GAMMA IRRADIATORS FOR RADIATION PROCESSING

INTERNATIONAL ATOMIC ENERGY AGENCY

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FOREWORD

Radiation technology is one of the most important fields which the IAEA supports and promotes, and has several programmes that facilitate its use in the developing Member States. In view of this mandate, this Booklet on "Gamma Irradiators for Radiation Processing" is prepared which describes variety of gamma irradiators that can be used for radiation processing applications. It is intended to present description of general principles of design and operation of the gamma irradiators available currently for industrial use. It aims at providing information to industrial end users to familiarise them with the technology, with the hope that the information contained here would assist them in selecting the most optimum irradiator for their needs. Correct selection affects not only the ease of operation but also yields higher efficiency, and thus improved economy. The Booklet is also intended for promoting radiation processing in general to governments and general public.

The Booklet is prepared by the IAEA's Industrial Applications and Chemistry Section, Division of Physical and Chemical Sciences with the assistance provided by consultant Mr. Kishor Mehta. The IAEA staff member responsible for this project was Mr. Andrzej G. Chmielewski. The IAEA is grateful to all persons and organizations that provided valuable information for the Booklet.

EDITORIAL NOTE

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INTRODUCTION

RADIATION PROCESSING INDUSTRY

Ionizing radiation can modify physical, chemical and biological properties of the irradiated materials. At present, the principal industrial applications of radiation are sterilization of health care products including pharmaceuticals, irradiation of food and agriculture products (for various end objectives, such as disinfestation, shelf life extension, sprout inhibition, pest control and sterilization), and materials modification (such as polymerization, polymer crosslinking and gemstone colourization) (see Fig. 1).

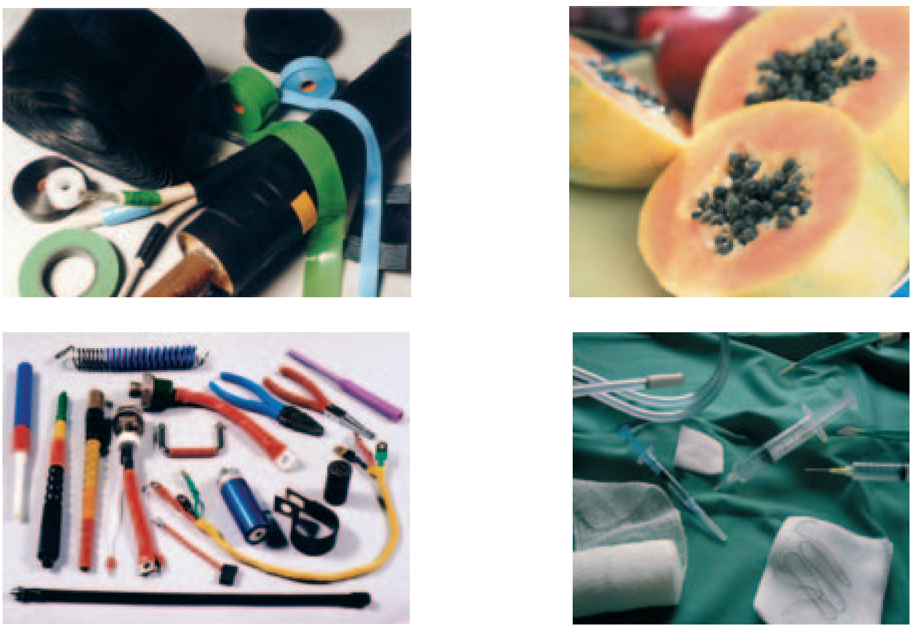


FIG. 1. Products processed by gamma radiation (courtesy of MDS Nordion, Canada and INCT, Warsaw, Poland).

Table I lists a few typical applications: product processed, intended effect and the dose range necessary to realize this effect. The dose ranges listed here are typical values for different product type/processes; the actual values depend on the specific product and process objectives, and are assigned by national authorities. Many review articles, reports, and books have been written over the last several years on the subject of radiation processing [1–9].

TABLE I. SOME TYPICAL RADIATION PROCESSING APPLICATIONS

Product	Intended effect	Typical dose range (kGy)
Blood	Preventing TA-GVHD	0.020–0.040
Potatoes, onions, garlic	Inhibiting sprouting	0.05–0.15
Insects	Reproductive sterilization for pest management	0.1–0.5
Strawberries and some other fruits	Extending shelf life by delaying mould growth and retarding decay	1–4
Meat, poultry, fish	Delaying spoilage, killing certain pathogenic bacteria (e.g. salmonella)	1–7
Spices and other seasonings	Killing a variety of microorganisms and insects	1–30
Health care products	Sterilization	15–30
Polymers	Crosslinking	1–250
	Grafting	0.2–30

A significant impetus was given to the radiation processing industry with the advent of nuclear reactors, which have the capability to produce radioisotopes. Gamma ray emitters like cobalt-60 became popular radiation sources for medical and industrial applications. Many gamma ray irradiators have been built and it is estimated that about 200 are currently in operation in Member States of the International Atomic Energy Agency (IAEA). In recent times, the use of electron accelerators as a radiation source (and sometimes equipped with X ray converter) is increasing. However, gamma irradiators are difficult to replace, especially for non-uniform and high-density products. This document describes only gamma irradiators, which are used for various radiation processing applications. Cobalt-60 is almost solely used as the gamma radiation source for industrial use now mainly because of its easy production method and its non-solubility in water.

Gamma processing has several advantages over other treatment methods; for example, sterilization of health care products using either EtO or wet steam as a sterilant. In the case of gamma sterilization, such advantages include:

– treated product can be used immediately,
– minimal rise in product temperature during the process,
– high penetrability (hence packaged product can be processed),
– very precise and reproducible treatment process, and
– easy to control the process (only dose to be controlled).

GROWTH OF INDUSTRY

The commercial use of gamma radiation to sterilize health care products began in the late 1950s, and the technology of processing products with gamma radiation is now well entrenched. With increasing experience and confidence in the technology, more applications are being investigated, and more facilities being built. This expansion in the industrial processing calls for not only larger irradiators but also novel designs to optimize each new application. Manufacturers of irradiators have taken up the challenge to keep pace with the expansion of the industry. Now several manufacturers offer a variety of designs that are optimized specifically for different applications, whether this is in the field of food irradiation or environmental applications. This in return has given impetus to the radiation processing industry regarding the types of applications and the size of irradiators.

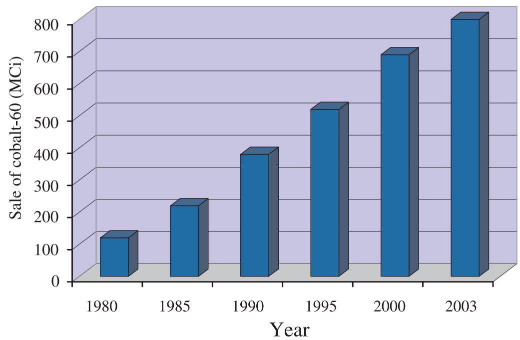


FIG. 2. Sale of cobalt-60 over years.

Figure 2 shows an estimate of the total cumulative sale of cobalt-60 by all the suppliers over the last 25 years. Based on these data, it can be estimated that the installed capacity of cobalt is increasing at the rate of about 6% per year. It is interesting to note that the worldwide use of disposable medical devices is growing at approximately the same rate (5–6%), which seems to be driving the growth in the cobalt sale.

