DESIGN OF A PORK IRRADIATION FACILITY

USING GAMMA RAYS TO BREAK THE TRICHINOSIS CYCLE

By

H. J. GOMBERG
S. E. GOULD

Michigan Memorial-Phoenix Project 54

J. V. NEHEMIAS
L. E. BROWNELL

Fission Products Laboratory
Engineering Research Institute
University of Michigan

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A. DESCRIPTION OF PROPOSED APPLICATION

The use of ionizing radiation to break the trichinosis cycle has been discussed previously.[1] The technical feasibility has been well established; economic feasibility is thus the major outstanding problem. Presented herewith are the results of a cost study of a meat processing plant designed to irradiate hog carcasses, using cesium-137 or waste fission products as the radiation source.

A radiation dose of 15,000 r will sterilize trichina encysted within a hog carcass[1] so that they cannot reproduce and cause infection. The irradiation level used in the cost study is 30,000 r to the surfaces of the carcass. Tests and calculations have shown that this radiation could produce a dose of 25,000 r at the center of a 14-inch thick carcass, using techniques which minimize attanuation due to geometry. The thickest sections of carcasses (the hams) are rarely more than 10 inches thick.

Flavor tests with ground pork show no detectable taste changes with doses up to 60,000 r. This radiation can also destroy microorganisms. The pasteurization achieved by 60,000 r increases the refrigerator shelf-life of the meat by approximately 100 percent; 30,000 r increases shelf-life by almost 30 percent. Pasteurization with gamma radiation will be discussed in more detail in a separate study covering this effect in a number of products.

The plant design outlined in the following pages was evolved.

B. PLANT SIZE

To obtain data on typical modern methods of pork processing, a study of the available literature on packing plants was made. In addition, a number of plants in the Detroit area were visited. For reference purposes, a two-story plant with a capacity of 2000 hogs per day was taken as representing modern practice and design.*

In such a plant, the live hogs are driven to the second floor, where they are slaughtered and the carcasses dehaired, gutted, headed, cleaned, split and spread. The spread carcasses are then transferred to the chill room, usually by overhead conveyor, where they remain for 24 to 48 hours. The chilling facilitates subsequent cutting and handling. Thus, there is a period of at least 24 hours during which the carcass is in cold storage and available for irradiation.

From our local study of pork plant operation, it was found that, with the exception of the head, all parts of the hog subject to invasion by trichina and which enter commerce as food, remain attached to the carcass when it is sent to the chill room, including the diaphragm which is a focal point of infection in trichinosis. Thus, except for the very small item of head and jowl trimmings, irradiation of the cleaned and spread carcass would effectuate irradiation of all hog muscle tissue which would be consumed by man or used as animal feed.

On this basis, the plant was designed to irradiate the 2000 carcasses in the 24-hour minimum delay period between carcass preparation and cutting. For convenience and access to the chill room, the irradiation unit is designed to operate at the second-story level. An outside irradiation room below ground level with an enclosed conveyor from the chill room and back was considered, but the added complication did not seem justified. The additional cost of the conveyor just about balances the cost of the additional shielding needed for the second-story irradiator design.

The irradiation source itself is a plaque 5 feet wide by 6 feet high, providing a broad uniform radiation field through which the carcass passes, suspended from an overhead conveyor. Details of plaque design are presented in the pertinent section. The selection of a suitable source of gamma radiation is essential.

C. SELECTION OF A GAMMA SOURCE

In selecting a source of gamma radiation for this design, mixed fission products of various ages are considered and compared with cesium-137. The "mixed" fission products are defined as the mixture of radioactive elements resulting from the fission of uranium after separation from process wastes. Since the composition and activity of the mixed fission products vary with their age, mixtures of various ages must be considered. In general the mixed fission products have the advantage of being available in much larger quantities than

*Hygrade Plant at Storm Lake; Wilson Plant at Albert Lea, Minn.

cesium-137, which is present to only about 6.2% by weight of the mixed fission products at the time of removal from the reactor. The other important gamma emitters, zirconium-95, its daughter product columbium-95, and cerium-144, have much greater gamma activity than cesium-137. However, using cesium-137 instead of mixed fission products has numerous advantages which will be pointed out by comparing cesium-137 with the properties of (1) the activity of mixed fission products, (2) the absorption characteristics of gamma radiation from mixed fission products, and (3) the economics of using mixed fission products.

1. The Activity of Mixed Fission Product Sources

The specific radiation flux R_o in r/hr at a distance of 1 cm from a 1.0-mc point source was determined as a function of the gamma energy in mev by Marinelli.[4]

The radiation coefficient, α, for a source of differential area expressed in r/hr per unit area of emitting surface at unit distance from the emitter can be calculated from R_o using the following relation:

$$\alpha = R_o \rho St = \frac{r}{\text{hr curie}} \frac{\text{gm}}{\text{cc}} \frac{\text{curie}}{\text{gm}} \text{ cm} \quad \text{at 1 cm} \tag{1}$$

$$= \frac{r}{\text{hr-cm}^2} \quad \text{at 1 cm}$$

$$= \frac{r}{\text{hr-in.}^2} \quad \text{at 1 in.}$$

$$= \frac{r}{\text{hr-ft}^2} \quad \text{at 1 ft,}$$

where

R_o = specific radiation flux, r/(hr-curie), at 1 cm;

ρ = density of emitter, gm/cc;

S = specific activity of emitter, curies/gm; and

t = thickness of emitter, cm.

