Chapter 14

Dosimetry Characterizations and Utilizations of Electron Accelerators

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In last few decades, electron accelerators have become very popular among researchers and industry to uplift the characteristics of materials to cater different societal needs. Electron accelerators capable to generate electron beam (EB) having energy in a range 0.3 MeV to 10 MeV. EB of less than 0.3 MeV can't penetrate the material thoroughly and therefore not suitable for radiation processing. Alternatively, EB having energy beyond 10 MeV has potential to cause neutron activations. EB enjoys more public acceptability and thus superior to gamma irradiation as it is fully controllable and can provide dose in order of kGy within few seconds [46]. Additionally the unique aspect of electron beam treatment is that it is carried out on the final stage of production, even post packaging at normal atmospheric conditions, which makes it very attractive over the conventional alternative approaches including chemical treatments, autoclave etc. When energetic electrons are impinged onto the materials, the amount of radiation energy absorbed per unit mass is known as radiation dose (D) and is measured in joules per kg or gray (Gy). The induced chemical changes are quantified as radiation chemical yield or "G" values, which is the number of molecular events arising per 100 eV of energy absorption. D and G are related by: $D(kGy) = 9.65 \times 10^6/(Gmol.wt.)$. For many reactions, G-values are typically ranging $0.1 - 10$. The relation between D and G evidences that industrial applications of EB are focused on organic materials having high molecular weights comparative to inorganic ones [46]. For organic materials the dose demand is quiet smaller as compared to inorganic that requires huge dose to up bring the same amendments. Basically the organic items generate active species (such as radicals) by absorbing radiant energy which leads to chain reaction. The energy deposition profile of EB is far different from that of gamma rays and therefore the dosimetry characterization of EB accelerators and its shielding compulsions are different from radioactive source based irradiation facility. In the present chapter dosimetry characterization of EB accelerators have been discussed along with some important results of accelerators at Electron Beam Centre (EBC), Kharghar, BARC. Further few important applications of EB accelerators carried out at EBC for last few years catering many areas like food preservation, agriculture, semiconductor industries and waste management. The shielding estimation and its technical aspects related to high power EB have also been elaborated.

14.1 Electron Beam Irradiation

Irradiation is basically termed as radiation treatment but the word radiation having broad meaning. In simple, radiation is a technique of moving energy from one point to another either in medium or in absence of medium. The atomic or nuclear happenings are the main source of radiation and any unit which gives off energy is categorized as radiating particle. The kinetic energy of radiating particle is expressed commonly in terms of electron volt (or eV), which is basically the kinetic energy achieved by an electron while moving through a potential difference of one volt. The most imperative parameter has to be known to perform irradiation is 'Absorbed Dose':

Absorbed Dose or Dose (D): It is the energy imparted per unit mass of material at point of interest. $D = dE/dm$, Its SI unit is gray (Gy) and traditional unit is radiation absorbed dose (rad). 1 Gy = 1 J/kg and 1 Gy = 100 rad. Electron irradiation is radiation treatment technique concluded with highly energetic electron beam (EB). Worldwide thousands of high energy high power EB accelerators are employed to modify the materials for different applications like research, medical, food, agriculture, and industry. The primary goal of it is to carry out physico-chemical amendments inside a product or destroy microbial bio burden. Typical dose values required for different applications along with energy brackets of electron beam are tabulated in table 14.1 [63].

Table 14.1: Energy of electron beam and required dose range for typical applications.

Applications	**Energy (MeV)**	**Dose (kGy)**
Cross linking of PE	0.5-10	25-350
Lubrication property of Teflon	2	100-500
Food Preservation	05-10	0.25-25
Sterilization of Medical Products	02-10	25-50
Polymerization & curing of surface coatings, adhesives & paints	0.25-0.5	20-500
Purification of Exhaust Gases	0.5-1.5	10-15
Demineralization of waste water	0.8-10	12-60
Colour enhancements of gems	05-10	In order of 'MGy'

14.2 Dosimetry Characterizations of Electron Accelerator

The dosimetry characterizations are integral part of irradiation process to get the desired goal. It standardizes the output beam parameters and establishes their relation with dose rate. Dose profile generation, beam energy corroboration, beam size verification, output dose rate correlation with product speed under a particular operating parameters and importantly selection of proper dosimeter having on site calibration [64].

