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 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 were to be lost or stolen and fall into the wrong hands, they could cause bodily harm, significant social disruption, and anxiety in the community. Just one of the results would be damage to the reputation and credibility of any organisation involved.

Although adequate security measures will significantly reduce the risks 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 and potential liability for your organisation.

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 an alternative technology; 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-nuclear replacements.

In this special publication, we describe the advantages and disadvantages of several alternative technologies used in medicine, industry, research and academia. 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 an alternative—particularly if the replacement is more effective, less burdensome, and less costly.

We also present a process that will help you decide whether to adopt an alternate 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 to support your considerations.

All of this information will give you the background necessary to address senior management if you determine that the adoption of an alternative technology is a sound approach. Appendix A provides a set of questions that will help you determine whether these changes would be viable in your circumstances.

In preparing this publication, we have considered the experience of medical, industrial and academic practitioners and regulators. We have also considered guidance material published by the IAEA, selected national regulators and two WINS workshops focused on the international community's experience with alternative technologies.

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

This document is not a technical report and should only be used as as starting point for familiarising yourself with alternative technologies and for identifying the key issues and steps necessary when considering adopting one of these new technologies. 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. (Note that wherever possible, this publication uses the same terminology as that found in IAEA publications.)

We Welcome Your Comments

We plan to update the information in this publication periodically to reflect changing information and new ideas. Therefore, we ask that you read it carefully and then 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 its primary task is to serve its membership.

Dr Roger Howsley
Executive Director

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HOW ALTERNATIVE TECHNOLOGIES CAN CONTRIBUTE TO YOUR OPERATIONS AND SECURITY

Radioactive sources have a variety of essential and beneficial applications. However, if they are used improperly, particularly with malicious intent, they have the potential to cause significant damage and injury. There are numerous examples of radioactive sources that have been stolen or gone missing; some of these have caused harm, whereas other have had the potential to cause harm but did not do so. For example:

- In 1987, in Goiânia, Brazil, an abandoned and unsecured teletherapy device containing a Cs-137 source was stolen and 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, with inestimable psychological effects.[2]
- In 1998 nineteen small sources of Cs-137 went missing from a locked safe in a Greensboro, North Carolina, hospital. The sources, each only 20 mm by 3 mm, 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.
- 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 the victim's office. The intended victim and 74 other staff members reported symptoms of radiation sickness.
- In Nigeria in 2003, an 18-Ci Am-Be source went missing during transit after it was used at a well logging operation. An extensive effort failed to locate the source. It appeared in Germany months later, with no clear trail.
- In 2009, a disgruntled ex-employee in Argentina stole a 2-Ci Cs-137 source from a service company vault for extortion purposes. He was apprehended and the source was recovered before it could cause any harm. It was not clear how he had gained unimpeded access. The speculation is that he had insider help.
- In 2012, a 15-Ci Am-Be source used in a neutron porosity tool in Texas went missing in transit between two wells in West Texas. The joint effort 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.

2 IAEA. (1988). *The radiological accident in Goiânia.* Retrieved from www-pub.iaea.org/mtcd/publications/pdf/pub815_web.pdf

— 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 on 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.[3]

A security event involving one of your sources—regardless of its health effects—has the potential to seriously damage your organisation's reputation and open it to a range of further liabilities. At a practical level, such an event 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 for clean-up 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 as defined by the IAEA.[4] (The IAEA[5] and WINS have published a number of guidance documents on this topic.) However, when considering your options for improving security, the most effective 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 threat reduction, would deliver similar results at a comparable cost with few additional complications.

THE ROLES OF VARIOUS STAKEHOLDERS

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

- Practitioners/ Users
- Regulator
- Device Manufacturers
- IAEA
- International Initiatives
- Professional Associations
- Other Government Agencies

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

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

5 http://www-pub.iaea.org/books/IAEABooks/Series/127/IAEA-Nuclear-Security-Series

PRACTITIONERS/USERS

The practitioners, or users, of radioactive sources are the key stakeholders. They are generally the best qualified to assess the applicability of alternative technologies to their operations and to determine whether or not to replace the radioactive sources they are currently using. If they decide to adopt a new technology, they will require training and likely participate in validation exercises. They are also in a strong position to contribute to the development of new procedures.

