**RADIOLOGICAL RISK REDUCTION THROUGH THE UTILIZATION OF LOW ENERGY ELECTRON BEAM**

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**Abstract**

While cobalt-60 and cesium-137 have typically been used to irradiate materials for both research and industrial sterilization, the Office of Radiological Security (ORS) and its partners are investigating the viability of electron beam for various applications to reduce this radioisotopic footprint and improve global radiological security. Advantages of electron beam irradiation include lower capital costs than isotope-based technologies, the ability to turn on and off the machined source, the ability to deliver highly customized doses for specific applications, and the possibility of harnessing various e-beam energies for different applications. Currently, electron beam systems greater than 1 MeV require customized shielding and capital expenditure greater than $ 1 million for turnkey systems. Low energy e-beam systems (80 keV – 300 keV) allow for self-shielding and the possibility of in-line use in industrial processing. Today, low energy e-beam systems are in commercial use for polymer crosslinking, grafting, curing of printing inks, sterilization of aseptic food packaging, surface disinfection of eggs and seeds, and spice disinfection, etc. Greater availability of low energy e-beam technologies will catalyze research and development in the adoption of low-energy e-beam technology. Increased familiarity with low-energy e-beam technology can lead to greater interest and possible adoption of medium (1 MeV – 5 MeV) and high energy (7 MeV – 10MeV) e-beam technology. There is an expanding interest in polymer modifications and other surface treatment processes in many regions of the world especially in the emerging markets in Latin America and Asia. Low energy e-beam technology is ideally suited for these applications. Presently, government programs provide cesium-137 irradiation users a financial incentive to switch to x-ray technology. The underlying hypothesis is that easy access to low energy electron beam technology by researchers can stimulate research and development programs in emerging countries in electron beam technology that in turn, can accelerate the transition away from cobalt-60 or cesium-137 technologies. This transition to machined sources such as electron beam will ultimately facilitate reduction of the risk while still maintaining current, and in some cases, enhanced irradiation capabilities.

## INTRODUCTION

As part of its mission to prevent radioactive materials from being used in acts of terrorism, the U.S. Department of Energy’s National Nuclear Security Administration (NNSA) promotes efforts to reduce the need for high-activity sources by supporting the adoption and development of alternative technologies to replace the most common devices that use high-activity radioactive sources. In order to address this mission, NNSA is currently focusing primarily on supporting site transitions from cesium-based blood irradiation to x-ray based blood irradiation through the Cesium Irradiator Replacement Program (CIRP). In the United States, site partners procure the X-ray based irradiator and NNSA eliminates the risk of the CsCl source by federally funding its removal and disposal through its Off-Site Source Recovery Project (OSRP) [Garrison, et al, 2018]. This transition has been very successful in both the United States and abroad. In May, Congress passed the John McCain FY19 National Defense Authorization Act (NDAA), setting a goal of transitioning all cesium-based blood irradiators to X-ray based devices by 2027. As of Oct 1, 2019, 43,000 sources have become disused and removed through the Offsite Removal Project (OSRP). Although this transition has been very successful for blood irradiation, there are still partner sites that struggle to transition from cesium-137 and cobalt-60 irradiation in the research and sterilization-based applications. Reasons for delayed adoption of alternatives include: financial resources, background understanding of the new capabilities in x-ray and e-beam irradiation practices, limited publications in the area, previously acquired large data sets using gamma and unwillingness to transition this data to new processes in the middle of the research activities, validating new technology, and understanding dose depth differences between modalities. This paper discusses opportunities for low energy e-beam devices to replace current irradiation processes using gamma irradiation techniques.

