FOOD IRRADIATION FACILITIES AND RADIATION MEASUREMENTS – JOURNEY, CHALLENGES AND FUTURE

Bhaskar Sanyal[*1,2] , S. Gautam[*1,2] and A. Sharma[1]
[1]Food Technology Division
Bhabha Atomic Research Centre
Mumbai - 400 085, India
[2]Homi Bhabha National Institute, Mumbai - 400 094, India

[*]Email: sanyal@barc.gov.in; sgautam@barc.gov.in

Abstract

Radiation processing technology is now available commercially for integration with the supply chains in Indian agricultural and food sectors. Dosimetry techniques and dose measurements are the two most essential components of any food irradiation system both in R&D and commercial use. Selecting appropriate dosimetry technique and dose measurement method are fundamental to the efficacy of various applications that have been developed over the years since the inception of the food irradiation program at BARC. Accurate delivery of the standardized doses to the food products is governed by a reliable dosimetry system and its traceability to the national and international standards.

1. Introduction

Radiation processing of food or food irradiation is a technology that can help reduce food spoilages, enhance safety and promote trade. Irradiation facilities are the backbone of the food irradiation program. Since the start of R&D in early 1960's a number of irradiation facilities have been procured and installed at the Food Technology Division, BARC. These facilities include small experimental irradiators for R&D as well as irradiators that allow large scale irradiation of food and agricultural commodities for studying technoeconomic feasibility. The effectiveness of processing of food by ionizing radiation depends on proper delivery of absorbed dose and its reliable measurement. It is important that the dosimetry techniques and dose determination are carried out as per the nationally and internationally accepted protocols. For exportable commodities the process may also require approval of a mutually accepted dosimetry protocol between the importing and exporting countries. Several dose measurements procedures have been used to get reliable quantification of radiation doses. Finding a single dosimeter system covering the entire range of applicable doses likely to be used in food processing, 20 Gy to 25 kGy, is a challenging proposition. Different dosimetry systems may be required for different dose range used for processing of food. External environmental influences such as the temperature during dose measurement, and accuracy in a rather narrow dose range, are the other problems that confront dosimetry. Therefore, attempts have been made to explore and design novel materials for food irradiation dosimetry.

2. Food irradiation facilities

R&D at Food Irradiation Processing Laboratory (FIPLY) at FTD, BARC started with the laboratory scale experiments using small imported irradiators like Gamma Cell 220 (AECL, Canada), later replaced with the indigenous Gamma Cell 900, and Gamma Chambers 5000 supplied by BRIT, BARC. These irradiators are used even today for exposing various experimental materials including food, to gamma rays at various doses, and also needed for standardizing dosimetry protocols for industrial food irradiation facilities.

In the year 1967, a panoramic wet storage type cobalt-60 gamma irradiation facility called Food Package Irradiator, the first plant in India, and in this part of the world, along with a demineralized water (DM) plant for the water to be used in source storage pool, was procured from Atomic Energy Canada Ltd (AECL). FTD also has a portable cesium-137 gamma irradiator. A dry storage type grain irradiator with a screw type grain conveyor system (AECL) was installed in FIPLY, however this facility is now not in operation (**Fig 1**).

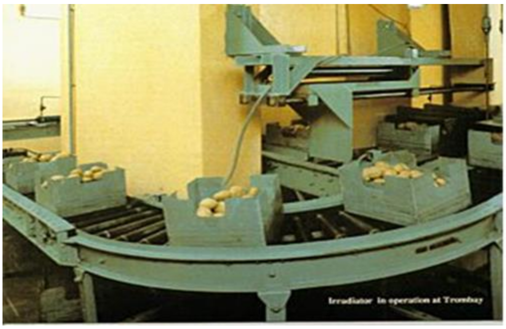
For carrying out the food processing, various food, plant machinery, instruments, safety systems etc. were procured, installed, operated and maintained by the trained personnel of the division. A small engineering workshop was set up for development, fabrication and maintenance of various food plant machinery and gadgets. Irradiation facilities in FIPLY were also used for the R&D on sterilization of medical products before the ISOMED plant in BARC was commissioned into operation.