As the radiation flux at a given distance from a source of differential area is inversely proportional to the square of the distance from the source and directly proportional to the area of the source, the units of distance squared and of area cancel each other. Thus, the radiation coefficient, α, is independent of the distance and area units providing that consistent units are used. To calculate the flux for a source of finite area, the following integration must be performed over the area of the source:

$$I = \alpha \iint \frac{da}{\gamma^2} \quad . \tag{2}$$

The constituents of mixed fission products at 3, 6, 12, and 24 months after removal from a reactor, including all isotopes present in excess of 1%, are listed in Tables I-IV. The second column of these tables lists the percent of the total activity contributed by each radioisotope. The contribution of cesium-137 is less than 1% of the total activity until the fission products are almost one year old and therefore does not appear in the second columns of Tables I and II. Cesium-137 contributes 1.5% of the activity of one-year-old fission products and 4.0% after two years, as shown in Tables III and IV respectively. The radiation coefficients, α, are listed in the last columns of Tables I-IV.

The factor limiting specific activity is the rate of heat absorption within the source material. This heat absorption is chiefly the result of beta-particle activity. An upper limit of 10,000 total curies per pound has been suggested from these thermal considerations.

If mixed fission products are concentrated to 10,000 curies per pound, the useful gamma-emitting isotopes will be present to the extent determined by the percent composition as listed in the second columns of Tables I-IV. The specific activity in curies per pound of each gamma-emitting isotope is listed in the fourth columns. The total gamma specific activity is plotted in Fig. 1 as a function of time after removal from the reactor. Figure 1 shows that the optimum storage time, from the point of view of useful gamma activity per 10,000 curies of total activity is approximately six months.

It may be seen from Tables I-IV that even for the optimum case (6 months), the coefficient α is appreciably lower than that previously computed for cesium-137 (340,000). Using identical geometrical configurations, a gamma source containing 6-month-old mixed fission products would have to be 1-1/2 times as active (including both beta and gamma activity) as a gamma source containing cesium-137 to produce the same levels of gamma radiation in air.

2. The Absorption Characteristics of Radiation from Mixed Fission Products

The absorption characteristics in meat of the complex of gamma energies from mixed fission products must be considered. Figure 2 illustrates the absorption characteristics of each important component as well as the total absorption effects, using broad-beam absorption coefficients.[4] The resultant total absorption does not differ appreciably from that found for cesium-137. A gamma source containing 6-month-old mixed fission products would approximate the absorption efficiency of a source containing pure cesium-137.

TABLE I

COMPOSITION OF MIXED FISSION PRODUCTS
THREE MONTHS AFTER REMOVAL FROM REACTOR

Isotope	Percent[2] Contribution	Gamma Energy[2,3]	Gamma Specific Activity, curies/pound	R_o[4]	α
Cb^{95}	18	0.758	1800	4.4	70,000
		0.216	1800	1.2	19,000
Zr^{95}	14	98% 0.708 2% 0.216	1372 28	4.2 1.2	51,000 300
Sr^{89}	13	none	---	---	---
Y^{91}	11	none	---	---	---
Ce^{141}	8.6	0.14	860	0.75	5700
Ru^{103}	7	0.3, 0.5	700	2.3	14,000
Rh^{103}	7	none	---	---	---
Ce^{144}	6	none	---	---	---
Pr^{144}	6	0.7	600	4	21,000
La^{140}	2	10% 1.6 20%, 0.5,.1,1.6 70%, .8, .1,1.6	20 40 140	8 11.5 15.5	1400 4000 19,000
Ba^{140}	2	40% .3, .2	80	3	2100
Pr^{143}	2	0.7	200	4	7000
		Total	7640		214,500

TABLE II

COMPOSITION OF MIXED FISSION PRODUCTS
SIX MONTHS AFTER REMOVAL FROM REACTOR

Isotope	Percent[2] Contribution	Gamma Energy[2,3]	Gamma Specific Activity, curies/pound	R_o[4]	α
Cb^{95}	25	0.758	2500	4.4	97,000
		0.216	2500	1.2	26,400
Ce^{144}	12	none	---	---	---
Pr^{144}	12	0.7	1200	4	42,000
Zr^{95}	15	98% 0.708 2% 0.216	1470 30	4.2 1.2	54,000 320
Y^{91}	11	none	---	---	---
Sr^{89}	8.5	none	---	---	---
Ru^{103}	4.2	0.3,0.5	420	2.3	8600
Rh^{103}	4.2	none	---	---	---
Ce^{141}	2.5	0.14	250	0.75	1650
Pm^{147}	2.0	none	---	---	---
Ru^{106}	1.0	none	---	---	---
Rh^{106}	1.0	0.5,0.7	17	3.5	530
		Total	8387		230,000