The kinds of applications that use gamma radiation have also steadily increased; from crosslinking/polymerization and sterilization of health care products to food irradiation and environmental applications such as flue gases, wastewater and sludge treatment. Emerging applications could be in the fields of nanomaterials, structure engineered materials (sorbents, composites, ordered polymers, etc.) and natural polymers. Some of the irradiators are operated for single product/process, while others for multipurpose. A recent IAEA survey [10] showed that a very large fraction (85%) of the gamma irradiators treats health care products for the purpose of sterilization. Similar percentage of irradiators treats food and agriculture products for various end objectives. About 50% of the units process pharmaceutical products, including raw materials, for the purpose of sterilization or microbial load reduction, while about 30% treat polymers, including cables and tubings for property modification.

RADIATION PROCESS

In a radiation process, a product or material is intentionally irradiated to preserve, modify or improve its characteristics. This process is carried out by placing the product in the vicinity of a radiation source (such as cobalt-60) for a fixed time interval whereby the product is exposed to radiation emanating from the source. A fraction of the radiation energy that reaches the product is absorbed by the product; the amount depending on its mass and composition, and time of exposure. For each type of product, a certain amount of radiation energy is needed to realize the desired effect in the product; the exact value is determined through research.

Radioactive material, such as a cobalt-60 source, emits radiation. However, the product that is irradiated with gamma rays does not become radioactive, and thus it can be handled normally. This is similar to X ray examination in a hospital for diagnostic purposes; the patient is exposed to radiation (X rays) but he/she does not become radioactive.

Some of the commonly used terms in radiation processing are:

absorbed dose
amount of radiation energy absorbed by material while exposed to a radiation source

gray (Gy)
unit of absorbed dose, equivalent to 1 joule per kilogram of material

radioactivity
strength (or power) of a gamma radiation source (like cobalt-60)

curie (Ci) or becquerel (Bq)
unit of radioactivity of a gamma radiation source (like cobalt-60)

half-life
characteristic of a gamma radiation source;
time taken for the activity of a radiation source to decay to half of its value

These and other concepts and terms relevant to radiation processing are discussed in Appendix A.

RADIATION SOURCES

GENERAL

Within the electromagnetic radiation spectrum, gamma radiation is located near the high energy end along with X rays. The energy associated with gamma radiation (for example, gamma rays emitted by cobalt-60) is high enough to break the molecular bonds and ionize atoms, but not high enough to affect structure of the atomic nucleus (avoiding induction of radioactivity). Gamma radiation may, therefore, modify chemical, physical or biological properties of the irradiated material/product; however, the irradiated product does not become radioactive. Radiation with such high energy is referred to as ionizing radiation. All radiation processing is performed with ionizing radiation, which includes – besides gamma radiation – high energy electrons (generally >80 keV) and X rays generated from high energy electrons (e.g. 5–10 MeV).

Cobalt-60 and caesium-137 are the most suitable gamma radiation sources for radiation processing because of the relatively high energy of their gamma rays and fairly long half-life (5.27 years for cobalt-60 and 30.1 years for caesium-137). However, the use of caesium-137 has been limited to small self-contained, dry-storage irradiators, used primarily for the irradiation of blood and for insect sterilization. Currently, all industrial radiation processing facilities employ cobalt-60 as the gamma radiation source.

COBALT-60 RADIATION SOURCE

The radionuclide cobalt-60 (Co-60 or $^{60}Co_{27}$) is the most commonly used source of gamma radiation for radiation technology, both for industrial and medical purposes. Production of radioactive cobalt starts with natural cobalt (metal), which is an element with 100% abundance of the stable isotope cobalt-59. Cobalt-rich ore is rare and this metal makes up only about 0.001% of the earth’s crust. Slugs (small cylinders) or pellets made out of 99.9% pure cobalt sintered powder and generally welded in Zircaloy capsules are placed in a nuclear power reactor, where they stay for a limited period (about 18–24 months) depending on the neutron flux at the location.

While in the reactor, a cobalt-59 atom absorbs a neutron and is converted into a cobalt-60 atom. During the two years in the reactor, a small percentage of the atoms in the cobalt slug are converted into cobalt-60 atoms.

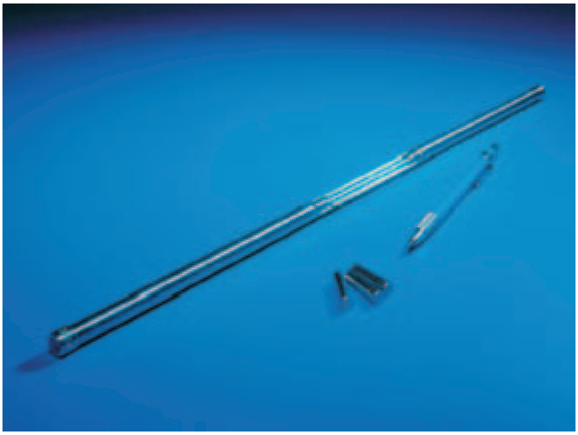


FIG. 3. Slugs and pencil of cobalt-60, which are the building blocks of a radiation source rack (courtesy of MDS Nordion, Canada).

Specific activity is usually limited to about 120 Ci/g of cobalt (about 4×10^{12} Bq/g). After irradiation, the capsules containing the cobalt slugs are further encapsulated in corrosion resistant stainless steel to finally produce the finished source pencils in a form such that gamma radiation can come through but not the radioactive material (cobalt-60) itself (see Fig. 3). The required source geometry is obtained by loading these source pencils into predetermined positions in source modules, and distributing these modules over the source rack of the industrial irradiator (see Fig. 4).

Cobalt-60 ($^{60}Co_{27}$) decays (disintegrates) into a stable (non-radioactive) nickel isotope ($^{60}Ni_{28}$) principally emitting one negative beta particle (of maximum energy 0.313 MeV) with a half-life of about 5.27 years (see Fig. 5).

Nickel-60 thus produced is in an excited state, and it immediately emits two photons of energy 1.17 and 1.33 MeV in succession to reach its stable state. These two gamma ray photons are responsible for radiation processing in the cobalt-60 gamma irradiators. With the decay of every cobalt-60 atom, the strength or the radioactivity level of the cobalt source is decreasing, such that the decrease amounts to 50% in about 5.27 years, or about 12% in one year. Additional pencils of cobalt-60 are added periodically to the source rack to maintain the required capacity of the irradiator. Cobalt-60 pencils are eventually removed from the irradiator at the end of their useful life, which is typically 20 years.

