HOW SUPPORT FOR MACHINE-BASED SOURCES OF RADIATION CONTRIBUTES TO SUSTAINABLE DEVELOPMENT

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Abstract

As stated by the International Atomic Energy Agency (IAEA), radiation-generating technologies can be used in support of 9 of the 17 United Nations Sustainable Development Goals (UN SDGs). The U.S. Department of Energy/National Nuclear Security Administration's (DOE/NNSA) Office of Radiological Security (ORS), with the mission to prevent radioactive materials from being used in malicious acts, is working to improve options for and adoption of advanced machine-based sources of radiation. In addition to supporting radiological security, these activities directly support the broader development goals of the IAEA. This paper will focus on how the following three areas of ORS work contribute to both security and sustainable development: cancer therapy with medical Linear Accelerators (LINACs), X-ray blood irradiation, and electron beam (e-beam) technologies for reuse of resources and wastes.

Machine-based sources of radiation often provide key advantages over traditional, radioactive source-based means of generating radiation. For instance, X-ray blood irradiators allow consistent, and typically higher throughput across the lifespan of the device. E-beam technology can also play a significant role in providing clean water for growing urban populations around the world. While these technologies having operational, business, and security benefits, ORS recognizes that these technologies present challenges in terms of needing reliable power supply, trained/educated staff, and accessible service providers. This paper will highlight these challenges and ORS's perspectives on how the international community can work to address them. Time is of the essence, and advanced machine-based, radiation-generating technologies are essential to confronting the challenges associated with ensuring sustainable development.

1. INTRODUCTION

According to the International Atomic Energy Agency (IAEA), radiation-generating technologies can be used to support 9 out of the 17 United Nations Sustainable Development Goals (UN SDGs), as they have the ability to affect human health, food growth and safety, and environmental remediation, among sectors [1]. These radiation-generating technologies can include devices that rely on radioisotopes to generate radiation and machine-based radiation generators. While radioactive materials have social benefit across a variety of applications, these benefits must be considered alongside the concern of radioactive materials being misused, and the negative societal and economic impacts such an incident, accidental or intentional, could bring.

The U.S. Department of Energy/National Nuclear Security Administration's (DOE/NNSA) Office of Radiological Security (ORS) works to prevent the use of radioactive materials in acts of radiological terrorism and encourage the development and use of non-radioisotope-based technologies where possible. ORS supports the development and implementation of advanced machine-based ionizing radiation technologies, including electron beam (e-beam) and X-ray, in a variety of application spaces, including cancer care, the blood supply, food security, and environmental remediation. In many cases, these technologies provide equivalent (or superior) results to their radioisotopic counterparts. However, challenges remain to consistent implementation, including the need for reliable electricity supply, trained/educated staff, and consistently accessible service providers. Finding solutions to these challenges across a variety of application spaces can allow the meeting of joint goals of an improved radiological security environment and widespread access to beneficial radiation technologies, with benefits for humans and the planet writ large.

2. THE USE OF RADIATION TECHNOLOGIES FOR SUSTAINABLE DEVELOPMENT GOALS

In 2015, the UN adopted 17 aspirational SDG goals, meant to serve as a "universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity" [2]. These goals cover a wide range of social, environmental, and human security challenges and are meant to be implemented in a sustainable manner for long-term benefit.

The use of ionizing radiation technologies, both gamma and machine-based, is a key step in countries aiming to achieve the SDGs by the 2030 deadline. These technologies, many in service for decades, are used commonly throughout the world and provide benefits to human health, food security, and environmental remediation efforts. The use of gamma radiation was often the first foray into using radiation technologies in these applications, and many gamma devices remain in use today; however, many technologies that rely on machine-generated radiation have been developed and have gained more widespread acceptance in recent years. The figure below highlights some intersections between ionizing radiation technologies and the SDGs.

