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**AUSTRALIAN NUCLEAR SCIENCE
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LUCAS HEIGHTS RESEARCH LABORATORIES

**DOSIMETRY AND IRRADIATION METHODS FOR THE ANSTO
GAMMA TECHNOLOGY RESEARCH IRRADIATOR (GATRI)**

by

M. E. IZARD

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ABSTRACT

The Australian Nuclear Science and Technology Organisation's gamma technology research irradiator (GATRI) at Lucas Heights, New South Wales, has been modified for use as a research and small-scale commercial irradiation facility to be available to government agencies and private industry for the technical and economic evaluation of irradiation processing.

The new source rack was designed around existing mechanical components to optimise the limited space available within the irradiation cell. Irradiation parameters investigated during commissioning included the effect of source-to-target distance on relative dose rates within targets of the same density; the effect of density on dose-rate distribution within targets irradiated at the same distance from the source; and the contribution of transit dose to low absorbed doses as the source is raised and lowered. The efficiency of the irradiator was determined for various target densities and overdose ratios.

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The following descriptors have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. For further details please refer to IAEA-INIS-12 (INIS: Manual for Indexing) and IAEA-INIS-13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

COBALT 60; DOSE RATES; EFFICIENCY; EXPERIMENTAL DATA; GAMMA DOSIMETRY; GAMMA RADIATION; IRRADIATION; IRRADIATION DEVICES; IRRADIATION PLANTS; IRRADIATION PROCEDURES

EDITORIAL NOTE

The Australian Nuclear Science and Technology Organisation replaced the Australian Atomic Energy Commission on 27 April 1987. Reports issued after April 1987 have the prefix ANSTO with no change of the symbol (E, M, S or C) or numbering sequence.

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1. INTRODUCTION

The Australian Nuclear Science and Technology Organisation's gamma technology research irradiator (GATRI) at Lucas Heights, New South Wales, was originally built as a 740 TBq (20 000 Ci) line source and used to initiate polymerisation reactions in the production of ion exchange resins [Bolton and Clouston 1972]. The conclusion of the polymerisation work and the growing interest in food irradiation in Australia prompted the development and use of GATRI as a research and pilot-scale food irradiation facility.

The facility consists of the irradiation cell and an operations room which houses the source hoist machinery and control console. A motorised concrete door safeguarded by several interlocks gives access to the cell. The source is stored in a 5 m deep tank of demineralised water and raised by remote control into the 3.5 m x 4.0 m x 3 m high irradiation cell which is shielded by 1.5 m thick concrete walls and roof. Material to be irradiated is arranged around the source on removable benches or air-driven turntables. A full description of the facility, its operation and safety equipment was given by Izard [1985].

As the irradiation facility building and ancillary services were already available and suitable, only minor modifications were necessary to implement the food irradiation program. A higher activity plaque source was designed and installed and compressed air, electricity and refrigeration lines were run into the irradiation cell. After installation of the cobalt, extensive radiation dosimetry was carried out to determine the dose-rate distributions throughout the cell.

2. PLAQUE SOURCE

The 1 m x 1 m plaque source may contain up to a hundred 150 mm x 8 mm cobalt-60 rods in a symmetrical array of 20 columns and 5 rows. The peripherally augmented plaque was loaded with 3.7 PBq (100 000 Ci) of cobalt-60 in November 1983 and replenished in March 1986. The activity was distributed within the plaque to produce parabolic isodose curves at distances greater than 300 mm and a parallel uniform field at distances less than 300 mm from the plaque. The distribution of activity in the plaque after the 1986 replenishment is shown in figure 1. The four outermost columns contained about 40 per cent of the total activity and the uppermost and lowest rows about 25 per cent.