TABLE III

COMPOSITION OF MIXED FISSION PRODUCTS
ONE YEAR AFTER REMOVAL FROM REACTOR

Isotope	Percent[2] Contribution	Gamma Energy[2,3]	Gamma Specific Activity, curies/pound	R_o[4]	α
Ce^{144}	27	none	---	---	---
Pr^{144}	27	0.7	2700	4	95,000
Cb^{95}	15	0.758	1500	4.4	58,000
		0.216	1500	1.2	16,000
Zr^{95}	7	98% 0.708 2% 0.216	686 14	4.2 1.2	25,000 150
Pm^{147}	6	none	---	---	---
Y^{91}	4	none	---	---	---
Sr^{89}	3	none	---	---	---
Ru^{106}	2.5	none	---	---	---
Rh^{106}	2.5	0.5,0.7	42	3.5	1300
Sr^{90}	2	none	---	---	---
Y^{90}	2	none	---	---	---
Cs^{137}	1.5	none	---	---	---
Ba^{137}	1.5	0.7	300	4	10,000
		Total	6742		205,500

TABLE IV

COMPOSITION OF MIXED FISSION PRODUCTS
TWO YEARS AFTER REMOVAL FROM REACTOR

Isotope	Percent Contribution	Gamma Energy	Gamma Specific Activity, curies/pound	R_o	α
Ce^{144}	30	none	---	---	---
Pr^{144}	30	0.7	3000	4	105,000
Pm^{147}	14	none	---	---	---
Sr^{90}	5.2	none	---	---	---
Y^{90}	5.2	none	---	---	---
Cs^{137}	4	none	---	---	---
Ba^{137}	4	0.7	400	4	14,000
Ru^{106}	3.5	none	---	---	---
Rh^{106}	3.5	0.5,0.7	60	3.5	1850
		Total	3460		120,850

