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**INTERNATIONAL CONSULTATIVE GROUP ON FOOD IRRADIATION
(ICGFI)**

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THE DEVELOPMENT OF X-RAY MACHINES FOR FOOD IRRADIATION

(PROCEEDINGS OF A CONSULTANTS' MEETING)

Vienna, Austria
16-18 October 1995

CONSULTANTS' MEETING ON THE DEVELOPMENT OF X-RAY MACHINES FOR FOOD IRRADIATION

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EXECUTIVE SUMMARY

Food irradiation is currently accepted to be safe up to an overall average dose of 10 kGy. This is based on scientific evidence (Joint FAO/IAEA/WHO Expert Committee on the wholesomeness of irradiated food, 1980) and is recognized by an international standard to this effect (Codex Alimentarius General Standard on Food Irradiation, 1983).

Three types of radiation source are currently permitted for food irradiation processing.

(i) The radionuclides Cobalt-60 or Cesium-137. Cesium-137 is not currently available in commercial quantities.

(ii) Electrons (bremsstrahlung) generated by a machine at maximum energy of 10 million electron volts (MeV).

(iii) X-rays generated by a machine at a maximum energy of 5 MeV.

Additional radiation sources will be needed, not only to meet the expected increased demand for the radiation processing of large volumes of product in a short time, but also to provide the food industry with different options of irradiation facilities. One option could be the use of X-rays generated from machines with a maximum energy above 5 MeV. This could combine the advantages of the penetration power of cobalt-60 and the ability of machine sources to be switched on and off at will.

In considering this option, the Consultation highlighted three areas of prime importance - the process must not induce radioactivity, it must be efficient and it must be economical.

<u>Induced radioactivity</u>

It is accepted that there must be no measurable radioactivity induced in the food after radiation processing. (Measurable was defined as more than 1/1000 of the natural radioactivity that is found in all food). In addition, it was agreed that no radioactivity should accumulate in the components of the X-ray machine or surrounding environment (processing room, conveyor system etc.).

The Consultation reviewed theoretical and experimental data on the possible induction of radioactivity when food is processed using X-ray energies above 5 MeV. It was concluded that radiation processing with X-rays up to 7.5 MeV can be used without concern about induced radioactivity in food.

The type of material which should be used to convert electrons to X-rays (the converter) was considered in detail. The commonly used converter materials (tungsten,

tantalum and gold) can produce photo-neutrons if the electron energy is raised to 10 MeV. However, limiting the energy to 7.5 MeV would prevent production of photo-neutrons in gold converters and limit the photo-neutrons produced in tungsten and tantalum converters to an insignificant number.

The Consultation also concluded that the radiation safety requirements for machines operating at 7.5 MeV would not be different from those imposed upon machines operating at lower energies. It was also concluded that existing dosimetry methods for X-ray processing would be appropriate for machines operating at 7.5 MeV.

Efficiency

If the commercial application of radiation processing using X-rays is to be a success then the technology must be at least as efficient in utilizing energy, and so achieving throughput of product, as existing methods (primarily radionuclide facilities). The various factors which affect energy efficiency were considered (photon utilization, conversion efficiency, self-absorption) and it was concluded that an overall efficiency of approximately 8% could be achieved using 7.5 MeV compared to 4% which can be achieved using X-rays generated from machines with a maximum energy of 5 MeV. Thus, the efficiency achievable at 7.5 MeV is comparable to that achieved in radionuclide facilities.

Economics

An economic model was used to investigate how various parameters (the dose required, the beam power and the energy generated by the machine) affected the cost of the process. The use of 7.5 MeV was found to be more cost effective than using X-rays generated from machines with a maximum energy of 5 MeV. For example, at a dose of 2.5 kGy, using a beam power of 100 kW, treatment with a 5 MeV machine would cost US$ 52.5 per tonne of material, compared to US$ 35 per tonne using 7.5 MeV.

CONCLUSIONS

It was concluded that X-ray machines for food irradiation with energy up to 7.5 MeV can be used without any concern about induced radioactivity but would be a satisfactory, efficient and cost effective addition to other radiation sources available for food processing.