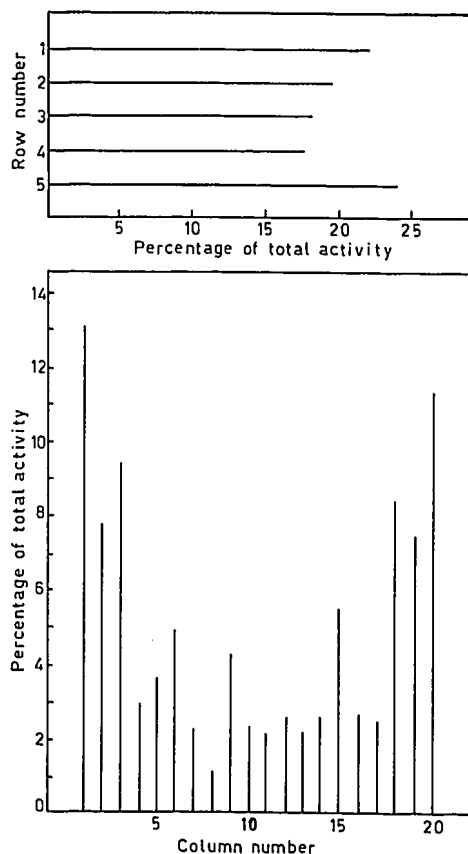


Figure 1 Distribution of activity in the source plaque after the 1986 replenishment, shown as a percentage of the total activity. Cobalt rods are arrayed in twenty 1 m long columns, each containing up to five sources.

3. DOSE MEASURING SYSTEMS

The Fricke ferrous ammonium sulphate, ceric/cerous liquid chemical dosimeters, a capacitor discharge dosimeter and an ionisation chamber dosimeter were used initially to calibrate the facility and later, during normal operations, to monitor absorbed doses and estimate irradiation periods.

3.1 Ion Chambers

A Farmer type 2502/3 capacitor discharge dosimeter and a Farmer type 2570A ionisation chamber were used extensively throughout the commissioning. Both dosimeters give a direct readout of exposure by measuring the quantity of charge produced in a remote 0.6 cm^3 ionisation chamber exposed to the radiation field.

3.2 Chemical Dosimeters

3.2.1 Ceric/cerous dosimeter

The ceric/cerous dosimeter [Matthews 1972] may be prepared at various concentrations to measure radiation doses in the range 10 to 10^6 Gy. The dosimeters used in this calibration contained 0.01 mol L^{-1} ceric sulphate and 0.01 mol L^{-1} cerous sulphate in 0.4 mol L^{-1} sulphuric acid. The dose range of these dosimeters was 5 to 34 kGy. For routine use, 2 mL aliquots of the dosimeter solution were flame-sealed in $30 \text{ mm} \times 12 \text{ mm}$ glass ampoules. The concentration of cerous ions produced during irradiation is proportional to the absorbed dose and may be determined spectrophotometrically, or by measuring the difference in electrochemical potential between irradiated and unirradiated solutions in an electrochemical half-cell.

3.2.2 Fricke dosimeter

The dosimeter developed by Fricke and Morse [1927] and Hart and Fricke [1966] contains 0.001 mol L^{-1} ferrous ammonium sulphate and 0.001 mol L^{-1} sodium chloride in 0.04 mol L^{-1} sulphuric acid, and is used for gamma radiation doses in the range 40 to 400 Gy. For routine use, the dosimeter solution (4 mL) is dispensed into 10 mm diameter polyethylene pill packs. The concentration of ferric ions produced during irradiation is proportional to absorbed dose and may be determined spectrophotometrically.

4. PRELIMINARY ESTIMATION OF DOSE RATES

Theoretical estimates of dose rates at distances greater than 1.0 m from the plaque were made in order to estimate the amount of material that could be put through the irradiator. Each of the twenty columns in the plaque was considered to be a point source of 185 TBq (5000 Ci) rather than a line source. Self-absorption in the cobalt was neglected, but shielding loss for each rod was estimated to be four per cent.

The contribution of a cobalt source element to the dose rate at any point in the irradiation cell depends on its location in the plaque and its distance from the point. The dose rates at 1.0, 1.5 and 2.0 m from the centre of the plaque along radii subtended at 22.5, 45 and 90° to the plane of the plaque were calculated by summing the expected contribution at those points from each of the twenty source columns. Table 1 shows the expected values at all points and the dose rates determined by ion chamber dosimetry after installation of the cobalt.

The good agreement between the calculated and measured dose rates justified the simple mathematics used and made it possible to estimate dose rates and irradiation times during commissioning dosimetry.

5. COMMISSIONING DOSIMETRY

The vertical and horizontal dose-rate distributions within the irradiation chamber were determined by irradiating either Fricke or ceric/cerous dosimeters attached to a vertical $3 \text{ m} \times 2 \text{ m}$ board parallel to the source at various source-to-board distances. The dosimeters were positioned in rows 200 mm apart, where imaginary horizontal concentric circles around the centre of the plaque intersected the board.