14.2.1 Dosimeters and its Calibration

The selection of appropriate dosimeter is the prime task as the dose rate generated by EB accelerators are in order of kGy/min or even much more pulse dose in case of pulse accelerators (Linac). In addition to avoid the unpredicted error in connection with energy and current fluctuations, the in house calibration is preferable. The radio-chromic film dosimeters are

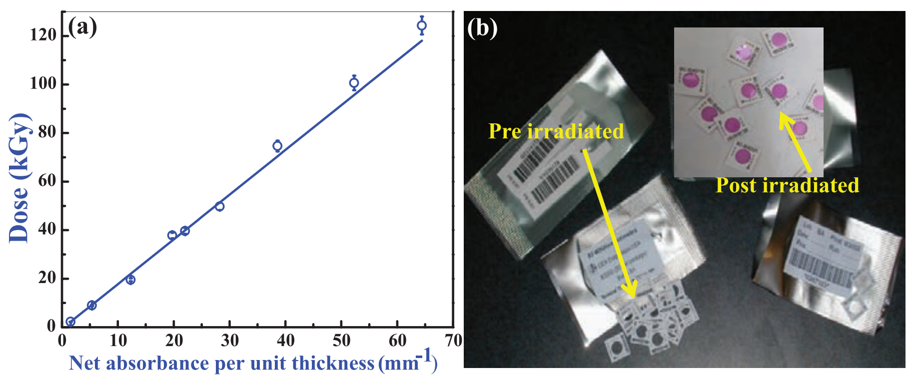

Figure 14.1: (a) In-house generated calibration plot of radio-chromic routine dosimeter, (b) routine dosimeters.

perfect for EB accelerator based routine dosimetry, which is based upon absorbance changes with respect to a fixed wavelength [64, 65].

14.2.2 Dose Uniformity Checks

The uniform dose delivery must be ensured throughout the full scan area of the system. It has been assured by generating the dose distribution profile over full scan length and hence it is one of the major dosimetry analysis. In case of industrial accelerators ±12% dose variation over full scan length is permissible. It is highly useful to fix the appropriate number of passes or time of irradiation for set operating parameters to attain the requisite dose output [41]. The dose distribution patterns of 10 MeV RF Linac in static and dynamic conditions are shown in Fig. 14.2. The same of 1-3 MeV DC accelerator in dynamic condition is given in Fig. 14.3a.

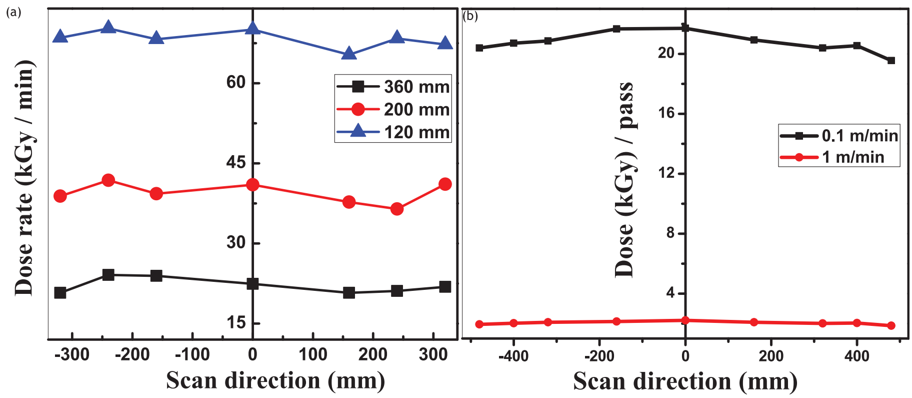

Figure 14.2: Dose Profile of 10 MeV accelerator at 3 kW Avg. beam power with scan length 1 m (a) static condition at different distances from exit window (variation ±8%.) and (b) dynamic condition under different speeds of conveyor (variation ±5%).

