WORLD INSTITUTE FOR
NUCLEAR SECURITY

Considerations for the Adoption of Alternative Technologies to Replace Radioactive Sources

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WHY YOU SHOULD READ THIS DOCUMENT

Radioactive sources are used every day in numerous medical, industrial, agricultural and research applications around the world. However, their mismanagement has the potential to cause significant harm to people, property and the environment. If these sources are lost or stolen and fall into the wrong hands, they can cause bodily harm, significant social disruption and anxiety in the community. Such results would be damaging to the reputation and credibility of any organisation involved.

Although adequate security measures will significantly reduce the risk posed by high activity radioactive sources, such as the Category 1 and 2 sources as defined by the International Atomic Energy Agency (IAEA)1, replacing the sources with alternative technologies would permanently reduce the risk.

On-going research, advancements in new technology and improvements in existing technologies have made many alternatives to radioactive sources attractive and cost effective. In some cases, there has been a strong movement to alternative technologies; this has been encouraged, at least in part, by the potential risks and liabilities posed by radioactive material. In other cases, complacency, a lack of incentives or a lack of viable alternatives have limited the movement to non-isotopic replacements.

In this special publication, we describe the advantages and disadvantages of alternative technologies to some of the most commonly used radioactive source applications in medicine, industry and research. Our goal is not to take a particular stance on the issue or to make specific recommendations; rather, it is to help you consider whether it would be appropriate to replace some or all of the radioactive source technologies that you currently use with alternatives, particularly if a replacement is equally effective, less burdensome and has comparable costs.

We also present a process that will help you decide whether to adopt an alternative technology, suggest several issues to consider when you are assessing the viability of such changes and discuss some of the challenges others have faced when making this decision. In addition, we provide references for further reading to support your considerations.

All of this information will give you the background necessary to engage decision-makers if you determine that the adoption of an alternative technology is a sound approach. The appendix provides a set of questions that will help you determine whether such a change would be viable in your circumstances.

1 IAEA. (2005). Safety Guide RS-G-1.9. *Categorisation of radioactive sources.*

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In preparing this publication, we have considered the experience of end-users and regulators associated with medical, industrial and research applications of radioisotopes. We have also considered the international community's experiences with alternative technologies that were shared during two WINS workshops[2] and the guidance material published by the IAEA and selected national regulators.

This document is not a technical report and should only be used as starting point for familiarising yourself with alternative technologies and for identifying the key issues and steps necessary when considering adopting one. When aiming to develop a comprehensive perspective on this topic, it is important that you enhance your own understanding by reading dedicated research and by participating in relevant forums that share your peers' experiences in this field.

A list of references and suggested further reading is provided at the end of the document to help you in this process. Please note that wherever possible, this publication uses the same terminology as that found in IAEA publications.

We welcome your comments

We plan to update this publication periodically to reflect changing information and new ideas. Therefore, we ask that you read it carefully and let us know how it can be improved. Please email your suggestions to info@wins.org. If you have ideas for additional WINS publications, we would like to hear about them. One of WINS' most important goals is to share best nuclear security practices and our primary task is to serve our membership.

Dr. Roger Howsley
Executive Director

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2 *Alternative Technologies to Radioactive Sources* (Brussels, Belgium. 8 and 9 October 2013) and *Alternative Technologies to High Activity Radioactive Sources Used in Medical Applications* (Rio de Janeiro, Brazil. 28 and 29 April 2015)

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WHY ALTERNATIVE TECHNOLOGIES CAN CONTRIBUTE TO YOUR OPERATIONS AND SECURITY

Radioactive sources[3] have a variety of essential and beneficial applications. However, if they are mishandled, particularly with malicious intent, or improperly disposed of, they have the potential to cause significant damage and injury.

There are numerous examples of radioactive sources being stolen or going missing. Some of those incidents caused serious harm and others, thanks to measures taken by the authorities involved or pure luck, did not.

A comprehensive list of all publicly reported radiological incidents can be openly accessed.[4] Here are a few examples to illustrate the risks and threats:

- In 1987, an abandoned and unsecured teletherapy device containing a Cs-137 source was stolen in Goiânia, Brazil. It was broken open, contaminating a wide area with radioactive caesium chloride. Four people died soon after as a result of their exposure and 20 more showed signs of radiation sickness. The clean-up cost tens of millions of dollars and had an inestimable psychological impact.[5]
- In 1993, a similar incident involving a Cs-137 source occurred in Tammiku, Estonia.[6] In this case, three brothers illegally entered a radioactive waste depository. One of them put the source in his pocket and removed it from the site. He died subsequently from his radiation exposure.
- In 1998, 19 small Cs-137 sources went missing from a locked safe in a hospital in Greensboro, North Carolina. The sources, each 20mm by 3mm, were being stored for use in the treatment of cervical cancer. Though local, state and federal officials scoured the city using radiation-sensing equipment, the sources were never recovered. Authorities believe whoever stole the Cs-137 tubes may have been trained to handle the material.

3 In this document all references to radioactive sources are to *sealed radioactive sources,* which are defined by the IAEA as "radioactive material that is either permanently sealed in a capsule or closely bonded and in a solid form".

4 Johnston, R. (2014). Database of Radiological Incidents and Related Events. Retrieved from www.johnstonsarchive.net/nuclear/radevents/index.html.

5 IAEA. (1988). *The Radiological Accident in Goiânia.* Retrieved from www-pub.iaea.org/MTCD/publications/PDF/Pub815_web.pdf.

6 IAEA. (1998). *The Radiological Accident in Tammiku.* Retrieved from www-pub.iaea.org/MTCD/publications/PDF/Pub1053_web.pdf.

- In 1999, a company stored two packages containing cobalt-60 radiotherapy sources in its general-purpose warehouse in Istanbul, Turkey.[7] The warehouse was later transferred to new owners who did not realise what was in the packages. They were sold as scrap metal. The purchasers broke open the shielded containers in a residential area. A total of 18 people, including seven children, were admitted to hospital, with 10 adults exhibiting symptoms of radiation sickness. Investigations found that there were several contributing factors to the accident, including inadequate security and inadequate inventory control, that allowed the unauthorized sale of the packages to take place. A failure to recognise the radiation symbol was also an important factor.

- In December 2001, three men found two hot metal objects in a forest while collecting firewood in the village of Lia, Georgia.[8] They used the objects as heaters, spending the night in the forest. Shortly afterwards, all three men had nausea, headaches, dizziness and vomiting. They ended up in hospital and within a few weeks, Georgia had to request assistance from the IAEA. Two of the patients survived after two years of treatment and one died in 2003. The objects contained high activity Sr-90 sources, which had been used by the former Soviet army as radioisotope thermoelectric generators for radiometric devices and navigational systems. Thousands of these sources were used across several former Soviet countries and some were abandoned or lost. Fortunately, most have been recovered.[9]

- In 2003, a scientist in Guangzhou, China, attacked a colleague by deliberately exposing him to an Ir-192 source by placing it above a ceiling panel in his office. The intended victim and 74 other staff members reported symptoms of radiation sickness.

- In 2003, an 18-Ci Am-Be source, which was being used in a well logging operation, went missing in Nigeria. Despite extensive efforts, the authorities could not find the source. A few months later, it was located in Germany, without a clear trail.

- In 2009, a 2-Ci Cs-137 source belonging to a service company in Argentina was stolen from its secure vault by an ex-employee for extortion purposes. Fortunately, the man was apprehended and the source secured before it could cause any harm. The police could not establish how he got unhindered access to the source. The only explanation given was that he probably had insider help.

7 IAEA. (2000). *The Radiological Accident in Istanbul.* Retrieved from www-pub.iaea.org/MTCD/Publications/PDF/Pub1102_web.pdf.

8 IAEA. (2014). *The Radiological Accident in Lia, Georgia.* Retrieved from www-pub.iaea.org/MTCD/Publications/PDF/Pub1660web-81061875.pdf.

9 Sneve, MK., (2006). *Remote Control.* IAEA Bulletin 48/1. Retrieved from http://large.stanford.edu/courses/2013/ph241/jiang1/docs/sneve.pdf.

- In 2012, a 15-Ci Am-Be source used in a neutron porosity tool in Texas went missing in transit between two wells in the state. The joint efforts of multiple federal, state and local agencies, in collaboration with the service company, scrap dealers and local hospitals failed to recover the source. Instead, it was found by a member of the public. It is not clear how the source was lost.
- In 2013, a vehicle carrying a disused Co-60 teletherapy source was stolen in Mexico. This Category 1 source was removed from its protective shielding and left in a field near the town of Hueypoxtla in the state of Mexico. According to Mexican authorities, the source was not damaged or broken apart, so the surrounding area was not contaminated.[10]

All these examples, and the many more that are well documented by the IAEA and other organisations, demonstrate the relative accessibility of radioactive sources and possibility of misuse. A similar incident involving one of your sources, regardless of the harm it causes, has the potential to seriously damage your organisation's reputation and expose it to legal and other sanctions. At a practical level, such an incident could disrupt your regular operations for days or months, or even permanently, if contaminated areas cannot be cleaned up to an acceptable level. The associated costs related to any cleanup and the relocation of individuals and businesses could be enormous.