TABLE 1

**CALCULATED AND MEASURED DOSE RATES AT 1.0, 1.5 AND 2.0 M
ALONG RADII SUBTENDED AT ANGLES OF 22.5, 45 and 90°
FROM THE CENTRE OF THE PLAQUE**

The calculated values are the summation of the contributions from each source column considered to be a point source.
Actual values were measured with a Farmer type 2502/3 ion chamber one month after loading the cobalt.

Distance along Radius from Centre of Plaque (m)	Subtended Angle (°) from Centre of Plaque	Dose Rate (kGy h ⁻¹)	
		Calculated	Measured
1	22.5	1.478	1.607
	45	1.290	1.353
	90	1.120	1.056
1.5	22.5	0.660	0.613
	45	0.570	0.582
	90	0.500	0.529
2.0	45	0.320	0.339
	90	0.280	0.322

Isodose points were found by interpolation between measured points, and vertical and horizontal isodose curves were drawn onto a plan of the irradiation chamber (figure 2). The floor of the irradiation cell was delineated in a 200 mm x 200 mm grid; these and similar horizontal isodose curves were marked on this grid to facilitate correct location of the targets for irradiation.

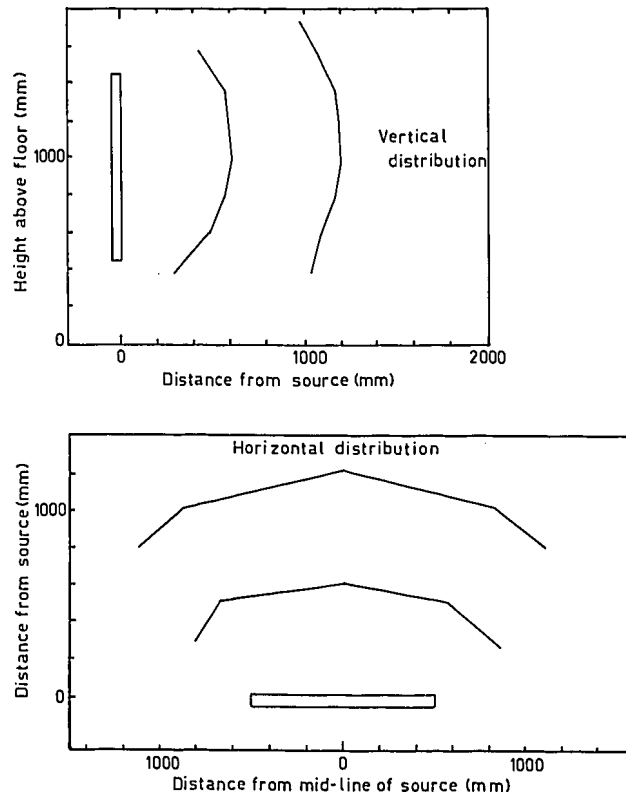


Figure 2 Typical vertical and horizontal isodose lines about the midpoint of the plaque. The dose rates determined by Fricke dosimetry were 1.82 kGy h⁻¹ and 0.65 kGy h⁻¹ on 1 January 1985.

6. IRRADIATION GEOMETRIES

Irradiation geometry is the term used to describe the spatial relationship between the irradiation source and the target. In practice, the irradiation geometry is selected to produce the most uniform distribution of absorbed dose throughout the target. It depends on such parameters as the quantity, dimensions and density of the target, dose and/or dose rate required and the maximum allowable overdose ratio, *i.e.* the ratio of highest absorbed dose to lowest absorbed dose.

Various irradiation geometries have been routinely used in GATRI including

- (a) fixed position irradiation;
- (b) irradiation with a 180° rotation at the half-way point of the irradiation period; and
- (c) irradiation with continuous rotation.

6.1 Effect of Source-to-target Distance on Absorbed Dose-rate

As the distance from source to target increases, there is a decrease in both the dose rate in air and the rate of attenuation through the target. The effect of increasing source-to-target distance on dose rate within the target irradiated from one side is shown in figure 3. Target density and dimensions were fixed and Fricke dosimeters placed within the target at 60 mm intervals along an axis normal to the irradiation source. The front face of the target was aligned on the 300, 600, 1000 and 1500 mm isodose lines, respectively. Although the front-face dose-rate decreased from 3.2 to 0.4 kGy h⁻¹ with distance from the source, and irradiation periods increased accordingly, there was a beneficial effect. As the rate of attenuation within the target diminished, the ratio of maximum dose rate to minimum dose rate improved from 2.46 to 2.00.