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1. BACKGROUND

The increasing restrictions and prohibition on fumigation of foods for health and environmental reasons, the need to control a number of foodborne diseases - especially those related to consumption of food of animal origin, and increasingly strict sanitary and phytosanitary regulations in food trade, have resulted in an increasing interest in the commercial application of food irradiation. Currently, governments in 38 countries have approved the use of this technology for processing one or more food items. There is a trend in approval of irradiated food by food classes, e.g. fruits, vegetables, cereals, meat, etc. instead of by individual food items, following the recommendation of the International Consultative Group on Food Irradiation in 1994.

Irradiation of food is currently carried out on a limited commercial scale in 28 countries. International trade in irradiated food at present is limited to products such as spices but is expected to increase significantly based on the above mentioned reasons and the provisions of the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS), adopted during the GATT Uruguay Round. Under the SPS Agreement, governments could be required to furnish justification for food import restrictions based on national regulations which are stricter than recognized international standards, guidelines and recommendations.

1.1. RADIATION SOURCES

Three types of radiation sources are permitted for food irradiation processing according to the Codex General Standard for Irradiated Foods of the Codex Alimentarius Commission:

(i) The radionuclides Cobalt-60 (^{60}Co) or Cesium-137 (^{137}Cs). The latter is currently not available in commercial quantities.

(ii) Electrons generated by a machine at maximum energy of 10 million electron volts (MeV).

(iii) X-rays (bremsstrahlung) generated by a machine at a maximum energy of 5 MeV.

1.2. NEED FOR ADDITIONAL RADIATION SOURCES

^{60}Co and electron beam (EB) machine sources are well developed and are being used for treating food and sterilizing disposable medical products. High energy, high capacity industrial X-ray machines have also been developed but are not yet widely applied in food irradiation. Additional radiation sources are needed, not only to cope with the expected increase in demand for radiation treatment of large volumes of certain types of pre-packaged or palletized food, especially those which have to be treated in a relatively short time, but also to provide the food industry with different options of irradiation facilities. An example of such a situation is the treatment of Chilean grapes to satisfy quarantine regulations for importation in the U.S.A. Over 100,000 tonnes of grapes have to be treated within the space of a few months. Table 1 lists food items which could be advantageously treated by X-rays. Thus, efficient, economical, and high capacity X-ray machines could make an important contribution to food irradiation under specific circumstances and would reduce the burden on other types of radiation sources.

Table 1. Food and agricultural commodities which may be more efficiently treated by X-rays.

1. <u>Seasonal Fruits to Overcome Quarantine Barriers</u>
   Grapes, mangoes, papaya, carambola, lychees, rambutan, etc.

2. <u>Prepackaged, Fresh and Frozen Food of Animal Origin</u>
   Poultry, meat, seafood, processed food products (especially for bulky products for in-line irradiation facilities).

3. <u>High-Value Stored Food Products</u>
   Dried fish, dried meat, dried fruits and tree nuts, cocoa beans, etc.
   (especially those which have high volume and are seasonal in production)

4. <u>Cut-Flowers</u>
   Various types of prepackaged cut-flowers/foliages to overcome quarantine barriers

It is anticipated that there will be a significant demand for large quantities and a variety of radiation sources for food processing in the near future for the following major reasons:

(i) <u>Reduction of Foodborne Diseases</u>. The increasing awareness of the risks from foodborne diseases and the demand for microbiologically safe food by the consumer will lead to a wider use of irradiation as a cold pasteurization process of foods, especially those of animal origin.

(ii) <u>Replacement of Fumigation of Food</u>. The global phasing out of methyl bromide (the most widely used fumigant to control insect infestation of food and agricultural commodities) under the Montreal Protocol[1] by the year 2000 will have an important impact on trade in food and agricultural commodities which have to be treated to overcome insect problems. Irradiation is likely to replace the use of methyl bromide for a wide variety and large quantities of fresh and dried fruits and tree nuts, especially to overcome quarantine barriers.

[1] An international treaty for the regulation of ozone depleting substances worldwide and under the auspices of the United Nations Environmental Programme.

1.3. OBJECTIVES

A consultants' meeting was held in Vienna, 16-18 October 1995 which had as its objectives:

(i) To appraise the current status of the development of X-ray technology required for food irradiation.