## THREAT PROFILE OF RADIOISOTPIC IRRADIATION PRACTICES

While cobalt-60 and cesium-137 have typically been used to irradiate materials for both research and industrial sterilization, the Office of Radiological Security (ORS) and its partners are investigating the viability of electron beam for various applications to reduce this radioisotopic footprint and improve global radiological security. The cesium chloride included in cesium sources has been determined to be the highest threat for use in radiological dispersal devices (RDDs). The powder-like salt consistency results in increased dispersibility and a soluble makeup creates a material that is both highly dispersible and difficult to clean up as it binds to cement, soil, and other building materials [Committee on radiation source use and replacement, 2008]. It is because of these characteristics that cesium security has been escalated to one of the highest NNSA ORS priorities for enhanced security and replacement with alternative technology where technically feasible.

NNSA strives to introduce alternatives for any type of isotopic source when available, therefore promoting e-beam and x-ray based irradiation as a replacement for cobalt 60 is also a priority. Recently there has been increased interest in replacing gamma irradiation, using cobalt-60, with alternatives such as e-beam and x-ray based exposures. This increased interest in alternatives to the radioscopic irradiation process is due not only to the current security risks associated with the use of isotopic sources, but also due to the logistical costs and transportation risks associated with reloading Co-60 panoramic facilities, and enhanced sterilization/material processing capabilities being realized with e-beam/ x-ray systems.

## ELECTRON BEAM TECHNOLOGY- BASED IRRADIATION

Electron beam and x-ray technologies are examples of ionizing radiation technology that are fast becoming technologically superior, economically advantageous and radiologically safe alternatives to gamma sources such as cesium-137 and cobalt-60. The key differentiator of e-beam and x-ray sources are that they are based on commercial electricity (ie., machine sources) and therefore do not require radioactive materials. This differentiation along with the ability to switch and switch off the equipment when not in use adds significantly to the value proposition of e-beam and x-ray technologies. The dose rate of these machine sources are orders of magnitude greater than radioisotopic sources. The equipment that is used to generate e-beam and x-ray photons are called accelerators. Today, commercial accelerators are available with beam currents ranging from a few milliamps (mA) to hundreds of milliamps. This corresponds to beam power ranging from a few kilowatts to as high as 1000 kW. The dose rates of such commercially-available accelerators are in the range of 1000’s Gy/sec compared to gamma sources which have a dose rates multiple orders of magnitude lower even with very high specific activity sources. Accelerators can be categorized into different classes based on their maximum energy, maximum power and electrical efficiency. Commercially, e-beam accelerators can be broadly divided into Direct Current (DC) accelerators, Continuous Wave (CW) accelerators and pulsed accelerators (Table 1).

TABLE 1. Comparative differences between DC, CW and pulsed accelerators [9]

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | DC Accelerator | CW Accelerator | Pulsed Accelerator |
| Genre | Dynamitron-style | Rhodotron-style | LINAC style |
| Maximum energy used commercially | 5 MeV | 7.5 MeV - 10 MeV | 10 MeV |
| Power (commercial line speeds possible) | High power: as high as 100 kW | High power: as high as 800 kW | Increasingly high power up to 80 kW and higher |
| Electrical use efficiency | High | Medium | Low |
| Physical size | Large | Medium | Small |

A major advantage of these machine sources of e-beam technology is that they can be adapted for generating x-ray using the same core e-beam technology. Using so-called “convertors” (made up of, for example, tantallum), e-beam can be converted to x-ray photons albeit at a very low conversion efficiency. When high energy (5 MeV or 7.5 MeV) electrons collide with tantallum, x-ray photons are produced. These x-ray photons have penetration capabilities like the photons from gamma sources. Even though the conversion efficiency of e-beam to x-rays is low, the dose rate of x-rays from an accelerator are still ≥ 100 Gy/second. The increased dose rate of e-beam and x-ray technologies means higher line speeds which in turn translate into higher product or processing throughputs. High throughput makes these technologies economically very attractive for commercial scale applications in medical device sterilization, polymer crosslinking, food processing and potentially other emerging applications such as environmental remediation.