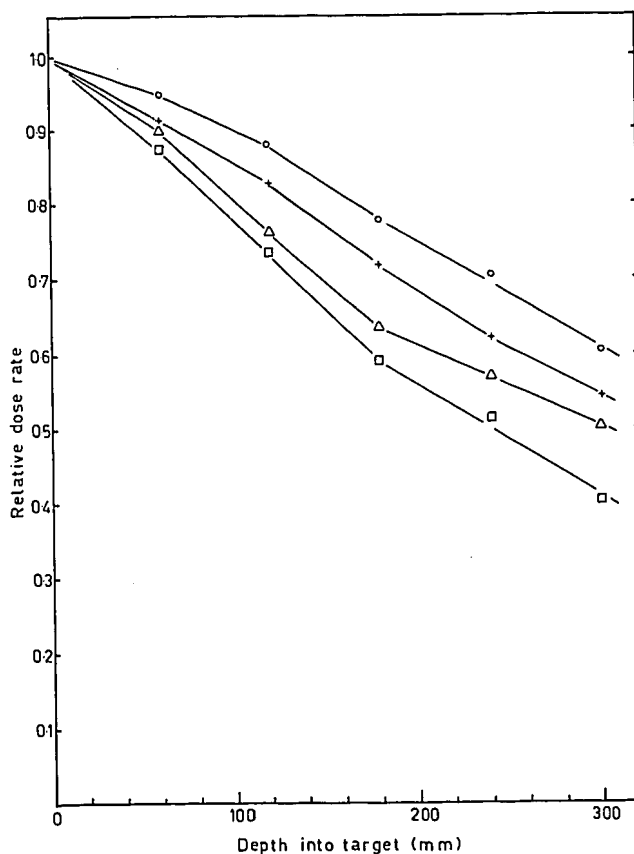


Figure 3 Effect of source-to-target distance on the dose rate within identical targets. The front face of target-to-source distance was 300 mm --□--, 600 mm --Δ--, 1000 mm --+--, and 1500 mm --○--, respectively, and Fricke dosimeters were placed within the target along an axis normal to the plane of the plaque. Target density was 220 kg m⁻³.

It can be seen from **figure 3** that a major factor influencing overdose ratios is the depth. The normal overdose ratio of a target of any given density irradiated at any source-to-target distance is proportional to target depth. In practice, targets are arranged with their shortest dimension normal to the plane of the source. For targets 300 mm from the source, the ratio of maximum to minimum dose rate decreased from 2.46 at a thickness of 300 mm to 1.49 at half that thickness.

6.2 Irradiation with a Half Rotation

Figure 4 shows the effect of single-sided irradiation and of a 180° rotation of the target half-way through the irradiation period. The front face of the target was on the 1000 mm isodose line and target depth was 300 mm. Fricke dosimeters were placed along an axis normal to the midpoint of the front face of the target. Irradiation without rotation resulted in an overdose ratio of 2.88 between the front and rear faces. The overdose ratio between the outside and the midplane was reduced to 1.13 with a half rotation. For a homogeneous target, the minimum dose rate will occur at the midplane and absorbed dose distribution will be symmetrical about the midplane. If the target is inhomogeneous, the position of minimum dose rate will move from the midplane towards the region of higher density and absorbed dose distribution will no longer be symmetrical about the midplane.