(ii) To evaluate and recommend the maximum energy of X-ray machines which will not introduce radioactivity.

(iii) To encourage the industry to develop efficient and economical X-ray machines to meet potential demand of food irradiation.

1.4. PARTICIPATION

The meeting was attended by scientists/officials who have expertise on EB/X-ray machines required for food irradiation and representatives of major companies which produce such machines. Dr. Ari Brynjolfsson (USA) served as the Chairman of the meeting. The list of participants of the meeting is attached as an Annex.

2. INDUCED RADIOACTIVITY

It is generally accepted that no significant radioactivity is induced when food is irradiated by gamma rays from ^{60}Co and ^{137}Cs, electrons from 10 MeV accelerators, and X-rays from electrons with incident energy below 5 MeV, even when doses as high as 70 kilogray (kGy) are used.

The question often raised is: can the energy of the electrons and of the X-rays be increased beyond the above limits? Increasing the energy beyond this limit may result in a small amount of radioactivity at sterilization doses of 70 kGy. Any such radioactivity is proportional to the dose. At interim energies and lower doses, it must then be considered whether the induced radioactivity is significant, and if limits must be set or restrictions put on the applications. For example, if the dose is extremely low, as in X-ray inspections at airports which use less than 0.5 Gy (140,000 times smaller dose than the sterilizing dose), 10 MeV X-rays would not produce any significant radioactivity.

2.1. NATURAL RADIOACTIVITY IN FOODS

The natural background radiation consists of three main components: (i) the cosmic radiation which varies with altitude and geographical latitude, (ii) the terrestrial radiation, which varies greatly from one location to another and (iii) the radioisotopes in food and in the human body. Each of these three main components contributes about equally to the overall background radiation. The natural radioactivity in foods varies from one product to another. It is often in the range of 40 - 600 becquerel (Bq) per kg of food. For example, the radioactivity per kg from potassium (^{40}K) alone may be typically 50 Bq in milk, 420 Bq in milk powder, 165 Bq in potatoes, and 125 Bq in beef. Typical results of studies on the radioactivity in foods for ^{40}K, radium (^{226}Ra) and thorium (^{228}Th) showed that radioactivities in different foods vary from 45 to 650 Bq/kg, from 0.01 to 1.2 Bq/kg, and from 0.02 to 1.3 Bq/kg, respectively.

2.1.1. What is significant induced radioactivity?

The most sensitive analytical measurements can detect radioactivity at a level of 1% of the natural radioactivity in food. This limit, together with an additional safety factor of 10, allows induced activity to be defined as significant if it is more than 1/1000 of the natural background in food. As shown above, there can be considerable variation in the natural radioactivity in food, but assuming an average value of 200 Bq/kg, induced radioactivity would therefore not be significant below 0.2 Bq/kg.

2.2. RADIOACTIVITY INDUCED BY ELECTRONS, GAMMA-RAYS, AND X-RAYS

Presently, the Codex Alimentarius Commission permits that food be exposed to gamma-rays from ^{60}Co and ^{137}Cs, to fast electrons less than 10 MeV, and to X-rays less than 5 MeV. The maximum average dose is 10 kGy. These radiation sources do not induce measurable radioactivity in the food, and theoretical calculations show that any induced activity is actually many orders of magnitude less than the limits defined above. The theoretical calculations show that there are three main pathways for induction of radioactivity in food: (i) isomeric activation; (ii) photo-nuclear activation; and (iii) neutron activation.

The analysis further shows that in the case of irradiation by 10 MeV electrons and by 5 MeV X-rays, the neutron activation, although insignificant, is larger than the activation produced by the other two major pathways, and that the neutron activity produced by 5 MeV X-rays is in the order of 60 times greater than that produced by 10 MeV electrons. Therefore, neutron activation is discussed in more detail below.