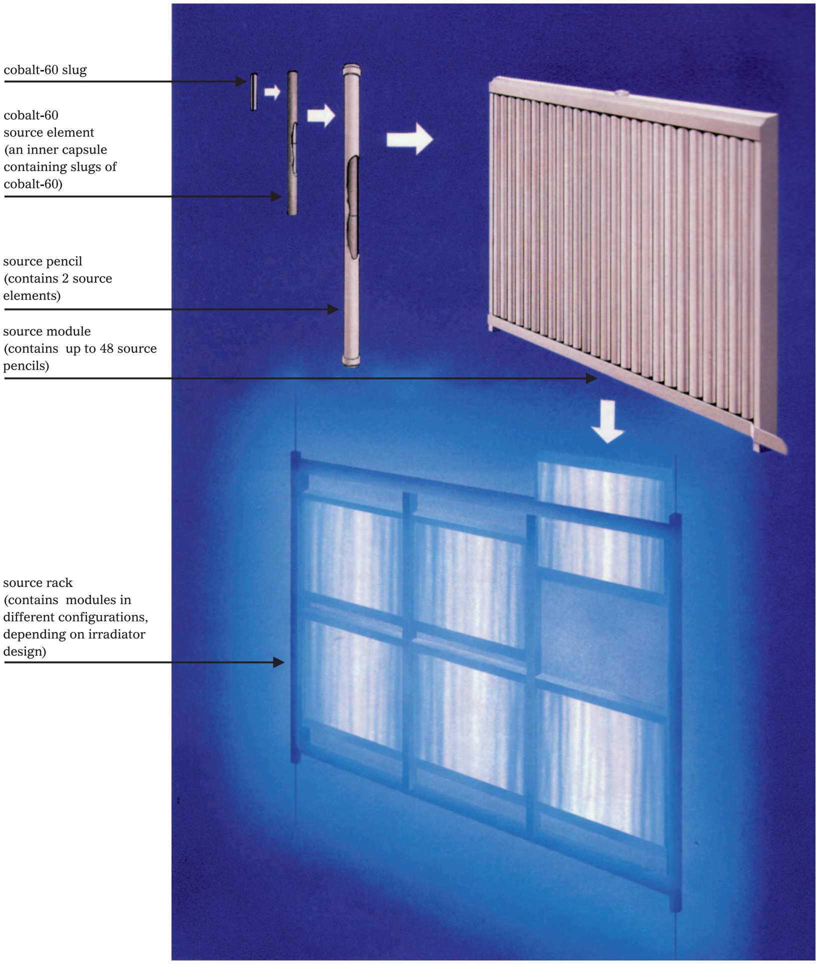


FIG.4. Schematic showing the build-up of a typical cobalt source rack from slugs, pencils and modules (courtesy of MDS Nordion, Canada).

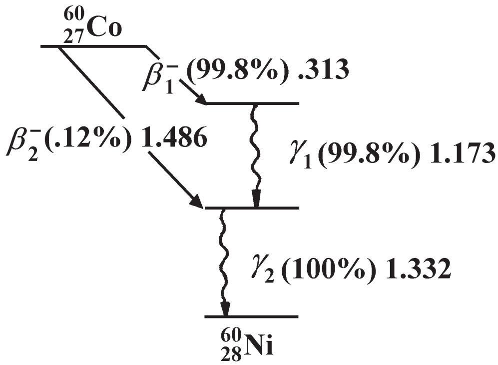


FIG.5. Decay scheme of radionuclide cobalt-60.

Generally they are returned to the supplier for re-use, recycling or disposal. In about 50 years, 99.9% of cobalt-60 would decay into non-radioactive nickel.

The current inventory of cobalt-60 in all the irradiation facilities around the world would amount to more than 250 million curies [6]. Thus, it is important to realize the vital role the nuclear power reactors play in bringing countless benefits to our lives through use of cobalt in medical as well as industrial radiation applications.

GAMMA IRRADIATION FACILITY

In a large irradiation facility, the irradiation room where the product is treated with radiation is the focal point of the facility (see Fig. 6). Other major components of an industrial facility include:

– shielded storage room (dry or wet) for the radiation source rack (cobalt-60),
– source hoist mechanism,
– radiation shield surrounding the irradiation room,
– control console (room),
– product containers (totes),
– product transport system through the shielding maze,
– control and safety interlock system,
– areas for loading and unloading of products, and
– supporting service equipment.

The radiation source is either in the irradiation room (during irradiation of the product) or in its shielded storage room (generally located under the irradiation room), which could be dry or wet. There is enough shielding provided by solid wall (dry storage) or water (wet storage) so that the personnel can work in the irradiation room, e.g. for maintenance, when the source is in the storage room. Water has several desirable characteristics as a shielding material; it is an easily available liquid that is convenient to circulate for heat transfer, and is transparent. For a wet-storage facility, nearly all materials used to construct source rack, guide system, and source containers are stainless steel, to eliminate galvanic corrosion.

Surrounding the irradiation room is the radiation shield, which is also referred to as biological shield, generally consisting of a concrete wall thick enough (normally 2 m in thickness) to attenuate the radiation emanating from the source, so as to maintain the radiation level at the location of the control console close to natural background. The concrete wall is constructed as a maze (labyrinth) so as to permit movement of the product and yet significantly reduce the scattered radiation reaching the control console, from where the operator can control or monitor the movement of the source and the product.

The transport mechanism for the product can be simple or can be quite elaborate depending on the irradiator design. For continuous irradiation (as shown in Fig. 6), the product containers (totes in Fig. 6) are moved around the radiation source on a conveyor bed that passes through the maze.

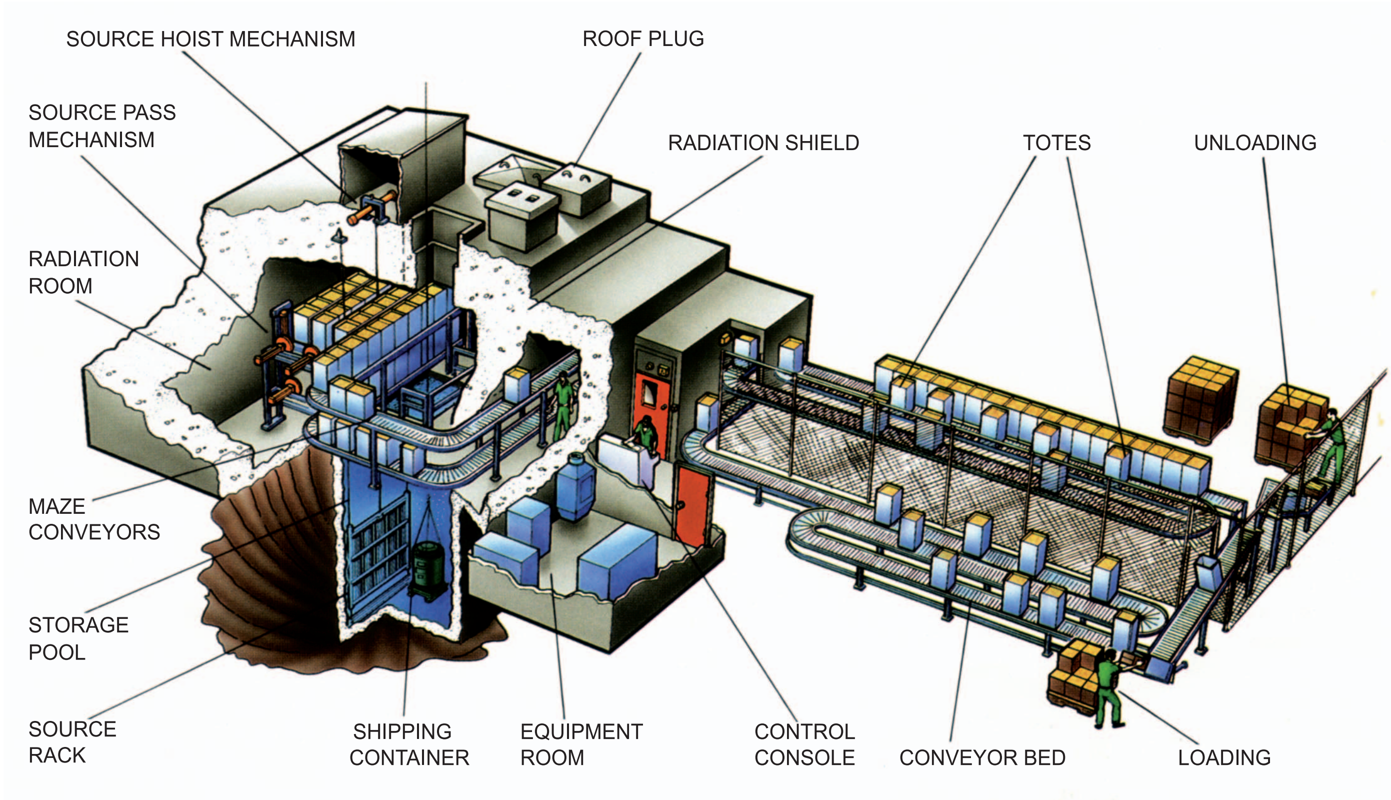


FIG. 6. Schematic diagram of a typical panoramic, wet storage gamma irradiation facility (courtesy of MDS Nordion, Canada).