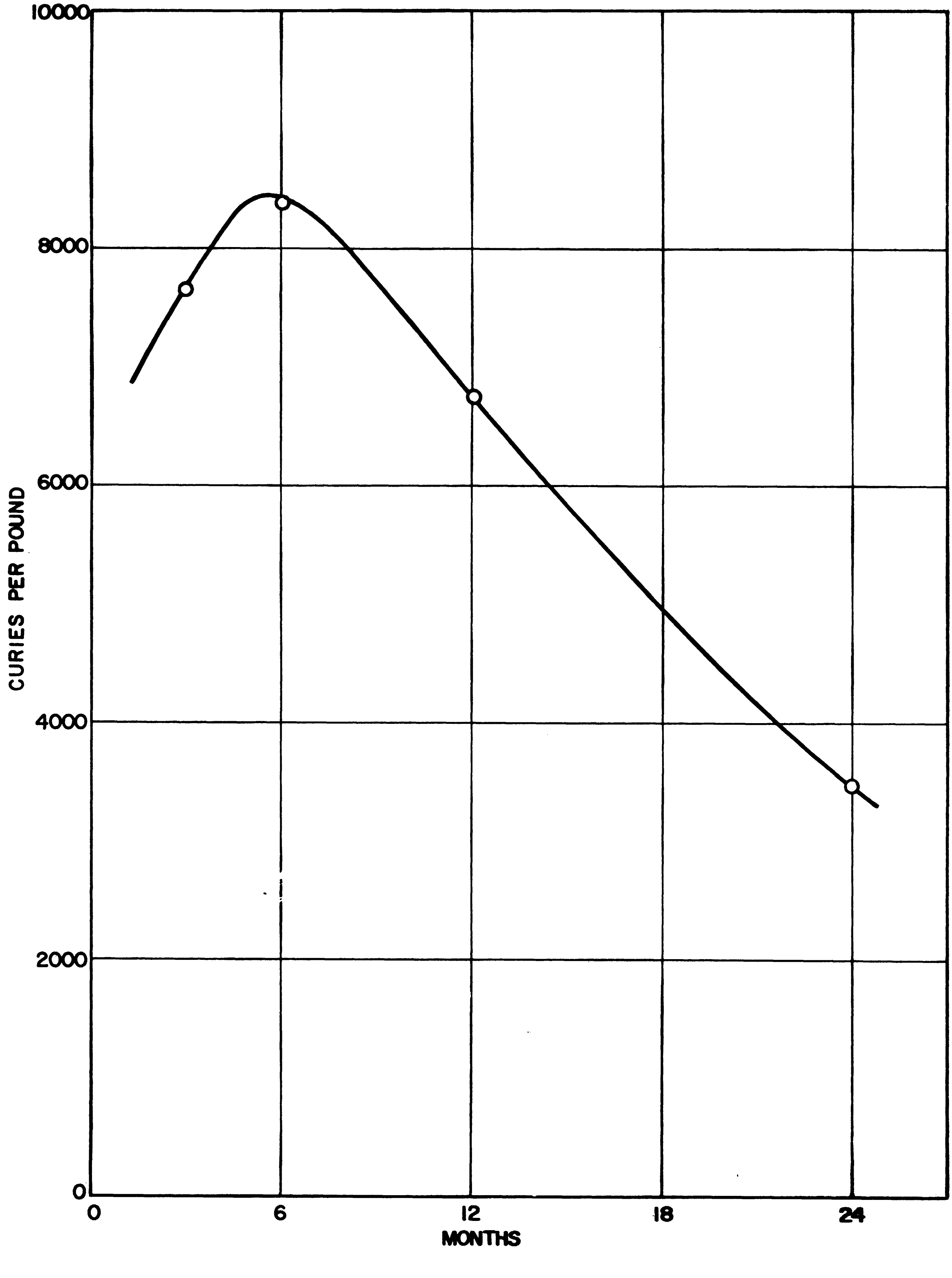

Fig. 1. Gamma specific activity in curries per sound as a function of age for mixed fission products.

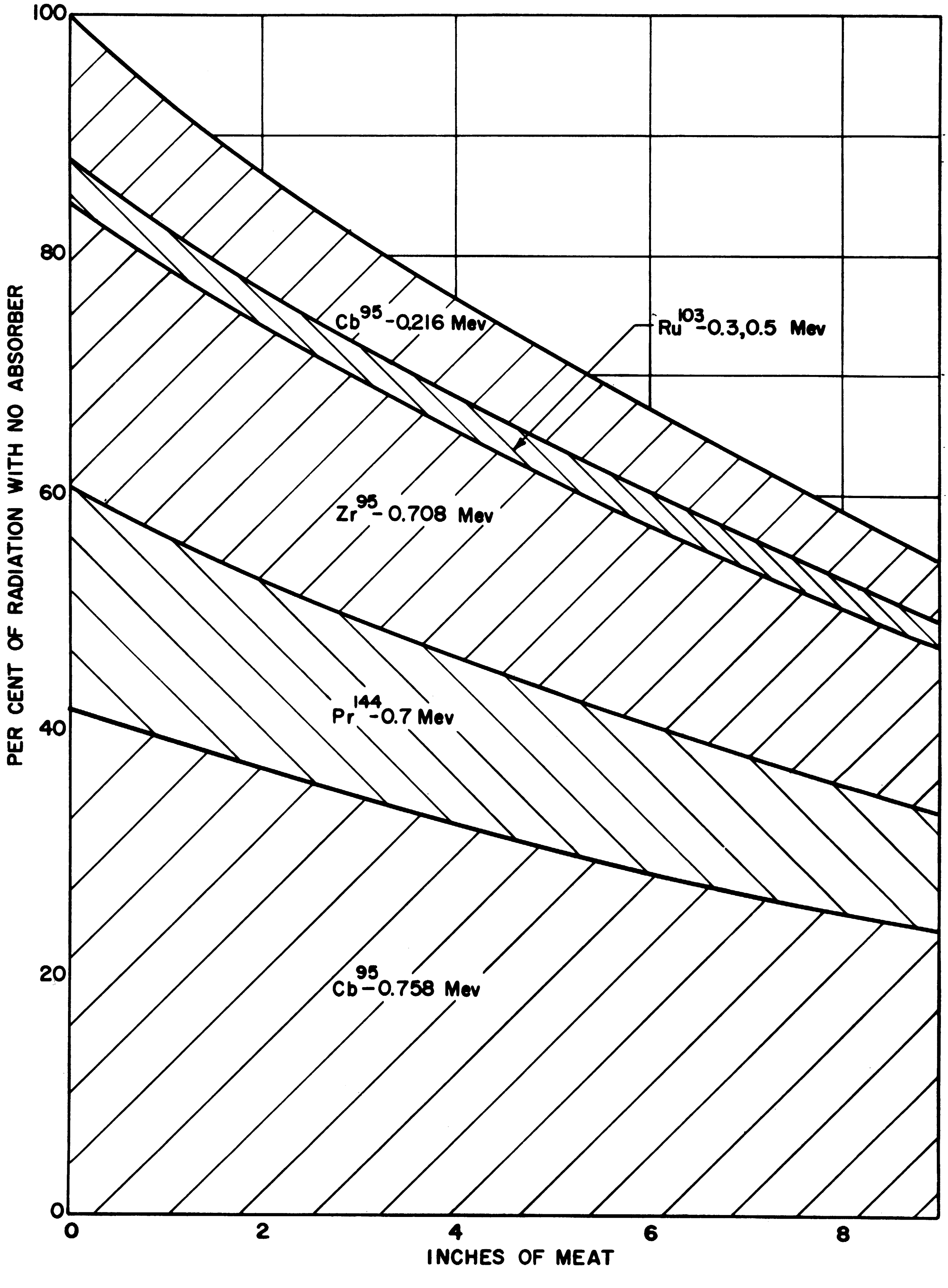

Fig. 2. Absorption in meat of mixed fission products six months old.

