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Status of Gamma Irradiator Design .

Bernard Manowitz
Brookhaven National Laboratory
Upton, New York

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Gamma irradiators are devices that make use of nuclear radiation for the destruction of bacteria and insects and for the initiation of chemical reactions. They have been designed for treating packages, flowing solids, and liquids.

About a dozen units have now been built around the world mainly for sterilizing medical supplies.⁽¹⁾ They are all characterized by very high on-stream times, very low maintenance, and very low labor costs.

Figure 1 illustrates a typical medical supply irradiator (the Ethicon plant at Sommerville, New Jersey), and Figure 2 is a line diagram showing the route of the monorail carriers through this plant. At a loading of $\approx 500,000$ curies of Co^{60} , the plant can sterilize about 600 lb/hr of medical supplies.

Figure 3 (model) and Figure 4 (construction) show views of a pilot plant unit for the disinfestation of grain; it is operated by the Department of Agriculture at Savannah, Georgia. This unit contains 1600 curies of Co^{60} and can treat 5,000 lb/hr.

Figures 5 and 6 are views of the Dow Chemical Company plant for the production of ethyl bromide. It uses ≈ 1800 curies of Co^{60} and has an annual production capacity of $\approx 1,000,000$ lb ethyl bromide.

A gamma irradiator consists simply of a radioactive source, a target, a means for getting the target in and out of the radiation field, and shielding.

In general, for package irradiators, the customer will specify the desired capacity (lb/hr), the desired absorbed dose (rads), the desired uniformity of treatment (max-min ratio), the package dimensions, the package density, and the maximum residence time permitted in the unit. It is up to the irradiator designer, then, to fix the target velocity, the source dimensions, the source specific activity, and the source-to-target configuration in such a way as to optimize the efficiency and minimize the cost of the unit.

Typical applications for irradiators, and estimates of the absorbed dose required, are indicated in Table 1.

Table I

Typical Applications for Gamma Irradiators

<u>Application</u>	<u>Approx. dose required, rads</u>
Meat sterilization	4.5×10^6
Medical supply sterilization	2.5×10^6
Fruit pasteurization	2×10^5
Insect disinfestation	2×10^4

At 100% efficiency the amount of radiation power required for an irradiator as a function of capacity and dose is indicated by the following equation:

$$1.26 \text{ kW} = 1000 \text{ megarads lb/hr.}$$

The radiation power emitted by Co^{60} is 65 curies/W, and that emitted by Cs^{137} is 207 curies/W.

With these relationships, quick estimates can be made of the required number of curies of these radioisotopes to do specific jobs.

For detailed irradiator designs one of the most important parameters to be considered is the utilization efficiency of the irradiator. This is generally defined as the ratio of the radiation power absorbed at the minimum dose point in the target divided by the total power emitted by the source. The determination of irradiator efficiency, then, requires a determination of the total power emitted by the specific source to be used in the irradiator, and requires the determination of the depth-dose distribution in the finite target from the finite source.

The gamma rays from two radioisotopes, Co^{60} and Cs^{137} , have the penetrating power and other characteristics that are useful for food and medical supply irradiation. Table 2 gives some of the pertinent characteristics of these two radioisotopes.

Table 2

Radiation Characteristics of Co^{60} and Cs^{137}

	<u>Co^{60}</u>	<u>Cs^{137}</u>
Typical source form	metal	CsCl pellets
Half-life	5.3 yr	30 yr
Available specific activity	1 to 400 curies/g	1 to 25 curies/g
Gamma energy	1.17, 1.33 MeV	0.66 MeV
Power	65 curies/W	207 curies/W

Several different types of Co^{60} and Cs^{137} sources are available and are described in the referenced literature. (2) (3) The following typical sources are described in order to make certain points pertinent to irradiator design.

Figure 7 illustrates a Cs^{137} source. It consists of twelve $\approx 1 \times 1 \times 1/4$ -in. CsCl pellets, doubly encapsulated in stainless steel envelopes, such that the final dimensions of the source are 13.35 in. long, 1.12 in. wide, and 0.38 in. thick.