One way to reduce this risk is to improve the physical protection of your radioactive sources, particularly Category 1 and 2 sources. The IAEA[11] and WINS[12] have published a number of guidance documents on this topic. However, when considering your options for improving security, the most effective measure would be to completely remove the target (radioactive source) and replace it with an alternative that does not use radioactive sources. Ideally, this option, which would achieve permanent risk reduction, would deliver similar results at a comparable cost with minimum additional complications.

10 IAEA. (2013). Mexico says stolen radioactive source found in field. Retrieved from www.iaea.org/newscenter/news/mexico-says-stolen-radioactive-source-found-field.

11 www-pub.iaea.org/books/IAEABooks/Series/127/IAEA-Nuclear-Security-Series.

12 See for instance the WINS International Best Practice Guide 5.1 on *Security of High Activity Radiaoctive Sources*

THE ROLE OF KEY STAKEHOLDERS

When it comes to developing and promoting alternative technologies, many different stakeholders play a role. Examples include:

- End-users
- Regulators
- Device manufacturers
- IAEA
- International initiatives
- Professional associations
- Other Government agencies

END-USERS

The end-users[13] of radioactive sources are the key stakeholders in any attempt to replace current equipment or instruments with non-isotopic alternatives. They are generally the best qualified to assess the applicability of alternative technologies and to determine whether to replace the radioactive sources they are currently using. If they decide to adopt a new technology, they will require training and will likely participate in validation exercises. They are also in a strong position to contribute to the development of new procedures.

However, in practice many end-users are not contemplating a change of technology or not involved in the debate about the need for change. Despite several international initiatives and extensive discussions at global level about radiological materials being a security concern, many end-users are not yet fully aware of the vulnerability of the equipment and instruments they are using and of the possible non-isotopic replacements. Some reports have described the difficulties in convincing end-users to switch to less dangerous materials.[14]

End-users and in particular senior managers have a responsibility to engage with regulators and other major stakeholders to familiarise themselves with the source-related security concerns and to raise awareness of possible options to reduce security risks, especially through the use of alternative technologies.

13 End-user here refers to organisations, companies, manufacturers, hospitals, laboratories, universities and any other enterprises or practitioners who have been licensed to use a source for specific purposes. Although an individual or a few individuals might be the only users of the equipment or instruments containing the source in any of the entities mentioned above, the responsibility for selection of the technology used would not normally be in their hands. So the entity as a whole is considered “end-user”.

14 Pomper, M. & Gluck, A. (2015). *1540 Compass.* Removing Risk: Replacing High-Risk Radiological Sources with Alternatives. Retrieved from http://spia.uga.edu/wp-content/uploads/2016/04/Compass9_english.pdf.

REGULATORS

Regulators play a major role in the adoption of alternative technologies. They provide end-users with information on these technologies and opportunities for benefiting from the experiences of those who have replaced radioactive sources. Regulators may also implement policies to facilitate the adoption of alternative technologies through disincentives for the continued use of sealed sources. Disincentives may appear in various forms, including increased regulatory requirements for the security of sources, financial guarantees for anticipating proper disposal, and the requirement that operators justify the need to use a high activity radioactive source before being authorised to do so. Another major role for regulators with regard to reducing the risk posed by radioactive sources is the promotion of adequate legislation and the introduction of additional regulations when necessary.

For example, mainly in reaction to the terrorist attacks in the United States in September 2001, many regulators introduced new requirements for security that included increased background checks on personnel, improvements in facility physical security and increased monitoring. The burden of these new measures has prompted some operators to switch to alternative technologies.

In some countries, such as Canada, France, Germany and Switzerland, regulators now require operators to provide a financial guarantee to address the decommissioning of their facilities and the disposal of their sealed sources.[15] The financial guarantee is not necessarily intended to discourage the use of radioactive sources, but to address the fact that neither licensees nor manufacturers currently bear the full lifecycle cost of such sources, including disposal costs. The financial guarantee in a funding plan for decommissioning should also address the actual disposal of sources.

To increase security, several regulators have banned or strongly discouraged some radiation sources. For example, Denmark no longer permits Cs-137 sources for blood irradiation[16] and Norway requires a compelling justification to license Cs-137 devices. Regulators in Finland and Sweden strongly encourage the use of X-ray devices for irradiating blood.[17]

In the United States, the Nuclear Regulatory Commission (NRC) has taken a different approach. In its 2011 policy statement related to blood irradiators,[18] the NRC said that it "supports efforts by manufacturers to develop alternate forms of Cs-137 and to strengthen device modifications that could further reduce the risk of malevolent use associated with CsCl." The NRC further stated that:

15 See Volders, B. and Sauer, T. (2016) on the Further Reading list.

16 Ibid.

17 Ibid.

18 NRC. (2011, April 18). Proposed final policy statement on the protection of cesium-137 chloride sources. Retrieved from www.nrc.gov/reading-rm/doc-collections/commission/secys/2011/2011-0058scy.pdf.

> *"While it is outside the scope of NRC's mission to conduct developmental research, the Commission encourages research to develop alternative chemical forms for large activity Cs-137 sources. Given the state of the current technology, and because a less dispersible form does not negate the risk or a potentially large clean-up and economic cost, the NRC believes that, for the near term, it is more appropriate to focus on continued enforcement of the United States security requirements and to mitigate risk through cooperative efforts and voluntary initiatives of industries that currently manufacture and use CsCl sources."*

This approach appears to be common to many countries, but it could change as new alternative technologies come on the market.

OTHER GOVERNMENT AGENCIES

Other government agencies may also play a role in encouraging the adoption of alternative technologies. In many countries, government agencies sponsor the development of or evaluation initiatives for alternative technologies and the improvement of non-isotopic methods. Very often health ministries have direct responsibility for the oversight of medical practices in public medical institutions and may influence their technological choices and associated budgets. In some countries, the influence exerted on medical institutions stems directly from security concerns. In others, mainly developing countries, cost remains the driving factor.[19]

In the United States, the Environmental Protection Agency participates in several intergovernmental groups dedicated to investigating alternative technologies. It has funded projects to foster the development and technical acceptance of alternative technologies for several devices used in industrial applications.

DEVICE MANUFACTURERS

Device manufacturers play a central role in the development of radionuclide-based devices and alternative technologies because they are continuously upgrading existing products and developing new ones. To promote their products, device manufacturers participate in trade shows, industry conferences and other forums. Although they primarily focus on selling their current products, manufacturers take customers' expectations and requirements into consideration and are ultimately driven by their needs. In other words, they're market driven.

It is essential to involve device manufacturers in any international effort to encourage the development of alternative technologies. One example of such an effort is the Advisory Group on increasing access to Radiotherapy Technology in low and middle income countries (AGaRT)[20] that was established by the IAEA, through PACT, in 2009. The IAEA invited radiation oncology end-users, international experts on radiation oncology and the manufacturers of radiotherapy equipment to establish the Group. One of AGaRT's major goals is to encourage radiotherapy equipment manufacturers and suppliers to develop high-quality and safe but less-costly linear accelerators for use in developing countries. Several manufacturers have already engaged in this effort.

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19 Samiei, M. (2013). Challenges of making radiotherapy accessible in developing countries. *Cancer Control.* Retrieved from http://cancercontrol.info/wp-content/uploads/2014/08/cc2013_83-96-Samiei-varian-tpage-incld-T-page_2012.pdf.

20 http://cancer.iaea.org/agart.asp

PROFESSIONAL ASSOCIATIONS

Professional associations can play an important role in reducing the risks related to radioactive sources by endorsing, promoting and encouraging the adoption of alternative technologies and where possible funding studies to evaluate their performance. For example, in the United States, the Gas Technology Institute and the utility industry cooperated to conduct evaluation and validation studies of alternatives to portable nuclear moisture density gauges. After analysing five non-nuclear alternatives to portable nuclear gauges used in construction activities, they selected one alternative device and optimised it for use in construction activities unique to utilities. The two organisations also created an ASTM standard [ASTM D5874] for a test method using the alternative technology.[21]

In France, the welding society (Institut de Soudure) managed and funded a similar programme in which they evaluated six possible technologies to replace the gamma radiography inspection of pipe welds. They subsequently prepared guidelines on how to use two of the technologies. They also created ISO standards (ISO 10863 and ISO 15626) for the methodology and acceptance criteria for one of the technologies.