3. The Economics of Using Mixed Fission Products and Cesium-137

Perhaps the most important consideration is the rate at which the radiation flux from such fission-product radiation sources decreases with time. Figures 3, 4, and 5 illustrate respectively the component and total time decay to be expected from the compositions calculated in Table II-IV.

As a practical consideration in operation of a radiation facility, the radiation flux must be kept from dropping excessively in order to prevent drop in capacity. Assuming that a 10 percent drop in flux is permissible, then 1/6 of a source containing 6-month-old mixed fission product must be replaced every week. For 1-year-old fission products this minimum replacement period is lengthened to 2 weeks, and for 2-year-old material to 5 weeks. Replacement of high-level gamma sources is expensive, time-consuming, and dangerous and therefore must be minimized. Prolonged storage of the gross fission products, however, tends to increase the cost per curie for two reasons: first, expensive storage facilities must be constructed and maintained; and second, the "natural" specific activity decreases tremendously and the degree of processing required to achieve 10,000 curies per pound is increased proportionately.

The mixed fission products have a short effective half-life during the first 2 years of decay, when they have high gamma activity. If the mixed fission products are allowed to decay for 4 years, about half the gamma radiation will be from cesium-137. However, for a given weight, such a source of 4-year-old mixed fission products would have only about 10 percent of the gamma activity of separated cesium-137, as a result of dilution by the other fission products and their decay products.

The value of 1-1/2 megacuries required for the radiation facility described will be used in the analysis of costs. As 6-month-old fission products have the optimum radiation coefficient, α, they will be compared to cesium-137.

A weekly replacement of 1/6 of a 6-month-old fission product source amounts to 8-2/3 total replacement each year. Cesium-137 would require replacement of 1/6 of the source every 5 years to prevent the activity from dropping more than 10 percent. Thus for a 1.5-megacurie source, the total activity of 6-month-old mixed fission products required in a 5-year period as compared to cesium-137 would be:

$$\frac{1.5 \text{ megacuries}}{(8\text{-}2/3 \text{ replacement}/1 \text{ yr})(5 \text{ yrs})} = \text{65 megacuries of 6-month-old fission products required}$$

$$\frac{1.5 \text{ megacuries}}{(1/6 \text{ replacement}/5 \text{ yrs})} = \text{0.25 megacurie of cesium-137 required}$$