UN Sustainable Development Goal (SDG)	SDG Description	Applications of Interest
Zero hunger	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	• Phytosanitary treatment & food irradiation • Sterile Insect Technique (SIT) • Plant mutation breeding • Seed irradiation
Good health and well-being	Ensure healthy lives and promote well-being for all at all ages	• Radiotherapy • Blood irradiation • Medical research • Medical product sterilization
Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all	• Wastewater treatment
Industry, innovation, & infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation	• Non-Destructive Testing
Life below water	Conserve and sustainably use the oceans, sea and marine resources for sustainable development	• Plastics/polymer reuse and recycling
Partnerships for the goals	Strengthen the means of implementation and revitalize the global partnership for sustainable development	• Contributions to the IAEA that facilitate the use of machine-based ionizing radiation technologies

FIG. 1- Synergies between radiation technologies and UN SDGs

Machine-based radiation generators have low security risks, whereas certain radioisotopes pose an inherent security risk, as they can be used by malicious actors as the basis for a radiological weapon. If these radioisotopes fall outside of regulatory control, or if proper end-of-life management is not factored into the lifecycle operation of a radioisotopic device, they are vulnerable to neglect and eventually misuse, which can cause substantial psychological and economic damage, even if accidental. In 1987, the city of Goiania, Brazil suffered significant economic, physical, and psychological disruption as a result of an accidental misuse and spreading of radioactive material from an abandoned device that had fallen outside of regulatory control. Machine-based radiation generators, conversely, do not generate radiation if the system components are not complete, operational, and powered on, minimizing the risk for a radiological weapon or an accidental misuse.

3. NNSA OFFICE OF RADIOLOGICAL SECURITY

ORS works to enhance U.S. and global security by preventing high-activity radioactive sources (primarily Cobalt-60, Cesium-137, Iridium-192, and Americium-241) from being used malicious acts, like acts of terrorism. ORS achieves this through its Protect, Remove, and Reduce programs. The Reduce program works to achieve permanent risk reduction both domestically and internationally by encouraging the development and use of non-radioisotopic alternative technologies. This program focuses on four strategic approaches to achieve these goals, including encouraging policy that that facilitates or incentivizes the development and implementation of non-radioisotopic technologies (primarily machine-based sources of ionizing radiation); supporting research and development efforts related to the use of existing and new non-radioisotopic technologies; providing tools and forums that facilitate information exchange among users, industry, academia, and government personnel; facilitating the implementation of machine-based technologies, which includes the provision of logistics and cost incentives for replacing some radioisotopic sources with technically viable and operationally sustainable alternatives. These efforts have resulted in the replacement of over 280 radioactive source-based devices worldwide, primarily Cesium-137-based (Cs-137), as of June 2022, alongside increased awareness of the ionizing radiation technology options, benefits of using of non-radioisotopic technologies, policy and regulatory enablers, and research meant to fill technical and policy gaps in the implementation of machine-based technologies.

As machine-based sources of ionizing radiation, which utilize electricity to generate radiation, are often viable replacements for radioisotopes, ORS is keenly interested in the continued development of these advanced radiation generators. These accelerator technologies are used in a variety of application spaces, some of which are highlighted below.

Machine-Based Radiation Generating Devices	Application Examples
• Self-shielded X-ray Irradiators	• Research Irradiation • Blood Irradiation • Sterile Insect Technique (SIT) • Seed irradiation • Plant Mutation Breeding
• Medical Linear Accelerators (LINACs)	• Radiotherapy
• Industrial Electron Beam and X-ray	• Medical Device Sterilization • Phytosanitary Treatment & Food Irradiation • Plastics and Material Modification • Wastewater Treatment
• Mobile X-ray	• Non-Destructive Testing

FIG. 2- Prominent Machine-Based Radiation Generating Devices and their Applications

4. ORS ENGAGEMENT ON MACHINE BASED RADIATION TECHNOLOGIES AND SDG'S

4.1. External Beam Radiotherapy

External beam radiotherapy is one of the primary tools for treating cancers. As cancer rates increase worldwide, the need for capable, accessible, and robust radiotherapy services will continue to grow. Cobalt-60 (Co-60) traditionally was used for external beam radiotherapy and continues to be used in some parts of the world. However, medical linear accelerators (LINACs) have substantially overtaken Co-60 as the most common means of delivering radiotherapy machines in the world and are now considered the standard for radiotherapy treatment.

Medical LINACs hold key advantages over Co-60 machines, and many of these advantages help to minimize the gap in overall patient treatment needed for the global cancer burden. Given the lack of source decay in a LINAC (Co-60's half-life is 5.26 years), treatment times can be consistent throughout the lifespan of the device. This, coupled with LINACs' improved patient treatment times (given the nature of their beam generation), allows for superior patient throughput without negatively impacting quality of care for patients. As LINACs are the standard treatment for radiotherapy and have been for some time, significant research and development efforts exist to optimize these systems, leading to improved access to advanced technical machinery, treatment options, and improved beam accuracy through advanced techniques, which minimizes the harm to healthy tissue for patients. New developments in LINAC technology aim to improve system resilience and function in challenging environments, while at the same time decreasing costs and improving treatment affordability. Lastly, medical LINACs do not require radioactive material security systems or costly and complicated radioactive waste management.