2.2.1. Neutron Activation

The threshold energy for the gamma-neutron, (γ, n), reaction is well above the 10 MeV energy limit for all the major isotopes in food. Thus, the threshold in the major isotopes of carbon, oxygen and nitrogen are 18.72 MeV (^{12}C), 15.67 MeV (^{16}O) and 10.55 MeV (^{14}N) respectively. However, a few isotopes have low photo-neutron thresholds; namely 2.225, 4.85 and 4.15 MeV in deuterium (hydrogen-2 (^{2}H)), ^{13}C and ^{17}O isotopes respectively. The concentration of these isotopes is low and the isotopes ^{1}H, ^{12}C and ^{16}O, which are produced when the neutron is ejected, are stable. Many of the trace elements and contaminants in food also have thresholds slightly below 10 MeV. The cross-sections (that is, the probabilities for the processes) are small and for most isotopes (except deuterium) increases in this range approximate to the third power of the excess energy of the electrons above the (γ, n) threshold (that is, ~ $(E - E_{th})^3$).

The neutrons emitted in these processes usually have initially an energy of a few MeV, but they will gradually be slowed down by collisions with the atoms of food and 'thermalized'. Some of the neutrons will escape the food and be absorbed in the conveyor and walls of the irradiation chamber, but some will be absorbed in the food. In a model food of average composition, about 89.4% of neutrons absorbed in the food will be absorbed in hydrogen to reform the stable isotope deuterium, about 8.5% will be absorbed in the ^{14}N to form the nearly stable and stable isotopes ^{14}C and ^{15}N respectively, about 1.1% will be absorbed in chlorine-35 (^{35}Cl) to form the nearly stable isotope^{36}Cl and 3000 times less of the isotope sulphur-35 (^{35}S) with half-life of 86.7 days, about 0.54% will be absorbed in ^{39}K to form the nearly stable isotope ^{40}K, and about 0.17% will be absorbed in ^{12}C to form the stable isotope ^{13}C. The remaining will be absorbed in other atoms to form stable isotopes, others will form isotopes that decay within microseconds, and a few will be absorbed in atoms to form isotopes with half-lives in excess of a few minutes.

The activities that are produced depend on the amount of trace elements in the food and the neutron fluence (that is, the total number of neutrons that cross each square centimeter of food). The fluence depends on how many neutrons are produced in the food and in the X-ray target, how many are scattered out of the food, and how many are slowed down and thermalized. The problem is best solved in two steps: (i) by calculating how much and what kind of radioactivity is produced in the food when the fluence is one neutron per square centimeter; (ii) by calculating or measuring the fluence of neutrons.

The principal, but still insignificant, radioactivity that results is from ^{38}Cl with a half-life of 37.3 minutes. Other isotopes with half-lives of a few hours, such as sodium-24 (^{24}Na) with a half-life of 15.0 hours and ^{42}K with a half life of 12.4 hours, are formed in smaller quantities, and are likely to decay significantly before the food is consumed. The radioactivity of phosphorus-32 (^{32}P) with a half life of 14.3 days is formed with a 100 times smaller activity than the short lived chlorine. (There is a tendency for the activity to decrease as the half life increases). Sodium chloride is often added to food (ham, corn beef etc.), and may then be found in quantities that are 20 to 30 times the normal physiological concentrations. More elaborate calculations can be made that take into account not only the radiological half-life, but also the physiological half life and maximum concentration of each element in the human body. Disregarding the radioactive decay, the radioactivity will be proportional to the dose. For economical reasons the X-rays will usually be applied to items that require low doses, such as fruit and vegetables with low salt concentrations, while electrons will be applied directly to items that require higher doses, such as meats, including ham and corn beef. In the comprehensive evaluation, the decay of natural radioactivity in food must also be taken into account. It can then be shown that in some cases the overall radioactivity may actually decrease due to the extended storage time of foods as an intended consequence of irradiation.

Calculations by various scientists have shown that the fluence of neutrons absorbed in food is about 60 times greater when it is irradiated with 5 MeV X-rays than when it is irradiated with 10 MeV electrons (2.2×10^5 neutrons per kGy at 5 MeV X-rays versus 3.6×10^3 neutrons per kGy at 10 MeV electrons). The calculations show also that the absorbed neutron fluence (produced from deuterium) increases only by a factor of about 1.5 when irradiated by 7.5 MeV X-rays instead of 5 MeV X-rays, provided the neutron production in the X-ray converter is insignificant. Immediately following irradiation with 7.5 MeV X-rays, the radioactivity of ^{24}Na would then be about 0.04 Bq per kg and per kGy. Increasing the electron energy for producing the X-rays beyond 7.5 MeV will result in neutron production in the X-ray converter, and to a lesser degree from some of the trace elements in food.