INTERNATIONAL INITIATIVES

Nuclear Security Summits[22]

In his 2009 Prague speech, the president of the United States stated that nuclear terrorism *"is the most immediate and extreme threat to global security."* To mitigate this threat, the president urged that *"we act with purpose and without delay,"* announcing *"a new international effort to secure vulnerable nuclear material around the world"* that would begin with *"a Global Summit on Nuclear Security that the United States will host."*

By focusing high-level attention on the threat of nuclear terrorism, the Nuclear Security Summits are designed to energise, enhance, empower and elevate the many existing multilateral and cooperative institutions and structures aimed at securing nuclear materials and preventing nuclear smuggling. In March 2010, nearly 50 heads of state gathered for the inaugural summit in Washington, the largest gathering of world leaders since the founding of the United Nations. A second summit was held in Seoul in 2012, a third took place in The Hague in 2014 and the fourth and final Summit took place in Washington in 2016.

> In the area of radiological security, the United States has 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 suppliers' countries.
>
> — Ernest Moniz, U.S. DOE Secretary, 2014 IAEA General Assembly

21 Farrag, K. (2006). Modification of the Clegg Hammer as an Alternative to Nuclear Density Gauge to Determine Soil Compaction. Gas Technology Institute. Final Report for U.S. Environmental Protection Agency.

22 www.nss2016.org.

The 2014 Nuclear Industry Summit Report of Working Group 3 (Managing Materials of Concern) stated that *"Other work to mitigate the security risk as early as possible in the lifecycle of sources has included the development of 'security by design' of devices containing sources, more robust physical and chemical forms, possible replacement of certain isotopes by others of lesser security concern, and alternatives to radioactive sources."*

At the 2016 Nuclear Security Summit, participating countries reinforced the importance of alternative technologies in their national statements and as a part of their follow-up engagements. As an example, as part of its national policies to minimise the use of high activity sources when technically and economically realistic, France announced in its Progress Report a gift basket on radiological security. It also highlighted its contribution to alternative technologies, including co-chairing with the United States an ad hoc working group of stakeholder states involved with alternative technologies. This working group is due to meet at least once in 2016 and once in 2017, and is designed to enable technical discussions on how to increase the use of alternative technologies in an economically and technically realistic fashion. End-users will be invited to share their experiences of implementing alternative technologies and the incentives and disincentives they face.

Other initiatives

In addition to these activities, the IAEA and a certain number of its donor Member States have developed projects supporting the transition to alternative technologies, in particular the replacement of cobalt-60 teletherapy devices in developing countries.

More recently, in the United States, the James Martin Center for Nonproliferation Studies and the National Cancer Institute, supported by the Stanley Foundation, have joined these efforts by launching targeted workshops with the aim of bringing together stakeholders from end-user cancer centres in developing countries and international experts to discuss practical ways of substituting linear accelerators for cobalt-60 teletherapy machines.

The IAEA AGaRT initiative mentioned above provides an important forum for discussion and the exchange of experience on radiotherapy. Its existence ensures that decision makers in developing countries have the necessary support for the safe and proper switch to alternative technology.

Major international stakeholders also coordinate their efforts to develop and share best practices regarding the adoption of alternative technology and the proper disposal of disused sources.

WHAT ALTERNATIVE TECHNOLOGIES ARE AVAILABLE?

Technologies that provide alternative methods of achieving measurement and treatment objectives are available for almost all applications using radioactive sources. The following is a brief review of some of the most prominent uses of radioactive sources in medicine and industry where the potential for changing to alternative technologies is promising.

See the references in the footnotes and the Suggested Reading section for additional information and website links.

MEDICAL APPLICATIONS

TELETHERAPY

Teletherapy is a general term for the use of high-energy ionizing radiation to treat cancers at some distance from the patient (as opposed to inside the patient). Teletherapy-based devices can deliver radiation to a patient's tumor in ways that range from simple to complex, depending on the treatment required and the sophistication of the device and planning system. Examples include delivering simply collimated radiation around a fixed isocenter from a few or many discrete points; delivering radiation continuously about a fixed isocenter with complex collimation to focus the radiation on the tumor; and focusing hundreds of radiation sources to a point in space and positioning the patient's tumor to that location.

The more precisely focused the radiation is on the tumor and the more dispersed the incoming beams, the less the surrounding non-cancerous tissue is exposed to radiation, thereby minimizing needless normal tissue toxicity. Modern teletherapy technologies are more precise and result in lower tissue toxicities than older technologies.

Radioactive Sources

The most common radioactive source used today is Cobalt-60, which is a synthetic radioactive isotope of cobalt-59. Co-60 is produced as a byproduct of nuclear reactors or by the neutron activation of Co-59. It generates two gamma rays with energies of 1.17 and 1.33 MeV during the radioactive decay process[23].

Teletherapy units using Co-60 were first developed in the 1950s and continuously modernised since. They are relatively simple and robust, so they generally require limited operational maintenance. These units are usually subject to regulatory requirements for the security of the radioactive sources they contain. They also do require periodic source changes owing to the radioactive decay resulting from Co-60's 5.27 year half-life. In recent years, as transport security has tightened and requirements for import and export permits for radiation sources have increased, trading in Co-60 sources has become much more costly and complicated, especially with regard to the logistics of transporting them across national and international borders.

23 Thomas, E, Popple, R, & Fiveash, J. (2016). Supplanting the old with the new: risks and waning benefits associated with medical use of cobalt-60 in the era of modern linear accelerators. Presented at the 2016 IAEA Conference on Nuclear Security: Commitments and Actions, Vienna. Retrieved from: https://www.wins.org/files/Supplanting_old_with_the_new-risks_and_waning_benefits_associated_with_use_of_Co-60.pdf

Alternatives

The most common alternative to a Co-60 unit is a medical linear accelerator (Linac). Linacs produce high energy X-rays in the process of e/X conversions. They achieve an energy range from ~4 MeV to 25 MeV by accelerating mono-energetic electrons of the same energy to near relativistic speeds and smashing them into a metal target. Linacs also offer other convenient options, such as on-board 2-D x-ray or volumetric CT imaging and electron doses for superficial treatments.

Although both types of teletherapy units are effective for cancer therapy, practitioners in the developed world have shown a distinct preference for Linacs for a variety of reasons. One is that they produce substantially higher energies that can penetrate deeper into the body. Another is that current Linac systems have outputs of up to 2400 MU/min (and even higher outputs are possible). This results in substantially faster patient treatments that are highly precise[24].

It has been argued that Co-60 teletherapy systems are more appropriate than Linacs for radiation therapy in developing countries due to Linac's initial cost and its requirements for reliable power, a skilled workforce and service costs. However new systems are being developed to address these issues. Furthermore when one factors in the costs of Co-60 security requirements, source replacement and eventual source disposal, Linacs become more financially viable, especially with the lower-cost models now commercially available.

Consequently, growing numbers of developing countries are replacing old Co-60 teletherapy technologies with Linacs[25]. According to the latest data published by the IAEA[26], approximately 3,035 of the 11,365 Linacs in the world are located in developing countries. Furthermore, many developing countries (including Algeria, Egypt, Libya, Morocco and Tunisia) have already introduced Linacs alongside their Co-60 machines. As Linacs become increasingly affordable, similar trends are expected to take place in many other countries.

The majority of new Linacs are purchased to replace decommissioned Co-60 teletherapy units. One of the greatest challenges in the move from Co-60 to Linac equipment is the safe and secure management of disused radioactive sources from the old Co-60 machines. All disused radioactive sources from decommissioned Co-60 machines remain a security concern until they are disposed of safely and securely according to IAEA guidance documents[27,28].

24 Samiei, M. (2013). Challenges of making radiotherapy accessible in developing countries. Cancer Control. Retrieved from http://cancercontrol.info/wp-content/uploads/2014/08/cc2013_83-96-Samiei-varian-tpage-incld-T-page_2012.pdf

25 Eid, R. (2016). Lessons learned from converting Co-60 teletherapy units. Presented at the International Conference on Nuclear Security: Commitments and Actions, Vienna. Retrieved from http://www-pub.iaea.org/MTCD/Meetings/PDFplus/2016/cn244/cn244FinalProgramme.pdf

26 IAEA (2016). DIRAC Directory of Radiotherapy Centers. Retrieved from www-naweb.iaea.org/nahu/dirac/query3.asp

27 IAEA. (2005). Disposal options for disused radioactive sources. Retrieved from http://www-pub.iaea.org/MTCD/Publications/PDF/TRS436_web.pdf

28 IAEA. (2014). Nuclear energy series no. nw-t-1.3. Management of disused sealed radioactive sources. Retrieved from http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1657_web.pdf

RADIOSURGERY

Radiosurgery (also called stereotactic radiosurgery or SRS) is a technique used to treat brain tumors and other intracranial abnormalities. It requires one—or at most a few—treatments. To perform the surgery, Co-60 radioactive sources are placed on a hemispherical device that focuses gamma radiation only on the brain tumor.