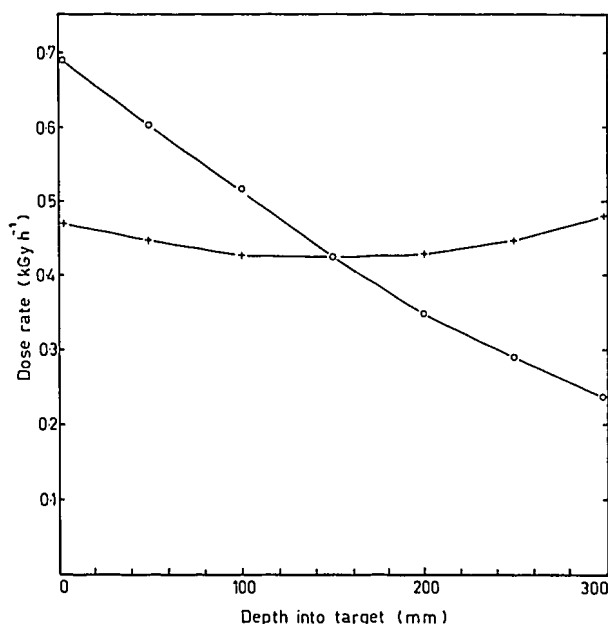


Figure 4 Dose rate distribution through a 300 mm deep target irradiated without rotation for the full irradiation period, --o--, and irradiated with one 180° rotation half-way through the irradiation period, --+--. Target density was 520 kg m⁻³.

7. EFFECT OF TARGET DENSITY ON DOSE RATE ATTENUATION

Figure 5 shows the effect of density on dose rate distribution within a number of targets of identical size but ranging in density from 1.1 to 1000 kg m⁻³. Each target was 300 mm thick and irradiated with its front face along the 1000 mm isodose line. Fricke dosimeters were placed at 50 mm intervals along an axis normal to the midpoint of the front face. **Figure 5** shows that for the same irradiation geometry, the overdose ratio at any depth within the target increased with the density of the target.

8. PRACTICAL DOSIMETRY

Because dose rate distribution, overdose ratio and irradiation period depend on a number of target-related factors, the best method for verifying the irradiation parameters is by dosimetry on the actual product. In practice, however, it is not always possible to place dosimeters in the product package so it may be necessary to estimate midplane or minimum dose rates from data obtained for comparable products (**figures 3** and **5**).

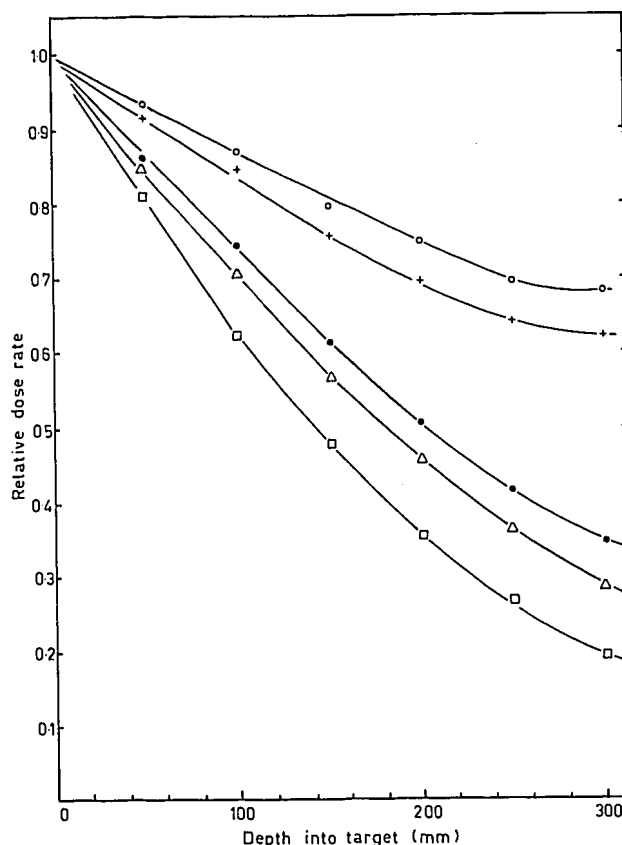


Figure 5 Effect of density on the dose rate distribution within identical 300 mm deep targets irradiated 1000 mm from the source. Fricke dosimeters were placed within the target along an axis normal to the plane of the plaque. --○-- 1.1 kg m⁻³, ---+--- 83.7 kg m⁻³, ----●---- 520 kg m⁻³, --△-- 696 kg m⁻³, --□-- 1000 kg m⁻³.

When depth-dose data for the product are unavailable and it is not possible to measure internal dose rates directly, an estimate of the linear attenuation coefficient of the target can be used to calculate the internal dose rate distribution and irradiation period. The linear attenuation coefficient of the product may be determined from preliminary dosimetry, where the absorbed dose will be less than the total dose required.