Figure 8 illustrates a Co^{60} source element designated as BNL Standard Mark I. It consists of strips of cobalt metal, 0.060 in. thick by 0.640 in. wide by 11 in. long, doubly encapsulated in stainless steel sheaths so that the final dimensions are 0.150 in. thick by 0.800 in. wide by $13 \frac{9}{16}$ in. long. The plaque type source for the Marine Products Development Irradiator, a pilot plant for fish preservation operated by the Bureau of Commercial Fisheries, consists of sixteen of these elements arranged in a rack in two rows of eight, back to back Figure 9. Six such racks make up the entire source which contains $\approx 250,000$ curies. A recent improvement on the Mark I source is an element designated as the Mark II, illustrated in Figure 10. In this strip the first stainless steel envelope is metallurgically bonded to the cobalt.

The Army Quartermaster Corp. has a facility called the Army Radiation Laboratory (ARL) for studying the radiation sterilization of food. Its source consists of 392 individually encapsulated

rods (Figure 11). Each rod is of solid cobalt metal, 0.75 in. in diam and is contained in a stainless-steel tube with welded end enclosures, which in turn are covered by an aluminum tube with welded end enclosures. The aluminum tube has over-all dimensions of 0.93 in. diam x 10.5 in. long. The source is arranged in the form of two parallel plaques. Each plaque consists of 49 vertical source-holder tubes mounted on a mandrel attached to a jig plate. Each source-holder tube contains four Co^{60} rods that are mounted end to end in a vertical array. The total assembly contains ≈ 1.0 million curies and is pictured in Figure 12.

As was mentioned earlier, one important measurement is the determination of the total power emitted by the source, i.e., the total curie content of the source.

Techniques have been developed⁽⁴⁾ using a remote source assay unit (pictured in Figure 13) that permits a rapid determination of the activity distribution of strip sources (see Figure 14) and the integration of this measurement for a curie content determination (see Figure 15). With this unit, the relative activity of one source to another can be determined.

within $\pm 1\%$. A reference standard source is given an absolute calibration in a gamma calorimeter such as shown in Figure 16. The Co^{60} source is placed inside a 465-lb high-density alloy cylinder. The cylinder will absorb 99.9+ % of the radiation energy emitted. By adiabatically insulating the calorimeter and measuring the linear rate of temperature rise in the high density cylinder, the absolute curie content of the reference standard source can be determined with an accuracy of $\pm 1\%$.

For food irradiation one of the most important design criteria is the uniformity of treatment. In food sterilization, dose uniformities, expressed as a ratio of maximum dose at any point in the package to the minimum dose at any point in the package, must bear ratios of 1.25 or lower; whereas for food pasteurization, ratios of 1.5 to 2.0 can be tolerated. The lower limit is to assure sterility and the upper limit is to assure wholesomeness. In any event, since the efficiency of the irradiator depends upon the minimum dose to the target, any dose above the minimum contributes to inefficiency and is to be avoided if possible. If one is to design for a max-min ratio of 1.25, i.e., a variation of $\pm 12.5\%$, then it must be possible to predict the dose in the target with a precision

greater than the variation permitted. One would like to be able to predict the dose at any point in a finite target with an accuracy of $\pm 5\%$.

Dose uniformity in a finite slab target depends upon target thickness, target density, and source-to-target geometry. For irradiators in which the target is in motion, say, in the horizontal direction, horizontal variation in dose is minimized. Vertical and depth dose variations, however, are not affected by horizontal motion. Vertical uniformity may be increased by overlapping the target with additional sources, by source specific activity augmentation at the top and bottom ends, and/or by the use of variable thickness absorbers in front of the target. Depth dose variation may be minimized by decreasing target thickness, by decreasing target density, by increasing the distance between source and target, and by the use of absorbers to decrease the gamma flux gradient within the target. Obviously some of these options affect irradiator efficiency adversely. The method that gives the best horizontal and vertical uniformity, accompanied by the least loss of efficiency, is to design the target to overlap the source and to permit target elements to have both horizontal and vertical motion in traversing the radiation field.