ORS Support for LINAC Use in External Beam Radiotherapy

ORS support for the adoption of medical LINACs continues to grow internationally. While ORS support is rooted in its security mission, this work is making a small contribution to the realization of the third SDG – "Good Health and Well Being." However, given the large capital investment inherent in procuring radiotherapy devices, ORS does not directly purchase medical LINACs. ORS does engage with the IAEA's Programme for Action for Cancer Therapy (PACT) and various regional Divisions within Technical Cooperation (TC) to provide funding, on a cost-sharing basis, for projects supporting procurement of LINACs in Member States. For example, ORS provided $4.5 million USD in 2021 in support of the procurement of four LINACs. ORS also pledged an in-kind contribution for maintenance and repair, to include spare parts, for the medical LINAC at IAEA Dosimetry

Laboratory in Seibersdorf, which was opened in 2019 to support Member States with dosimetry calibration and training, among other things. On a bilateral basis, ORS works with international partners to remove disused Co-60 radiotherapy devices that are being replaced with machine-based technologies. These sources are then placed in safe and secure long-term storage or disposal. ORS also has helped with infrastructure modifications for facilities looking to transition away from radioisotopes. One prominent example of this involves ORS support for bunker modifications needed to install a medical LINAC, as many Co-60 bunkers do not have adequate shielding to accommodate some of the modern medical LINAC systems. However, this issue has become less of a concern in recent years with the development of new LINAC systems that can be placed in existing bunkers. Reliable electricity is important for continued patient treatment and integrity of LINAC components, and another example of ORS-supported infrastructure modifications that facilitate machine-based technologies includes installation of uninterrupted power supply (UPS) systems to improve a facility's electrical resiliency. ORS also works with other offices in DOE/NNSA to support research and development aimed at developing medical LINACs that meet operational challenges present in markets with inconsistent power, are more affordable, use resilient components, and do not require complicated servicing.

4.2. Blood and Research Irradiation

In many countries, blood is irradiated before transfusion to ensure patient safety, a component of ensuring human health. Irradiation inactivates the donated blood's lymphocytes, eliminating the risk of transfusion-associated graft-vs-host disease (TAGVHD), a rare but typically fatal condition associated with transfusions. Traditionally, blood irradiation has been achieved with self-shielded Cs-137 irradiators containing Category 1 levels of radioactive material. Self-shielded irradiators refer to devices in which the shielding required for machine operation is integrated into the design of the device, leaving the irradiation chamber inaccessible during operation. Recently, X-ray blood irradiators have become more reliable and efficient, and have grown in recognition and use both domestically and internationally as viable replacements.

Research irradiators are used in a variety of studies involving cells, tissue or small laboratory animals as well as nonbiological material. Traditionally, these devices also rely on Category 1 levels of Cs-137 or Co-60, depending on the machine specifics. The use of X-ray machines, however, has continued to grow for many of these sub-applications as well.

X-rays offer several prominent advantages over radioactive-source-based options. X-ray sources do not decay over time, meaning that radiation times and throughput remain consistent through the lifecycle of the device, whether research or blood-oriented. X-ray devices also permit a broader range of energies to be used to conduct research areas across a range of subjects. Blood throughputs can also be higher with X-ray, allowing for improved facility efficiency. X-rays require less physical security than radioactive sources, which simplifies operation and workflow. Finally, the lack of radioisotopic sources means that no radioactive waste management needs to occur at the end of life of an X-ray system.