With the product in the irradiating position, the dose rate is measured at the rear face of the target. Then with the target removed, the unattenuated dose rate in air is measured at the same position using the same dosimetry geometry. The linear attenuation coefficient of the product can be calculated by substituting these values in the equation relating unattenuated dose rate and build-up factor to the attenuated dose rate:

$$I(x) = B \cdot I(0) \cdot e^{-\mu x} \quad (1)$$

where $I(x)$ is the intensity of attenuated radiation at depth x in the target; $I(0)$ is the intensity of unattenuated radiation with no target; B is the dose build-up factor in the target, and μ is the linear attenuation coefficient of the target. The dose build-up factor for food is assumed to be equivalent to that in water. The experimentally determined value of the linear attenuation coefficient can then be substituted in equation 1 to calculate internal dose rates within the same or similar products.

The linear attenuation coefficient of mangoes from one trial, irradiated in trays 1000 mm from the source, was calculated as 0.0036 mm⁻¹. Table 2 shows dose rates calculated for a later irradiation, using this value for the linear attenuation coefficient, and actual dose rates determined by Fricke dosimetry in 125 mm deep trays of fruit irradiated 1500 mm from the source (figure 6).

TABLE 2

ESTIMATION OF DOSE RATE AT THE REAR FACE AND MIDPLANE OF A 490 mm × 330 mm × 125 mm TRAY OF MANGOES USING AN EXPERIMENTALLY DETERMINED VALUE OF THE LINEAR ATTENUATION COEFFICIENT OF THIS PRODUCT

Target depth was 125 mm and the front face of the tray was 1500 mm from the source.

Dose rate in air 1500 mm from source	0.382 kGy h ⁻¹
Dose rate in air 1562.5 mm from source	0.364 kGy h ⁻¹
Dose rate in air 1625 mm from source	0.338 kGy h ⁻¹
Previously estimated linear atten. coeff., μ	0.0036 mm ⁻¹
Estimated dose build-up factor (mangoes), B	1.2
Calculated dose rate at rear face of tray	0.258 kGy h ⁻¹
Calculated dose rate at midplane of tray	0.348 kGy h ⁻¹
Measured dose rate at rear face of tray	0.250 kGy h ⁻¹
Measured dose rate at midplane of tray	0.320 kGy h ⁻¹

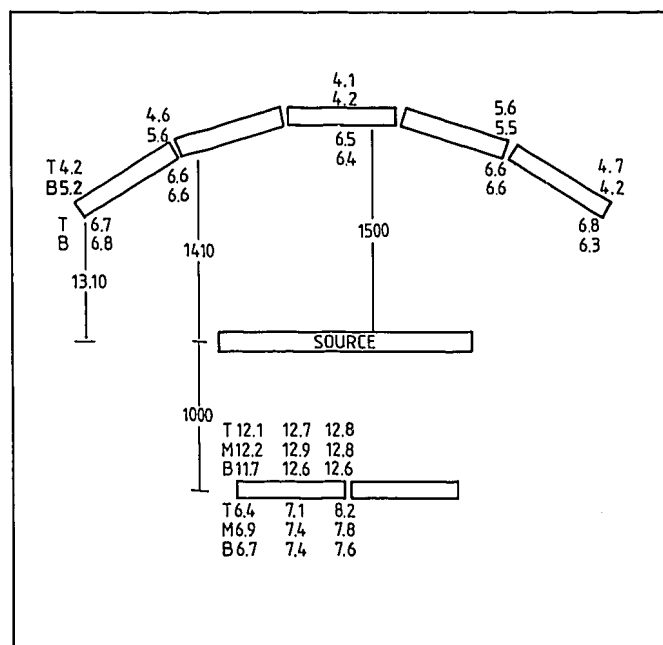


Figure 6 Dose rate distribution in mangoes irradiated in trays on the 1000 mm and 1500 mm isodose lines. Target depth 125 mm. Dose rates are shown in Gy min⁻¹. The dosimeters were in rows across the top (T), middle (M) and bottom (B) of the trays.

The calculated dose rates were within 10 per cent of the measured values and quite acceptable for the calculation of irradiation periods, which could be verified with concurrent dosimetry during irradiation of the product.