Depth uniformity measures require a precise determination of depth dose relationships. Methods have been developed at Brookhaven National Laboratory (BNL) that permit the prediction of the dose at any point in a finite homogeneous target from a finite BNL standard source with a high degree of precision. (5) The method involves the following:

(1) The dose at a point in an infinite medium of density one from a finite plane isotropic source is determined. This can be done both by a computer program and by tables of experimental data for both Co^{60} and Cs^{137} . The use of the experimental data permits a very rapid analysis for certain finite source sizes. They are very useful in preliminary design and in minimizing the computer time required. The computer code checks against the experimental data to $\pm 2\%$.

(2) A correction is applied to the selected normalized doses for finite boundaries. This correction is necessary because of the scattered radiation that escapes from the interface between the dense material of the target and the surrounding air and is thus lost to the target. This loss is greatest at the boundary, and the effect extends back approximately one mean free path inside the target.

(3) Corrections are made for source-to-target air gap and absorber thickness, taking into account actual thickness and

density and the thickness and densities of all absorbers between the source and the target.

(4) Adjustments can be made in the design for target densities other than unity by an appropriate scaling technique.

This method will permit one to predict the dose in certain finite rectangular slab targets for certain finite slab sources to within $\pm 5\%$. This accuracy is limited to thin sources (BNL standard type) and homogeneous targets. For thick sources (approximating one mean free path of the primary photon), there will be a significant low energy gamma component incident on the target face. This low energy component can be filtered out by an appropriate absorber at the cost of a loss in utilization efficiency.

Two problems involving nonhomogeneous targets are currently under study; one at BNL and the other at the National Bureau of Standards. The BNL study involves gathering of empirical data on certain heterogeneous targets such as boxes of canned goods. The effects measured thus far with Co^{60} seem to indicate that gamma rays streaming in the air spaces between cans decrease the expected minimum dose at a midplane corner of the target. The Bureau of Standards is conducting an analytical investigation of possible scattering of low energy photon components from a high Z steel container to the low Z food content. This effect

has been predicted to give higher doses to the food within the first millimeter of the metal container.

Since the energy of the primary photon from Cs^{137} is considerably less than that for Co^{60} , one would normally expect that the attenuation of the Cs^{137} photons would be considerably greater than that for Co^{60} in the same target. However, because of multiple photon scattering in low density targets a buildup of secondary photons occurs within the target, an effect that increases with penetration. A comparison of the attenuation in various low density targets from a Co^{60} slab source and a Cs^{137} slab source including buildup is indicated in Tables 3, 4, and 5. As can be seen, buildup compensates for the lower primary energy, and similar depth dose uniformities are predicted for low density targets from both Co^{60} and Cs^{137} . One would expect more marked effects at high Z interfaces for Cs^{137} sources.

Experimental studies are being conducted at BNL of dose-depth effects in heterogeneous targets for both Co^{60} and Cs^{137} . Experimental data are also being collected on such effects as target tilt during the traverse period, shadows caused by irradiator structure, and see-through effects for multiple pass targets.

Table 3

Co⁶⁰ - Cs¹³⁷ ComparisonTarget density = 1.0 g/cm³

25 x 21.28-in. source

Depth in target Z, in.	Co ⁶⁰	Cs ¹³⁷
	normalized dose at midpoint of target, D/D ₀	normalized dose at midpoint of target, D/D ₀
0	1.00	1.00
2	.5837	.6277
4	.3630	.3909
6	.2319	.2443
8	.1505	.1535
10	.09876	.09700
12	.06536	.06168
14	.04357	.03947
16	.02922	.02541
18	.01971	.01646
20	.01336	.01072
22	.009091	.007023
24	.006212	.004624
26	.004260	.003060
28	.002931	.002034
30	.002022	.001359
32	.001399	.0009109
34	.0009708	.0006132

