prioritize assistance in providing alternatives to radionuclide use.

Although specific knowledge about states' radioactive materials security regimes may be difficult to obtain, such knowledge is essential to prioritize assistance in providing alternatives to radionuclide use.

One interim step might be to prioritize states for action depending on an assessment of the effectiveness of, or even existence of, their radioactive material security regimes.[27]

Factors, for example, could include a significant commitment to radioactive material security and a supportive radioactive material security culture. Commitment to guidelines such as the IAEA's Code of Conduct on the Safety and Security of Radioactive Sources, participation in international activities and professional societies dealing with radioactive material, etc., are all indications of a robust radioactive

26. For example, the US Nuclear Regulatory Commission has promoted this position and has responded to concerns regarding high-risk sources with regulations aimed at increasing security.
27. See, for example, the Nuclear Threat Initiative's Nuclear Security Index, <http://ntiindex.org/>.

material security culture. Included in a such a culture is a responsive state regulatory framework that has an up-to-date registry of radioactive sources, and which engages in self-assessments and invites outside assistance to determine the health of their programs.

Establishing a Replacement Priority List

In order to properly to establish a broad and long-term replacement program for high-activity radionuclide devices and processes, the following initial studies need to be considered and evaluated in order to develop replacement criteria that are as objective as possible. These studies would need to be done to support both foreign and domestic replacement programs. In some instances, as mentioned above, the data may already be available and usable; in other instances, it may require quite an effort to collect and organize the data before priorities can be established. As a minimum, the tasks would include the following:

> 1. **Prepare a listing (database) of all radionuclides currently in use in a specific state or area of consideration for alternative replacement, or projected to be used**. The database should contain the radionuclide's characteristics, including half-life, decay energies, the IAEA's D value, principal physical characteristics, manufacturer, and the type of devices or processes in which they are used. At a minimum, the sixteen high-risk radionuclides from Table II of the "2010 Radiation Source Protection and Security Task Force Report" and perhaps the additional seven radionuclides that the 2010 report lists in its Table III.[28] In some states, such databases already exist and will require little modification, but in other states there may not even be a source listing from which to start.
>
> 2. **Prepare a listing (database) of all radionuclide providers and equipment manufacturers who produce, or are licensed to produce, products containing those radionuclides of concern.** Domestically, collecting this information may not be difficult, but it is a far more complex task on a global basis. The IAEA maintains a Catalog of Radioactive Sources that contains much of the required data. In addition, there appears to be a classified database, maintained in part by Idaho National Laboratory in the United States, that contains listings similar to the IAEA's Catalog of Sources.

The completion of items 1 to 2 will not be trivial. The following excerpt from a recent Government Accountability Office (GAO) report gives some indication of the scope of the collection efforts involved:

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28. Chairman of the US Nuclear Regulatory Commission, "The 2010 Radiation Source Protection and Security Task Force Report," Report to the President and US Congress Under Public Law 109-58, The Energy Policy Act of 2005, Washington, DC (August, 2010), <www.nrc.gov/reading-rm/doc-collections/congress-docs/correspondence/2014/feinstein-10-09-2014.pdf>. Table II on page 11 lists the lower limit for these radionuclides to be Category 2 IAEA RS-G-1.9 sources.

> According to GAO, radiological material is used across the United States in a wide range of industrial activities, from radiography to sterilization. As of September 2013, nearly 800 companies in the United States were licensed to use radiological material. Five hundred of those licenses were for radiographic purposes, with approximately 4,000 radiological sources (totaling 214,000 curies) of mostly iridium-192 and cobalt-60 associated with U.S. radiographic machines. An additional 1,736 radiological sources that use high-risk material are used for well logging (13,000 curies). In total, there are 1,400 facilities with high risk radiological material containing 126 million curies spread across the United States. To put that in perspective, the source whose theft and recovery in Mexico made headlines in December 2013 contained 3,000 curies of radioactive cobalt-60.[29]

Once these databases have been assembled, an objective scoring method can be developed to assign rankings based on perceived risk without consideration of external security for each of the devices and processes.[30]

Finally, from a security perspective, the devices and processes need to be considered in the context in which they are actually used, and the "guns, guards, gates" aspects of security needs to be quantified in order to become part of the overall risk and priority assessment that lead to the development of a replacement priority listing.