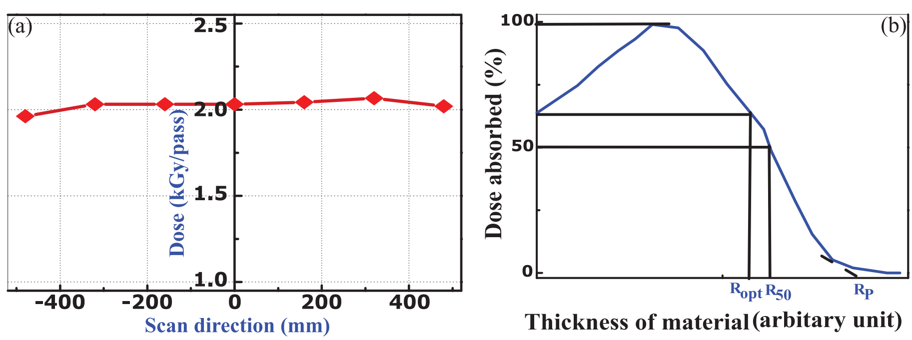

Figure 14.3: (a) Dose Profile of DC accelerator operating at 1 MeV, 1 kW with conveyor speed 2.2 m/min and 1 m scan length (variation is ±4%), and (b) Dose distribution of electron beam inside a material.

14.2.3 Energy Verification and Dose Profile within Target

The thickness of the product to be irradiated suitably will be decided by electron beam energy. Accelerator output EB energy is practically determined by generating the depth–dose profile along the beam axis in appropriate reference material like water, perspex or aluminium. The profile can be realized with material wedges by affixing the long strip dosimeters or with

individual thickness insertion through separate radio-chromic film dosimeters. A typical depth–dose profile of EB in a reference material is given in Fig. 14.3b. Three important parameters: optimum thickness (R_{opt}), half-value depth (R_{50}) and penetration thickness or practical range (R_P) are useful to design the suitable product container for irradiation.
In order to measure the mean EB energy (E_0) and the most probable EB energy (E_p), the parameters R_{50} and R_p can be used respectively with relationships:

$$E_0\ (MeV) = 0.33 \times R_{50}, \text{and} \quad (14.1)$$

$$E_p\ (MeV) = 0.22 + 1.98R_p + 0.0025R_p^2 \quad (14.2)$$

where, R_{50} and R_p are expressed in units of 'cm' in water [66].

14.2.4 Beam Size Determination

Beam spot size is also crucial beam characteristics to decide the degree of irradiation uniformity as well as to fix the product size, especially in case of static irradiation conditions. The beam spot-size at various locations from the exit window in 10 MeV is shown in Fig. 14.4, which indicates a linear variation with the distance from Ti exit window. The conclusion can be drawn that the system performs as 1 m long directional line-type radiation source.

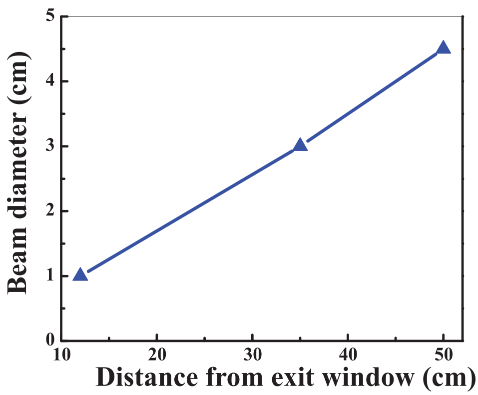

Figure 14.4: Beam spot size as function of distance in 10 MeV.