For stationary irradiation, the radiation source is moved into the irradiation room *after* the product containers have been arranged there for irradiation.

The irradiation facility also provides areas for the storage of the unprocessed product and the processed product. It is a regulatory requirement that the design of the facility is such that these two types of product cannot be mixed inadvertently (note the separating fence in Fig. 6). Also, all facilities have laboratories suitable for carrying out dosimetry measurements. Some facilities also have a microbiology laboratory or a materials testing laboratory.

GAMMA IRRADIATORS

DESIGN PRINCIPLES

There are several types of irradiators available commercially. A potential developer of an irradiation facility would therefore have an easy task of selecting one that is most suitable for the intended application. The design of an irradiator varies from being small, that is convenient for radiation research, to very large, which is suitable for hundreds of tons of product throughput per day. The main differences between these various irradiators are the activity level of the radiation source (i.e. amount of cobalt) and the method of moving the products in the radiation field. Besides, the method of operation of the irradiator can be selected to suite a specific application. In addition, manufacturers can and are willing to modify the design of an irradiator to suite more specific needs.

The basic design principles for all irradiators are:

- maximize radiation energy utilization,
- provide relatively uniform dose in the product, and
- ensure safe and easy operation.

These principles are addressed by incorporating the following elements in the design, which have been recognized from the beginning of the industry and have worked well:

– double encapsulated cobalt-60 source pencils,
– water (de-ionized) storage pool,
– several layers of product surrounding the source, and
– biological shield made of standard density concrete with a maze design.

SOURCE DESIGN CAPACITY AND INSTALLED ACTIVITY

The product throughput mainly depends on the activity of the radiation source currently installed in the irradiator and the dose requirements. The activity can vary from tens of kCi to several MCi. The installed activity should always be less than the maximum activity for which the irradiator is designed, which is referred to as the ‘design capacity’. The selection of the design capacity is based on the dose requirements for the intended application(s) and the expected maximum annual throughputs during the lifetime of the facility, including future needs. It is a common practice to start an irradiation facility with less source activity installed (as required by the current needs) than what it is designed for and, later, as higher throughput is needed, more cobalt is added. An irradiator is licensed to have no more source activity than the design capacity since it is specifically designed for that, especially the shielding requirements. Table II shows the distribution of design capacity and currently installed activity amongst 165 commercial gamma facilities for which such data are available [10, 11].

The dose rate in the product is directly related to the installed activity of the source. The operator controls the absorbed dose delivered to the product by adjusting the time that it is exposed to radiation, either by selecting the irradiation time interval or by selecting the conveyor speed. The only variation in the source output is the known reduction in the activity caused by radioactive decay; if not taken into account, this can have significant impact on the facility operation – financial as well as in scheduling. Activity of a cobalt source decreases by about 12% annually. The irradiator operator compensates for this loss of activity (which decreases the dose rate) by incrementally increasing the irradiation time by approximately 1% per month to maintain the same dose to the product. Eventually irradiation time becomes impractically long (reducing the throughput), requiring addition of cobalt-60 pencils to the source rack (source replenishment) at regular intervals, depending on the operational requirements.

For the currently available commercial gamma irradiators, typically 30% of the energy emitted by the radiation source is usefully absorbed by the product. Thus, an irradiator with 1 MCi (1 million curie) of cobalt-60 would process about 4 tonnes (Mg) of product per hour where the minimum dose requirement is 4 kGy (typically for food). If the dose were 25 kGy (sterilization of health care product), the throughput would decrease to about 0.65 tonnes per hour.

PROCESS DOSE AND DELIVERED DOSE

Process dose, that is the dose needed to achieve a desired effect in the product, is determined through radiation research, which involves determining the dose-effect relationship for the product/effect, be it sterilization of health care product or reduction of salmonella in chicken. Generally, the outcome of such research is identification of two dose limits: the lower dose limit

TABLE II. REGIONAL DISTRIBUTION OF DESIGN CAPACITY AND CURRENTLY INSTALLED ACTIVITY OF RADIATION SOURCE AMONGST 165 COMMERCIAL GAMMA FACILITIES

Activity of cobalt-60 (kCi)		All regions	Africa	East Asia and Pacific	Europe	Latin America	North America	West Asia
Design capacity	un-available*	28	3	9	12	0	1	3
	15–500	47	1	41	2	2	1	0
	500–1000	37	0	23	9	3	0	2
	>1000	53	1	13	8	4	27	0
Current activity	un-available*	70	0	44	11	1	14	0
	15–500	53	4	28	12	4	1	4
	500–1000	14	1	5	3	3	1	1
	>1000	28	0	9	5	1	13	0

* Information not available.

sets the minimum dose that is required to achieve the desired effect in the product, and the upper dose limit is set to assure that radiation will not adversely affect the functional quality of the product (e.g. plastic components of health care products may become brittle, or spices may lose some of their flavour). Usually, each product/process has a pair of these limits, and these values define the acceptable dose window, such that every part of the product should receive dose within that range. These dose limit values, especially for regulated products like foodstuff and health care products, are prescribed by national authorities. The ratio of the upper dose limit to the lower dose limit may be referred to as *dose limit ratio*.

During a radiation process, gamma radiation interacts with the product through several types of atomic interactions, such as Compton scattering, photoelectric effect and pair production [12]. Through these and subsequent interactions, it imparts energy and, thus, radiation dose to the product. As radiation proceeds through the product its intensity decreases, resulting in the decrease of dose with depth. This is referred to as *depth-dose distribution* (see Fig. 7, curve ‘a’ or ‘b’). The rate of decrease depends on the composition and

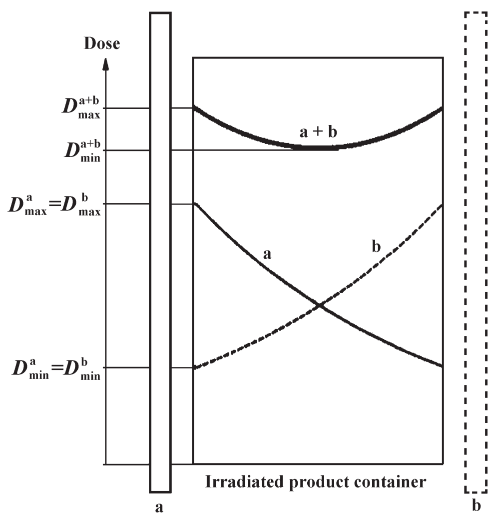


FIG. 7. Depth-dose distribution in a product container irradiated from two sides with a cobalt-60 source. The curve ‘a’ represents the depth-dose distribution when the product is irradiated from one side only (source is at position ‘a’). Similarly, when the source is at position ‘b’, the dose distribution is represented by the curve ‘b’. The total dose due to irradiation from two sides is then shown as the curve ‘a+b’. Notice that this total dose is much more uniform than that which is due to single-sided irradiation (curve ‘a’ or ‘b’).

density of the product, as well as the energy of the gamma radiation. Besides the variation of dose with depth, there is also dose variation in the lateral direction. This variation depends on the geometry of irradiation. Both types of dose variation contribute to the non-uniformity of the dose delivered to the product. Variation in dose in the irradiated product is unavoidable. One accepted method of describing this non-uniformity of dose is the concept of *dose uniformity ratio* (DUR), which is the ratio of the maximum dose in a product container to the minimum dose in the container. This ratio increases with the density of the product as well as with the size of the container (see Fig. 8).