ORS Support for X-ray Use in Blood and Research Irradiation

ORS support for the use of X-ray devices as self-shielded irradiators for blood and research irradiation is its most advanced and recognizable effort related to encouraging radiological risk reduction. Considering the advantages of using X-ray listed above, ORS support in this area also contributes to the realization of the third SDG – "Good Health and Well Being." In the United States, the Cesium Irradiator Replacement Program (CIRP) has led to the removal of over 245 radioactive source-based self-shielded irradiators (both blood and research) from hospitals, research facilities, and blood banks to safe and secure disposition. More importantly for sustainable development, ORS has replaced over 35 radioactive-source based irradiators internationally with X-ray systems since the program began in 2016. Financial support was provided for the safe and secure radioactive source removal and the X-ray purchase price, installation, and maintenance for one year. Finally, ORS has worked with other DOE/NNSA offices to support research and development efforts for new, more effective, more economical, or more robust X-ray systems that can handle challenging infrastructure environments and meet market demands. For example, ORS and its agency partners are supporting industry in the development of a series of flat-panel X-ray sources that would reduce the size and complexity of x-ray irradiators and improve reliability, dose uniformity, and dose targeting.

4.3. Irradiation for Environmental and Agricultural Problems

Growing populations, climate variability and extremes, and conflict challenge global food security. Foodstuffs can be treated with radiation to inactivate pathogens, which can improve the products' shelf life and food safety by minimizing the risk of foodborne illness; they also can undergo "phytosanitary" treatments, where radiation is used to inactivate pests that may be present in shipments of foodstuffs that could prove harmful to crops elsewhere. Given the positive impacts irradiation has in reducing product loss, enabling trade, and food safety (all related to the SDG of "Zero Hunger"), the irradiation of food and phytosanitary treatments will become increasingly important. Food can also be treated in several ways with radiation. Co-60 remains the predominant method of irradiating foodstuffs, though the use of electron beam and X-ray technology is increasing worldwide.

Though the technical requirements for food irradiation and phytosanitary irradiation differ, accelerator-based systems provide several distinct advantages over radioisotopic options. Accelerators can deposit dose at higher rates than Co-60, on the order of seconds (for electron beam) or minutes (for X-ray) instead of possible hours (for gamma). This provides different advantages between these modalities; for electron beam, the rapid dose deposition can allow for very high throughputs, although one must consider packaging or the use of two beams to achieve desired penetration depth. For X-ray, pallets similar to those treated in Co-60 panoramic irradiators can be treated in less time. In either case, improved throughputs can lead to improved economics if processing systems are optimized. Accelerator-based alternatives also provide a solution to supply chain challenges with Co-60, which in the best of circumstances requires years to manufacture in nuclear reactors. As economic and political pressures challenge the supply of Co-60, reliance on it for sterilization can prove logistically challenging. Additionally, not relying on a radioisotope eliminates the need for regularly transporting and handling hazardous material to re-source a sterilization facility.

Radiation technologies also can be used to treat a range of wastes to allow for reuse, including industrial and medical wastewaters, industrial sludges, and plastics. As wastewater disposal, water availability, and plastics waste become increasing concerns under a growing population and a changing climate, irradiation treatment will be an increasingly important resource in achieving the SDG of "Clean Water and Sanitation," among others. These treatments can have positive impacts on the environment and human access to resources. Radiation can be used at lower doses to treat pathogens in wastewaters, which can help in providing clean sources of water. At higher doses, radiation can be used to treat chemical sludges and plastics to improve recycling characteristics or create other products of value from the components of the sludges. Some pilot facilities have utilized electron beam facilities for wastewater treatments, both in the United States and internationally; notably, a pilot facility for treating dyes in wastewater recently opened in China. Co-60 can be used to treat certain types of sludges.

As in food irradiation, accelerator technologies allow for more facility design flexibility and are capable of depositing doses at a higher rate than radioisotopes. This is particularly of value in reuse applications, given the customization and high throughputs needed to ensure profitability. Additionally, accelerators facilitate independence from global radioisotope supply challenges, which is particularly significant in applications where hundreds of thousands of curies of activity may be needed from radioactive sources.

ORS Support for Use of E-Beam and X-ray for Environmental and Agricultural Irradiation

Given its short existence and early focus on self-shielded irradiators, ORS's Reduce program is only beginning to support the development and adoption of accelerators for larger commercial uses. Primarily, ORS supports subject matter experts and researchers in conducting comparison studies and sharing information and best practices with interested potential users. In this regard, ORS's partnership with and support for technology installation at Texas A&M University's National Center for Electron Beam Research (NCEBR), which is an IAEA Collaborating Center, is crucial. NCEBR works with U.S. and international partners to conduct testing on a variety of medical, food, and other products with accelerator and gamma technologies at a variety of energy levels and doses. By expanding the accelerator energy and power options at NCEBR, they will be able to offer additional and more diverse product testing and validation services, including to international partners. ORS also supports NCEBR in conducting of comparison, feasibility, and cost/benefit studies to support the international transition to accelerator-based systems.