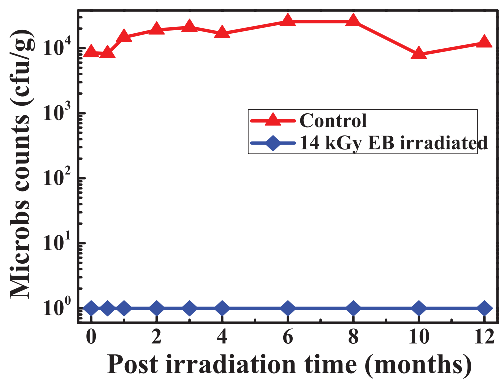

Figure 14.5: Microbial count levels in coriander powder, control and EB irradiated, stored at room temperature for a span of one year.

14.3 Applications of Electron Accelerators

14.3.1 Food preservation

Many food products including potato, mango, semolina, litti, dried apricots, thalipeeth, quiences, spices and coriander powder, have been irradiated with 10 MeV EB and the preservation goals have been achieved [54, 55]. The experiments have been carried out in dose window 0.4-14 kGy and the observed dose uniformity ratio facilitates the system to be used as food irradiator on commercial scale. Figure 14.5 shows the bio burden analysis of irradiated coriander powder at regular interval in a span of 1 year and it concludes that the microbial count remains nil even after 1 year post irradiation storage under normal room conditions. A generic class-based approval has been notified by Government of India in 2012 for increasing the product range for radiation processing [67]. The classes of food products and respective dose limits for radiation processing are mentioned in table 14.2. Also the dose limit of allied products are mentioned table 14.3.

14.3.2 Sugarcane Cultivation (Chitosan irradiation)

Chitosan acts as bio-stimulator (natural plant growth promoter) for sugarcane. It facilitates better germination, proper tillering of plant and regulates photosynthesis through minimizing the transpiration from leaves & stabilizing chlorophyll levels. The irradiation of chitosan was carried out in 10 MeV accelerator with optimized dose 50 kGy (shown in Fig. 14.6). It has been found that the sugarcane production is enhanced by 1.3 times as against un-irradiated chitosan. The work was successfully done for actual field applications in collaboration with Vasantdada Sugar Institute (VSI), Pune and NA&BTD, BARC.

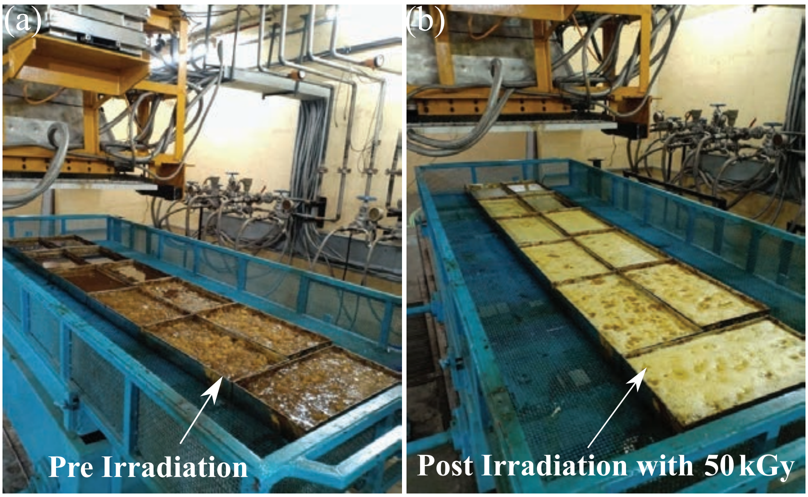

Figure 14.6: (a) Pre- and (b) post-irradiated chitosan with optimized dose of 10 MeV EB.

14.3.3 Seed Mutations

Mutation of seeds is foremost application of radiation technology in the field of agriculture. Several types of seeds have been muted with 10 MeV EB at different dose points and it has been proven that EB is an advanced mutagen. One important crop is cowpea which can grow in harsh climate condition especially drought like situations as well as requires very low investments and so it is also known as poor men's crop. VBN1 (white seeded) and P152 (Puff colored) are two popular varieties of cowpea and those are irradiated with doses 100 Gy, 200 Gy and 300 Gy. The conclusion has been drawn that in terms of effectiveness and efficiency EB technique is superior over gamma and other techniques to achieve the desired mutation [68].