Fig. 1: A dry storage type grain irradiator with grain lifting conveyor system (collaboration with AECL, Canada, currently the facility is not in operational state).

2.1. Food Package Irradiator

The Food Package Irradiator (FPI) is the workhorse for all major scale-up studies on food irradiation since 1967. After every 5-6 years, the radiation source replenishment work is also undertaken to keep the sources usable for covering applications in all dose ranges. This facility houses a split source frame for variable dose delivery, and therefore, suitable to cater to a wide spectrum of commodities. The current concept of multitasking irradiation facility has actually evolved from this facility. Because of more than 5 decades of service, various components of the facility gradually became unserviceable leading to difficulties in plant operation. Efforts were made to revamp the detailed design of the existing mechanical and electrical components in 2019-2020. Based on the information and operational experience the refurbishment of the facility was planned without altering existing civil structures. Several technical discussions were conducted and the following major scope of works were finalized in collaboration with DRHR, BARC to modernize the facility. The scope included a) Replacement of the old product handling system with upgraded design, b) Replacement of the entire source drive systems including source lifting ropes as per the present AERB safety standard (AERB/RF/SS-6), and c) Up-gradation of control console by replacing relay-based logic with PLC-SCADA interface. Several advanced safety interlocking systems such as ozone delay interlock, exit conveyor interlock, radiation interlock at DM plant and watch dog timer for product safety are now installed. The structural integrity of the source storage pool was assessed for the first time since commissioning ensuring safe storage of source. The facility has now been refurbished and deployed for regular routine operation after complying all the safety requirements from the regulatory agencies of BARC since 2022 (**Fig.2a, b, c & d**).

a)



b)

c)

d)

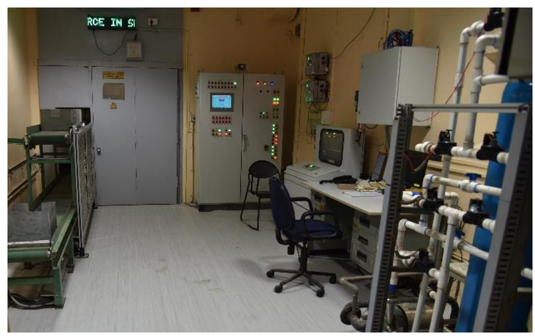


Fig. 2: (a) Food Package Irradiator (FPI) during installation in 1967 and (b) control room during 2004, (c) Food Package Irradiator - Upgraded (FPI -U) during 2023- 2024, (d) Refurbished control room of FPI-U in 2024.

2.2. Cesium Irradiator

FIPLY houses one of the oldest cesium-137 based marine product mobile irradiator (Brookhaven National Laboratory, USA). The facility was installed in 1968 and recently refurbished with the new control console (**Fig. 3**). The current source strength (cesium-137) of the irradiator is 30 kCi. It was designed to be portable primarily for on board fishing and simultaneous irradiation on large ships. The control mechanism of the cesium irradiator has been refurbished and various detailed engineering drawings of the facility were reconstructed and digitized for future reference.