Significant technological advances are occurring in machine- electron beam and x-ray technologies. These advances especially in linear accelerator-based technology include major increases in accelerator power capabilities, compactness, user-friendly control systems, and remote diagnostics and troubleshooting [10]. Advances in Rhodotron technologies include miniaturization of key components enabled through solid state electronics, etc. [12]. In addition to the advances taking place in high energy e-beam technology, interestingly, there is a similar growing interest in low energy e-beam and low energy x-ray technologies. The actual definition of low energy e-beam can vary. The working ASTM definition of low energy e-beam are electrons with an energies below 300 keV [13]. However, practically speaking, low energy e-beam can also be defined as e-beam technology that can utilize self-shielding rather than requiring concrete bunkers for shielding. The acute security issues associated with cesium-137 stimulated the commercial development of low energy x-ray technology using x-ray tubes. However, there is also commercial R&D taking place to develop accelerator-based low energy x-ray technologies. Accelerator-based low energy x-ray technology will have major advantages over presently used x-ray tube technology. These include the ability to fine tune dose delivery and dose distribution and very importantly, avoiding the need to periodically replace expensive x-ray tubes. Though the actual market size for specialized applications such as sterile insect technology (SIT) is limited, there is a growing interest by accelerators manufacturers to cater to this application by investing in R&D to develop compact, shelf-shielded “x-ray in a box”, and similar concepts [10].

## LOW ENERGY ELECTRON BEAM APPLICATIONS AND ADVANTAGES

The primary advantages of electron beam technology compared to isotope-based technologies include: 1) significantly lower regulatory burden to acquire electron beam technology compared to gamma sources, 2) the ability to turn on and off the equipment machine, 3) ability to deliver highly customized and uniform doses for specific applications, 4) independence from skyrocketing costs for cobalt-60, and 5) the ability to acquire off the shelf commercial electron beam technologies that can be custom-designed for various research applications and commercial needs.

The ability to custom-design low energy e-beam or x-ray technology for specific applications provides a rather immediate replacement solution for radioactive sources that are used for research purposes in many parts of the world. The Gamma cell is a workhorse as a research irradiator in many parts of North America, Asia, Europe, and Latin America. Low energy e-beam and accelerator-based low energy x-ray technologies can be viewed as a paradigm shift in our thinking of a replacement technology for gamma cells and similar technologies.

Current large scale commercial applications of low energy e-beam (LEEB) technology are in aseptic packaging in food industry and in the printing industry for curing of printing inks [9]. The concept of aseptic packaging is not new and a number of excellent references on this technology exist (Nelson, 2010; David et al., 2013). There are well over 500 different aseptic systems for the manufacture of retail packages and bulk containers in the U.S. and over a dozen manufacturers of aseptic filling equipment worldwide (Pillai, 2016).

The LEEB technology entered the commercial space only in 2012. Today, LEEB technology is offered around the world as an integrated technology by TetraPac (https://www.tetrapak.com/tetra-pak-e3-ebeam). The advertised advantages include reduced operational costs, greater production flexibility, and reduced environmental impacts. Specifically, LEEB has resulted in about 80% less energy consumption for sterilization, 40% reduction in carbon dioxide footprint and 33% less electrical power usage [15]. The LEEB technology is emerging as a commercial sterilization/disinfection solution in the food industry, seeds industry, vaccine production and seed treatment industries. Buhler, a Switzerland based company has launched Laatu™, a LEEB based microbial reduction solution for industrial dry food processing (https://digital.buhlergroup.com/laatu/). The technology is capable of achieving 5-log reduction of pathogens such as Salmonella spp. for the sterilization of spices. The technology is advertised as a replacement solution for chemicals, up to 80% reduction in the use of energy, and a total replacement of radioactive sources for microbial reduction for spices and other dry foods. In addition to this commercially available technology, Fraunhofer in Germany is pioneering the development of LEEB technology for the pharmaceutical industries and the seed industries [5]. They reported the successful application of LEEB to deliver high doses (50 kGy) to sterilize an impedance sensor for the biotechnology industry without any loss of functionality. Interestingly, they report successful delivery as high as 300 kGy to samples. The ability to deliver such high doses in a self-shielded ionzing radiation source is paradigm shifting.