9. TRANSIT DOSE

The timing of an irradiation period in GATRI starts when the source reaches its operating height. For the low doses frequently required in food irradiation, calculation of the irradiation period must allow for the dose absorbed by the target during the raising and lowering of the source. This transit dose decreases with distance from the source and, at any position in the irradiation cell, also decreases with height above the floor. At its normal operating height, the bottom of the source is 425 mm above the floor of the irradiation cell. During a complete transit, targets irradiated at or near floor level are thus exposed to the full height of the plaque during the two passes, whereas targets above this height are traversed by only part of the plaque, so their absorbed dose is accordingly lower. Figure 7 shows the vertical distribution of dose in air 500 mm from the plane of the source during one complete raising and lowering. The transit dose on 1 January 1985 was 5.5 Gy at a height of 160 mm and 3.2 Gy at 950 mm.

To calculate the correct irradiation time, the dose measured during transit is subtracted from the specified dose; the irradiation time for the resultant dose is then calculated from the measured dose rate.

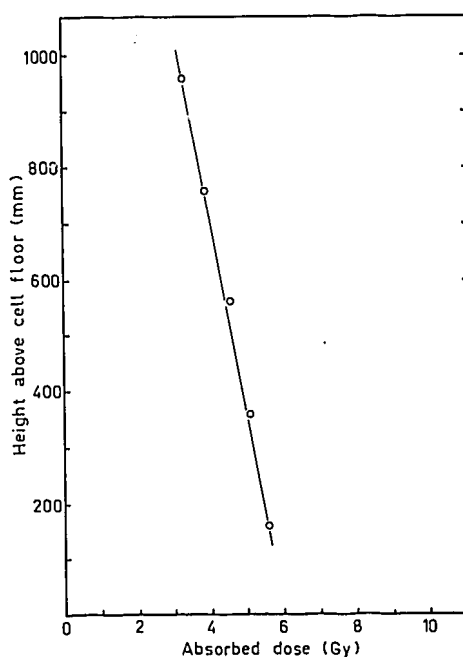


Figure 7 Vertical distribution of dose absorbed in air 500 mm from the centre of the plaque during one transit of the source. The source takes about 35 s to travel from its shielded position to its operational heights and return.

10. EFFICIENCY

Efficiency in a commercial irradiator incorporating a target conveyor system and fixed irradiation geometry depends directly on product density and the acceptable overdose ratio. However in GATRI, where there is no set geometry, irradiation efficiency and product throughput depend on the chosen geometry which, in turn, depends on the dimensions, density and quantity of material to be irradiated. Calculation of the maximum possible throughput for the source strength on 1 January 1985 at a theoretical irradiation efficiency of 100 per cent is shown in table 3.

The calculated throughput of 424 kg h⁻¹ irradiated to 10 kGy is based on the assumption that all available radiation energy is absorbed by the target. However much of the radiation is absorbed by the floor, walls, ceiling and fittings within the irradiation cell and, in practice, efficiencies of 40-50 per cent are generally achieved.

TABLE 3

WATTAGE AND MAXIMUM THROUGHPUT OF THE GATRI FACILITY WITH A THEORETICAL IRRADIATION EFFICIENCY OF 100 PER CENT

Energy radiated from 37 GBq cobalt-60	$14.85 \times 10^{-3} \text{ W}$
Energy radiated from GATRI source (3 PBq at 1:1:85) - 4% absorption loss	1.18 kW
1 kW of radiation, fully absorbed, can irradiate 360 kg per hour to 10 kGy	
Throughput at 100 % efficiency irradiated to 10 kGy	424 kg h^{-1}
Expected throughput where η is the irradiation efficiency	$\eta \times 424 \text{ kg h}^{-1}$

Figure 8 shows the position of the source and the vertical distribution of dose rate at the front face of four rows of product boxes (300 x 300 x 300 mm) irradiated on the 1200 mm isodose line. Up to twenty boxes per row can be irradiated with this geometry, the number of rows irradiated simultaneously depending on the acceptable overdose ratio.