EB is used as mutagen for rice variety ADT 37 and a high frequency of desirable grain type variation has been observed. Dose delivered were 200 Gy to 600 Gy and total 25 grain-type mutants were obtained in M4 generation of ADT-37 variety. This study revealed that the percentage contribution of the EB is more than double of that for GR in obtaining desirable slender and medium slender grain-type mutants [69]. The loading tolerance induced in EB muted rice variety ADT 45 is a major achievement in the area of rice cultivation (shown in Fig. 14.7). Other crops like blackgram (Vigna mungo (L) Hepper) was also irradiated with dose

Table 14.2: Classes of food products and their respective dose limit for radiation processing [67].

Class	Food	Purpose	Dose Limit (kGy)	
			Minimum	Maximum
Class 1	Bulbs, stem and root tubers, and rhizomes	Inhibiting sprouting	0.02	0.2
Class 2	Fresh fruits and vegetables (other than class 1)	Delay ripening	0.2	1.0
		Self-life extension	1.0	2.5
		Quarantine application	0.1	1.0
Class 3	Cereals and their milled products, pulses and their milled products, nuts, oil seeds, dried fruits and their products	Insect disinfestations	0.25	1.0
		Reduction of microbial load	1.5	5.0
Class 4	Fish, aquaculture, seafood, and their products (fresh or frozen), and crustaceans	Elimination of pathogenic microorganisms	1.0	7.0
		Self-life extension	1.0	3.0
		Control of human parasites	0.3	2.0
Class 5	Meat and meat products including poultry (fresh and frozen) and eggs	Elimination of pathogenic microorganisms	1.0	7.0
		Self-life extension	1.0	3.0
		Control of human parasites	0.3	2.0
Class 6	Dry vegetables, seasonings, spices, condiments, dryherbs and their products, tea, coffee, cocoa and plant products	Microbial decontamination	6.0	14.0
		Insect disinfestations	0.3	1.0
Class 7	Dry foods of animal origin and their products	Insect disinfestations	0.3	1.0
		Control of moulds	1.0	3.0
		Elimination of pathogenic microorganisms	2.0	7.0
Class 8	Ethnic foods, military rations, space foods, ready to eat, ready-to cook/ minimally processed foods	Quarantine application	0.25	1.0
		Reduction of microorganisms	2.0	10.0
		Sterilization	5.0	25.0

Table 14.3: Dose limits for radiation processing of allied products [67].

Sr. No.	Allied product	Purpose	Dose Limit (kGy)	
			Minimum	Maximum
1	Animal food and feed	Insect disinfestations	0.25	1.00
		Microbial decontamination	5.00	10.00
2	Ayurvedic herbs and their products and medicines	Insect disinfestations	0.25	1.00
		Microbial decontamination	5.00	10.00
		Sterilization	10.00	25.00
3	Packaging materials for food/allied products	Microbial decontamination	5.00	10.00
		Sterilization	10.00	25.00
4	Food additives	Insect disinfestations	0.25	1.00
		Microbial decontamination	5.00	10.00
		Sterilization	10.00	25.00
5	Health foods, dietary supplements and nutraceuticals	Insect disinfestations	0.25	1.00
		Microbial decontamination	5.00	10.00
		Sterilization	10.00	25.00
6	Body care and cleaning products	Microbial decontamination	5.00	10.00
		Sterilization	10.00	25.00
7	Cut flowers	Quarantine applications	0.25	1.00
		Self life extension	0.25	1.00

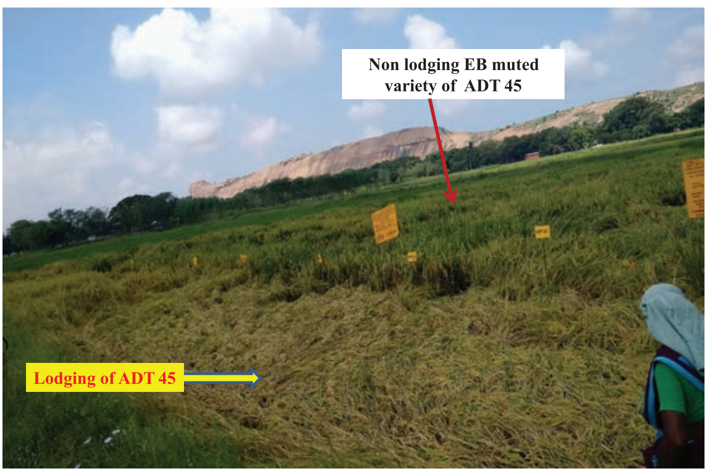

Figure 14.7: Lodging tolerance induced in ADT 45 variety of rice using electron beam as mutagen.