The first and most prevalent of these devices is called a Gamma Knife (GK). GK treatments are used where surgery is too dangerous or where intracranial surgery would have many more complications than non-invasive GK treatments. Each highly collimated Co-60 source in a freshly loaded Gamma Knife emanates ~30 Ci (curie) of radioactivity for a total of ~6000 Ci. From a patient's perspective, one of the biggest challenges to GK is that a rigid frame must generally be bolted to the patient's skull, and treatments can last from ~30 minutes to three hours or longer depending on the number and complexity of the targets and the age of the original source[29].

Another issue is that after five to ten years, the radioactivity decays to a point that treatment times become impractically long. The sources then need to be reloaded or completely removed, which can cost upwards of $1,000,000[23]. Although GK treatment is highly effective, security and disposal issues related to cobalt sources remain a concern and are an increasing topic of discussion given current world events.

Alternatives

Linear accelerators have begun to provide an alternative to cobalt-60 devices for the treatment of brain cancer. Co-60 devices were initially simpler to operate than Linacs, but over the past 15 years this type of radiation delivery has become increasingly more sophisticated and can now be used to treat any part of the body. In the past five to ten years, researchers have found that Linac-based radiation for brain tumors achieves dosimetry, safety and efficacy comparable to that achieved by Gamma Knife treatment. In fact some researchers have found that Linacs provide superior treatment efficiency[30].

The end result of the deployment of new Linac-based technologies has been improved treatments and an uptake of Linac-based radiosurgery. As evidence, Park[31] reports that the use of Linac surgery to treat brain tumors increased in comparison to Gamma Knife, from 3.2% in 2003 to 30.8% in 2011. These trends are likely to continue.

29 Lindquist C., & Paddick, I. (2007). The Leksell Gamma Knife perfexion and comparisons with its predecessors. Neurosurgery, 61, 130–140. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/17876243

30 Chen, C., Schulz, R., Lau, S., et al. (2016, December). Linac & Co-60 are comparable options for cranial radiosurgery: University of California, San Diego Experience. Presented at the 2016 IAEA Conference on Nuclear Security: Commitments and Actions, Vienna.
Retrieved from https://www.wins.org/files/Linac_&_Co-60_are_Comparable_Options_for_Cranial_Radiosurgery.pdf

31 Park, H.S., Wang, E.H., Rutter, C.E., et al. (2016). Changing practice patterns of Gamma Knife versus linear accelerator-based stereotactic radiosurgery for brain metastases in the US. Neurosurg. 2016 Apr;124(4):1018-24. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/26473783.

BRACHYTHERAPY

Internal radiation therapy, or brachytherapy, is used for treating some cancers. The procedure is most commonly used in conjunction with external beam radiotherapy, surgery or chemotherapy for treating endometrial, cervical, prostate and pancreatic cancer. It involves placing small amounts of a radioactive source next to tumours inside the body for certain periods of time to provide localised doses with minimal damage to surrounding tissues. Brachytherapy is also the primary treatment for soft tissue sarcomas, vaginal and rectal cancers, early-stage lip and tongue cancers, and endobronchial carcinomas.[32] The treatment involves inserting a radioactive source into or near the affected area requiring treatment. This allows a higher dose of radiation to be given to a smaller area than might otherwise be possible with treatments using teletherapy devices.

Radioactive sources

The radioactive sources normally used in brachytherapy are: Cs-137, Co-60, Ir-192, Iodine-125 and Palladium-103. Currently, no perfect radionuclide exists for all brachytherapy applications. To select the best application for the purpose, one needs to consider issues such as specific activity, half-life, the type and energy of emission, and shielding requirements. For example, Ir-192 has a high specific activity, which means that a very small amount can provide a very high dose rate. With effective photon energy of around 350 keV, a sufficient absorbed dose is ensured to treat the target area homogeneously. However, a shortcoming is that Ir-192 has a half-life of 74 days; this means that sources must be replaced approximately every three to four months to maintain an acceptable treatment time.[33]

Cs-137 is often used in gynaecological applications. Because it has a long half-life (30.2 years), it only needs to be replaced every 10 to 15 years. Some implants are even placed in the tumour permanently. For instance, prostate cancer and brain tumours are often treated with Iodine-125 seeds due to their short half-life (59 days) and the fact that photons generated are of such low-energy that they are absorbed within the patient.

Alternatives

In some cases, Linacs have replaced brachytherapy machines, in particular to treat oesophagus, lung, breast and skin cancer, even though the Linac treatment is generally more costly. However, radioactive sources are still considered to be the best treatment for some types of cancer, while more effective external-beam radiotherapy with Linacs is being investigated.[34] It is doubtful that the use of radioactive sources for brachytherapy can be replaced by equally effective non-isotopic radiation therapies anytime soon. Other types of treatment are also being investigated.

32 World Health Organization. (2011). *Remote-afterloading brachytherapy system.* Retrieved from www.who.int/medical_devices/innovation/remote_afterloading_brachytherapy.pdf.

33 IAEA. (2013). Radiation safety in brachytherapy. Retrieved from https://rpop.iaea.org/RPOP/RPoP/Content/InformationFor/HealthProfessionals/2_Radiotherapy/RadSafetyBrachytherapy.htm.

34 Kilic, S., Racchiolo, B., Mahmoud, O. (2015). Non-brachytherapy alternatives in cervical cancer radiotherapy: Why not? *Applied Radiation Oncology.* Retrieved from: http://appliedradiationoncology.com/articles/non-brachytherapy-alternatives-in-cervical-cancer-radiotherapy-why-not.

When two types of radiation therapy, such as external-beam radiation and brachytherapy, provide good results, the choice of treatment is exclusively a medical decision based on the particular circumstances of the patient and the equipment and expertise available.

BLOOD IRRADIATION

Blood is routinely irradiated in self-shielded gamma irradiators to prevent transfusion-associated graft versus host disease, a rare but usually fatal complication of transfusion where white cells from a donor's blood attack the receiver's tissue. The objective is to deliver the recommended dose of ionizing radiation to eliminate the proliferative capacity of lymphocytes.

Radioactive sources

Devices containing Cs-137 are commonly used in blood irradiation. They are preferred primarily because they have a large capacity and provide an even and rapid irradiation. Furthermore, the 30-year half-life of Cs-137 means that the source does not generally have to be replaced during the device's working life. They are also easy to use, reliable and have low maintenance and calibration needs. However, Cs-137 sources are in the form of a caesium chloride salt that is easily dispersed and extremely dangerous should the source capsule be breached (this is what happened in the Goiânia incident – see page 4). The salt is also easily soluble in water. The potential for harm is causing growing concern among regulators and end-users, and leading some countries to seek alternatives. Incentives range from encouragement to convert to outright bans on Cs-137 irradiators and have had varying degrees of success.

Alternatives[35]

X-ray source devices have been found to be equally effective in irradiating blood. They do not require a radioactive material licence, their safety requirements are less onerous and they eliminate security issues. A particular advantage of X-ray source devices is that they are much lighter so they have fewer structural limitations. They also provide a relatively quick irradiation cycle capacity that is almost as good as Cs-137 devices.

However, X-ray irradiators also have some distinct disadvantages that are of particular concern in developing countries. For example, they have a shorter lifespan than Cs-137 devices and more frequent down times, particularly if the power supply is erratic. Furthermore, most models require a cooling water supply that must be kept under constant pressure. They also require more frequent preventive maintenance, including periodic X-ray tube replacement or repair.

35 Pomper, M., Murauskaite, E., & Coppen, T. (2014). *Promoting Alternatives to High-Risk Radiological Sources: The Case of Cesium Chloride in Blood Irradiation.* Retrieved from www.nonproliferation.org/wp-content/uploads/2014/03/140312_alternative_high_risk_radiological_sources_cesium_chloride_blood.pdf.

Some consideration has been given to the use of Linacs to irradiate blood units, which would provide a homogeneous dose distribution. However, this application has not been widely adopted because the blood units must leave the blood bank for an indeterminate length of time, where they are subject to uncertain temperature control. Furthermore, the approach is cumbersome and may lead to delays. However, some recent reports indicate successful results using hospital Linacs with a different approach.[36] Another procedure that is gaining attention is the use of ultraviolet irradiation, which is advantageous because it abolishes lymphocyte mitotic activity and inactivates T-cells. It is already in use as a treatment for patients with blood infections. In addition, this technique does not require a radioactive material.

