Dosimetry for radiation processing

Malcolm McEwen

Ionizing Radiation Standards Institute for National Measurement Standards National Research Council Canada

SIM workshop, 10th November 2011
1. What is radiation processing?
2. Radiation Sources
3. Dosimetry requirements
4. Examples of dosimetry systems
1. What is radiation processing?

“The use of radiation to modify the characteristics of a material or artefact.”

This includes:

Food irradiation
Sterilization of medical goods
Materials modification
## A. Food irradiation

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inactivation of harmful organisms in food ingredients</td>
<td>Various spices and herbs. Onion powder. Mineral supplements</td>
</tr>
<tr>
<td>Extension of refrigerated shelf life</td>
<td>Meat and fish</td>
</tr>
<tr>
<td>Prevention of spoilage</td>
<td>Strawberries, cocoa beans, mangoes, papayas</td>
</tr>
<tr>
<td>Control of mould</td>
<td></td>
</tr>
<tr>
<td>Control of insect infestation</td>
<td></td>
</tr>
<tr>
<td>Minimizing deterioration</td>
<td></td>
</tr>
<tr>
<td>Control of parasites and insects to meet quarantine</td>
<td>Parasites in meat and insects in exotic fruits and beans</td>
</tr>
<tr>
<td>requirements</td>
<td></td>
</tr>
<tr>
<td>Inhibition of sprouting in crops during storage</td>
<td>Potatoes, onions and garlic</td>
</tr>
</tbody>
</table>

Typical dose for food irradiation is 1-10 kGy
A. Food irradiation

<table>
<thead>
<tr>
<th>Low dose applications (up to 1 kGy)</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprout inhibition in bulbs and tubers</td>
<td>0.1 kGy</td>
</tr>
<tr>
<td>Delay in fruit ripening</td>
<td>0.5 kGy</td>
</tr>
<tr>
<td>Insect disinfestation including quarantine treatment and elimination of food borne parasites</td>
<td>1.0 kGy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Medium dose applications (1 kGy to 10 kGy)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction of spoilage microbes to prolong shelf-life of meat, poultry and seafoods under refrigeration</td>
<td>2 kGy</td>
</tr>
<tr>
<td>Reduction of pathogenic microbes in fresh and frozen meat, poultry and seafoods</td>
<td>5 kGy</td>
</tr>
<tr>
<td>Reducing the number of microorganisms in spices to improve hygienic quality</td>
<td>10 kGy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High dose applications (above 10 kGy)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sterilization of packaged meat, poultry, and their products that are shelf stable without refrigeration</td>
<td>50 kGy</td>
</tr>
<tr>
<td>Sterilization of Hospital diets</td>
<td>50 kGy</td>
</tr>
</tbody>
</table>

US figures (per year):
80,000 tons of spices
14,000 tons tropical fruit
7,000 tons ground beef/poultry
B. Sterilization of medical goods

How do you sterilize single-use medical goods such as plastic syringes, valves, absorbent pads, bandages, etc?

Autoclave
Sterilizing gas (ethylene oxide)
Ionizing radiation

Typical dose for sterilization is 15-25 kGy
(Definition of sterile: < 1 viable organism in 10^6 product units)
C. Materials modification

Wide range of materials are modified using ionizing radiation:

- Insulation for telecom cable
- Heat-shrink tubing
- Car tyres
- Composite materials – radiation (“cold”) curing
- Floppy disks (anyone remember these?)
- Gem stones

Typical dose for materials modification is 100 kGy
2. Radiation sources for processing

Co-60 (1.25 MeV)
MeV electron beams (2 – 10 MeV)
MV photon beams (~ 6 MV)
keV electron beams (80 – 120 keV)
keV photon beams (<250 kVp) under development

The radiation processing industry is presently focussed on Co-60 and high energy electron beams
Source activity can be up to a few megacuries

Canada a major supplier (side-effect of CANDU reactors)

2-sided irradiation required
MeV electron beams

Usually 5 or 10 MeV systems
- Beam powers from 10 kW to 100 kW
- Energy limited by activation thresholds

2-sided irradiation also required
keV electron beams

Monte Carlo calculations normalized to this measurement.

Step dose profile
AEB, 6 mA, 50 fpm
- 80 keV (B3 film)
- 90 keV (B3 film)
- 100 keV (B3 film)
- 81.3 keV (Monte Carlo)
- 91.4 keV (Monte Carlo)
- 101.5 keV (Monte Carlo)

Excellent for surface treatments (e.g., sterilizing surfaces and curing of inks on packaging)
Bremsstahlung sources

- MV photons beams
  - Penetration greater than for cobalt-60 gamma rays
  - Scattering and shadowing less important than for electrons
  - Inefficient due to bremsstrahlung process – IBA Rhodotron
  - **700 kW** electron beam accelerator is currently only device operating
Q. Do we need dosimetry for industrial processes?