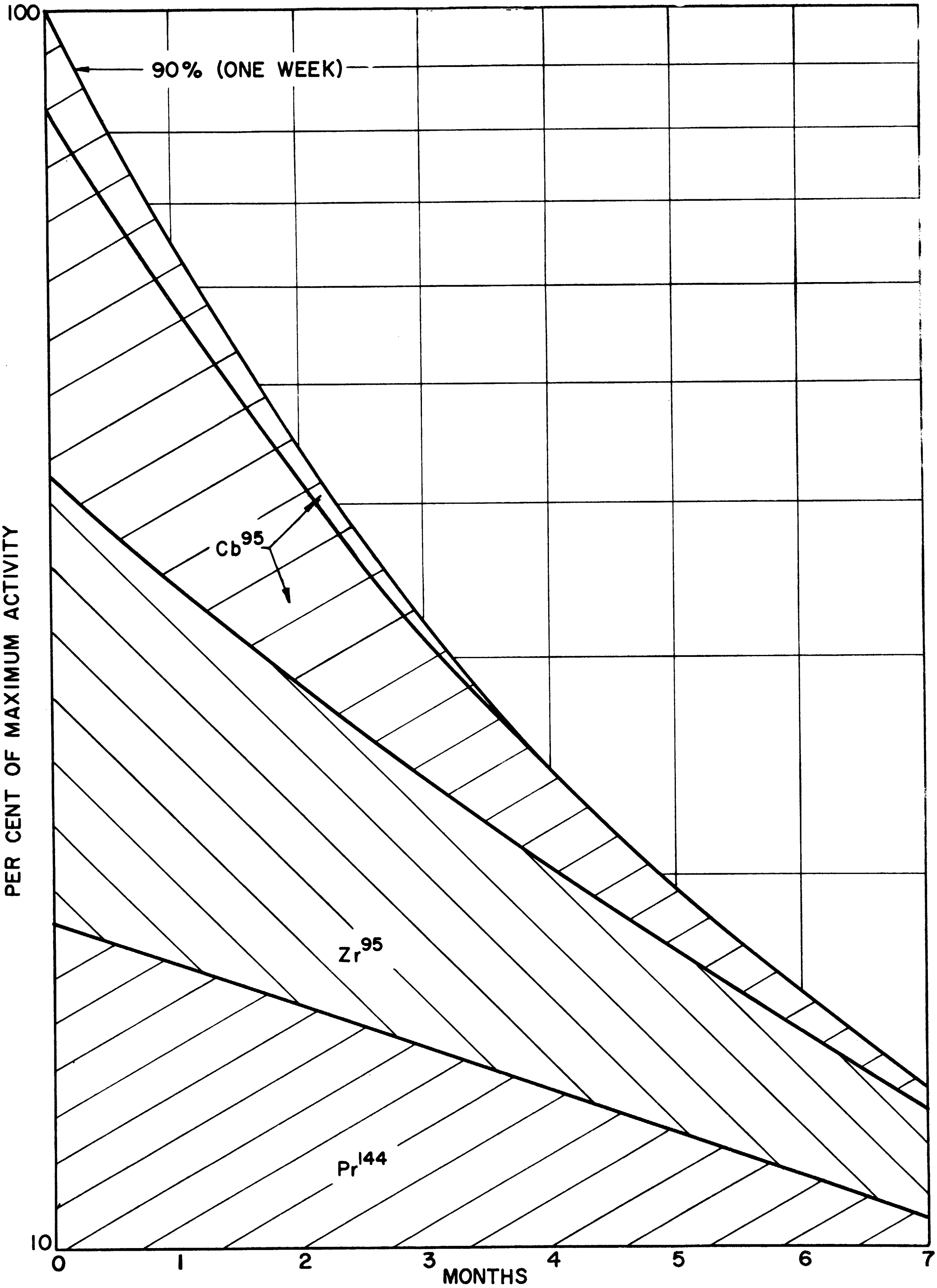

Fig. 3. Time decay characteristics of six-month-old mixed fission products.

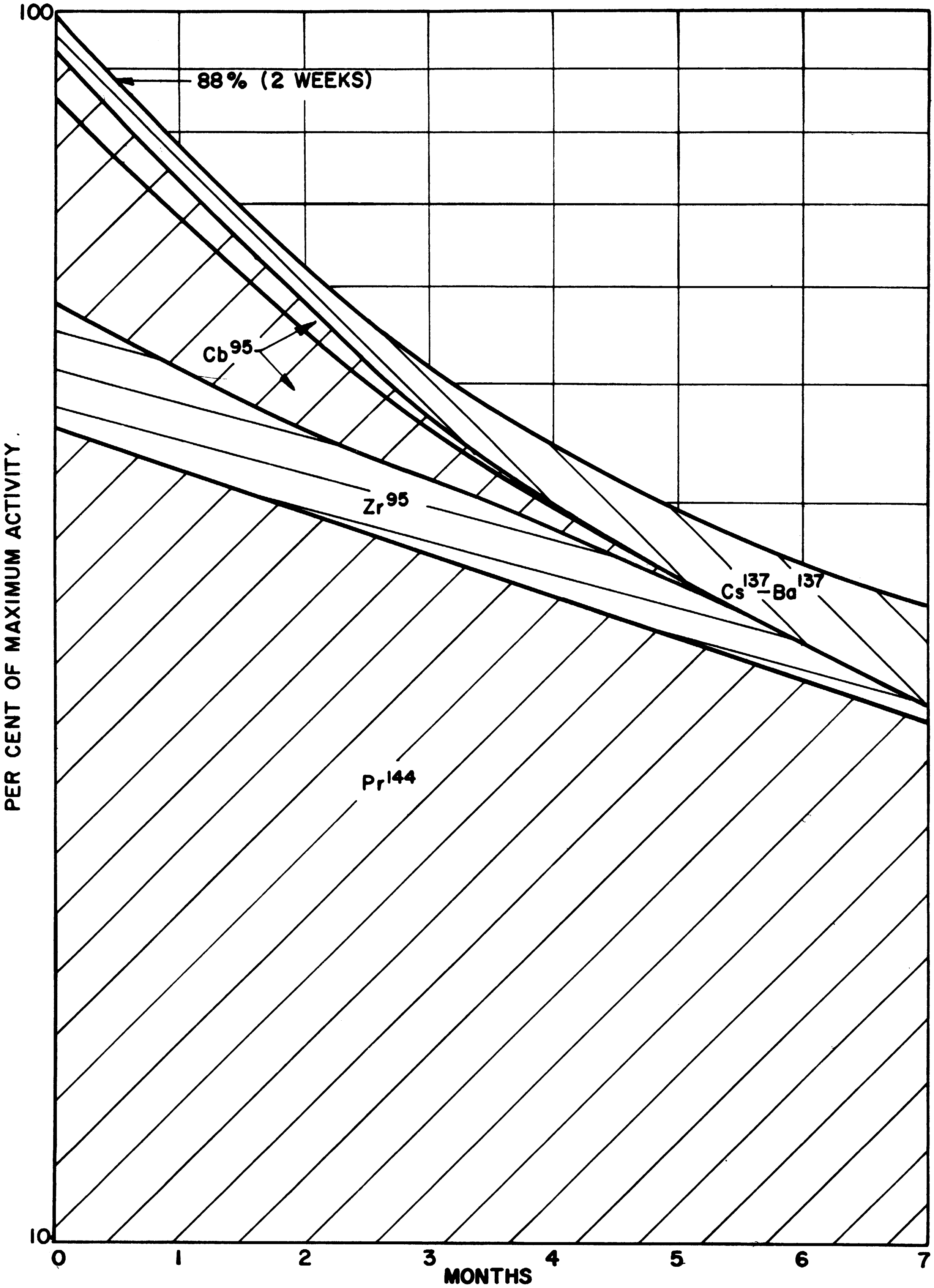

Fig. 4. Time decay characteristics of one-year-old mixed fission products.