Although concern is growing, most regulators, with the exception of those in a few countries, have not yet introduced incentives that encourage or oblige the replacement of Cs-137 blood irradiator devices. Rather, regulators are focused on upgrading and enforcing physical protection systems that safeguard such devices from potential misuse. In addition, efforts are continuing to further increase security and reduce the risk by developing the design of irradiators, in recognition of the fact that, at the same time as we adapt and try to close security gaps, there are people who are working with malicious intent to uncover new security vulnerabilities.

INDUSTRIAL APPLICATIONS:

INDUSTRIAL IRRADIATORS[37]

Industrial irradiators expose products and packages to ionizing radiation for a wide range of reasons, such as sterilisation of medical devices and health care products, food preservation (improving food safety and shelf life) and modification of physical and chemical properties of materials (cross-linking, grafting or bonding of industrial polymers and plastics). Radiation can come from radioactive sealed sources (generally thousands to millions of curies of Co-60), electron beams or e/X-ray generators. More than 85% of industrial irradiation worldwide is related to the sterilisation of medical devices and instruments.[38]

Radioactive sources

Gamma sterilisation is a simple, proven process that is safe, reliable and highly effective. A 2008 IAEA report, *Trends in Radiation Sterilization of Health Care Products*[39], found that over 200 gamma irradiators are in operation for a variety of purposes in 55 countries; 120 of these are located in Europe and North America. Gamma irradiation has the ability to penetrate products while they are sealed in their final packaging, so it economises the manufacturing and distribution process while ensuring full sterility of the product.

36 Shastry, S., et al. (2013). Linear accelerator: a reproducible, efficacious and cost effective alternative for blood irradiation. Transfus Apher Sci.;49(3):528-32.

37 IAEA. (1996). *Manual on Panoramic Gamma Irradiators (Categories II and IV).* Retrieved from www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/025/28025757.pdf.

38 IAEA. (2010). *The Use and Management of Sealed Radioactive Sources.* Retrieved from https://www.iaea.org/About/Policy/GC/GC56/GC56InfDocuments/English/gc56inf-3-att6_en.pdf.

39 IAEA. (2008). STI/PUB/1313. *Trends in Radiation Sterilization of Health Care products.* Retrieved from www-pub.iaea.org/MTCD/publications/PDF/Pub1313_web.pdf.

In the medical field, the process is used to sterilise a growing number of items, including syringes, surgical gloves, artificial joints and implantable devices, such as orthopaedics and heart valves. Treated products can be used immediately and the entire treatment process is precise and reproducible.

Two types of commercial irradiators use radioactive sealed sources: underwater and wet-source-storage panoramic models. Underwater irradiators use sources that remain in water at all times, with the water shielding workers and the public. Items to be irradiated are placed in water-tight containers, lowered into a pool, irradiated and removed[40]. Wet-source-storage panoramic irradiation involves the submersion of a radiation source in water in an underground storage pool. Items to be irradiated are transported into the area on a conveyor and once there, the source is raised into the air to irradiate them. After the items have been irradiated, the source is lowered back into the pool. When the radiation source is above ground, it is fully shielded by a concrete shell that is almost two metres thick.

Alternatives

Electron beam accelerators are increasingly being used for a variety of sterilisation applications. Employing electron beams as a radiation source has many attractive features, such as nearly instantaneous dose delivery, scalability for different throughput and the ability to be integrated into an in-line process. However, electron beams have penetration limitations and are consequently somewhat inflexible when used in processing.

Gamma processing has several advantages over other sterilisation methods. Where irradiation of food (meat, poultry, fresh fruits and vegetables) is permitted, gamma radiation is generally preferred because it can penetrate deeply; in contrast, electron beams penetrate food to a shallower depth. Furthermore, ethylene oxide gas is used for most of the medical products that are incompatible with radiation exposure, such as catheters, IV tubing and endotracheal and angiographic balloons. However, this gas is carcinogenic and requires very strict measures to prevent its release into the environment where it is used.

High-energy X-rays (based on e/X convertors), which are running routinely for more than a decade, are capable of irradiating thicker items, but the process is more expensive owing to low energy conversion efficiency. The acquisition cost of X-ray irradiators make the technology competitive versus gamma for medium to large processing volume requirements. The higher the processing volume is, the more economical X-ray technology becomes. It is commonly accepted that X-ray becomes more economical that gamma from gamma equivalent capacities higher than 1.5 - 2 MCi. The use of electron accelerators as a radiation source is increasing, but it continues to be challenging to replace gamma irradiators, especially for non-uniform, high-density products.

40 U.S. Nuclear Regulatory Commission. (2014). Background on Commercial Irradiators. Retrieved from www.nrc.gov/reading-rm/doc-collections/fact-sheets/commercial-irradiators.html.

RADIOGRAPHY FOR NON-DESTRUCTIVE TESTING

Industrial radiography is a non-destructive procedure that uses ionizing radiation to view objects in a way that cannot otherwise be seen.[41] The procedure needs to provide sufficient energy to penetrate the material and produce an image of acceptable contrast and definition on processed radiographic film or a digital image in an acceptable amount of time. A special camera, called a radiography camera, is used to capture the images. Most industrial radiography activity is performed to examine welds for cracks and other flaws in gas and oil pipelines, metal welding, boilers, and vehicle, ship and aircraft components. Thousands of these devices are in use or in transport at any time around the world.

Radioactive sources

Radioactive sources (commonly Cs-137, Ir-192, Se-75 and Co-60) provide a source of ionizing radiation for the devices used in this procedure. The devices use a compact physical envelope and do not require any electrical power. Their small size means that they are easily transportable and that the radioactive source can move through small diameter pipes to make radiographs without difficulty. However, they have major safety and security disadvantages because the cameras house a high-risk Category 2 or 3 radionuclide and are frequently transported or used in areas where security measures may not be adequate. Where the amount of radioactive material is substantial, as in the case of industrial radiography sources, accidents have had severe or even fatal consequences.[42,43]

Another downside is that some of the sources used have a limited service life owing to their half-life, which means they must be replaced frequently. In addition, although the high energy of such sources means they have more penetration power, the resulting radiographs generally provide less contrast than X-ray equipment. Furthermore, they cannot be switched off and their intensity cannot be adjusted.

Alternatives

X-ray sources, in contrast to radionuclides, generate a continuous range of energies up to a certain maximum (depending on the operating voltage). However, conventional X-ray sources generally require 220 volt power, which can be challenging to acquire. They also require room for a cooling system (often water-based) and they are too large to move through most pipes. Therefore, X-rays have not traditionally been the best option for radiography. However, recent advancements in X-ray design have led to the development of pulsed X-ray sources that operate using battery power and have a physical size close to that of radioactive source housing.[44]

41 United States Environmental Protection Agency. (2016). EPA. Industrial Radiography. Retrieved from: https://www3.epa.gov/radtown/industrial-radiography.html.

42 IAEA. (1998). *Lessons Learned from Accidents in Industrial Radiography.* Retrieved from www-pub.iaea.org/MTCD/Publications/PDF/STIPUB1058-14815945.pdf.

43 Coeytaux, K., et al. (2015). Reported Radiation Overexposure Accidents Worldwide, 1980-2013: A Systematic Review. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4366065.

44 Light, GM. (2007). *Comparison of Pulsed X-ray Source Digital Radiography with Isotopic Radiography on Pipe.* Retrieved from: www.ndt.net/article/mendt2007/papers/light1.pdf.

As advances are made in computational resources and as more sophisticated analysis software becomes available, the number of inspections by gamma radiography could be further reduced. However, movement towards alternatives is relatively slow as traditional radioactive sources are easy to use and the new non-isotopic alternatives would not offer a major improvement in terms of cost or quality.

WELL LOGGING FOR THE OIL AND GAS INDUSTRY

In the search for hydrocarbons, oil and gas companies drill wells. In order to determine the viability of a well and the presence of hydrocarbons, various physical, chemical, electrical and other data relating to the geologic formations penetrated by the drilling must be recorded. This process is known as well logging.

There are various ways of capturing this data. Wireline logging involves the lowering of specially housed radioactive sources and detectors into existing well holes. Sources and detectors can also be mounted on collars behind drill heads to take measurements while wells are being drilled. This approach is called logging while drilling.[45]

Radioactive sources

Gamma sources are used to measure the density of rock strata around the borehole of an oil well. The process used is called backscatter measurement. The source must be well protected to withstand the high external pressures, temperatures and corrosive environments deep inside wells. In addition, a neutron log is the primarily method used to evaluate formation porosity. The measurements produced by these processes, combined with others, give an indication of the presence of hydrocarbons.