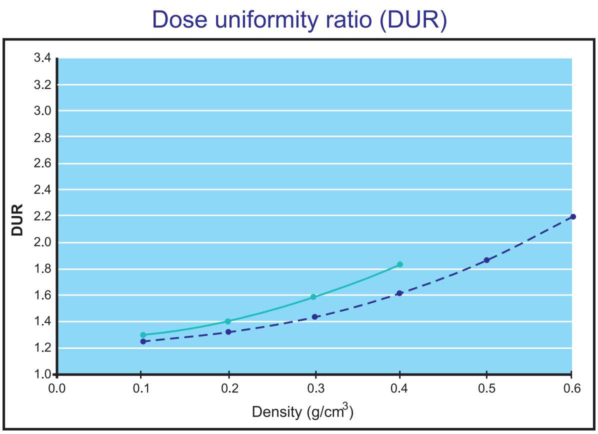


FIG. 8. Dependence of dose uniformity ratio (DUR) on product density for two different irradiator designs (courtesy of MDS Nordion, Canada).

This ratio should be close to unity (for example, less than 1.05) for radiation research samples, where the research objective is to correlate radiation effect in the sample to the dose. This is generally achieved by reducing the size of the sample. For commercial operation, this is not possible for economic reasons. A typical product container can be 60 cm × 50 cm × 150 cm, and some irradiators are designed to irradiate entire pallets of product, 120 cm × 100 cm × 150 cm. The dose uniformity ratio would be significantly larger than unity for such large containers. However, for a large majority of applications, there is fortunately a wide window of dose that is acceptable to achieve the desired effect without detrimentally affecting product quality. For example, the dose limit ratio is between 1.5 and 3 for many applications, and sometimes even larger, depending on the product and the process.

Thus, the guiding principle is:

> the measured *dose uniformity ratio* should be smaller than the *dose limit ratio* prescribed for the application.

There are different ways to reduce the *dose uniformity ratio* (that is, for making dose more uniform) in a product container. The variation along the depth is easily reduced by irradiating the product from more than one side (as illustrated in Fig. 7). This can be accomplished either by rotating the product container during irradiation or the product container travelling around a radiation source. All gamma irradiators use one of these techniques for the purpose. The lateral dose variation may be reduced in several ways, including placing the higher-activity source pencils near the periphery of the source rack (source augmentation), and relative arrangement of the product containers and the source (source overlap or product overlap, elaborated later). Different irradiators apply different methods to improve dose uniformity.

TYPES OF IRRADIATORS

Over the years, the manufacturers and suppliers of gamma irradiators have put much effort in response to the growing needs of the industry. The main elements that have been the focus of continuous attention include cost effectiveness of the radiation process, dose uniformity in product, turn-around time and operational reliability. These elements have seen steady improvement with time. These measures have resulted in a variety of sizes and designs of irradiators that are suitable for specific applications. Thus, commercially available irradiators could almost meet current requirements of the industry. Besides, the designs can be modified to suit more specific needs of an application. Various design concepts and some specific irradiator designs are discussed in Ref. [13].

Basically, gamma irradiators may be divided into two broad types:

– self-contained irradiators, and
– panoramic irradiators.

Self-contained irradiators (IAEA categories I and III)

Self-contained irradiators are specially designed for research and applications that need small doses and relatively small throughputs, such as blood irradiation for preventing TA-GVHD and reproductive-sterilization of insects for pest management programmes. A large majority of these are dry-storage irradiators and the source activity is limited to about 25 kCi (see Fig. 9). These irradiators house the radiation source (either cobalt-60 or caesium-137) within a protective shield of lead or other suitable material, and have a mechanism to move the sample from the loading position to the irradiation position. Such units can be placed very conveniently in an existing laboratory or a room without needing extra shielding. The principal advantages of such small irradiators are that they are easy to install and operate, that they provide high dose rate and good dose uniformity that are essential for radiation research. These characteristics are achieved by surrounding the sample with radiation source pencils, such that it receives radiation from all directions. Such design arrangement places restriction on the sample size limiting it to typically 1–5 litres. This volume however is quite adequate for research and small-scale irradiations. To irradiate, the sample is placed in the irradiation chamber while it is in the loading (shielded) position, and the timer is set to deliver pre-selected dose (see Fig. 9). On the push of a button located on the control panel, the irradiation chamber along with the sample is automatically moved to the irradiation position and is returned to the unloading (shielded) position at the end of the pre-set irradiation time.

FIG. 9. Self-contained dry-storage gamma irradiator suitable for research and small-scale irradiations. In preparation for irradiation, a sample holder is being placed in the irradiation chamber when it is in the loading position. Depending on the dose rate of the day, the timer on the control panel (bottom right) is set to give the desired dose.

These self-contained irradiators are classified by the IAEA as Category I (dry storage) and Category III (wet storage). Applications and the procedures for the use of these two categories of irradiators are described in a Practical Radiation Safety Manual published by the IAEA [14].

Panoramic irradiators (IAEA categories II and IV)

For pilot-scale and full commercial-scale irradiations, panoramic irradiators are more suitable, where the source consists of either several cobalt-60 pencils arranged in a plane (like a source rack in Fig. 6) or a cylinder (Fig. 11) that can be moved into a large irradiation room. When retracted from this room, the source is shielded either by water (wet storage), or lead, or other appropriate high atomic number material (dry storage). Because a radionuclide source emits gamma rays in all directions, it may be surrounded by product containers to increase the energy utilization efficiency. Thus, several (sometimes 100 to 200) containers are typically irradiated simultaneously. For such an arrangement, the average dose rate is significantly lower and the product needs to be irradiated for longer time periods. However, this is compensated by the fact that several large containers are irradiated simultaneously.

Radiation processing facilities may be categorized by the operating mode – batch or continuous. Products may be moved into the irradiation room (where irradiation will take place), either while the source is fully shielded (batch operation) or while it is exposed (continuous operation). To reduce dose variation in a product container, it is either rotated on its own axis during irradiation (suitable for batch operation) or is moved around the radiation source; this is more suitable for continuous operation, but also for some batch irradiators.

For high throughput requirements, continuous operation is preferable. Depending on the design of the irradiator, the product containers go around a radiation source on a conveyor (or are hung from a track on the ceiling) a few times (generally, 1 to 4 passes), and may also travel at different levels. The principal objective is to absorb as much radiation energy as possible and yet have relatively uniform dose in the product. For low dose requirements, the containers may travel continuously; the conveyor speed is selected to give the required dose. For high dose applications, however, the conveyor speed would be generally too low and hence shuffle-dwell mode is preferable. In this mode of operation, the product containers stay (dwell) at the designated irradiation positions around the radiation source for a certain dwell time (usually a few minutes), and then they all move (shuffle) to the next positions, such that each container eventually resides at each position (in all loops around the source) before leaving the irradiation room. In this mode of operation, dwell time is selected based on the dose required. Figure 10 shows a typical sequence of movements of product containers around the source rack (plaque) for four passes at single level for a shuffle-dwell irradiator.

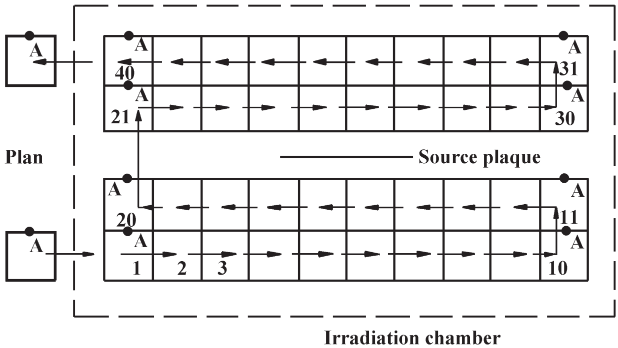


FIG. 10. Example of a sequence of irradiation for a shuffle-dwell irradiator for four passes, single level. Each product container occupies each of the 40 positions in sequence before exiting the irradiation room (chamber). 'A' is a fixed point (arbitrary and imaginary) on the side surface of the container, which indicates the orientation of the container with respect to the radiation source rack (plaque) as the container passes around the source. In this way, each container is irradiated twice from each of two sides.