Table 4

 Co^{60} - Cs^{137} ComparisonTarget density = .25 g/cm³

25 x 21.28-in. source

Depth in target Z, in.	Co^{60}	Cs^{137}
	normalized dose at midpoint of target, D/D_0	normalized dose at midpoint of target, D/D_0
0	1.00	1.00
2	.693	.7114
4	.500	.5235
6	.3715	.3954
8	.2822	.3047
10	.2186	.2385
12	.1721	.1892
14	.1374	.1518
16	.1111	.1230
18	.09076	.1006
20	.07486	.08282
22	.06226	.06868
24	.05216	.05730
26	.04399	.04806
28	.03732	.04051
30	.03182	.03429
32	.02726	.02915
34	.02346	.02467

Table 5

 Co^{60} - Cs^{137} ComparisonTarget density = 0.1 gm/cm³

Depth in target Z, in.	Co^{60}	Cs^{137}
	normalized dose at midpoint of target, D/D_0	normalized dose at midpoint of target, D/D_0
0	1.00	1.00
2	.7116	.7114
4	.5214	.5201
6	.3931	.3928
8	.3036	.3051
10	.2393	.2426
12	.1922	.1966
14	.1568	.1620
16	.1297	.1353
18	.1086	.1144
20	.09198	.09769
22	.07865	.08418
24	.06783	.07310
26	.05894	.06392
28	.05157	.05624
30	.04540	.04975
32	.04020	.04422
34	.03577	.03948

One of the advantages generally quoted for the radiation treatment of foods is that it is a cold sterilization technique; that is, that the target is not heated appreciably by the treatment. This is not necessarily so in all designs. For example, because of self-absorption there is a considerable buildup in temperature in the ARL gamma sources previously described.⁹ A surface temperature of $\approx 200^{\circ}\text{C}$ is estimated for the ARL assembly in still air. The thermal radiation from this source alone causes significant target heating in the ARL system. For thin sources, such as the BNL standard, the thermal radiation is not sufficiently high to cause any target heating. Although the radiant heat problem can be solved by design, there will always remain the problem of absorbed dose heating. The maximum temperature rise in the target can easily be estimated if one knows the specific heat of the target and assures that it is absorbing the radiation energy adiabatically. Table 6 shows the maximum temperature increases to be expected in foods (i.e., water) under these assumptions.

Table 6

Estimated Maximum Temperature Increases in Foods as a Function of Absorbed Dose and Initial Food Temperature

Initial food temperature	Temperature increase, $^{\circ}\text{C}$ at 4.5 megarad	Temperature increase, $^{\circ}\text{C}$ at 2.5 megarad	Temperature increase, $^{\circ}\text{C}$ at 0.2 megarad
Room temperature	10	6	0.5
Hard chill (-30° to 0°C)	22	12	1
Liquid N_2 freeze (-196°C)	70	40	3

In general, because of heat losses, actual food temperatures will be lower than those predicted by Table 6. Figure 17 indicates experimental data of the temperature gradient in a thick phenolic target as a function of time and depth. The gamma intensity at the target face was $\approx 9.2 \times 10^6$ rad/hr and at a point 5" within the target, the dose rate was $\approx 2.4 \times 10^6$ rad/hr. At a distance of 2 to 4 in. within the target the measured temperature is close to one predicted by adiabatic absorption. The temperatures at the edges are lower than the adiabatic prediction. Figure 17 also illustrates that the radiant heat from the thin BNL type source does not contribute to target heating.

Target heating problems for Cs^{137} sources are expected to be similar to those described for Co^{60} sources, i.e., target heating due to absorbed dose will not be much of a problem and the radiant heat of the source must be eliminated by source cooling or the use of thin sources.

A few words may be pertinent on the importance of specific activity. As was noted in Table 2, Co^{60} is available in specific activities up to ≈ 400 c/g whereas Cs^{137} can be procured in specific activities not exceeding 25 c/g.