NUCLEAR REGULATOR

The regulator plays a role in the adoption of alternative technologies by providing users with information on these technologies and opportunities for benefiting from experience and lessons learned from those who have replaced sources. Regulators may also implement policies to facilitate the adoption of alternative technologies via 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.

For example, in reaction mainly 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 prompted some operators to switch to an alternate technology.

In some countries, such as Canada, France, Germany and Switzerland, regulators are now requiring operators to provide a financial guarantee to address the decommissioning of their facility and the disposal of their sealed sources. 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 guarantees covered in a funding plan for decommissioning should also address the actual disposal of the 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, 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.

In the United States, the Nuclear Regulatory Commission (NRC) has taken a different approach. In its 2011 policy statement related to blood irradiators,[6] 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:

6 NRC. (2011, April 18). Proposed final policy statement on the protection of cesium-137 choloride sources. Retrieved from http://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 cleanup 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 in many other countries as well, but it could change as new alterantive 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 development or evaluation initiatives for alternative technologies and the improvement of non-nuclear methods. Very often, Ministries of Health 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 in developing countries, cost remains the driving factor.[7]

In the United States, the Environmental Protection Agency (EPA) participates in several intergovernmental groups dedicated to investigating alternative technologies and 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 since 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.

7 Samiei, M. (2013). Challenges of making radiotherapy accessible in developing countries. Cancer Control 2013. Retrieved from http://globalhealthdynamics.co.uk/cc2013/wp-content/uploads/2013/04/83-96-Samiei-varian-tpage-incld-T-page_2012.pdf

PROFESSIONAL ASSOCIATIONS

Professional associations can play an important role by endorsing, promoting or encouraging the adoption of alternate technologies and sometimes fund studies to evaluate them. For example, in the United States, the Gas Technology Institute (GTI) and the utility industry cooperated together 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 alternate 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.

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

INTERNATIONAL INITIATIVES

The 2014 Nuclear Industry Summit Report of Working Group 3 (Managing Materials of Concern) stated:

> *Other work to mitigate the security risk as early as possible in the life cycle 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.*

Also during the 2014 Nuclear Security Summit, the United States announced that:

> *The US plans 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*

> 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

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.[8]

8 http://www.nss2016.org

As an example, in its Progress Report, France announced a gift basket on radiological security and highlighted its contribution on alternative technologies to high-activity radioactive sources, including co-chairing with the United States an ad hoc working group of stakeholder States involved with technological alternatives. This working group will meet once every year in 2016 and 2017 at least and will enable technical discussions on how to spread such technologies in an economically and technically realistic fashion. Operators will be invited to present the lessons learned while implementing alternative technologies and the incentives and disincentives they face. These efforts came along with French national policies to minimize the use of high-activity sources when technically and economically realistic.

Finally, in addition to these activities, the IAEA and a certain number of countries have developed projects supporting the transtition towards alternative technologies, in particular the replacement of cobalt-60 teletherapy devices in developing countries. 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 alternate methods of achieving measurement and treatment objectives are available for almost all applications using radioactive sources. Following is a brief review of some of the most prominent ones. (See references in the footnotes and the Suggested Reading section for additional information and website links.)

TELETHERAPY

Teletherapy devices use high-energy ionizing radiation at a distance from the body to treat deep-seated tumours within areas such as the brain, bladder and lungs. These devices either rotate radiation around a patient or use multiple sources of ionizing radiation focused on the tumour. Both techniques focus multiple beams that precisely intersect at the tumour, which lowers the dose received by surrounding normal tissue. Co-60 sources provide an energy profile that has a relatively high discrete energy of 1.125 MeV. Commercially available medical Linacs produce X-rays and electrons with an energy range from 4 MeV up to around 25 MeV.

Radioactive sources

One way to treat a patient's tumour with the prescribed dose is to use an array of several thousand curies of Co-60 sealed sources. These high activity devices, first developed in the 1950s and continuously modernised since then, emit gamma rays that precisely deliver the desired exposure to the targeted tumours. They are also relatively simple and robust so they generally require limited operational maintenance.

Such units require security measures at facilities, but they are not generally overwhelming since the normal safety measures and barriers provide a starting point for effective physical protection. However, the units do require regular source changes due to the radioactive decay resulting from Co-60's 5.27 year half-life. In recent years—as requirements for transport security and import and export permits for radiation sources have increased—this exchange has become much more costly and complicated, especially the logistics of transporting sources across national and international borders.