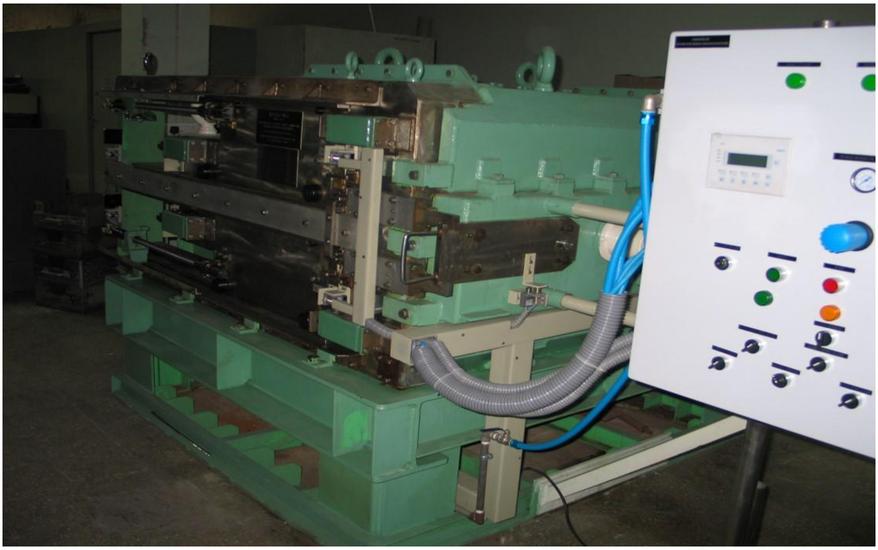


Fig. 3: A batch type Cesium-137 Gamma Irradiation facility in collaboration with the Brookhaven National Laboratory, USA (1968)

2.3. KRUSHAK Irradiator

In 1994, Government of India gave clearance for the commercial radiation processing of certain foods including potato, onion and some other agricultural commodities. FTD, BARC initiated the process for identifying land and setting up a 30 T/ d technology demonstration facility for potato and onion (POTON) irradiator, later named KRUSHAK, (Krishi Utapdan Sanrakshan Kendra), at Lasalgaon in Nashik district of Maharashtra. The POTON irradiator was designed, and built indigenously through the collaborative effort of several divisions of BARC, but majorly DRHR, TSD and CED. Before commissioning, the name POTON was changed to KRUSHAK, and the facility was dedicated to the nation by the Late Prime Minister Shri Atal Behari Vajpayee in 2002. For a few years KRUSHAK was managed and commercially operated by the engineers and scientists of FTD (**Fig. 4a & b**). Several collaborative experiments were undertaken with the local farmers and traders on onion and other agricultural commodities. Consequently, this operational experience gave practical inputs for handling of commodities, regulatory, operational and administrative experience. Since then, the expertise of FTD has been continuously utilized in installation, operation, dosimetry and safety of the operation of various irradiators across the country. During 2006-07, the KRUSHAK facility was upgraded for phytosanitary treatment of fruits specially to overcome quarantine trade barriers enabling export of Indian mangoes to USA. KRUSHAK became the first cobalt-60 gamma irradiation facility in the world, outside US, to be certified by USDA-APHIS for phytosanitary treatment of mango. In order to make the facility multi-tasking, various modifications were carried out in the control systems relating to conveyor speed and in product box dimensions. Concept of movable lead shield was introduced for the first time to attenuate the radiation dose to process low dose requiring agricultural commodities. Further to ensure adequate dose delivery in the low dose range with lead shield, several experimental dose measurement exercises were carried out. Currently, the facility is capable of processing bulbs and tubers for control of sprouting, insect disinfestation of cereals, pulses, their products, spices and quarantine treatment of fresh fruits and vegetables. Since 2007, KRUSHAK has been successfully processing Indian mangoes for quarantine requirement of export to USA and other countries. Since then, the facility is being operated under PPP mode.

a) **b)**

Fig. 4: a) KRUSHAK irradiator, BARC at Lasalgaon, Nashik, (b) Mango irradiation at KRUSHAK for export to USA since 2007.

2.4. Small Experimental Irradiators

There are four Gamma Chambers housing cobalt 60 sources to carry out lab-scale R&D activities not only in food and biological samples but for radiation sensitivity testing of various equipment of departmental interests. The first gamma cell (Gamma cell-220) was received from the Atomic Energy Canada Ltd in 1967 (**Fig. 5a**) and still maintained in full operation for various research works. In 1995 a Gamma Chamber 900 and subsequently in 2005 another Gamma Chamber 5000 of BRIT, DAE were commissioned (**Fig. 5b & c**). In order to cater to the R&D need, a new Gamma Chamber 5000 (BRIT, DAE) has also been installed with enhanced dose rates in 2017 and deployed for utilization (**Fig. 5d**).

Today India has 28 food irradiation facilities, 5 in Government sector and 23 in private sector. Further, a greater number of commercial irradiation facilities are expected to come up in various parts of the country showing good prospects for radiation processing of food in the country.

a)

b)

c)

d)

Fig. 5: (a) Gamma Chamber (Gamma Cell 220) of FTD, BARC commissioned in 1967 in collaboration with AECL, Canada, (b) Gamma Cell 900 designed by BRIT, DAE commissioned in 1995, (c) Gamma Chamber 5000 of BRIT, DAE commissioned in 2005, (d) Gamma Chamber 5000 designed by BRIT, DAE commissioned in 2017.