The LEEB technology is already at a very high technical readiness level (TRL) as a suitable replacement of the Gamma cell technology. The ability to deliver very high doses in seconds compared to the Gamma cell offers a wide range of research capabilities. Active research is also under way to demonstrate the value of LEEB for the surface disinfection of eggs [15], vaccine production [16] and surface decontamination of seeds. A commercial-scale facility has started operation recently for seed treatment (https://www.fep.fraunhofer.de/en/press\_media/Pressemitteilungen2018/12\_2018.html). One can envision research institutions around the world equipped with this powerful technology for performing high value basic and translational research in the life sciences (agriculture, vaccine production, biotechnology, tissue grafting, etc.) and in the physical sciences such as materials, solutions, and polymers.

After decades of refinement and integration LEEB continues to offer the potential of significantly enhancing production efficiencies and environmental benefits for manufacturing and brand owners focusing on sustainability, consumer safety, cost competitiveness and product differentiation. Optimizations focusing on smaller footprint, availability of access and affordability will continue to popularize interest in low-energy electron beam for emerging product applications.

In addition to LEEB technology that currently operates in the 80 keV -300 keV energy spectrum there is also active R&D to commercialize panoramic LEEB irradiation systems that operate in a self-shielded 1 MeV – 3 MeV range. Self-shielding can still be effective at this energy range thereby avoiding the need for costly labyrinthine concrete bunkers. The availability of such technologies can totally obviate the needs for cobalt-60 sources for research and development and customized commercial sterilization needs. A case in point is the 2.5 MeV panoramic LEEB irradiation capability in the Philippine Nuclear Research Institute. With their recent acquisition of a LEEB irradiation capability through IAEA-support they are now able to conduct research as well as carry out semi-commercial irradiation services of specific products (https://www.pnri.dost.gov.ph/index.php/ services/facilities/irradiation-services). The LEEB facility irradiates semi-conductors, automobile parts, wires and cables and other industrial products.

There is no doubt that increased familiarity with low-energy e-beam technology can lead to greater interest and possible adoption of high energy (10 MeV) irradiation technology. The issue of familiarity with technology is a key driver for adoption of new technologies [17] [32018].

### EMERGING MARKETS FOR LOW-ENERGY E-BEAM

The current limitations for high energy electron beam systems such as time delays for installation and validation and construction of specialized shielding bunkers, can be avoided by switching to low energy self-shielded electron beam systems (100-900 keV) for R&D and industrial applications that do not require the depth penetration of irradiation of 10 MeV electrons. Applications such as polymer modification for crosslinking and grafting, curing of inks, surface sterilization of packaging, fruits, seeds, eggs, and surface modifications of materials and harvested tissues topically fall into this application space. In many regions of the world and in many commercial applications, LEEB may be a technological and economical alternative to high energy electron beam (HEEB). In addition to these applications, there is data that suggests many new emerging markets will develop in the low energy e-beam category by finding applications that are suited to the customized self-contained nature of these systems. The self-contained nature of these sterilization platforms allows for the equipment to be brought in-house for either in-line or end of line applications.

Current techniques for tissue preparation for transplantation include disinfection and crosslinking using glutaraldehyde. However, glutaraldehyde-associated toxicity as well as rapid calcification and premature graft failure represent major modes of failure.

Gamma based irradiation is not feasible for this application due to the observed damage to fibril reorganization, protein denaturization, collagen fragmentation, and condensation of collagen rich tissues [walker et al, 2018]. Low energy election beam irradiation has been proposed as an alternative to glutaraldehyde [Walker et al, 2018].