Alternatives

The most common alternative to a Co-60 unit is the linear accelerator (Linac), which produces high energy X-rays. Linacs are especially versatile because they can provide variable dose rates and have the ability to deliver very high-energy radiation. Moreover, they offer the option of imaging and electron doses for superficial treatments.

Although both types of teletherapy unit are effective for cancer therapy, practitioners in the developed world have shown a distinct preference for Linacs. Today the vast majority of radiation therapy devices in high income countries are Linacs[9]. Nevertheless, Co-60 treatment still has a useful role to play in certain applications, such as radiosurgery.[10] Furthermore, since Co-60 machinery is relatively reliable and simple to maintain compared to Linacs, it is still in widespread use worldwide. For an organisation, the decision to convert to Linacs usually depends on radiotherapy experience, financial and technical capacity, access to reliable electricity supply and the availability of a demonstrably competent workforce.

BLOOD IRRADIATION

Blood is routinely irradiated in self-shieled gamma irradiators to prevent Transfusion-Associated Graft Versus Host Disease (TA-GVHD), a rare but fatal complication 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 described above.) The potential for harm is creating growing concern among both regulators and practitioners and leading some countries to seek alternatives. Incentives have ranged from encouragement to outright bans on Cs-137 irradiators, with varying degrees of success.

9 Samiei, M. Challenges of making radiotherapy accessible in developing countries. Cancer Control 2013. Retrieved from http://globalhealthdynamics.co.uk/cc2013/wp-content/uploads/2013/04/83-96-Samiei-varian-tpage-incld-T-page_2012.pdf

10 Elekta, Inc. Radiosurgery. Retrieved from https://www.elekta.com/radiosurgery/

Alternatives[11]

X-ray source devices have been found to be equally effective in irradiating blood. They do not require a radioactive material license, their safety requirements are less onerous, and they eliminate security considerations and requirements. A particular advantage is that the devices are much lighter in weight 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 source is erratic. Furthermore, most models require a cool water supply that must be kept under constant pressure. They also require more frequent preventive maintenance, including periodic X-ray tube replacement or repair.

Some consideration has been given to the use of linear accelerators 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. Such requirements basically eliminate the use of Linacs for blood irradiation. Another procedure uses ultraviolet irradiation, which has an advantage because it abolishes lymphocyte mitotic activity and inactivates T-cells. In addition, this technique does not require a radioactive material license.

Although concern is growing, most regulators have not yet instituted incentives to encourage or require the replacement of Cs-137 blood irradiator devices. Rather, they have focused on upgrading and enforcing the physical protection of such devices from potential misuse. In addition, efforts are continuing to further develop the security by design of the irradiators and to reduce the risk, recognizing that as we adapt and try to close security gaps, the adversary also adapts, opening new gaps.

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. Brachytherapy is also the primary treatment for soft tissue sarcomas, vaginal and rectal cancers, early-stage lip and tongue cancers, and endobronchial carcinomas.[12] 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.

11 Pomper, M., Murauskaite, E., & Coppen, T. (2014). *Promoting alternatives to high-risk radiological sources: A case of cesium chloride in blood irradiation.* James Martin Center for Non-Proliferation Studies. Retrieved from https://www.nonproliferation.org/wp-content/uploads/2014/03/140312_alternative_high_risk_radiological_sources_cesium_chloride_blood.pdf

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

Radioactive sources

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 an effective photon energy of around 350 keV, a sufficient absorbed dose is ensured to treat the target area homogeneously. A shortcoming, however, is that Ir-192 has a half-life of 74 days; this requires that sources be replaced approximately every three to four months to maintain an acceptable treatment time.[13]

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 low photon energy in which the radiation is absorbed within the patient.

Alternatives

In some cases, Linacs have replaced brachytherapy machines that use radioactive material—in particular to treat oesophagus, lung, breast and skin cancers —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. When two types of radiation therapy, such as external beam radiation and brachytherapy, both 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.

RADIOGRAPHY FOR NON-DESTRUCTIVE TESTING (NDT)

Industrial radiography is a non-destructive procedure that uses ionizing radiation to view objects in a way that cannot otherwise be seen. 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. Most of the industrial radiography activity is performed to examine welds for cracks and other flaws. This typically is performed for pressurized piping, pressure vessels and some structural welds. Thousands of these devices are in use or in transport at any time all over the world.