up to 600 Gy and achieved the desired mutations [70]. Moringa is a miracle tree species with abundant nutrients, high protein and biological value. Different muted varieties of moringa (PKM 1 variety), horsegram and cluster bean (MDU 1 variety) have been developed with 10 MeV EB irradiation and the modification can be visualized through Fig. 14.8.

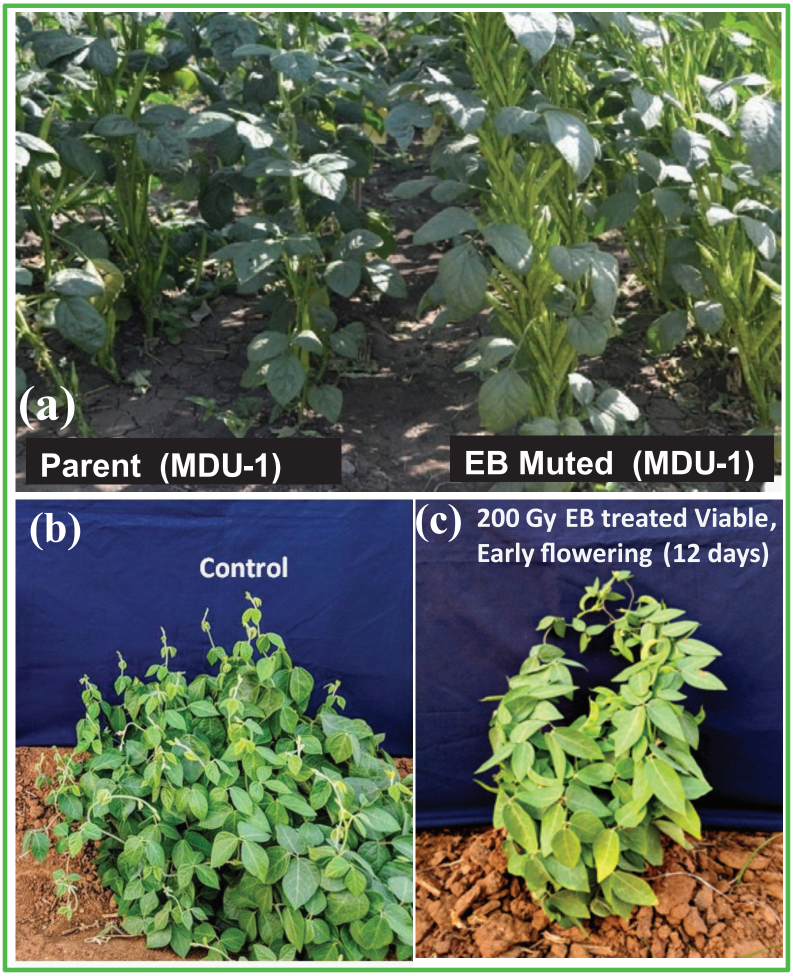

Figure 14.8: (a) Development of high yielding cluster bean mutant, (b) and (c) desirable mutants for altered duration and growth in horsegram.

14.3.4 Radiation Tests of Photovoltaics

The radiation endurance tests of multi-junction solar cells, InGaP/GaAs/Ge, have been done for ISRO. In geosynchronous orbit, the accumulated electron fluence is 10^{15} electrons/cm^2 for a span of 15 years which is the common time period of a satellite. This testing was done in both 10 MeV and 1 MeV accelerators by delivering such accumulated fluence and conclusion has been drawn that the efficiency was dropped from 28% to 18%. The objective of this scientific analysis is to supports ISRO to prepare the solar panel matrix correspondingly, on a satellite [71, 72].