For applications requiring high throughput and high dose, as, for example, the sterilization of bacon on a commercial scale, high specific activity Co^{60} is highly favored. High intensities

are necessitated by the additional requirement for bacon sterilization that the time from the removal of the untreated meat packages from refrigeration to the conclusion of the radiation treatment not exceed 22hr. At 4000 lb/hr throughput, a bacon sterilizer will require about 20 Ci/g of thin strip Co^{60} in order to maintain a retention time within the sterilizer of 20 hr. For higher throughputs a higher specific activity will be needed. Even at this throughput there will be obvious advantages in going to higher specific activities. Fewer cobalt strips must be prepared for neutron irradiation, fewer must undergo the costly remote encapsulation after irradiation, ⁽⁷⁾ and perhaps of paramount importance, the higher the specific activity the smaller the internal volume of the irradiator that must be shielded. Of course, these advantages must be balanced against the greater cost of preparing the high specific activity. Cs^{137} might possibly meet the specifications described but would require very thick (≈ 1 -in.) sources to match the intensity of the equivalent specific activity thin Co^{60} sources.

For applications requiring high throughputs and intermediate doses, as, for example, the pasteurization of fruit, both Co^{60} and Cs^{137} at about 20 Ci/g could be used providing that the throughput requirement does not exceed $\approx 10,000$ lb/hr and the retention time in the system need not be < 1 hr.

For applications requiring very high throughputs and low doses, as, for example, the disinfestation of grain, both Co^{60} and Cs^{137} could be used. The specific activity required once again would depend upon the throughput and retention time specified. For flowing grain at a rate of 200,000 lb/hr, the disinfestation dose could be delivered in about a minute with 25-Ci/g specific activity Co^{60} . In the case of grain, very low specific activities might be used if the grain could be treated in temporary storage bins.

It should be noted that in the above discussion of specific activity it is assumed that the rates of both the biological and chemical reactions involved are independent of radiation field intensity, an assumption that is generally held to be valid for the cases described.

One of the advantages of Cs^{137} that should be noted is its considerably longer half-life. Co^{60} decays at a rate of $\approx 12\%$ per year, and must be replaced at this rate to keep the power of the irradiator constant. Cs^{137} decays at a rate of only 2% per year.

Another factor to be considered in comparing Cs^{137} with Co^{60} is that the lower energy primary photon from Cs^{137} generally requires less shielding than that of Co^{60} . This is particularly true in shielding transportable irradiators.

Thus far, this discussion has concerned itself with package irradiators in which no movement is assumed within the contents

of the package, so that once the path of the package through the radiation field is determined, the dose to each element of the package is completely predictable. The design problem can take on somewhat different aspects when one is considering flowing-solid irradiators or liquid irradiators. In these cases if one has a detailed knowledge of the character of the flow pattern and the fluid flows through a uniform radiation field, one can once again predict the dose to each element of the fluid. When the radiation field is nonuniform, a detailed knowledge of the path of each element through the system may be necessary to characterize the depth dose relationships in the irradiator. This general problem is considered in more detail in reference 7.

A comparison of the general ranges of utilization efficiencies in already designed package, flowing solids, and liquid irradiators is given in Table 7.

Table 7

A Comparison of Utilization Efficiencies

<u>Irradiator type</u>	<u>Package</u>	<u>Flowing solids</u>	<u>Liquid</u>
Ethicon Irradiator	25%		
USDA Bulk Grain Irradiator		38%	
Dow Ethyl Bromide Irradiator			70%

An attempt has been made herein to highlight the elements of gamma irradiator design. Many additional features are involved in actual designs, including ozone generation and removal, radiation damage to components of the system, and the design of control systems for product treatment and system safety. Hopefully this introduction will serve to attract the reader to the growing literature in the field.

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FIG. 1

FIG. 2

COBALT-60 BULK GRAIN IRRADIATOR

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

BNL STANDARD ^{60}Co GAMMA RADIATION SOURCE BONDED TYPE MARK 2

PHOTOGRAPH OF CROSS SECTION PERPENDICULAR
TO MAJOR AXIS

FIG. 10

FIG. II

FIG. 12

FIG. 13

FIG. 14

FIG. 15

FIG. 16

FIG. 17