Radioactive sources

Radioactive sources (commonly Ir-192 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.

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

The downside is that each source has a limited service life due to its half-life, which means it must be exchanged 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. In addition, they cannot be switched off and their intensity cannot be adjusted.

Alternatives

On the other hand, X-ray sources generate a continuous range of energies up to a certain maximum (depending on the operating voltage). However, conventional X-ray sources generally require 220-V power, which can be challenging to acquire in the field. 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 field radiography. Recent advancements in X-ray design, however, have led to the development of pulsed X-ray sources that operate using battery power and that have a physical package whose size is close to that of the radioactive source housing.

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

INDUSTRIAL AND OTHER LARGE GAMMA IRRADIATORS

INDUSTRIAL IRRADIATORS

Industrial irradiators expose products to ionizing radiation for a wide range of activities, such as sterilisation of health care products and food preservation. Radiation can come from radioactive sealed sources (generally thousands to millions of curies of Co-60), X-ray tubes, or electron beams. The most commonly irradiated items are healthcare products, food containers and spices.

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*,[14] 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. 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.

14 IAEA. (2008). STI/PUB/1313. *Trends in radiation sterilization of health care products.* Retrieved from http://www-pub.iaea.org/MTCD/publications/PDF/Pub1313_web.pdf

Two types of commercial irradiators use radioactive sealed sources: underwater and wet-source-storage panoramic models. Underwater irradiators use sources that remain in the water at all times, providing shielding for workers and the public. The item to be irradiated is placed in a water-tight container, lowered into the pool, irradiated, and then removed.[15] Wet-source-storage panoramic irradiators submerge the radiation source in water in an underground storage pool. When the item moves into the room on a conveyor, the sources are raised into the air to irradiate it. Once this has taken place, 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 2m thick.

Alternatives

Electron accelerators are increasingly being used for a variety of 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, e-beams have penetration limitations and are consequently somewhat inflexible when used in processing.

Gamma processing has several advantages over other treatment methods. Where irradiation of food (meat, poultry, fresh fruits, 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 (EtO) is used for most of the medical products that are incompatible with radiation exposure, such as catheters, IV tubing, endotracheal and angiographic balloons.

High energy X-rays are capable of irradiating thicker items, but the process is more expensive. Large amounts of food would have to be irradiated to make this approach cost effective. 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.

SELF-SHIELDED IRRADIATORS

Research irradiators are used to expose biologic and non-biologic materials to radiation of various types. This enables researchers to evaluate the response of target materials to different doses, dose rates, and energies from the applied radiation source.

Radioactive sources

The sealed sources in a self-shielded irradiator are completely contained in lead shielding inside a dry container; consequently, human access to the sources is not possible. The activity of the radiation source, which typically consists of Co-60 or Cs-137, can be thousands of curies. It is well suited for irradiating small animals and biological samples, sterilising insects, and calibrating radiation detection instruments.

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

Alternatives

High-powered X-ray irradiators are also being adopted for these purposes and can provide an alternative to self-shielded gamma irradiators. Such irradiators have been made possible by the advent of large, distributed, anode emitting photons in almost 4π geometry.[16] 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. 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 would help.

WELL LOGGING FOR THE OIL INDUSTRY

Well logging is the practice of measuring the properties of the geologic strata through which a well has been or is being drilled. A well log is the trace or record of the data from a down-hole sensor tool that is plotted against well depth. It is most commonly used in oil and gas industries that are looking for recoverable hydrocarbon zones. Companies in oil and gas production need different kinds of information about a geologic layer, such as the hydrocarbon content. To measure these properties, sources and sensors are loaded into housings and then lowered into an existing borehole. (This technique is called *wireline logging.*) They can also be mounted in a collar behind the drilling head to take measurements while the well is being drilled. (This is called *logging while drilling,* or *LWD*).

Radioactive sources

Gamma sources are used to measure the density of rock strata around the borehole of an oil well using backscatter measurement. The source must be ruggedly constructed to withstand the high external pressures, temperatures and corrosive environments deep inside the wells. A neutron log is primarily used to evaluate formation porosity. These measurements, 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 sources to measure neutron porosity. Californium-252 is an alternative for Am-Be sources. The short half-life (2.65 years) of Cf-252 requires frequent replacement of the isotope and recalibration of the tool. 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.