14.3.5 Characteristics Modifications of Semiconductor

The reverse recovery time (t_{rr}) of power diode (rated as 2.6 kV, 700 A) is reduced from 15 μs to 6 μs after imparting optimized dose of 4 kGy with 10 MeV EB. Also the leakage current and forward voltage drop are around 20 mA and 2 V respectively whereas the same have been achieved with gold doping as 150 mA and 2.3 V respectively (Fig. 14.9). This is the first time an EB accelerator is used for control of semiconductor device parameters in India and exemplary of joint venture between research institution (EBC, BARC) and industry (Bharat Heavy Electricals Limited).

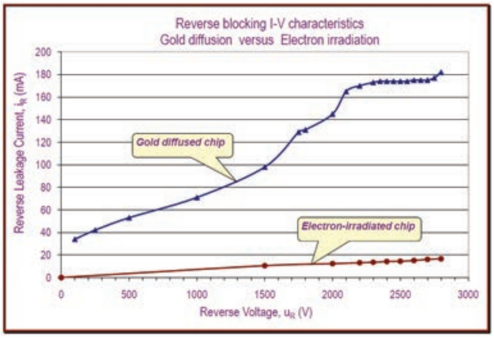

Figure 14.9: Gold diffusion resulting in higher leakage current compared to 10 MeV EB irradiation process.

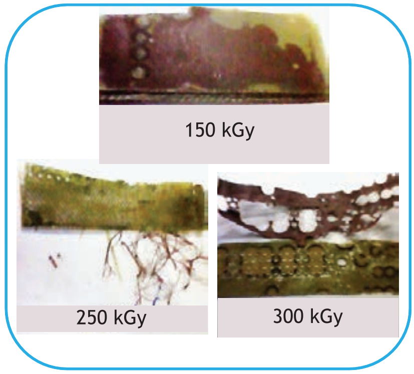

Figure 14.10: 150 kGy , 250 kGy and 300 kGy EB irradiated sample of PCB.

14.3.6 Demineralization of Waste Water

EB irradiation is an advanced oxidation process (AOP) to mineralize or degrade the heavy organic molecules which ultimately leads to reduce chemical oxygen demand (COD) from textile and municipal waste water. The simulated textile dye water is irradiated with 75 kGy dose of EB and achieved COD is less than 100 ppm (well below the allowed limit of 250 ppm) in comparison to 2500 ppm original along with 90% mineralization [43]. The study also demonstrates that EB approach is more economical as compared to other AOPs such as gamma radiolysis, ozonolysis, UV treatment and photo-catalysis [43].

14.3.7 Electronic Waste Management

Now days electronic waste management has become a major challenge especially printed circuit board (PCB) disposed from used electronic devices like computers, TVs, mobiles etc. EB treatment leads a way in this direction and it has successfully been demonstrated that the adhesion between base and top layer (metallic) of PCBs was broken with dose 300 kGy (Fig. 14.10). In this process the 99.9% pure copper has been recovered for reuse and afterwards the remaining components are easily degradable. No chemical catalysts have been used and treatment is carried out in normal atmospheric condition.

14.4 Conclusions

Dosimetry techniques of EB and their details have been briefed including selection of proper dosimeters & at site calibration, depth dose, dose profile and beam size. These are the most vital articles to utilize the accelerator as it assures the desirous modifications in the product as result of EB treatment. In addition the physical dimensions of product and associated infrastructures are ascertained with the help of dosimetry. Many research and commercial applications of EB accelerators have been talked about in concise. These perform like building block to convert EB irradiation technique from laboratory level to commercial scale. In order to ensure the radiation safety and economical aspects, the shielding estimation techniques have also been elaborated with suitable shielding materials options. Accelerator facility has to satisfy the two eminent obligatory standards dosimetry and shielding. The present chapter may also be advantageous to establish a new accelerator facility to attain the desired goal of industry as well as research institutions.