The principal X-ray converter materials are:

(i) <u>tungsten</u> with (γ, *n*) thresholds of: 8.1 MeV in ^{182}W (26.3%), 6.2 MeV in ^{183}W (14.3%), 7.4 MeV in ^{184}W (30.7%) and 7.2 MeV in ^{186}W (28.6%).

(ii) <u>tantalum</u> with thresholds at 6.6 MeV in ^{180}Ta (0.012%) and 7.6 MeV in ^{181}Ta (99.988%).

(iii) <u>gold</u> with a threshold at 8.1 MeV in ^{179}Au (100%).

Thus increasing the energy of X-rays above 7.5 MeV would result in increased cross-section (probability) of neutron production in the X-ray converter and, consequently, in possible induction of radioactivity in the irradiated food.

2.2.2. Control of energy

Direct current (DC) electron accelerators usually have a well defined maximum energy. Linear accelerators, when well tuned and properly operated, also have a rather well defined maximum energy. The width of the electron energy spectrum at half maximum may then be less than 0.25 MeV. However, if the accelerator is not tuned for optimally small energy distribution the width may be much greater. As in all measurements, the variations in parameters must be taken into account. The (γ, n) thresholds for copper-63 (^{63}Cu) is 9.91 MeV and ^{62}Cu has a half life of 9.8 minutes; the threshold for ^{65}Cu is 10.84 MeV and ^{64}Cu has a half life of 12.9 hours. These isotopes can be used to determine the 10 MeV electron energy. The positron radioactivity increases $\sim(E - E_{th})^3$ for each isotope, and then can easily be used to define the energy within 0.1 MeV by measuring how the activity increases with energy. Coincidence measurements of the two 0.511 MeV quanta produced in the decay of the positrons can be used to reduce or eliminate the background. Such measurements can therefore detect minute radioactivity produced in copper wires exposed to the electron beam. Similarly, the energy and the design of the converter area in an X-ray facility can be controlled by having a competent laboratory measure the neutron induced radioactivity in a gold foil placed at the center of a 15 cm x 15 cm x 15 cm water phantom in the sample area. If calibrated foils indicate a fluence of more than 3.5×10^5 neutrons per kGy dose in the sample, the energy is too high.

2.3. CONCLUSIONS

The review of the literature and the analysis presented here indicate that radiation processing with X-rays up to 7.5 MeV can be used without any concern about induced radioactivity, provided special care is taken in the design of the X-ray converter so as to eliminate significant neutron production in the converter.

3. ENERGY CONVERSION EFFICIENCY

There are three main factors governing overall electron-power utilization efficiency: photon-power utilization, conversion efficiency in converter, and self-absorption correction.

(i) <u>photon-power utilization</u>: as in case of ^{60}Co-gamma rays, not all of the photons produced in the X-ray converter are absorbed in the products being irradiated. Electromagnetic energy is attenuated in matter following exponential laws. Consequently, the fact that some part of the impinging energy leaves the products cannot be avoided.

(ii) conversion efficiency: the impinging electrons in an X-ray facility are stopped in the converter and only part of their kinetic energy is converted into photon-radiation (or decelerated radiation and hence 'bremsstrahlung'), while the remaining is converted into heat.

(iii) self-absorption: for technical reasons (eg mechanical strength) the converter must be manufactured to a thickness greater than the optimum thickness for complete stopping of electrons. This leads to self-absorption in the lower layers of the converter of photon-radiation produced in the upper layers of the material.

The situation varies according to the design of the facility. However, several generalized estimations are possible.

3.1. PHOTON-POWER UTILIZATION

Reported data in the literature and from experimental studies under commercial scale conditions have shown that a 30% utilization is achievable; the optimum might be even higher at 40%. However, as in gamma-facilities, the geometry of the product when passing through the irradiation zone (e.g. gaps between succeeding carriers or boxes) will result in a certain amount of radiation not being utilized; this might be up to 10% of the achievable utilization. The difference in these figures for 5 MeV to 10 MeV is marginal. The determining factor of achievable utilization is product thickness which will depend on tolerable maximum to minimum dose ratio; where a product requires a lower value of this ratio, product thickness needs to be reduced and hence, less complete photon absorption is achieved.

