X-RAY STERILIZATION FOR MEDICAL DEVICE: THE X FACTOR

Although X-ray sterilization has been used in medical device applications for approximately 15 years, uptake of the technology has been relatively slow. The recent introduction of high-power, high-energy accelerators that achieve desirable dose uniformity ratios may change that dynamic.

Sourcing sterilization methods for medical devices

Deciding on a sterilization strategy for a medical product is not easy. Today, three main irradiation sterilization technologies are available, all of which have advantages and drawbacks. They are summarised in Table I. The materials used to fabricate the medical device, ultimately, will determine the sterilization method that is used: different materials react differently to radiation, and each type has its own tolerance level.

The physical properties of some plastic materials can degrade when they are treated with ionising radiation and exposed to ozone, which is produced by irradiating air in the treatment area. The degradation is more noticeable when the material is exposed to gamma rays than when X-ray or E-beam sterilization methods are used, because of the lower dose rates and longer exposure times required by gamma rays. However, some radiationresistant plastic compounds are now available that withstand gamma, X-ray and E-beam sterilization.

The Dose Uniformity Ratio (DUR) is the ratio between the maximal and minimal dose that is required to effectively process a product. The DUR is not as crucial for materials that have a good tolerance to irradiation; devices made of materials that have a limited resistance to irradiation, however, will require an optimal DUR to prevent unacceptable levels of degradation.

X-ray sterilization of medical products has been studied theoretically and in practice by the US National Institute of Standards and Technology, universities and accelerator manufacturers for more than 40 years. Commercial use began about 15 years ago, but the low output power of early accelerators hindered industrial uptake. That is changing with the recent introduction of high-power, high-energy accelerators.

Modern industrial accelerators have increased throughput, making X-ray sterilization competitive with medium and large cobalt-60 facilities. Today there are X-ray sterilization facilities in Europe, Japan and North America.

TABLE I. A comparision of the three main irradiation sterilization technologies.

	E-beam (boxes)	X-ray (pallet)	Gamma (pallet)	Gamma (tote)
Dose uniformity ratio	Average	Excellent	Good	Excellent
Cost efficiency	Excellent	Good	Good	
Dose rate	Very high	Medium	Low	
Product penetration	Low	Very high	High	
Labour requirements	Labour intensive	Labour efficient	Labour efficient	Labour intensive
Source energy	Electricity	Electricity	Cobalt 60	

X-ray sterilisation enables increased penetration

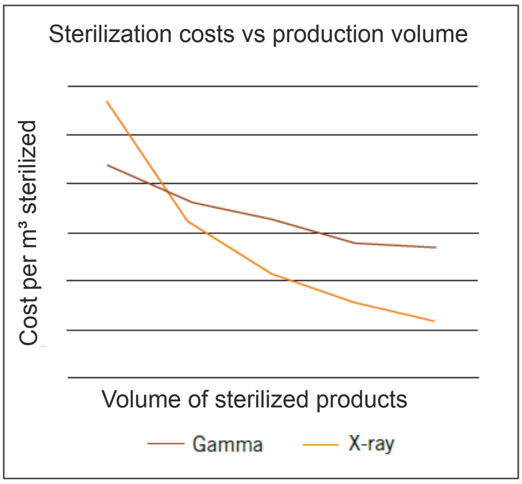
Processing materials and commercial products with high-energy X-rays can produce beneficial changes that are similar to those obtained by the use of gamma rays emitted by cobalt-60 sources.

Both X-rays and gamma rays are electromagnetic radiations with short wavelengths and high photon energies that can stimulate chemical reactions by creating ions and free radicals in irradiated materials.