For relatively small throughput requirements, irradiators with batch processing capabilities are very useful. Figure 11 shows a schematic for a simple batch irradiator where the source is a single cobalt-60 cylinder. In this mode of operation, several product containers (a batch of containers) are placed manually or automatically in the irradiation room while the source is in its shielded position in the storage room. After the irradiation room is vacated and closed, the source is moved into the irradiation room to a fixed pre-set position in the centre of the containers for the required time interval. The containers may be rotated on their own axis or may revolve around the source while they are irradiated to improve dose uniformity. After completion of irradiation, the source is moved to its shielded position, and the irradiated product containers are replaced with a new batch of containers for the next irradiation.

Batch irradiators are very suitable for pilot-scale irradiation since they are easy to operate. In addition, they are more amenable to providing possibility to change dose rate as well as source/product irradiation geometry for optimization study.

These panoramic irradiators are classified by the IAEA as Category II (dry storage) and Category IV (wet storage). Applications and the procedures for the use of these two categories of irradiators are described in a Practical Radiation Safety Manual published by the IAEA [15].

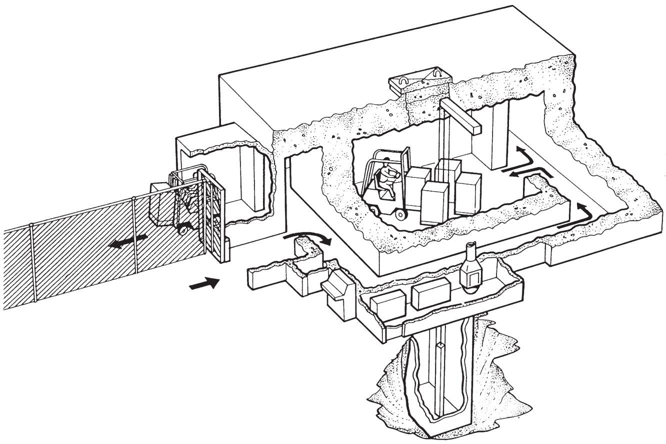
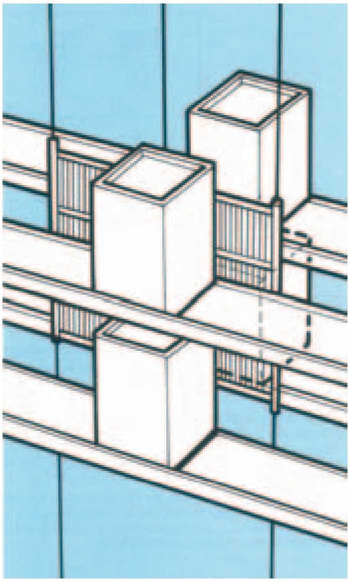


FIG. 11. Batch irradiator. In its simplest form, a forklift truck operator positions four pallets of products on turntables inside the irradiation room. After the operator has left and the irradiation room is closed, the source is raised and the turntables rotate the pallets during the entire irradiation. Automated features can be added to increase product throughput (courtesy of MDS Nordion, Canada).

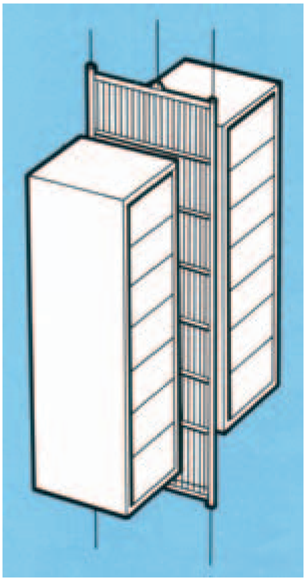
COMMERCIALLY AVAILABLE PANORAMIC IRRADIATORS

With the growth of the industry, the range of products being treated with gamma radiation for different objectives is widening. Today there are many kinds of materials being irradiated for various applications. The constant challenge faced by the designers of the irradiators is however always the same: how to expose this product to the radiation source to maximize energy utilization and dose uniformity, yet in a simple and reliable way. The characteristics of the new products, such as shape, density and composition invariably demand modifications to the design. Different applications also demand different throughputs. Some products have special requirements, such as frozen and chilled foods. To meet this variety of challenges, designers have developed several types of irradiators some of which are described here.

Product overlap irradiators: The most basic design is to place the product in metal containers for irradiation. Such containers are sometimes referred to as totes. Tote irradiators are very versatile as they can treat products contained in boxes, bags or drums. Depending on the irradiator design, a tote can accommodate a few hundreds of kg of product. These totes are moved around the radiation source on roller bed conveyors generally in four rows (two on either side of the source rack) and at two levels. An elevator shuttles the totes between the two conveyor levels. The combined height of two totes is more than the height of the source rack, which makes this arrangement *product overlap* (see Fig. 12), which helps dose uniformity in the product. In addition, the product intercepts more of the radiation emitted from the source, and thus the energy utilization efficiency is relatively high for product-overlap



Product overlap



Source overlap

FIG. 12. Two types of irradiation geometry: product overlap and source overlap. Notice that for product-overlap arrangement, the combined height of two containers is more than the height of the source rack and each container travels at two levels. For source-overlap arrangement, the height of the source rack is more than that of the product container and each container travels at one level only (courtesy of MDS Nordion, Canada).

irradiator. However, traversing at two levels makes the transport mechanism more complex.

Source overlap irradiators: With a view to simplifying the transport mechanism, the product containers in this irradiator type move generally in four or more rows but only at one level. The container (sometimes referred to as carrier) is longer than the one in the product-overlap design, but the height is less that that of the source rack, which makes this arrangement *source overlap* (see Fig. 12). These containers are often hung from a track in the ceiling. Dose uniformity is comparable to that in the case of product overlap, but the energy utilization efficiency is lower.

Pallet irradiators: These irradiators are designed to irradiate an entire pallet of product as received by the irradiation facility. The products arrive at the facility in standard size pallets (containers), which are suitable for other segments of the production process (including transportation). In other aspects, these irradiators are similar to product-overlap design. There are two main advantages of a pallet irradiator. It saves the extra effort of removing the product boxes from the pallet and arranging them in an irradiation container (e.g. a tote) for irradiation and then, after the process, replacing them into the pallets for transportation out of the facility. This also avoids any damage to the product due to handling. Recognizing that the pallet size differs in different regions of the world, the suppliers could customize the irradiation system, if requested.

Batch irradiators: These are relatively simple and convenient irradiators suitable for small-scale irradiations. The product containers are arranged in the irradiation room while the source is in its shielded position. To achieve required dose uniformity, each container is placed on a turntable that continuously rotates during irradiation. Alternatively, the containers may revolve around the source.

Special features: There may be specific requirements for some processes that could be incorporated in some of these designs. These include:

– Irradiation of products in frozen or chilled condition: This is generally accomplished by the use of insulated containers.
– Incremental dose delivery: For a continuous mode of operation, this feature allows irradiating products with different dose requirements together. Products requiring less dose exit the irradiation room after less number of revolutions, while other products continue to go around the source for more dose.

– Low absorbed-dose applications: Because of mechanical speed limitations, various techniques may be used to reduce the absorbed-dose rates for such processes. These techniques include using only a portion of the source (e.g. raising one of several source racks to the irradiation position), using attenuators, and irradiating at greater distances from the source (which may be a separate loop).

Computerized control system: On-line management computer software with visual display is now standard equipment on many irradiators (see Fig. 13). It facilitates several aspects of the operation and safety of the irradiator by providing continuous and instant information about, for example:

– values of all the key parameters that can affect dose to the product; this information is necessary for process control,
– status of the source position and all interlocks; this information is necessary for safe operation of the facility, and
– location and status of the product containers in the facility; this information is necessary for product control.