For domestic US users, this type of security evaluation can be made at the facility-level, as is done from time to time by NRC and DOE. However, for the initial ranking, it is probably not useful to scrutinize and rank each individual facility, but rather to consider facilities in a generic manner, grouping hospitals, portable construction vehicles, etc., together for assessment purposes. For international users, perhaps the best that can be done in terms of determining risk is to assess the security ranking of the state, similar to the manner in which the Nuclear Threat Initiative has developed its Nuclear Security Index. The combination of a radionuclide hazard with a device-, process-, and location-specific assessment would enable a long-term program to prioritize work on alternative device(s), and process replacements depending on risk associated with the device or process, coupled with an assessment of the user states' ability to protect the source.

Even when all these factors have been considered, the economic and social factors must still be considered in determining alternative replacement priorities. If the cost of the alternative technology is too high, and there is no regulatory driver to incentivize a replacement, the indirect policy making

29. Nikolas Roth, "GAO Report on Radiological Security, Nuclear Security Matters," Harvard- Belfer Center, July 2014, <http://nuclearsecuritymatters.belfercenter.org/blog/gao-report-radiological-security>.
30. Security inherent in the device or process should be considered in the evaluation. For example, a very high dose rate source might be evaluated as self-protecting. However, when assessing devices and processes, no consideration should be given to the security provided by the location of the source, i.e., the "guns, guards, and gates" aspects of security. The external security, security culture, and other security factors will be evaluated separately.

aspects of NNSA efforts may need to be brought into play. Social and cultural factors may also come to bear and some states and/or organizations may be reluctant to accept alternative technology or training donated or provided by other states.

Encouraging Replacement

Obtaining an objective numerical grading of the need to replace radionuclides as described above should proceed in parallel with a number of efforts to work with manufactures and users of high-activity radionuclide devices and processes in order to encourage replacement.

Government can play a crucial role in replacing radionuclides by alternative technologies. It can simply mandate the replacement, as several states already have. However, some governments may want to avoid such a forceful approach, which may be too broad and overshadow the benefit side of the risk-benefit determination. Other, softer, or more indirect governmental actions—such as financial assistance to purchase alternative technologies, or tax breaks to encourage replacement—may be more effective.

Another governmental option could include financial assurance strategies that require radioactive material users to post a deposit or bond that would be forfeited if the source is not returned to the manufacturer or propertly disposed of when it is no longer used. Disposal costs are often quite high and users often have tended to try and avoid them by illegally disposing the sources in scrap streams or simply abandoning them altogether. Although source abandonment has not proved to be a significant domestic issue, there are a number of international examples that have led to fatalities and serious consequences, such as the Goiânia incident. Continuation on a domestic level of low or no cost source recovery and expansion of international efforts in this area is an important government practice, but one that has no direct impact on alternative replacement. In fact it might encourage continued use of radioactive sources and materials if users felt that they could avoid disposal costs.

Market forces such as liability concerns and the actions by the insurance industry can, under certain circumstances, play an important role in potentially persuading radioactive material users to opt for lower risk alternative technologies. If users, or potential users, of radioactive materials find that they cannot get reasonably priced liability coverage for such devices and processes, then non-radioactive alternative uses will be far more attractive. Educating the insurance industry as to the risks and potential damages may influence the industry to decline issuing liability policies that cover high-risk sources and materials.[31]

The encouragement of alternative replacements is in need of a strong organizational and structural support vehicle. An international coalition is needed to work together to support this transformation and the United States should be a principal in such a coalition. Such a group could help tackle concerns about a shift to lesser known alternative technologies as well the financial issues surrounding potential shifts to alternative technologies. It could draw public attention to the importance of radioactive

31. See Pomper, "Mind the Gap."

security and raise awareness of the importance of shifting to alternative technologies. It could also generate a global strategy for alternative technologies. This coalition should involve industry groups—both end users and device manufacturers—the international scientific and policy research communities, and government policy makers and regulators. Where feasible, developed states need to provide developing states with assistance to support this transition.