The two radionuclides that have been used for over 50 years for this purpose are Cs-137 (usually about 2-Ci), to measure density, and Am-241 (typically 16-20 Ci) in Am-Be neutron sources, to measure porosity (and thus the presence of hydrocarbons). Cf-252 is an alternative for Am-Be sources. The short half-life (2.65 years) of Cf-252 requires frequent isotope replacement and tool recalibration. New Am-Be neutron sources are expensive and hard to obtain. In contrast, Cf-252 is cheaper and its neutron energy is comparable to Am-Be.

Alternatives[46]

For a number of years, the petroleum industry has been investigating the use of alternative sources for well logging. However, efforts to replace current radioactive sources face a number of technical, logistical and financial challenges. Alternative tools are not as accurate as radioactive source devices in determining porosity.

45 The US National Research Council. (2008). Radiation source use and replacement: Abbreviated Version. Committee on Radiation Source and Replacement, Nuclear and Radiation Studies Board. Published by The National Academies Press. Washington DC.

46 U.S. Department of Energy. (2011). *Evaluation of Non-Nuclear Techniques for Well Logging: Final report.* Retrieved from www.pnnl.gov/main/publications/external/technical_reports/PNNL-20831.pdf

In addition, owing to physics and hardware limitations, wireline nuclear magnetic resonance (NMR) logging tools operate at much slower logging speeds than other logging tools. Some techniques do provide validation of source-based porosity and are currently being used to complement nuclear-based methods (i.e. acoustic to determine rock mechanical properties and NMR for fluid typing).

Another issue is that the tested alternatives noted here may not be generally available because the associated technologies are complex, making it difficult for small logging companies to design, test and deploy related devices successfully. In fact, to date generator-based porosity techniques have been deployed by only one major logging company. Services involving NMR logging tools are generally provided by major integrated logging service companies.

Replacing current methods could create interpretation issues, including changed porosity and lithology sensitivity, because of physical differences. Despite the ability to calibrate and assess new nuclear tool designs using computer simulation, considerable laboratory calibration and vendor field tests would still be required.

Users would have to adapt to new calibration charts and possibly develop new correlations for the tools' responses to geology. Years of experience with a tool in a given field may be needed, especially if the physics is significantly different.

Nevertheless, work is under way to improve both generator-based and non-isotopic porosity techniques. Further improvements in developing novel generators or other techniques are expected in the near future, but progress has been slow.

MOISTURE DENSITY GAUGE FOR THE CONSTRUCTION INDUSTRY

A vital element in any civil engineering project is compacted soil. To control the process of soil compaction, in-situ soil density and moisture content are commonly measured using a nuclear density gauge (NDG). The NDG is currently the standard device for control of soil compaction in construction around the world. Although these gauges usually use Category 3 or 4 sources (i.e. not high activity sources), they are included in this report because of the global scale of their use and the often lax security measures related to their operation.

Radioactive sources

The common NDG uses Cs-137 to measure density and Am-241 to measure moisture. The gauge operates by producing small doses of backscattered gamma waves. The radiation reflected from the soil is detected at the base of the gauge and converted to soil density when the gauge is calibrated to the specific soil. The gauge also has a neutron source to determine the moisture content by detecting the hydrogen content in a soil sphere around the gauge.

The use of NDGs is governed by regulations on storage, transmission and disposal, and these tools should only be used by licensed technicians who have received specific training. Because of their small size and their common use on construction sites, these devices are frequently lost or stolen, often together with the theft of a vehicle or other equipment. If gauges are damaged, there is the possibility that radioactive material could be released, contaminating the immediate area and exposing the public to radiation. Such an incident would have serious financial and reputational consequences for the construction company involved.

Alternatives

Efforts to develop alternative means of monitoring compaction performance and replace NDG use in the construction industry have been successful.[47] For example, Clegg impact soil testers measure soil densification and can be successfully used when calibrated to compaction efforts and moisture conditions for various soil types. They can also correlate soil compaction parameters (i.e. soil density and moisture content) on site.

The electrical density gauge (EDG) is a non-isotopic alternative for determining the moisture and density of compacted soils used in roadbeds and foundations. It measures the electrical dielectric properties and moisture levels of compacted soil using high radio frequency waves traveling between darts driven into the soil being tested. The EDG is a portable, battery-powered instrument that can be used anywhere without the concerns and regulations associated with radiation safety. It is easy to use and generally provides performance and measurement results that are highly comparable to those achieved with nuclear gauges.[48]

The non-isotopic, non-invasive soil density gauge uses electromagnetic impedance spectroscopy (EIS) to measure the density and moisture content of soil. This gauge is already on the market and is being tested with other alternatives[49,50]. EIS is the measurement of a material's dielectric properties (permittivity) based on the interaction of an external field with the electric dipole moment of the material under testing over a known frequency range. The density or compaction level is measured by the response of the soil density gauges' electrical sensing field to changes in electrical impedance of the material matrix. Since the dielectric constant of air is much lower than that of the other soil constituents, the combined dielectric constant increases as density/compaction increases because the percentage of air in the soil matrix decreases.[51]

47 Berney, E.S., Kyzar, J.D., & Oyelami, O. (2012). Device Comparison for Determining Field Soil Moisture Content. ERDC/GSL TR-11-

48 Humboldt Manufacturing. Electrical Density Gauge. Retrieved from www.humboldtmfg.com/electrical_density_gauge_2.html.

49 Berney, E.S., Mejias-Santiago, M. & Kyzar, D., (2013). *Non-Nuclear Alternatives to Monitoring Moisture-Density Response in Soils.* Geotechnical and Structures Laboratory. U.S. Army Engineer Research and Development Center. Retrieved from www.dtic.mil/dtic/tr/fulltext/u2/a583071.pdf.

50 Wells, J.E.R., (2014). Calibration of Non-nuclear Devices for Construction Quality Control of Compacted Soils. Theses and Dissertations–Civil Engineering. Paper 20. http://uknowledge.uky.edu/ce_etds/20.

51 Pluta, S.E., & Hewitt, J.W. *Non-Destructive Impedance Spectroscopy Measurement for Soil Characteristics.* Retrieved from www.transtechsys.com/pdf/sdg%20paper1.pdf.

RESEARCH APPLICATIONS:

SELF-SHIELDED IRRADIATORS

Self-shielded (or self-contained) irradiators are designed to deliver accurate and uniform radiation doses to small volumes of various biological and non-biological materials and products for mainly research purposes. This enables researchers to evaluate the response of target materials to different doses, dose rates and energies from the applied radiation source. Beyond that, the principal advantages of such small irradiators are that they are easy to install and operate, which is essential for radiation research. These irradiators are classified by the IAEA as Category I (dry source storage) and Category III (wet source storage).[52]

Radioactive sources

The sealed sources in a self-shielded irradiator are completely contained in lead shielding inside a dry container (or wet container, depending on the design). Consequently, human access to the sources is impossible. The activity of the radiation source, which typically consists of Co-60 or Cs-137, can be thousands of curies (normally limited to 25 kCi). It is well suited for irradiating laboratory animals and biological samples, sterilising insects and calibrating radiation detection instruments.

Alternatives

High-powered X-ray irradiators are being adopted for these purposes and can provide an alternative to self-shielded gamma irradiators. Such development has been made possible by the advent of large, distributed anode-emitting photons in almost 4ϖ geometry[53,54]. However, they have smaller photon energies.

Acceptance of small, low-energy X-ray irradiators will depend on their performance with respect to dose rate, dose uniformity, throughput, reliability, safety and ease of operation. There are promising efforts under way to develop such irradiators.[55]

The main obstacles to more widespread use of X-ray irradiators appear to be that users lack experience with these devices and have years of data based on existing techniques (using CsCl 660 keV energy). More side-by-side comparative studies showing the equivalence of X-ray irradiators and their application to different areas of research is needed to encourage further development of X-ray irradiators and their more widespread use.

52 IAEA. (1996). *Manual on Self-Contained Gamma Irradiators (Categories I and III).* Retrieved from www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/025/28025756.pdf.

53 Mehta, K. (2010). *Practical X-ray Alternative to Self-shielded Gamma Irradiators.* Retrieved from http://radsourcetechnologies.blogspot.co.at/2010/11/practical-x-ray-alternative-to-self.html.

54 Mehta, K. & Parker, A. (2011). *Characterization and dosimetry of a practical X-ray alternative to self-shielded gamma irradiators.* Radiation Physics and Chemistry.

55 S. Boucher, S., Ding, X., & Murokh, A. (2010). *Design of a Compact, Inexpensive Linac for Use in Self-contained Irradiators.* Applications of Accelerators, Technology Transfer and Industrial Relations. Proceedings of IPAC'10, Kyoto, Japan. Retrieved from https://accelconf.web.cern.ch/accelconf/IPAC10/papers/mopea047.pdf.