FIG. 13. Control room monitor displays current status of the irradiator (right-top). Photo at right-bottom indicates the location of the control room within the facility. Two photos on left visually identify locations of all the product containers (courtesy of IPEN, Brazil).

Such information eliminates duplication, reduces errors and boosts productivity at the same time ensuring that all products are received, processed and released without delay.

IRRADIATOR SELECTION CRITERIA

For the efficient operation of the irradiation facility, it is critical that the requirements of the intended application(s) are clearly understood before the facility is designed and built. It is also equally important that these requirements are unambiguously conveyed to the supplier of the irradiator. When listing the requirements, it is essential that not only the present needs are considered but also the future ones (but realistic) are included. These requirements should then be matched against the characteristics of various available irradiator types, and the selection made based on the best judgement. The following is a list of some of the technical criteria that would help through the selection process:

- type of product to be irradiated (size, density, homogeneity),
- seasonality of product (some food products may be seasonal),
- dose and dose uniformity requirements for the intended product(s) and process,
- throughput requirements; Fig. 14 illustrates how product density can affect throughput,
- is the irradiator part of a manufacturing or other process, or a service facility, and
- is this a single or a multi purpose facility.

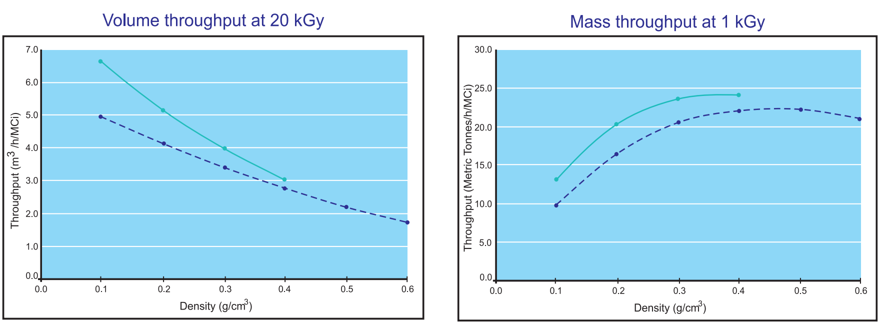


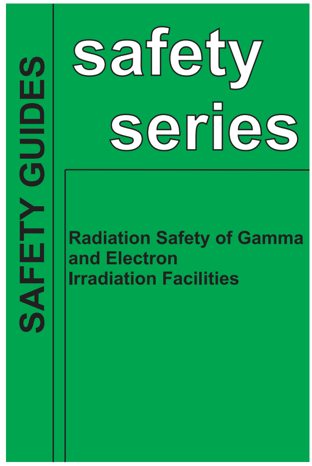
FIG. 14. Dependence of product throughput on product density for two different irradiator designs (courtesy of MDS Nordion, Canada).

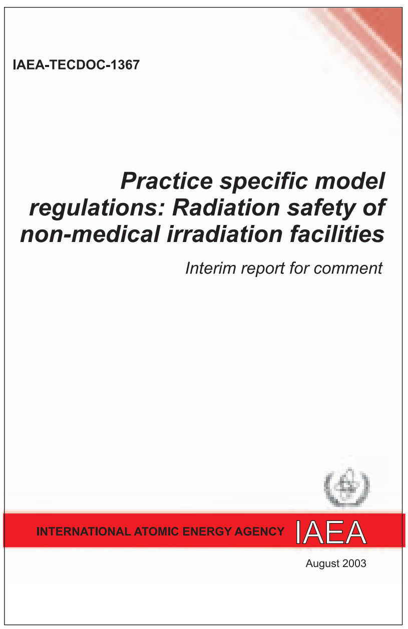
Besides these technical criteria, there are others that should also be considered during the selection process. These include:

- capital and operating cost of the total facility,
- utility requirements such as electrical power and water supply, and
- technical expertise available in the region, including human resources.

Depending on the national regulations of the country, it would be necessary to obtain a licence to construct and operate the facility. Several departments or ministries could be involved depending on the product to be processed, such as atomic energy authority, health ministry, food ministry, industry ministry, etc.

RADIATION SAFETY





Radiation processing is a regulated industry that has been operating safely for more than 40 years in usual commercial and business parks. The workers in these facilities wear normal everyday clothing and comply with standard health and safety regulations. Yet it is recognized that large quantities of radioactive material located at one place for any purpose pose a potential hazard to people (workers as well as general public) and the environment, indicating the need to achieve a high degree of safety and reliability in the use of these sources. In view of this, the IAEA in collaboration with several international organizations (FAO, ILO, NEA of OECD, WHO and PAHO)* issued basic safety standards (BSS) for protection against ionizing radiation and for the safety of radiation sources [16]. The standards comprise basic requirements to be fulfilled in all activities involving radiation exposure. They are aimed at serving as a practical guide for public authorities and services, employers and workers, specialized radiation protection bodies, enterprises, and safety and health committees. These requirements are fulfilled by effective quality control procedures together with careful design, manufacture, transportation, installation, operation and decommissioning of the radiation sources. In 2003, the IAEA published a report that provides information and guidance regarding the design and safe operation of the industrial irradiation facilities to organizations intending to purchase and operate them [17]. This information satisfies the requirements of the BSS in that a code is provided to ensure that during normal operation, maintenance and decommissioning and in emergency situations, radiation exposure of the workers and public is within set limits and is kept *as low as reasonably achievable* (ALARA). In 1992, the IAEA published a safety guide that provides device specific guidance regarding design, operation and regulation of industrial irradiators [18]. This applies to all types of irradiation facilities, whether operated on a commercial basis or for research and development purposes.

Manufacturers of irradiators follow established procedures that satisfy national and international regulations regarding the design and manufacture of radiation sources, such as those in ISO Standard 2919 [19]. The design of the transportation containers for radioactive material (such as cobalt-60) as well as the transportation procedures are governed by the IAEA regulations for the safe transport of radioactive material [20] and other existing national legislation. These containers are heavily shielded in accordance with stringent

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* FAO – Food and Agriculture Organization of the United Nations
ILO – International Labour Organization
NEA of OECD – Nuclear Energy Agency of the Organization for Economic Co-operation and Development
WHO – World Health Organization
PAHO – Pan American Health Organization

design specifications. Also, they are able to withstand significant impact and high temperatures without losing integrity.

The design of Category IV (panoramic, wet storage) irradiators is governed by an ANSI Standard [21] and other international standards. Also, before an irradiation facility can be constructed and operated, license from the national competent authorities is necessary. This ensures that the facility is constructed so that during normal operation any radiation exposure of workers will be within the dose limits set by the IAEA basic safety standards [16], that there is no significant exposure to public, and that the radiation protection and safety devices and procedures are in place. Operators and other workers at the facility are a critical group that could be potentially exposed to high radiation levels. This is prevented through interlocks and critical design features of the operation of the irradiator. These safety systems and devices are expected to meet certain criteria [18], including:

– defence in depth: multiple levels of protection should be provided, thus minimizing the need for human intervention. Irradiation facilities should only be operated if all levels of defence are in place and functioning;
– redundancy: principal components should be duplicated;
– independence: fault in the irradiator should not impair the safety system; and
– fail-to-safe: failure of a safety system should always result in safe conditions.