The United States, for example, has several programs in this regard:

- The DOE/NNSA Office of Defense Nuclear Nonproliferation's R&D department supports efforts to develop alternatives where no commercially available alternative exists. DOE/NNSA has established an integrated R&D program that focuses on replacing radiological sources (medical, sterilization, geophysical well logging) with alternatives that contain no radiological material.

- The DOE/NNSA Office of Radiological Security works to protect high-risk radiological materials from theft through a sustainable threat reduction model. In a similar manner, their Mobile Source Tracking System Project focuses on the security of high-activity mobile sources (Ir-192, Se-75, Co-60, and Cs-137) that are primarily used in the well-logging and industrial radiography fields.

Certainly, DOE and NRC need to fund and/or continue funding research and development programs in the United States to assist in developing alternative sources and should consider supporting similar research by other states.

Another vehicle for promoting the use of alternative technologies is national and international industry and professional society groups. Involvement by developing country governments and professionals should be encouraged and subsidized to assist in raising levels of awareness and technical knowledge about the issues. Government officials and/or government contractors can use these forums to present state-of-the-art alternative replacements and ensure that members of these societies and groups are well aware of the hazards associated with the materials and their potential liability, should there be a problem at their facilities.

A governmental program might also consider other direct efforts that might assist in convincing manufacturers and users to convert to alternative methods and materials. For example, many of the major accidents or incidents with high-activity sources throughout the world have occurred when sources have been abandoned due to disuse and bankruptcy of the users. One effective but simple change could be to alter bankruptcy regulations requiring bankruptcy trustees to communicate with state licensing bodies, the NRC and/or DOE, or with the regulatory body in foreign countries, in order to determine whether the bankrupt entity possessed radioactive sources and materials. Such a move could prevent loss of control of radioactive materials and therefore prevent a number of incidents and fatalities.

In summary, encouraging replacement can be done by a number of ways and it should be part of any program dealing with alternative replacement. As noted above, industry, professional, and public awareness of the replacement issues and potentials should be part of governmental outreach to industry and public education efforts.

Replacement Timeline

It is recommended that DOE/NNSA establish a schedule for replacement activities that will extend into a reasonable future. The schedule operates on a ten-year timeline because, even though the replacement with alternative may extend well past ten years, any program starting now should have a reasonable term, but will obviously need to be re-evaluated and restructured in the not-too-distant future. A projection for ten years seems to reasonably meet that goal.

The rough timeline sketched out in Table 1 on the next page is fairly general. The actual establishment of both a domestic and international program would probably require the development of at least two timelines and would have differing metrics, completion dates, and perhaps somewhat different tasks. However, the following lays out a broad outline from which specific plans can be developed. In some instances, the tasks include items that are already ongoing or may have been completed (at least domestically), all or in part. In such cases, the tasks in the following Table 2 represent a checklist of items that can be compared with current levels of accomplishment in the task area.

Table 1. Replacement Activities Timeline and Metrics for Evaluation

Years	Tasks	Accomplishment Metric
1-2	Establish the databases and evaluation methodologies to prioritize replacement of current radioactive devices and processes.	1. Databases created. 2. Ranked order of devices and processes targeted for replacement in various domestic and international locations.
1-2	Obtain budget funding for R&D programs with initial concentration on the oil and gas industry and for the purchase of alternative replacement equipment.	Funding for R&D in place.
Continuous	As soon as methodology for prioritization is developed and funding is available, begin to replace the highest risk sources. Re-evaluate the priority listing annually to reflect R&D advancements and risk impacting global events.	Produce an annual report of alternative replacements made and an annual update of the priority rankings for alternative replacement by source type and country.
Continuous	Outreach to professional societies and manufacturing groups.	Numbers of papers presented. Number of societies and groups approached.
Continuous	Fund R&D on highest priority replacement devices and processes.	Reports from R&D activities.
1-5	Work with Congress on legislative solutions including tax credits and/or other tax and financial incentives.	Legislation enacted.
6-10	Continue program and monitor.	Annual reports to Congress on numbers of devices and processes replaced.
3-10	Starting with year 3 and at years 5, 7, and 9, conduct a review of criteria and information collected and update as necessary.	Status report upon completion of review.
1-10	As soon as criteria have been determined, target the highest priority devices and processes and review the targets annually.	Annual targeting statement describing device and process and goals and achievements for replacement.