Consideration must also be given to the fact that certain parts of the product will absorb an excess amount of energy. This over-dosing cannot be avoided completely but can be minimized through efficient design of the process e.g. through the use of two- or multi- sided irradiations. This has the advantage of reducing the range between minimum and maximum absorbed dose.

Therefore in the industrial situation a utilization value greater than 30% can be achieved.

3.2. CONVERSION EFFICIENCY

In a converter of optimum thickness (thick enough to stop all electrons and thin enough to minimize self-absorption) the conversion efficiency from electrons in X-rays in the forward direction is approximately 8% for 5 MeV, 14% for 7.5 MeV and about 20% for 10 MeV. These values are estimated from computer models; real measurements are difficult and generally not available. At high energy of incident electrons most of the bremsstrahlung is emitted in the forward direction, over a certain angle (club). Some of this energy will not reach the product. The width of this angle decreases as the excitation energy increases and so forward conversion efficiency is also increased. If the converted X-ray energy is integrated over the full angle of the X-ray emission (ie a situation where the product is very close to the converter) up to 20% conversion efficiency may be reached, as also that part of the produced bremsstrahlung is absorbed in the goods.

3.3. SELF-ABSORPTION

In a properly designed X-ray converter only 10 to 20% of the photons produced are absorbed in the convertor itself.

3.4. OVERALL ELECTRON-POWER UTILIZATION

The following (Table 2) combines the components discussed above.

Table 2. Factors contributing to energy conversion efficiency.

	5 MeV (%)	**7.5 MeV (%)**
Photon utilization	30	40
Conversion efficiency	14	22
Self-absorption correction	80	90
Overall	4	8

In conclusion, an overall energy conversion efficiency (ie electrons to photons absorbed) of 4% at 5 MeV is achieved; increasing this limit to 7.5 MeV can increase efficiency up to 8%. Taking into account the power in the electron beam of commercially available accelerators, and the conversion efficiencies to X-rays of 4 - 8%, it is concluded that X-ray radiation processing facilities of throughput capacities comparable to isotope facilities are available.

4. ECONOMICS OF HIGH ENERGY, HIGH CAPACITY X-RAY MACHINES

Modern accelerators are made to industrial standards and specifications and such machines at high power and high electron energy are operated on an industrial scale at many installations and the records for availability are very good. Trained and qualified personnel are needed to maintain such facilities; however, with the help of modern computer technology and by the design and engineering of the components for greater reliability such accelerators are now typically operated by a trained staff who do not need a professional background in accelerator, high-voltage and other techniques.

Significant progress has been made in the development of X-ray machines for radiation processing. Ten years ago high power machines with average power up to 150 kilowatt (kW) had a maximum energy of 4.5 MeV. More recently, this energy has been increased to 5 MeV by at least two manufacturers. New radiofrequency (RF) technologies with energies up to 10 MeV have been demonstrated at power levels up to 100 kW and are operating commercially at 50 kW. The life time cumulative availability of the latest of these machines matches the established reliability of DC machines. Plans are underway to extend these power levels to 200 kW at the 10 MeV level.

The opportunity to reevaluate the maximum energy of X-ray machines may be done with the knowledge that accelerators are available with electron energies above 5 MeV. It can be concluded that technologies are now a matter of choice between DC and RF machines and the choice will be driven by fundamental economic issues.

An economic model, based on the cost of an irradiation facility recently built in Canada, was used to study how the cost of the irradiation of food relates to the cost and performance of some key parameters (Table 3). While these costs were taken from experience, the main objective was to demonstrate the effect of those parameters under control of facility designers and users.

Table 3. Examples of the effect of (i) increasing the energy (ii) increasing the power and (iii) reducing the dose.