16 Mehta, K. (2010). Practical X-ray alternative to self-shielded gamma irradiators. Poster presented at the Health Physics Society annual meeting, Salt Lake City, UT. Retrieved from http://radsourcetechnologies.blogspot.co.at/2010/11/practical-x-ray-alternative-to-self.html

Alternatives[17]

The petroleum industry has for a number of years 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. In addition, due to physics and hardware limitations, wireline 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 the generator-based porosity techniques have been deployed by only one major logging company. Service with NMR tools is generally provided by major integrated logging service companies.

Replacing current methods could create interpretation issues, including changed porosity and lithology sensitivity, because of the physics 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 underway to improve both generator-based and nonnuclear 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

The Nuclear Density Gauge (NDG) is the current standard device for the quality control of soil compaction in civil construction. Although these gauges generally use Category 3 or 4 sources, not high activity sources, they are included in this document because of their wide global distribution and commonly lax security measures in the field.

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 in a soil sphere around the gauge.

17 U.S. Department of Energy. (2011). *Evaluation of non-nuclear techniques for well logging: Final report.* PNNL-20831. Retrieved from http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-20831.pdf

NDGs require training and operation by a licensed technician and are governed by regulations for storage, transmission and disposal. Furthermore, NDG gauges are operated in very mobile conditions in the field. Because of their small size and common use in construction sites, these devices are frequently lost or stolen, often in conjunction with the theft of a vehicle or other equipment. Should such gauges be damaged, they could result in the release of radioactive material that could cause contamination and radiation exposure to the public, as well as serious financial and reputational consequences for the construction company.

Alternatives

Efforts to develop alternatives to monitor compaction performance and replace the NDG in roadway construction have been successful. 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) in the field.

The Electrical Density Gauge (EDG) is a nuclear-free 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 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 nuclear safety. It is easy to use and generally provides performance and measurement results that are highly comparable to those achieved with nuclear gauges.[18]

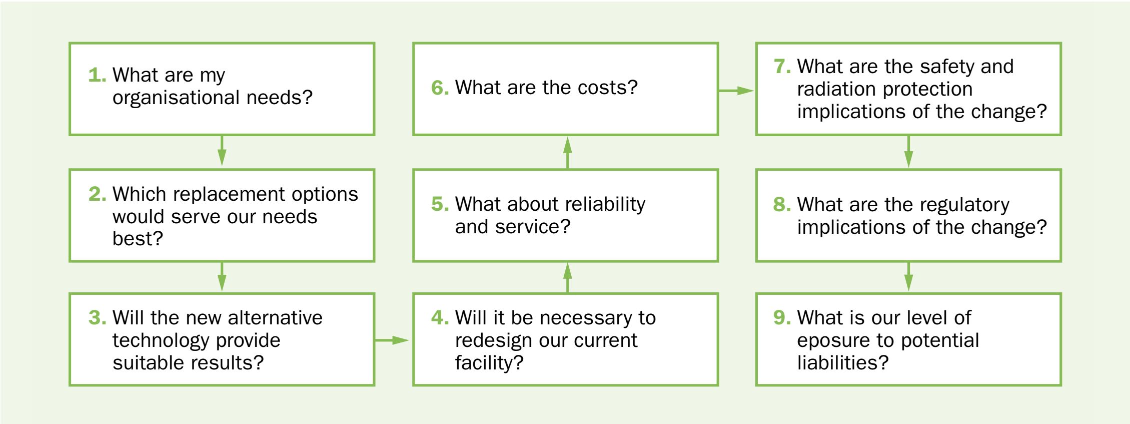
Electromagnetic impedance spectroscopy (EIS) is used in a non-nuclear, non-invasive instrument to measure the density and moisture content of soil. EIS is the measurement of a material's dielectric properties (permittivity) based on the interaction of an external field with the electric dipole moment of the material under test 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.[19]

18 Humboldt Manufacturing. Electrical Density Gauge. Retrieved from http://www.humboldtmfg.com/electrical_density_gauge_2.html

19 Pluta, S.E., & Hewitt, J.W. *Non-destructive impedance spectroscopy measurement for soil characteristics.* Retrieved from http://www.transtechsys.com/pdf/sdg%20paper1.pdf

EVALUATING ALTERNATIVE TECHNOLOGIES IN LIGHT OF YOUR NEEDS

There are numerous issues to consider when weighing 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 will want the transition to be as seamless as possible. To provide assistance in conducting such an analysis, we present a number of questions for you to consider.