3. Radiation measurements-past and present

3.1. Dosimetry activities

It is the responsibility of a food irradiation facility to ensure delivery of the required dose of radiation, uniformly and within the legal limits prescribed under the relevant regulations, adequate to achieve the desired objective. In view of this, a Food Dosimetry Section was created within FTD to standardize the dose requirement of various foods for meeting various technological objectives set by food scientists. A dosimetry laboratory was specially created to monitor and administer absorbed dose (maximum and minimum dose) that a food can tolerate and without compromising its nutritive and sensory quality. Each food has a specific minimum and maximum dose tolerance. The dosimetry systems used then were Fricke (for low doses) and ceric-cerous (for higher doses) dosimeters. The product box size was reduced to one-third of its original size to accommodate all the products ensuring uniform distribution of the absorbed dose. The periodical dosimetry was carried out with each product to obtain accuracy and precision in desired dose delivery. In order to carry out lab-scale experiments, a cobalt-60 based gamma chamber (Gamma Cell-220) was used, and the dose output of the machine was estimated periodically. Collaborative programs with other divisions like RPD were also carried out to gain experience.

3.2. Current R&D in dosimetry

3.2.1. Experimental routine dose measurements

In radionuclide-based irradiation facility, quantification of radiation is essential to characterize the facility in operational qualification (OQ), dose distribution evaluation in exposed commodities during performance qualification (PQ) programs and routine dosimetry during processing to ensure the desired objectives of the technology. The energy imparted to the product in a radiation facility is influenced by the optimized dwell time or conveyor speed. Dose also depends on the bulk density of the process load. Time to deliver the same dose to a product becomes longer as the bulk density increases. These relationships should be established during facility qualification. In view of this, a detailed experimental dosimetry is carried out in Food Package Irradiator-Upgraded (FPI-U) periodically using food as medium and employing Fricke or ceric cerous sulphate dosimetry systems. The dose distribution profile inside the product box is experimentally measured to find out the positions of the D_{max} and D_{min} positions and the dose rate of the facility during shuffle-dwell movement of the conveyor. The dose outputs of all the gamma chambers (4 Nos) are also periodically measured for precise dose delivery to all the experimental samples.

Dose mapping experiments of the product trays of the cesium-137 facility were also carried out to find the dose distribution profile and dose uniformity ratio using Fricke dosimetry system. The improved dose uniformity was also experimentally determined with modified irradiation geometry. The operational approval of the refurbished facility for R&D applications is under process.

Industry interest in the deployment of linear accelerators (LINAC) for food irradiation is gradually increasing. Absorbed dose to food commodity is the function of several operational parameters of the LINAC. In order to assess the feasibility of a 10 MeV, LINAC for food irradiation, alanine-EPR dosimetry system was used to measure the process parameters at Electron Beam Centre (EBC), APPD, BARC, Kharghar. Experiments were performed with different foods such as mango, potato and semolina in one sided and two-sided irradiation geometries. The dose distributions (0.25 to 1 kGy) were evaluated in each set of trials. The depth dose pattern in food and scan width of the electron beam were observed suitable for large scale irradiation of food. Subsequently, to determine the dose uniformity with statistical variation, an experiment with packets of semolina was conducted. The dose uniformity ratio was observed to be within 2.2 indicating that the facility is suitable for commercial food irradiation. Table 1 shows the list of dosimeters available for routine dosimetry and to ensure traceability.