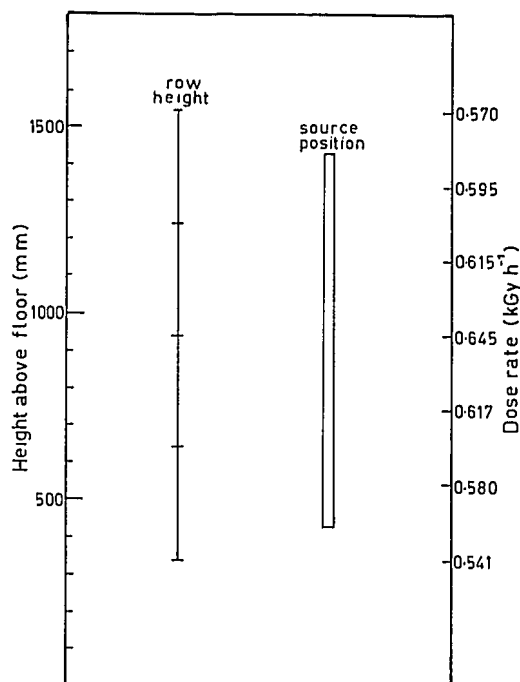


Figure 8 Geometry for irradiating up to four rows of targets each side of the plaque. The source is shown at its maximum operating height and the vertical distribution of dose rate was determined on the front face of the targets aligned on the horizontal 1200 mm isodose line.

Irradiation efficiency was calculated for the simultaneous irradiation of eighty targets (density 818 kg m^{-3}) in four rows with 180° rotation of the targets half-way through the irradiation period (table 4). The irradiation efficiency was 15.3% at an overdose ratio of 1.365 for a minimum absorbed dose of 10 kGy. In table 5, similar calculations for two and three rows at the same density and up to four rows at a lower density show the effect of density and overdose ratio on irradiation efficiency. A twofold increase in the number of targets almost doubled the efficiency, but at both densities the overdose ratio increased by about 10 per cent.

TABLE 4
ACTUAL THROUGHPUT AND CALCULATION OF IRRADIATION EFFICIENCY OF THE FACILITY

Target dimensions	300 x 300 x 300 mm
Target density	818 kg m ⁻³
Distribution of dose rate in target (front face:middle:rear face)	1 : 0.55 : 0.26
Minimum dose required	10 kGy
Min. (max.) front dose rate (figure 7)	0.541 (0.645) kGy h ⁻¹
Min. (max.) middle dose rate	0.297 (0.354) kGy h ⁻¹
Min. (max.) rear dose rate	0.141 (0.168) kGy h ⁻¹
Irradiation period (10 kGy)	33.7 h (16.85 + 16.85)
Overdose ratio	1.365
Number of targets irradiated	80
Total weight	2192 kg
Throughput at 10 kGy	65 kg h ⁻¹
Irradiation efficiency (η)	15.3%

TABLE 5
THE RELATIONSHIP BETWEEN OVERDOSE RATIO, EFFICIENCY AND DENSITY FOR TARGETS IRRADIATED 1200 mm FROM THE SOURCE WITH ONE HALF ROTATION AT THE MIDPOINT OF THE IRRADIATION PERIOD

Density (kg m ⁻³)	Number of Rows	Targets	Overdose Ratio	Efficiency (%)
818	4	80	1.365	15.3
	3	60	1.296	12.1
	2	40	1.246	8.4
520	4	80	1.278	11.2
	3	60	1.208	8.8
	2	40	1.157	6.1

11. CONCLUSIONS

An introduction has been given to the principle dosimetric parameters encountered in the use of the GATRI irradiation facility. The unattenuated doses and dose rates quoted here are not reproducible because of the decay of the cobalt sources; attenuated dose rates will depend on the chosen irradiation geometries. However, the underlying factors influencing these results and the methods used to obtain them are set and hence applicable, irrespective of cobalt activity, irradiation geometry, target density and dimensions. While the original source remains unchanged except for radioactive decay, dose rates may be determined at any time after the commissioning dosimetry by carrying out simple radioactive decay calculations. Regular replenishment of cobalt will change the dose rates, but dose rate distribution throughout the irradiation chamber can be reproduced by similar allocation of activity in the source plaque to that shown in figure 1.

The operating parameters cannot be preset in this type of irradiator as they depend on the nature of the material to be treated, product density and dimensions, the number of targets in a batch and the specified absorbed dose, dose rate and overdose ratio. However, if this report is used in

conjunction with the operation manual [Izard 1985], recorded details of all previous irradiations and published dosimetry methods will provide the operator with sufficient information to operate the irradiation facility effectively.

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