A. Product evaluation may be sufficient
3. Requirements for Dosimetry in Radiation Processing

Standards such as EN/ISO 11137 (medical device sterilization) contain detailed requirements related to dosimetry e.g.

“4.3.4 Dosimetry used in the development, validation and routine control of the sterilization process shall have **measurement traceability** to national or International Standards and shall have a known level of **uncertainty**.”
Traceability Chain

Standards Laboratory - National Standards
Calorimeters, Ionization chambers
\[ D_w \text{ Gy} \ (\pm 1\%) \]
\[ D_w \text{ kGy} \ (\pm 2\%) \]

| Reference Standard Dosimetry Systems (\pm 3\%)
Fricke, Ceric, Dichromate
Alanine, Calorimeters |

| Routine Dosimetry Systems (\pm 5\%)
Radiochromic films,
Plastics, Dyed plastics |
Calorimetry is the default primary standard for radiation processing.

Generally, the primary standard for radiation processing is a radiotherapy level device.

Calorimeters have been developed to pass through irradiation plants.
In situ challenges

Complex product path limits options for on-line measurements

High radiation doses affect sensitive electronics (e.g., wireless)
4. Selection of a dosimetry system

First consideration:
- Which measurements do you want to carry out?
  - Routine dosimetry
  - Dose mapping dosimetry
  - Gamma
  - Electron

Second, take account of:
- Dose range
- Radiation type
- Influence quantities
- Stability of dosimeter response
- Required level of uncertainty
- Required spatial resolution

There is no “ideal” dosimeter
Example 1 - Alanine dosimeter

Irradiation of the amino acid alanine produces stable free radicals:

\[
\begin{align*}
&\text{H} \\
&\text{H}_3\text{C}-\text{C}-\text{COOH} \\
&\text{NH}_2 \\
\rightarrow & \quad \text{Ionising} \\
\text{Radiation} \\
&\text{H}_3\text{C}-\text{C}-\text{COOH} \\
&\text{H}
\end{align*}
\]

The concentration of the radicals is proportional to the absorbed dose and can be measured by Electron Paramagnetic Resonance (EPR) spectroscopy.
Summary

- Measurement of free radical concentration
- Pellets or films
- Dose range: **10 Gy – 100 kGy**
- Stable signal for more than one year
- Reproducibility better than 0.5%, 1.s.d
- Measurement instrument - EPR spectrometer

- 90% alanine, 10% paraffin wax (m.p. 98°C)
- 55 mg mass (nominal)
- 5 mm diameter, ~2.5 mm thick
- ~1.2 g cm$^{-3}$ density
Concentration of free radicals measured by EPR (= ESR)

Derivative of absorption spectrum used for analysis

Peak-to-peak height is robust parameter except at very low doses (<50 Gy)
Alanine dosimeter - readout

- microwave source
- microwave bridge
- detector and amplifier
- modulator
- sample
- cavity
- magnet power and sweep
Example 2 - Dichromate dosimeter

Dichromate solution in ampoules for measurement at gamma facilities

Use: Reference dosimetry
Dichromate dosimeter

- Measurement of colour change
- Liquid in glass ampoules
- Dose range: 10 kGy – 50 kGy
- Stable signal for more than one year
- Reproducibility less than 0.5%, 1.s.d
- Measurement instrument - Spectrophotometer
Response - Change of colour

Risø B3 film
Thickness 20 µm
Measured at 554 nm

FWT film
Thickness 10, 50 µm
Measured at 605 nm and 510 nm
Response functions for FWT and Risø B3

**Use:**
- Dose mapping
- Routine dosimetry
Example 4 - PMMA dosimeters

Range of dyed and un-dyed PMMA dosimeters.

Optical absorbance measurement - strips designed to fit into standard spectrophotometers.

Packaged to prevent changes in water content.
PMMA dosimeters – dose response

Dose range 100 Gy to 150 kGy depending on dosimeter type and measurement wavelength.

Use: Gamma dose mapping and routine dosimetry.
Radiation processing is a growing industry.

Uncertainty requirements for dosimetry may not be as strict as for radiotherapy.

**BUT** unique challenges related to in-situ measurement, high doses, inhomogeneous products, etc.

Few national dosimetry laboratories involved in this field worldwide.
Acknowledgements

Peter Sharpe (NPL, UK)
Mark Bailey (NPL, UK)

Thank You