Table 1. Dosimetry systems and their useful dose ranges

Compound	**Applicable for**	**Measurement method**	**Dose Range (Gy)**
Radiochromic Film	Electron/ Photons (γ and X-rays)	Spectrophotometer	$1 - 1.5 \times 10^5$
Polymethyl methacrylate	Photons (γ and X-rays)	Spectrophotometer	$10^2 - 1.5 \times 10^5$
Radiochromic Optical wave guide	Photons (γ and X-rays)	Spectrophotometer	$1 - 10^5$
Dichromate	Photons (γ and X-rays)	Spectrophotometer	$2 \times 10^3 - 5 \times 10^4$
Ethanol chlorobenzene solution	Photons (γ and X-rays)	Spectrophotometer, colour titration, high frequency conductivity	$10 - 2 x 10^5$
Alanine	Electron/ Photons (γ and X-rays)	Electron Paramagnetic Resonance spectrometer	$1 - 10^5$
Calorimetric	Electron	Calorimeter	$10^2 - 5 \times 10^4$
Cellulose tri acetate	Electron/ Photons (γ and X-rays)	Spectrophotometer	$5 \times 10^3 - 3 \times 10^5$
Fricke solution	Photons (γ and X-rays)	UV spectrophotometer	$20 - 4 \times 10^2$
Ceric-Cerous Sulfate	Photons (γ and X-rays)	Potentiometry	$5 \times 10^2 - 5 \times 10^4$

3.2.2. Development of novel dosimetry systems

The dose uniformity inside the product box of any radiation facility is strongly dependent on the bulk density of the process load. During the routine operation of a radiation facility, the dimension of the product box and the source pencil distribution pattern cannot be altered. To observe the role of bulk density of the product on absorbed doses in a cobalt 60 based radiation facility (FPI-U), a range of bulk densities (0.01 to 0.8 g/cc) were prepared using different materials. D_{max}, D_{min} and Dose Uniformity Ratio (DUR), the three most crucial parameters exhibited significant variation with the change in bulk densities of the product.

There has been a continuous requirement to prepare simple, stable and accurate dosimeters for food irradiation dosimetry. For perishable foods, irradiation is carried out at sub-ambient temperatures like chilled (2±1 °C) and frozen (-20±2 °C) and therefore, radiation doses are required to be measured at these low temperatures. In view of this, solid state dosimeters could be the most suitable options in comparison with aqueous systems. Passive dosimeters such as thermoluminescent (or photoluminescent) solid state systems are simple and already established as useful options for personnel monitoring application. However, these systems show multiple and changing luminescence peaks with increasing dose. Moreover, in the higher doses for food irradiation application, these dosimeters exhibit nonlinear response because of filled traps and/or trap competition/trap damage. In order to address this problem two thermoluminescent phosphors ($CaSO_4$:Dy and $CaSO_4$:Dy, Bi) have been studied by pre-irradiation thermal treatments and established their efficacy in measurement of food irradiation dose at sub-ambient temperatures. The results showed that the polycrystals as host matrices of the dosimeters showed limitations in the high dose measurements and amorphous systems such as glass could be of paramount importance for this application because of their inherent inertness toward radiation. Several studies have recently been carried out demonstrating utility of thermoluminescence of borophosphate, aluminosilicate, and lithium borate glasses as promising candidates to measure food irradiation doses. One potential glass system, lithium borate doped with dysprosium has been recently developed in collaboration with GAMD, BARC.

In electron beam irradiation, thin film dosimeters are useful. The radiochromic dyes have shown their potential as reliable dosimetry systems since a long time because of their simple mode of operation and reliability. In order to develop radiochromic thin film dosimeter, a basic study has been conducted to optimize the appropriate ingredient of a dosimetric formulation of leuco crystal violet as the leuco dye and 2,2,2-trichloroethanol as sensitizer in acetonitrile solution. In order to make the dose evaluation tool cheaper, the response of the leuco crystal violet film was measured using two image analysis methods – single and a novel double channel readout. It was shown for the first time that the dose measurement of leuco crystal violet-based film can be carried out using an inexpensive desktop scanner-based color analysis.

There is a need to develop simple and cost-effective dosimeter as an import substitute for low dose phytosanitary application of food. An indigenous dye-based dosimeter has been developed and validated. This new system has immense potential of deployment for the measurements of low dose radiation processing of food. This dosimeter is an aqueous system used for measuring gamma radiation doses in cobalt-60 irradiation facilities and may not be suitable for electron beam facilities. The technology has recently been made available on BARC website for further dissemination to the users.