However, one interesting application of alternative technology to self-shielded irradiators has already been pioneered by the IAEA through its sterile insect technique (SIT) programme.[56] Traditionally, SITs uses self-shielded irradiators with Co-60 or Cs-137. In 2006, the IAEA purchased a standard low-energy X-ray machine and initiated a project to adapt, improve and validate the machine for insect sterilisation at its own Insect Pest Control Laboratory in Seibersdorf, Austria.[57] In 2012, the IAEA reported that its efforts to develop alternatives to the use of gamma irradiation in SIT applications had succeeded. The IAEA expressed its hopes that these results would stimulate the development of more X-ray based irradiation systems in order to increase competition and reduce the price of equipment for wider applications.

56 For over four decades the SIT has been a major subject of the Joint FAO/IAEA Programme on Nuclear Techniques in Food and Agriculture. It is "a method of pest control using area-wide inundative releases of sterile insects to reduce reproduction in a field population of the same species". It is therefore a type of „birth control" in which wild female insects of the pest population do not reproduce when they are inseminated by released, *radiation-sterilized males.* Sterilization is induced through the effects of irradiation on the reproductive cells of the insects.

57 IAEA. (2012). Nuclear Technology Review 2012 - Report by the Director General to 56th General Conference. Retrieved from https://www.iaea.org/About/Policy/GC/GC56/GC56InfDocuments/English/gc56inf-3-att1_en.pdf.

EVALUATING ALTERNATIVE TECHNOLOGIES IN THE LIGHT OF YOUR NEEDS

There are numerous issues to consider when weighing up the possibility of adopting an alternative technology. So, it is important to analyse all of the potential impacts that such a move could have on your organisation's operations. If you decide to adopt an alternative technology, you want the transition to be as seamless as possible. In conducting an analysis on adopting an alternative technology, you should consider the questions set out below.

1. What are your organisational needs?
2. Which replacement options would serve your needs best?
3. Will the new technology provide comparable results?
4. Will it be necessary to redesign your current facility and re-train your staff?
5. What about reliability and service?
6. What are the costs?
7. What are the safety/radiation protection implications of the change?
8. What are the regulatory implications of the change?
9. What is your level of exposure to potential liabilities?

It is recommended that you thoroughly consider examples of other organisations that have switched to the alternative technology you are contemplating. Their experiences, particularly if their organisation is similar to yours, will potentially provide important insight and help you to fully respond to these questions.

Details of some of these experiences are available in the public domain (including those relating to teletherapy,[58] blood irradiation,[59] well logging,[60] industrial irradiators[61] and self-shielded irradiators).[58] Some can be found in the documents listed in the Further Reading section.

58 There are quite a few reports and papers on this issue in the public domain. In addition to references in footnotes 28 and 29, the following three articles provide detailed discussions and reports on experiences related to the use of Linacs in developing countries:
- Salminen, E.K., et al. (2011). International Conference on Advances in Radiation Oncology (ICARO): Outcomes of an IAEA Meeting. *BioMed Central.* Retrieved from http://ro-journal.biomedcentral.com/articles/10.1186/1748-717X-6-11.
- Grovner, S., et al. (2015). A Systematic Review of Radiotherapy Capacity in Low- and Middle Income Countries. *Frontiers in Oncology.* 2014; 4:380. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4302829.
- McClement, M., Radiation Therapist at Wits Donald Gordon Radiation Oncology, Johannesburg, South Africa. Presentation at Med TEC Africa. Retrieved from www.slideshare.net/MelissaMcClement/africa-is-capable-of-using-linear-accelerators-in-radiotherapy-rather-than-cobalt-units-47107396.

59 Pomper, M., Murauskaite, E., & Coppen, T. (2014). *Promoting Alternatives to High-Risk Radiological Sources: The Case of Cesium Chloride in Blood Irradiation.* Retrieved from www.nonproliferation.org/wp-content/uploads/2014/03/140312_alternative_high_risk_radiological_sources_cesium_chloride_blood.pdf.

60 U.S. Department of Energy. (2011). *Evaluation of Non-Nuclear Techniques for Well Logging: Final Report.* Retrieved from www.pnnl.gov/main/publications/external/technical_reports/PNNL-20831.pdf.

61 U.S. Department of Energy. (2006). Report to the U.S. Congress on Alternatives to Industrial Radioactive Sources. Retrieved from http://c.ymcdn.com/sites/www.productstewardship.us/resource/resmgr/imported/07-%20NE_Task_Force_Report_May_30.pdf.

1. WHAT ARE YOUR ORGANISATIONAL NEEDS?

Start by identifying the procedures in your organisation that require the use of radioactive material. What benefits do they provide? Then consider whether the organisational needs are fully satisfied by using these procedures or whether the disadvantages of radioactive material make it important to consider alternative technologies that will accomplish the same goals. Look at each procedure separately. The objective should not necessarily be to eliminate all radioactive sources from your organisation, but to consider each one individually.

2. WHICH REPLACEMENT OPTIONS WOULD SERVE YOUR NEEDS BEST?

Identify the alternative technologies that could replace your radioactive sources. One or more of the options discussed in this report might work well for your organisation. In addition, you will need to conduct your own research, consult with other end-users who use similar techniques and discuss the issue with colleagues in professional associations. A great deal of valuable information exists on the internet.

3. WILL THE NEW TECHNOLOGY PROVIDE COMPARABLE RESULTS?

When adopting any new technology, you want it to deliver results that are either comparable to or better than those you have now. If you are researching medical procedures, two important questions are:

1. Is the cure rate the same or better?
2. Is the patient throughput comparable?

If you are researching either industrial or academic applications, it is vital to consider how comparable the data generated by the new system are to the data generated by the existing system.

4. WILL IT BE NECESSARY TO REDESIGN YOUR CURRENT FACILITY AND RE-TRAIN YOUR STAFF?

Adopting an alternative technology may present challenges in terms of your existing infrastructure. New equipment may require more space or increased power consumption. Large X-ray devices might require cooling water or additional air conditioning. In some cases, facility modifications may be required to address the increased weight of or increased noise generated by new equipment. The introduction of new technology may also demand new competences or skills that require the re-training of existing staff, which generates additional costs. You should carefully study the specifications and skill requirements for new equipment and determine what changes would be required to your infrastructure.

5. WHAT ABOUT RELIABILITY AND SERVICE?

You should investigate the reliability of the new technology and consider its impact on your organisation. Be sure to find out what the response time is from the manufacturer and/or equipment supplier; this is particularly important if you are considering purchasing equipment from a foreign supplier. If the new technology requires more maintenance or is prone to more frequent failures and expensive repairs, investigate whether a service agreement can be included with the original equipment purchase. If your organisation provides its own maintenance service, find out whether your existing personnel are capable of maintaining and repairing the new equipment. If you decide to rely on an outside service, find out what their service availability and response times are.

6. WHAT ARE THE COSTS?

Be sure to consider all lifecycle costs, not just the purchase price. In some cases, the purchase price may represent only a small portion of the total cost over the lifetime of the device. The cost of modifications could easily exceed the purchase price of a new device. The weight and dimensions of the new equipment, the need for additional staff, the cost of safety and security arrangements, etc., all need careful analysis. The following graph presents some of the major factors to consider.

The initial purchase price	Cost of facility modifications	Operating costs such as electricity and consumables	Throughput of patients, i.e., any loss of income
The cost of security	The cost and frequency of maintenance	Additional staff and training	The cost of developing new processes and procedures
Insurance	The cost of downtime (lost production, back-up contracting, etc.)	The cost of repair and replacement parts	End-of-life costs (disposal)

All of these issues should be carefully considered before making a purchase to ensure that you are not surprised when you begin to implement the new technology. The total cost for an alternative technology should be comparable to and preferably lower than what you have now. Most importantly, your productivity should not suffer.

7. WHAT ARE THE SAFETY/RADIATION PROTECTION IMPLICATIONS OF THE CHANGE?

When working with radioactive sources, there is an inherent safety risk associated with radiation exposure. This is particularly true in applications where the radiation source is exposed outside of its shield, such as with teletherapy, radiography and well logging. These safety issues are eliminated with technologies that do not use radioactive sources. However, X-ray radiation sources also have safety concerns, in particular in medical applications where much higher levels of exposure control, dosimetry and dose calibration are required. Also, higher shielding requirements will apply and a newly trained radiation safety officer will need to oversee operations.

8. WHAT ARE THE REGULATORY IMPLICATIONS OF THE CHANGE?

Because you are currently working with radioactive sources, you are no doubt familiar with the regulations governing the safe and secure management of these materials, as well as with the challenges inherent in transporting them. If you replace your radioactive sources with an alternative non-isotopic technology, you will experience some relief from the regulatory burdens associated with radioactive material. You might in particular experience a reduction in licensing activities, regulatory inspections and sealed source inventory reporting.