Obviously, any program such as the one outlined in the timeline above in Table 1 would have both domestic and international components. Workshop participants from various states have all stressed the importance of coordinating efforts between the IAEA, the World Institute for Nuclear Security, the Global Initiative to Combat Nuclear Terrorism, and other international organizations working in the field.

Conclusions

The replacement of high-activity radionuclides in devices and processes is a critical element of permanent threat reduction. Both domestically and internationally, radioactive material from these devices and processes pose a risk that they can be used by terrorists for criminal or intentional unauthorized purposes.

Replacement of the high-risk, high-activity radionuclides by non-radioactive devices or processes will be a significant step forward in increasing domestic and international security.

Decisions on replacement need to consider a variety of topics and insofar as possible an objective numerical scale needs to be developed to establish priorities for replacement. Much of the data necessary to develop such a scale is available but organizing and verifying the data and creating useful databases of the relevant information will be a significant task requiring technical expertise and oversight.

DOE/NNSA should consider using the roadmap of tasks in Table 2 for establishing domestic and international programs. Although task items may have been accomplished or are ongoing in some areas (i.e. a domestic database may exist but international databases may not exist in targeted countries), Table 2 provides an outline to develop, assess, and/or modify alternative source replacement efforts.

Table 2. High-Risk Radionuclides and Potential Replacements.[32]

Industry	Use	Device and Radionuclide(s)	Possible Alternative	Feasibility of Substitution
Medicine	Cancer treatment-teletherapy	Teletherapy machines using Cs-137 or Co-60.	Linear Accelerator (LINAC) using proton beam for treatment.	Availablility of substitution limited by increased cost, training and maintenance costs, and demands for stable power source.
Medicine	Radiosurgery for cancer and non-operable tumors	Gamma knife using Co-60.	LINAC for some application.	Gamma knife is still preferred method.
Medicine	Instrument Sterilization	Cs-137 or Co-60 sterilizer.	X-ray machines or return to prior methods such as steam/heat sterilization methods.	Cost and reliability are major factors for x-ray. Efficiency and quality control are major issues for older less effective measures.
Medicine	Blood irradiation	Blood irradiators which are primarily Cs-137 with some Co-60.	X-ray blood irradiation units. LINACs can perform blood irradiation, but such use is inefficient. UV light method shows promise.	Cost and reliability major factors. Current Cs-137 machines have a long life and do not typically need replacement for quite some time.
Construction	Radiographic cameras	Field use for x-ray-like non-destructive testing. These devices use an assortment of radionuclides including Co-60, Cs-137, Ir-192, Se-75.	Portable x-ray machines with increasingly portable power supplies are now available but due to size issues can't replace radiographic cameras in all applications.	Cost is a problem. The nondestructive testing industry has shown flexibility on reducing dose and threat by, for example, shifting away from loner lived radionuclides to the use of relatively short-lived Ir-192.

32. Table 2 lists devices and processes involving Category 1, 2, and 3 amounts of radionuclides. It does not consider either military uses of radionuclides or the uses of radionuclides for power generation, such as the use of Sr-90 or Pu-238 in Radioisotopic Thermal Generators.

Food Processing	Food sterilization	Large underground facilities using tens of thousands of curies of primarily Cs-137 but also some Co-60.	At present, there are no x-ray alternatives available that can handle the required throughput.	Cost of x-ray units (which would be large units) and maintenance and reliability problems would probably preclude x-ray alternative, even if one were available.
Oil and Gas	Well logging	Density measuring devices primarily with Cs-137. Am-Be neutron sources for detection and well mapping and Am-241 for minerology.	Both current devices can be replaced. Small D-T accelerators can provide neutron sources and small x-ray units can replace Cs-137 for density measurements. A new alpha particle accelerator with a Be target is under development.	The oil and gas industry is reluctant to replace the current use devices primarily because of cost and reliability and the fear that new devices' output can't be correlated with historic data that has been obtained at significant cost.
Oil and Gas	Pipeline inspection	See discussion above on radiographic cameras.	See discussion above on radiographic cameras.	See discussion above on radiographic cameras.
Nondestructive Testing	Radiography	See discussion above on radiographic cameras.	See discussion above on radiographic cameras.	See discussion above on radiographic cameras.

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