1. WHAT ARE MY ORGANISATIONAL NEEDS?

Start by identifying the procedures in your organisation that use radioactive material. What benefits do they provide? Then consider whether the needs are fully satisfied by using these procedures or whether the downsides to radioactive material make it important to consider alternative technologies that will accomplish the same purpose. 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 OUR NEEDS BEST?

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

3. WILL THE NEW ALTERNATIVE TECHNOLOGY PROVIDE SUITABLE RESULTS?

When adopting any new technology, you want it to deliver results that are either comparable to what you have now or better. If you are researching medical procedures, two questions of prime concern 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, be sure to consider how comparable the data generated by the new system are to the data generated by the initial system.

4. WILL IT BE NECESSARY TO REDESIGN OUR CURRENT FACILITY?

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 increases in the weight or noise generated by the new equipment. You should carefully study the specifications for the new equipment and determine which changes would be required for 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 (especially after they have received any required training). 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 of the equipment, the need for additional staff, the cost of safety and security arrangements, etc., all need careful analysis. The following graphic 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 so you are not surprised when you begin to implement the new technology. The total cost for an alternative technology should be comparable and preferably lower to what you have now. Most importantly, your productivity should not suffer.

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

There is an inherent safety risk associated with radiation exposure when working with radioactive sources. 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 radiation. However, X-ray radiation sources also have safety concerns. For example, shielding requirements will remain, and a radiation safety officer will still 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 use and storage of these materials, as well as with the challenges inherent in transporting them. If you replace your radiation sources with an alternative technology, you will experience some relief from the regulatory burdens associated with radioactive material. You might also experience a reduction in licensing activities, regulatory inspections and sealed source inventory reporting, as well as a reduction in regulatory-mandated security requirements.

Depending on which alternative technology you are considering, you may be faced with new regulations, however, so be sure to investigate what these might be. For example, X-ray devices are subject to safety regulations, but they may be less onerous than those for radioactive sources.

9. WHAT IS OUR 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 are not taking into account when they make decisions related to the sources' purchase, use, storage and disposition. 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 as opposed to being disposed of).

REPLACING RADIOACTIVE SOURCES: SOME POSSIBLE CHALLENGES

Complacency | Changes to operations | Lack of legacy data

Lack of codes and standards | Management of Disused Sources

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

COMPLACENCY

It is human nature to resist change. Many of the staff will feel satisfied and comfortable with the current, familiar procedures and resist the need to learn new processes and techniques—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 and suggestions to the process.

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. In other cases, such as switching from a Cs-137 blood irradiator to an X-ray blood irradiator, the amount of training for operators 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 where many 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.

When gamma radiation is replaced with X-rays, for example, 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 many 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-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.

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 the newer alternative technology.

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

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. Other organisations, however, did not. 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 this 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.

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APPENDIX A

QUESTIONS TO FACILITATE DISCUSSIONS RELATED TO THE ADOPTION OF ALTERNATIVE TECHNOLOGIES

This appendix contains a series of questions that members of an organisation can use to evaluate their understanding of alternative technologies and how to evaluate whether any of the applications they use that require radioactive sources can be replaced by a non-nuclear alternative. 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 opportunity to replace your radioactive source technologies with alternative non-nuclear options?

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

What are the potential costs and liabilities to your organisation should the radioactive sources it currently uses go out of control and be used for malicious purposes?

What benefits, drawbacks, costs and challenges would you face when converting to a non-nuclear alternative?

How would replacing applications using radioactive material significantly reduce your organisation's risk?

Which technologies can best replace your radioactive source applications?

What is the primary driver for replacing your radioactive sources with an alternative technology (e.g. security, cost, efficiency, better outcomes, regulatory requirements)?

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?

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

Will new staff or competencies be needed to operate the new device?

What will the financial impact be of the conversion? What are the short-term direct costs (e.g. purchase of equipment and modification of the facility) and the medium- and long-term costs (e.g. maintenance, spare parts)?

How prepared are you to manage the process? Have you created a process to support the transition?

Do you have a plan in place for change management? 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?

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

Does your organisation have an active radioactive waste management or disposal policy?

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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To be the leader in professional development and certification for nuclear security management.

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