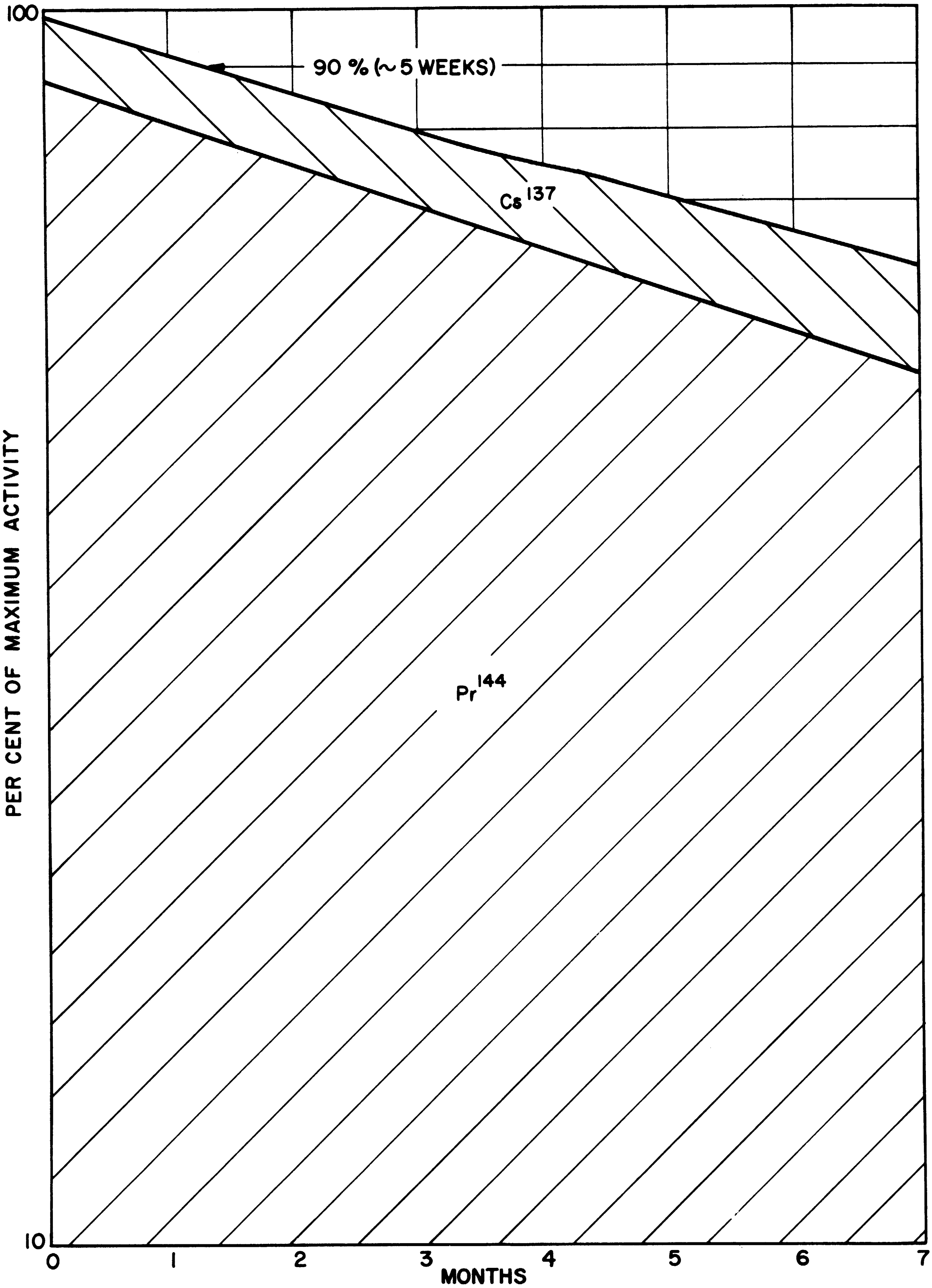

Fig. 5. Time decay characteristics of two-year-old mixed fission products.

In other words in a 5-year period 65/0.25 or 250 times as many curies of 6-month-old mixed fission products would be required as cesium-137.

If the values of the two sources are compared on the basis of replacement of activity without regard to shipping and installation costs or to the differences in interest on the investment, the cesium-137 will have a value as a source of radiation 250 times as great as the 6-month-old mixed fission products. Thus, if the 1.5 megacuries of cesium-137 used in the pork irradiation facility described herein has an initial value of $483,000 (as calculated in the section on design), the corresponding value for the 6-month-old mixed fission products would be $483,000/250 or $1,930 for 1.5 megacuries of 6-month-old mixed fission products.