Based on these criteria, several safety systems are incorporated in the design of an irradiator that either give early warning on any potential problems or prevent them from occurring. These systems are designed to protect product, facility, workers and, in the worst case scenario, the surrounding environment. Alarm signals from these safety systems are transferred to the control room for immediate attention of the operator. Such systems include:

– High temperature detector: it quickly recognizes abnormal heat build-up, which could lead to product damage and the increased potential for fire.
– Ozone time delay: when air is exposed to ionizing radiation, ozone and other toxic gases are formed, which decay quickly and are also removed by the ventilation system. This safety system prevents entry in the irradiation room for a short time period after the source has been moved to the shielded position till safe level of these gases is reached.
– Pool water level sensor: it continuously monitors the water level in the storage pool and alerts the operator of unusually high or low levels.

– Radiation monitor: it continuously monitors radiation level and alerts the operator if there is abnormal level; two most likely locations for these monitors are the product exit port and water deionizer tank.
– Source-down detector system: it provides direct indication of the position of each source rack when it reaches the bottom of the storage pool.
– Earthquake detector: it provides a means of automatically returning the source to the safe storage position in the event of a seismic event.
– Product over-exposure detector: it senses any malfunction in the product movement mechanism and automatically returns the source to the storage position to avoid over-exposure of the product.

The operators and workers wear radiation dosimeters (badges) during working hours to monitor the amount of radiation dose they receive. These badges are read at regular intervals (for example, every two weeks) to determine the dose received by the wearer of the badge. The IAEA, in collaboration with several international agencies, has set guidelines regarding safe limits of radiation dose that workers may receive [16], which are based on the ICRP recommendations [22]. The radiation badges are thus used to confirm that no individual is receiving dose above the set limits. The irradiator design and the work procedures are such that individual doses are kept under limit. According to the IAEA, it is incumbent on the facility operator not only to keep the doses under the limit but also to reduce all individual doses to the level that can be reasonably achievable (called ALARA principle). Thus, generally, doses received by workers in radiation processing industry are well below these dose limits, almost close to the background levels.

It is part of the requirements of the IAEA's basic safety standards [16] to provide security for radiation sources so as to prevent theft or damage and to prevent any unauthorized person from carrying out any of the operations at the irradiation facility. This may be fulfilled by, for example:

– not relinquishing control of a radiation source without compliance with all relevant requirements specified in the registration or licence,
– notifying immediately national regulatory authority information regarding any decontrolled, lost, stolen or missing source,
– not transferring a source unless the receiver possesses a valid authorization, and
– conducting a periodic inventory of movable sources at the facility at appropriate intervals to confirm that they are in their assigned locations and are secure.

In response to these requirements, some large irradiation facilities are planning to establish physical security perimeters, control and monitor access through these perimeters, ensure that persons with authorized access to the radiation source are trustworthy and reliable, and train all their employees on the importance of security.

LABORATORIES

Many irradiation facilities include various laboratories, such as dosimetry laboratory, microbiology laboratory, food testing laboratory and materials testing laboratory depending on the products being irradiated at the facility. For all irradiation facilities however, a dosimetry laboratory is absolutely necessary. Figure 15 shows equipment related to some dosimetry systems that are generally used at a radiation processing facility.

FIG. 15. Some typical equipment in a dosimetry laboratory at a radiation processing facility (courtesy of NCRRT, EAEA, Egypt).

Dosimetry is needed for the following objectives [23]:

– determination of the process dose limits (along with microbiology and/or materials testing laboratories),
– operational qualification of the irradiation facility on regular basis,
– performance qualification for each product/process, and
– process control during routine production.

The dosimetry laboratory must be staffed with qualified and trained personnel. Every facility should select at least one accurate and reliable routine dosimetry system suitable for the relevant radiation applications [24]. There are many good dosimetry systems currently available commercially; selection should be based on comparing the requirements of the relevant radiation application(s) with specifications of these dosimetry systems. The selected dosimetry system should then be thoroughly characterized including calibration [13], and should be used according to nationally or internationally recognized procedures, such as those described in ISO/ASTM Standards [23–26]. This dosimetry system should be traceable to nationally or internationally recognised standards [27]. This is a very important requirement, especially for regulated products and international trade, since the measurements do not have much validity without such traceability. It is also advisable to regularly participate in intercomparison exercises amongst dosimetry laboratories to help maintain the quality of the dosimetry system in use.

If the primary irradiation process were for sterilization or microbial load reduction, it would be useful to have an access to a microbiology laboratory where bioburden can be estimated and tests conducted with a view to setting sterilization dose. Similarly, if the primary process were for materials modification, such as polymerization, a materials testing laboratory with equipment for testing mechanical and physico-chemical properties can be very useful.

GENERAL REMARKS

Radiation technology is now well established and is contributing to the industrial development, thus playing its legitimate role. Taking into account the total value of the products treated with ionizing radiation, the economic scale of this technology is enormous. Some well established applications like sterilization, and polymers and semiconductors modification are in common use. This is especially true for health care products in industrial countries like the USA and Canada, where it is estimated that more than half of these products is currently sterilized using ionizing radiation.

At the same time, radiation technology is expanding. More facilities are being built, and new applications are being added. These new applications follow the general trends of technological development and social needs, like nanotechnology, natural polymers, composites and environment protection. With continuous increase in the use of radiation for industrial and medical needs, the manufacturers and suppliers are responding by improving and modifying the existing types of irradiators as well as designing new types. Such a proliferation of designs is a boon for the potential facility operator, but it also places a responsibility on him to meticulously compare various available irradiators and make the best selection for his needs. Correct selection affects not only the ease of operation but also yields higher efficiency, and thus improved economy.

APPENDIX A

Several concepts and terms that are used to describe a radiation process and the gamma irradiators are discussed here.

Radiation absorbed dose is the measure of absorbed radiation energy, and is defined as the radiation energy (in joule, J) absorbed by unit mass (in kilogram, kg) of the product; it is measured in units of gray (Gy) [28].

Thus,

$$1 \text{ gray (Gy)} = 1 \text{ J/kg}$$

Table A.I shows different levels of radiation dose that are relevant for various major radiation applications. The commercial industrial applications are generally referred to as 'radiation processing' and the relevant dose range may be referred to as 'radiation processing dose' or 'high dose'.

TABLE A.I. MAJOR RADIATION APPLICATIONS AND RELATED DOSE RANGES

Application	Dose range
Medical – diagnosis	10 – 100 mGy
Medical – therapy	1 – 10 Gy
Industrial – food and agriculture	0.1 – 10 kGy, or more
Industrial – sterilization	10 – 30 kGy
Industrial – materials modification	50 – 100 kGy, or more

Dose rate is the dose given in unit time and is determined by the activity of the radiation source and the irradiation geometry. It is measured in, for example kGy/h or Gy/s. Dose rate in a research irradiator can be up to 20 kGy/h. In an industrial facility (for example, with 3 MCi of cobalt-60), it can be as high as 100 kGy/h near the source, but on the average it is around 10 kGy/h.

Radioactivity level is the strength (or power) of a radiation source, which is defined as the number of disintegrations of radioactive nuclides per second. The special name of the SI unit is becquerel (Bq) [28]. However, this is a very small amount of activity, and traditionally activity is measured in units of curie (Ci).

Thus,

1 becquerel (Bq) = 1 dis/s = 1 s^{-1}
1 curie (Ci) = 3.7 × 10^{10} Bq

And, for example, 100 kCi = 100,000 Ci = 3.7 × 10^{15} Bq = 3.7 PBq. Table A.II explains the SI prefixes that are commonly used in radiation processing.

TABLE A.II. PREFIXES FOR SI UNITS

Factor	Prefix	Symbol
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

Radiation processing throughput is the amount (mass or volume) of product processed per unit time (such as, kg/h or m^3/h) and is determined by the radioactivity level (power) of the radiation source, product density and the product absorbed dose. For a gamma irradiator, source power may be calculated from the source activity; such that 1 million curie of cobalt emits about 15 kW of power. Figure 14 shows dependence of the throughput on the product density.

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