ECONOMICS OF X-RAY IRRADIATION OF FOOD				
Energy (MeV)	**Beam Power (kW)**	**Absorbed Dose (kGy)**	**Cost/tonne (US$) at 50 % utilization**	**Cost/tonne (US$) at 100% utilization**
5	100	2.5	77	52.5
7.5	100	2.5	51.6	35
7.5	200	2.5	28.3	20
7.5	200	1.0	11.3	8

5. DOSIMETRY

Food irradiation specifications usually include a pair of absorbed-dose limits: a minimum necessary to ensure the intended beneficial effect and a maximum to avoid product degradation. For a given application, one or both of these values may be prescribed by regulations. Therefore, it is necessary to determine the capability of an irradiation facility to process within these absorbed-dose limits prior to the irradiation of product for consumption. Once this capability is established, it is necessary to monitor the maximum and minimum absorbed dose in the irradiated product for each production run with an acceptable level of confidence to verify compliance with the process specification.

Reliable and accurate dosimetry is a major component of a total quality assurance program for an irradiation facility. The most commonly used routine dosimeters today are perspex and radiochromic films.

The American Society for Testing and Materials (ASTM) has published several practices and quidelines for the selection and use of dosimetry systems to be implemented by radiation processing industry (18 standards will be published in volume 12.02 of the 1995 Annual Book of ASTM Standards). Two of the standard practices[2] relate specifically to X-ray processing (although they were developed for energies up to 5 MeV, their adaptation to higher energies can easily be accomplished).

[2] E1431:Standard Practice for Dosimetry in Electron and Bremsstrahlung Irradiation Facilities for Food Processing.
E1608:Standard Practice for Dosimetry in an X-ray (Bremsstrahlung) Facility for Radiation Processing.

6. RADIATION SAFETY

6.1. SAFETY PHILOSOPHY

The radiation safety considerations of X-ray machines with energies between 5.0 and 7.5 MeV will not be appreciably different from those with energies less than 5.0 MeV.

6.2 SHIELDING

Increasing the energy above 5 MeV will require the radiation shield thickness (concrete) to be increased by a few centimeters. However, the procedures for checking the effectiveness of the shield are no different from those used with X-ray machines with energies less than 5 MeV.

6.3. INDUCED INACTIVITY

Increasing the energy to 7.5 MeV will not significantly increase the radioactivity in the food or the concrete shielding material, the structural materials of the machine or the conveyor system.

An X-ray converter made of gold will not produce any photo-neutrons, as the threshold for gold is 8.1 MeV. For tungsten with a threshold energy of 6.2 MeV and tantalum with a threshold energy of 6.6 MeV only a few photo-neutrons will be produced. Therefore, the neutron induced activity in the food and in the irradiation room will be insignificant.

6.4. MEASUREMENT INSTRUMENTS

Commercial radiation measurement instruments are available and they are applicable for X-ray irradiation facilities even with those operated with a maximum energy of 7.5 MeV.

6.5. CONCLUSIONS

Based upon the above, the radiation safety requirements for machines with 7.5 MeV electrons should not differ from those imposed upon machines with lower energy electrons. These machines should be required to comply with the safety requirements for an industrial facility and should not be required to comply with the regulations for nuclear materials.

7. RECOMMENDATIONS

1. To assess the real need for radiation sources for all types of radiation processing including food irradiation, the IAEA should conduct urgently a global survey of such a need for both isotopic and machine sources in its Member States.

2. The conclusions of this meeting, especially with regard to increasing energy levels of X-ray machines for food irradiation to 7.5 MeV, should be brought to the attention of the International Consultative Group on Food Irradiation (ICGFI) with a view to recommend to the Codex Alimentarius Commission to amend the Codex General Standard for Irradiated Foods at an earliest opportunity.

3. The electron beam/X-ray machine manufacturers should make every effort to optimize the conversion efficiency of EB to X-raysm, including an improvement of converter materials and design.

4. The IAEA should increase its information dissemination concerning the availability of industrial X-ray machines for food processing. It is requested that additional efforts be made by the IAEA to train scientists/engineers from developing and other countries on the application of machine sources for food irradiation.

5. The IAEA should recommend to its Member States that they evaluate the establishment of pilot plants or demonstration facilities using machine sources, in addition to the traditional use of ^{60}Co facilities, for food irradiation.

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CONSULTANTS' MEETING ON DEVELOPMENT OF X-RAYS MACHINE FOR FOOD IRRADIATION

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