New generation medical devices often cannot be sterilized by standard autoclaving or sterilization gases, as they are temperature sensitive, contain electronic components like sensors or microchips, or consist of polymers. Gamma irradiation for sterilization of such products is also problematic due to long processing times under highly reactive conditions resulting in material degradation or loss of functionality. Low energy e-beam treatment could enable irradiation sterilization of medical surfaces within seconds. The speed of this sterilization method can reduce or even prevent the degradation of polymers, and electron penetration depth is precisely controlled to prevent damage to sensitive components like electronics [8].

### TRANSITIONING FROM GAMMA TO LOW ENERGY E-BEAM

It is proposed that easy access to low energy electron beam technology by researchers can stimulate research and development programs in emerging countries that in turn can accelerate the transition away from cobalt-60 or cesium-137 technologies. This transition to machined sources such as electron beam will ultimately facilitate reduction of the security risk posed by cobalt or cesium while still maintaining current and in some cases enhanced irradiation capabilities. In order to increase the availability and accessibility of technology such as e-beam, outreach and technical exchanges between international partners from the user community and industry partners need to occur to exchange information on the status of technology, invest in and encourage the improvement of technologies and overcome obstacles preventing implementation.

As with current x-ray and electron beam based irradiators, new systems are being marketed with enhanced imaging, tracking and programmable settings. These vendors are investing more resources in enhancing new capabilities as the market and competition in the market grows. Although e-beam as an alternative has already been adopted and is in use at many facilities, there is still a need to address the lack of data and incentives for switching to these lower risk alternatives. In order to transition from gamma to low energy e beam, many users are blocked by the ability to understand material comparisons between the two modalities. These types of comparison studies can be costly and often require subject matter experts in this field of radiation physics and dosimetry. The DOE NNSA is currently funding several studies for transition from gamma-based sterilization to x-ray and e-beam [i.e., Murphy et al, 2018] with the hope that filling the basic gaps will enable private industry to make industry transitions to alternatives with reduced risk to their product line and validation of products within the FDA. Current comparison projects are tailored towards high energy e-beam processing due to the high capital costs in obtaining both capabilities at one facility. Because low energy e-beam systems are lower in cost, smaller in size, these types of comparison studies can be more easily completed within the user community. The financial model for current CIRP activities within the United States, by which DOE assumes costs associated with disposal of the cesium source being removed from service, could be leveraged into the research and sterilization activities to promote such a transition. By leveraging this model for research and sterilization activities, the industry could see a large transition to e-beam and x-ray based techniques.

## SUMMARY AND RECOMMENDATIONS

As with other NNSA alternative technology projects, the challenge is determining the best way to support sites transitioning to LEEB use over traditional gamma-based irradiation. Currently, financial incentives exist in many countries including Europe and the U.S. (for example CIRP), which gives end-users of cesium-137 irradiators a financial incentive to exchange them with x-ray irradiators. It is proposed that this model may fit well as low energy e-beam develops into a proven alternative to Co-60 and Cs-137 for proven research and sterilization applications. Unlike high energy electron beam capabilities, the costs associated with low e-beam energy are more aligned with the costs associated for the Cesium Irradiator Replacement Program (CIRP). Accordingly, the proposal may be to leverage this model to promote transition of sites to e-beam irradiator systems from gamma related sources. Partnerships with key stakeholders through the low-energy electron beam value chain, from public utilities to universities, will continue to be indispensable before e-beam becomes a common household word [https://www.pcimag.com/articles/101173-electron-beam-laboratory-systems. In addition, it is understood that there is certainly a need for more effective information sharing about these technologies in order to support widespread adoption of these alternative irradiation options and to identify potential advantages and disadvantages for specific applications. Information sharing that addresses: technology capabilities, materials and methods for success, validation procedures, and costs associated with procurement, installation, training, and operation. In order to gauge programmatic success related to the investment in this transition, US DOE will require solid metrics of success. Suggested programmatic metrics of success could focus on the deployment of low-energy e-beam technology emerging markets, and the initiation of new research activities using low energy e-beam, as well as new publications in these application areas and the number of sites transitioning away from gamma irradiation practices and curies removed from service.

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