A significant difference between X-rays and gamma rays, however, is the radiation's angular distribution: nuclear gamma rays are emitted in all directions, hereas high-energy X-ray photons are concentrated in

the direction of the product being sterilised. The narrow angular distribution of X-rays enables increased penetration of materials, because the most intense zone of emitted radiation is perpendicular to the surface of the target products. By contrast, the nearly isotropic radiation in an industrial gamma facility has a wide angular distribution. Consequently, gamma-ray emission is more divergent than high-energy X-ray emission, penetrating the products at larger angles from a perpendicular direction.
These properties partially explain why X-ray sterilized products have a significantly better DUR than gamma-sterilised products.
The other key reason is the wider energy spectrum generated by accelerated electrons at energies higher than 5 MeV.
From a practical point of view, X-ray sterilization systems irradiate full pallet loads by moving them continuously through the X-ray beam. The loads are irradiated from the side as they pass in front of a long, vertically oriented target and on opposite sides at both high and low elevations. A nearly uniform vertical dose is obtained. A virtual animation of the X-ray irradiation process is available for viewing on the IBA website: ***www.iba-industrial.com/animis.***
Irradiation tests performed in a new X-ray facility located in Europe used a full pallet load measuring 100 x 120 x 180 cm with a homogeneous density of 0.15 g/cm3. Alanine dosimeters were placed on a horizontal grid at various heights inside the load to identify the maximal and minimal dose locations. The load was irradiated by multiple pass cycles, each cycle consisting of four passes in front of the X-ray target (both sides, top and bottom of the pallets).
Several irradiation tests were performed to identify optimal irradiation parameters. Following optimization, a DUR value of 1.25 was achieved when processing full pallets of homogeneous products with densities similar to medical devices. This is a significantly better result than the typical 1.45 DUR obtained with the same pallet irradiated by a cobalt-60 source.
The DUR of the X-ray process permits pallet-based sterilization of medical devices, which could only be processed previously by means of gamma-based tote sterilization. The simulated cost per volume of sterilized medical devices (cost per m³ of sterilised products, for example) shows that, compared with gamma sterilization, the economic advantages of X-ray sterilization increase in relation to the production volume of the facility.
(Figure 1). The tipping point at which X-ray sterilization becomes economically advantageous compared with gamma sterilization is mainly a function of the price of cobalt-60 and the cost of the irradiation solution and electricity. These costs vary by project and by location. As a rule of thumb, however, X-ray sterilization should be taken into consideration starting with 1.5 MCi capacity facilities.

FIGURE 1: The economics of X-ray sterilization compared with gama sterilization



X-RAY STERILIZATION DESIGN STRATEGIES

When designing an X-ray sterilization facility, various power strategies can be considered:

- **Non stop production**

A nonstop sterilization facility operates more than 8000 hours per year. With this configuration, initial investments are reduced since the required power is optimized for nonstop production. When more capacity is needed, X-ray generator power can be increased with minimal downtime.

- **Operating only during off-peak hours**

Under some circumstances, it may be feasible to operate an X-ray sterilization facility only during off-peak hours (when electricity costs are reduced). It is possible to set up an X-ray sterilization operation in this manner by installing an accelerator with more power than is required, allowing the manufacturer to treat the same volume in less time. This extra power is also available to react to surges in production volumes.

- **Temporary power licenses**

X-ray sterilization technology allows the introduction of new cost models such as temporary power licenses. Depending on the facility and system installation, temporary power licenses can be purchased to manage a sudden temporary peak in production because of an unanticipated customer request or to get caught up after a production delay, for example. The cost of temporary licenses depends on additional power needs and duration.

An alternative to traditional medical device sterilization technologies

Medical device manufacturers seeking a sterilization solutionhave more options today. It's not just about gamma, E-beam or EtO, anymore: X-ray sterilization can be an attractive alternative, thanks to recent developments in high-energy, high-power electron accelerators. X-ray sterilization facilities are operating successfully today in Europe, Japan and North America. The technology offers the capability to turn off the radiation source, to control the X-ray intensity and to process products on pallets whilst achieving a desirable DUR. Irradiation tests performed in the newest industrial X-ray facility have shown that a DUR of 1.25 can be achieved for pallet loads of low-density materials compared with a DUR of 1.45 for pallet loads in a cobalt-60 irradiation facility.

In our view, there will be a slow but steady migration from gamma to X-ray sterilization driven by market demand for better sterilization quality and in response to the increasing cost of cobalt-60, the regulatory constraints underpinning its use and its shrinking availability.

The Rhodotron® TT1000, with power up to 700 kW, has made X-ray sterilization viable as an industrial processing technology

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