Regarding irradiation for water and plastics reuse, ORS is supporting research and bilateral technical exchanges related to the use of accelerator technologies. Additionally, ORS is supporting the IAEA's NUclear

TEChnology for Controlling Plastic Pollution (NUTEC), which will facilitate the growth of Member State expertise on and capabilities for using accelerator technologies for plastic upcycling and downcycling [5].

5. CHALLENGES

Although the use of machine-based ionizing radiation technologies presents many valuable operational and security benefits, ORS recognises that several significant challenges continue to hinder adoption of these technologies, and particularly in low- and middle-income countries. For example, accelerator technologies, particularly high-power sterilization systems and medical LINACs, can have higher initial procurement costs than their radioactive source-based options. In addition, these technologies require adequate and reliable electricity supply for continuous operation, and inconsistent power can lead to machine damage in some cases. Trained staff also are required for effective operation and maintenance, requiring an educational pathway to develop the necessary skills. Finally, as machine-based ionizing radiation technologies are typically more complex than radioactive source-based options, access to viable service providers and spare parts is crucial to keep systems in operation.

Global input from government, users, and industry is needed to meet these challenges. First, awareness raising of technology options is important. One way that ORS supports awareness raising is by connecting prospective users with experienced users or researchers who can share information and experience about using the machine-based technologies (it is important to note ORS's vendor-agnostic approach in these engagements). Another example of awareness raising is the annual Ad Hoc Working Group on Alternatives to High-Activity Radioactive Sources, which is co-chaired by France, Germany, and the United States and aims to facilitate an international exchange of experience and perspectives on machine-based technology adoption, use, and development. This meeting is open to governments, technology users, non-governmental organizations, and sometimes industry. Whatever the venue may be, new and diverse perspectives always are needed. As awareness of the value of machine-based ionizing radiation technologies increases, ensuring that these forums continue and grow is essential.

For technical challenges, the need to develop resilient, affordable, and easy-to-use technologies that can operate effectively in resource-constrained environments is important. Industry must understand and respond to market and user demands, but governments can also help catalyse innovative technology development. Another important aspect in the sustainability of machine-based technologies is having affordable, local service providers and accessibility to spare parts. ORS encourages governments and users to talk to vendors about how to ensure service and spare parts are quickly accessible in the case of downtime, and to reach out to the international community when support is needed.

Lastly, in order to address resource limitations preventing the adoption of machine-based technologies, there is an opportunity for the security and research communities to engage more with government and international organizations and banks focused on sustainable development. The lack of reliable electricity and water, or the absence of relevant education and training programs, cannot be addressed overnight; however, bridges can be built with the sustainable development community to discuss the relevance of ionizing radiation technologies to Sustainable Development Goals, and specifically *how* to make machine-based ionizing radiation technologies a sustainable option.

6. CONCLUSION

Machine-based ionizing radiation technologies can provide results that are meaningful to the UN's Sustainable Development Goals, including those that address healthcare, food security, and clean water. These results are delivered without the additional security risks and costs that come with the use of radioactive sources. While real challenges exist to implementing sustainable accelerator systems, including meeting power requirements and guaranteeing spare part accessibility, momentum to meet these challenges continues to expand. Further engagement and projects aimed at encouraging the adoption of accelerator technologies will have positive impacts for security, human health, and the planet.

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REFERENCES

[1] International Atomic Energy Agency. "Sustainable Development Goals". International Atomic Energy Agency. (2021), https://www.iaea.org/about/overview/sustainable-development-goals

[2] United Nations. "The SDGs In Action". UNDP. (2021), https://www.undp.org/sustainable-development-goals

[3] International Irradiation Association. "A Comparison of Gamma, E-Beam, X-ray, and Ethylene Oxide Technologies for the Industrial Sterilization of Medical Devices and Healthcare Products". IIA, 2017.

[4] International Irradiation Association. "A Comparison of Gamma, E-Beam, X-ray, and Ethylene Oxide Technologies for the Industrial Sterilization of Medical Devices and Healthcare Products". IIA, 2017.

[5] International Atomic Energy Agency. "NUclear TEChnology for Controlling Plastic Pollution". International Atomic Energy Agency, 2021.