The adequate dose delivery depends on source configurations, product geometry and conveyor speed to ensure uniform dose distribution. Mathematical models to estimate the dose profile inside the product box are required for various functions: 1. to optimize several plant-running parameters, 2. to optimize precise dose delivery, 3. to plan adequate source pencil distribution, 4. to assess the process control capabilities of any commercial irradiation facilities. In this regard, simulation of radiation absorbed doses in the food products are also being carried out using Monte Carlo N-Particle Transport (MCNP) code.

4. Current challenges and future possibilities

4.1. Irradiation facility design

A major challenge in designing food irradiation facility is finding the optimized design for making a multitasking facility capable of delivering all the required dose ranges in food applications (20 Gy to 25 kGy). In addition, the facility should operate in a cost-effective manner both in capital investment during construction, and O&M expenditure. The majority of the food and agriculture produces amenable for radiation processing are seasonal in nature. In view of running the facility throughout the year with a viable commercial goal the facility should be designed in a way that different commodities can be processed with different technological objectives. In order to achieve this, innovative plant design are required e.g a) split source frame configuration to obtain a wide range in dose delivery, b) product conveying system with wide range of speed control to ensure absorbed dose delivery with accuracy and operational safety, c) the source lifting assembly needs innovative design to reduce the transit dose, d) control system with reliable programmable logic control and user-friendly interface, e) the safety interlock systems with redundant features to ensure both the operational and product safety. In comparison with traditional food processing practices the radiation installations require higher capital investment in civil construction. In order to address this, several novel ideas are used such as a) small modular irradiator (SMI) with adequate process rate, b) mobile irradiator with accelerator as source of ionizing radiation with adequate safety and security, c) innovation in civil design and material usage without compromising with radiological safety, d) innovative design of the category III type land based irradiator where source is stationary in water pool and the water-proofed product boxes would go into the water for adequate dose delivery. This novel concept would help in reducing considerable cost involved in the construction of irradiation cell with 1.5 to 3 m thick concrete wall.

Accelerator based systems have certain advantages over radionuclide-based irradiators. However, there are some limitations too. These are mainly related to poor penetration of electrons, and their conversion efficiency to X-rays. In view of these, there is a huge scope of research in designing accelerator-specific product conveying system to achieve desired process rates, both in one-sided and two-sided irradiation geometries. An exclusive design for product handling in free-flow grain irradiator would also be required. A novel accelerator-based low energy beam technology is also being currently explored globally for surface decontamination of food commodities. The efficacy of surface treatment using low energy electron beam for food such as spices, herbs, or grains has already been reported. A deeper understanding on the interactions of low energy electron beam (LEEB) and low energy X-ray (LEEX) with foods is required.

4.2. Dosimetry challenges

Measurements of radiation dose at sub-ambient temperature has always been a challenging task. Development of amorphous systems with suitable dopants is therefore of importance for this specific application. Thermoluminescence is a potential and cost-effective option.

Electron accelerators are becoming popular in the field of radiation processing technology. Radiochromic thin film capable of measuring high radiation dose is therefore essential. Commercially available films are imported mainly for medical use. These are not readily usable for food dosimetry. Hence, indigenous development of these films for food use is of interest. Radiation processing of food using LEEB and LEEX will be of interest in certain application areas of food industry. Measuring surface dose and its penetration depth will be a challenging dosimetry problem. Thin foil dosimeters could be potential candidates, but a dedicated research effort would be required.

5. Conclusion

Considerable efforts have been put to design and construct various food irradiation facilities catering to the need of basic and applied R&D, scale-up trials, and subsequent commercial deployment. Significant research has been carried out in the past six decades to develop and standardize dosimetry and dose measurement techniques in food products to achieve uniform dose delivery and establish its traceability. There is an ample scope to conceptualize, design and develop novel need-based food irradiation facilities considering the growing interest of the entrepreneurs in deployment of the technology in India’s food and agricultural sector. Design and development of novel radiation dosimetry systems will remain a major endeavor.

6. Acknowledgement

Endeavors and contributions from the former and current colleagues of Food Technology Division towards the progress and advancements made in the food irradiation program is highly acknowledged.