Depending on which alternative technology you are considering, you may be faced with new regulations. It is important to investigate what these might be. For example, converting from Co-60 to Linac increases quality assurance, dosimetry and radiation safety requirements. The use of X-ray devices will also involve adhering to new safety regulations, but those regulations may be less onerous than those for radioactive sources.

9. WHAT IS YOUR LEVEL OF EXPOSURE TO POTENTIAL LIABILITIES?

There may be costs (in the form of liability risk) related to the possession of sealed sources that licensees (end-users) are not taking into account when they make decisions related to the sources' purchase, use, storage and disposal. There is potential for radioactive material licensees to be held liable for third-party damages related to the misuse of their sources, though few nations have clarified how liability law may apply in such a case. Additionally, licensees may be expected to cover costs associated with government resources deployed to search for and recover missing or stolen sources (even if the source is eventually returned to the licensee rather than being disposed of).

REPLACING RADIOACTIVE SOURCES: SOME POSSIBLE CHALLENGES

When adopting an alternative technology, you are certain to face some challenges. Some of the most common include:

- Complacency
- Changes to operations
- Lack of legacy data
- Lack of codes and standards
- Management of disused sources

RESISTANCE TO CHANGE[62]

It is human nature to resist change. Many employees will feel satisfied and comfortable with current, familiar procedures and will resist the need to learn new processes and techniques associated with alternative technologies, even if they understand that the change is in the best interests of the organisation. Rather than simply forcing a change upon employees, it is important to work closely with them, make sure they understand why a change is necessary and know how it will ultimately benefit everyone in the organisation. In other words, obtain their support before any changes take place. This starts with support from senior management and may include employee engagement meetings that enable employees to express concerns, have their questions answered and contribute their ideas to the process.

It is also important to link the change of technology to other issues that the organisation's personnel already care about, such as concerns about improved security and public safety. Taking this step is an opportunity to strengthen employee engagement and increase support for the changes you are making.

CHANGES TO OPERATIONS

In most cases, the change to an alternative technology will impact your operations to some degree. For example, employees who are responsible for operating and maintaining the equipment will likely require training, and employees in other departments may require awareness training. Depending on the technology, some personnel may even need to develop new qualifications to perform and interpret the results from a new process, such as a non- destructive testing technique.

62 There is significant material on this topic in the public domain. Here is one recent article: Heathfield, S.M. (2016). *How to Reduce Employee Resistance to Change.* Retrieved from https://www.thebalance.com/how-to-reduce-employee-resistance-to-change-1918992.

In medical applications, the switch from Co-60 to a more complex Linac involves significant changes to quality assurance procedures (radiation protection, dosimetry and calibration) and additional training and education for staff. Patient, operator and public safety is a priority.[63]

In other cases, such as switching from a Cs-137 blood irradiator to an X-ray blood irradiator, the amount of training that operators have to undertake may be minor. However, in this case, training for service personnel could be more significant. In addition to training, other challenges for your organisation might include the need to write and validate new procedures.

LACK OF LEGACY DATA

Although an alternative technology may provide the results and data you need, the output may be of limited value if you cannot interpret it or if you have nothing to compare it to. Similarly, it is important to know that the radiation dose being delivered has the effect that you expect. Consider the case of medical research using gamma irradiators about which decades of data exist. The relationship between the radiation dose from a given radioisotope and the corresponding physical, chemical and biological effects on compounds and living cells may be well known. This issue also applies to research irradiators, well logging and radiography. In the case of down-hole applications in the oil and gas industry, enterprises involved are reluctant to replace current isotopic-based instruments for density measurements, hydrocarbon detection and well mapping because they fear that new instruments' outputs cannot be correlated with historic data that has been collected at substantial costs over many decades.

For example, when gamma radiation is replaced with X-rays these relationships will likely change. If new studies using X-ray irradiators are to build on existing research, the effects of

X-rays will first need to be correlated with the effects of gamma radiation. In the case of well logging, interpreting the data collected is always a challenge. The decades of existing records form a valuable library of information. The interpretation of subtle features contained in these records is of significant value to the oil and gas exploration community and helps to correctly characterise a well.

The demonstration of equivalence and correspondence/correlation between established and new sensing modalities and their relationship to historic records is critical to ensuring accurate data interpretation. Sufficient time and resources for establishing these relationships need to be provided during the changeover to an alternative technology.

63 Page, B.R. Et al. (2013). Cobalt, Linac, or Other: What is the Best Solution for Radiation Therapy in Developing Countries? *International Journal of Radiation Oncology,* vol. 89, issue. 3, pp. 476-480. Retrieved from http://dx.doi.org/10.1016/j.ijrobp.2013.12.022.

LACK OF CODES AND STANDARDS

Codes and standards establish a common agreement on the processes, practices and criteria required to achieve the greatest practicable uniformity of product or service. In some cases, the existing codes and standards are slow to change and may not yet recognise newer alternative technology.

Codes and international consensus standards are particularly important in the case of

non-destructive testing (NDT). The codes of practice not only prescribe the use of specific inspection techniques but can also affect the choices made in selecting alternative inspection techniques. In some cases, radiography using radionuclide sources is specified, whereas in others radiography is described without specifying whether the source is a radionuclide or an X-ray machine. Fortunately, in recent years, standards have been developed for new NDT techniques and most processes are now governed by a consensus standard.

EFFECTIVE MANAGEMENT OF DISUSED SOURCES[64]

Before you make the commitment to switch to a new technology, it is important to determine what needs to be done with the soon-to-be disused source. Some organisations made arrangements for disposal when they signed the original purchase contract, so disposal costs will not present a problem for them. However, other organisations have not made such arrangements. This means they will have to find a way to properly dispose of their old sources, which could be a significant and costly challenge. In fact, disposal costs can be a major reason for an organisation's reluctance to adopt alternative technologies.

If your organisation is in such a position, contact the original source supplier to determine whether they can take the source back. The supplier may offer a return option, either for free or for a fee. Ask about any buyback options and be sure to ask about any hidden fees, such as transportation and export permits. If the original supplier cannot help, other source suppliers may be able to accept and recover your source. Some countries have government-run source recovery programmes. Be sure to investigate whether such a programme exists in your country and whether your radioactive source is eligible. Also be sure to contact your regulator for additional options, suggestions and solutions. Another important source of support and advice is the guidance documents and other technical publications of the IAEA in Vienna.[65] Developing countries in particular can receive assistance from the IAEA with regard to the removal and disposal of their disused radioactive sources.[66]

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APPENDIX

QUESTIONS TO FACILITATE DISCUSSION RELATED TO THE ADOPTION OF ALTERNATIVE TECHNOLOGIES

This appendix contains a series of questions that organisations can use to evaluate their understanding of alternative technologies and to determine whether any of the applications they use that require radioactive sources can be replaced by non-isotopic alternatives. The questions make excellent prompts for generating discussion. Such a process helps individuals at all levels of an organisation reflect critically on their personal involvement and responsibility.

Have you considered the possibility of replacing your radioactive sources with non-isotopic alternatives?

What would you like to achieve? What needs, expectations and constraints do you need to consider when deciding whether or not to change?

What are the potential costs and liabilities faced by your organisation in the event of an accident involving or misuse of the radioactive sources it currently uses?

What benefits, drawbacks, costs and challenges would your organisation face should it change to non-isotopic alternatives?

How would replacing applications using radioactive sources reduce risk levels at your organisation?

Which technologies can best replace your radioactive source applications?

What is the primary driver for replacing your radioactive sources with alternative technologies (security, cost, efficiency, regulatory requirements, etc.)?

Who will promote the change in your organisation? Who will benefit from it? Is your executive leadership supportive of such a change? Is your regulator involved?

Have you researched and carefully vetted potential suppliers of alternative technologies? Have you received feedback from other organisations about potential suppliers, including their quality of customer support and lead times?

Have you sought advice or assistance from other organisations similar to yours? Or multilateral organisations such as the IAEA?

Will new staff or competencies be needed to operate new devices?

What financial impact will the change have? What are the short-term direct costs (e.g. purchase of equipment and facility modifications) and the medium- and long-term costs (e.g. maintenance and spare parts)?

How prepared are you to manage the conversion process? Have you established a plan for change management and created procedures to support the conversion process? Do you have a plan in place? Does it include engaging with all employees to be sure they understand and support the need to convert?

What happens to disused sources in your organisation? Does your organisation have an active radioactive waste management or disposal policy?

What costs and administrative actions are required to dispose of the radioactive sources you are planning to replace?

OUR VISION

All nuclear and other radiological materials and facilities are effectively secured by demonstrably competent professionals applying best practice to achieve operational excellence.

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 Graben 19, A-1010 Vienna (Austria)
Tel.: +43 1 23060 6081 | Fax: +43 1 23060 6089 | Email: info@wins.org | Internet: www.wins.org
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