It appears very unlikely that 1.5 megacuries of mixed fission products could be concentrated and prepared into a suitable source for $1,930. Furthermore, the shipping and installation cost associated with replacing 0.25 megacurie every week would in itself exceed $1,930 appreciably.

D. DESIGN OF SOURCE

There are many shapes and types of containers which might prove suitable for holding concentrated radioactive fission products. Some preliminary calculations were made using cylindrical rods and rectangular strips, each of which has certain inherent advantages.

The chief advantages of using cylindrical containers are the simplicity of filling and the structural strength, while the chief advantage of the strips is the reduced number of source pieces required. A rectangular strip can be used to irradiate samples on either side and presents a continuous, uniform plane from which rays are emitted, which is advantageous in irradiating food conveyed by mechanical means through an irradiation chamber. In such an application it is desirable to introduce a minimum of direction changes, and preferably no change in conveyor mechanism, so as to minimize maintenance problems in the irradiation chamber. Preliminary calculations indicate that it is not feasible to use cylindrical source rods at 2-foot intervals, because rods so spaced must be unduly large if a high radiation flux is desired. Source rods of large diameter are undesirable because self-absorption of the radiation causes generation of heat in the rods. The alternative is to use shorter intervals between the rods. This process can be continued until the limit is reached, at which the rods are adjacent to one another. Then the rods form a plaque for purposes of flux calculations, and a very large number of rods would be required. For these reasons the calculations have been limited to designs involving the use of a plaque made up of plane strips.

1. Disk-Shaped Source

Calculating the radiation field emitted from a finite rectangular plaque is not a simple problem. The calculation is simpler for a disk-shaped plaque. In the accompanying calculations the radiation from a plaque 6 ft by 5 ft by 1 cm is compared with that from a disk 6 ft in diameter, and also with a disk 6.1 ft in diameter. The latter disk has the same area as the 6-ft by 5 ft plaque. A calculation was also made for an infinite strip 6 ft wide. These calculations are for radioactive fission wastes having an activity of 10,000 curies/lb. The calculations which may be of interest follow.

Required: A plane source 6 ft high and as long as necessary to provide a dose of approximately 30,000 rep to the surface of carcasses moving approximately 20 ft/min, 21 in. from the source, assuming 10,000 curies/lb for the source. To estimate the order of magnitude of the length required, compute the dose at a point P, 21 in. from a 6-ft disk, from Fig. 6:

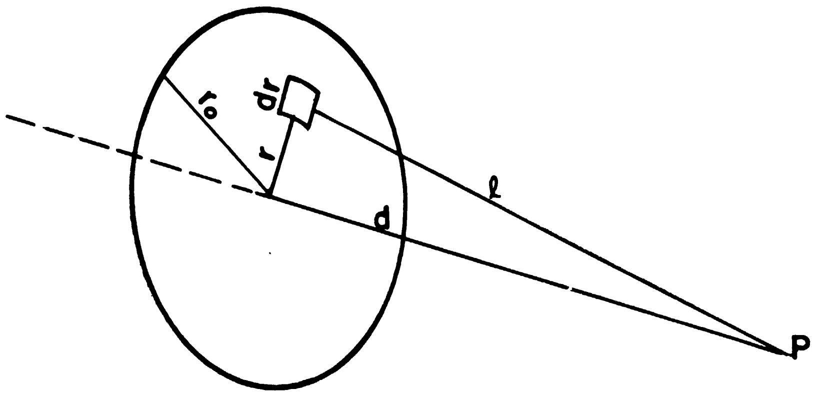

Fig. 6. Geometry of a Disk-Shaped Plaque.

$$I\ (r/hr) = \alpha \iint \frac{dA}{l^2} = 2\alpha \int_0^{r_o}\int_0^{\pi} \frac{r\,dr}{r^2 + d^2}$$

$$= 2\pi\alpha \int_0^{r_o} \frac{r\,dr}{r^2 + d^2} \qquad (3)$$

$$= \alpha\pi \ln\left(1 + \frac{r_o^2}{d^2}\right) ,$$

where α, the radiation coefficient, is

$$\alpha = R_o \rho S t$$

and

R_o = 3.8×10^3 r/hr-curie at 1 cm for cesium-137,[4]

ρ = 4 g/cm^3, typical salt density,

S = specific activity, 10,000 curies/lb, and

t = 1 cm.

Thus

$$\alpha = (3.8 \times 10^3)\ (4)\ (10{,}000)\ (1)\ (2.2 \times 10^{-3})\ \text{lb/g})$$

$$= 340{,}000\ \text{r/hr-cm}^2 \quad \text{at 1 cm.}$$

At 21 in. from a 6-ft disk:

$$I = (340{,}000)\ \ln\ [1 + (36/21)^2]$$

$$= 1{,}470{,}000\ \text{r/hr}\ .$$

The dosage rate at 21 in. from a plaque of finite length and 6 ft high should have approximately the same value. This is a feasible radiation level, requiring approximately 1 minute of radiation time to provide the specified dose of 30,000 rep.

Therefore, a plaque 6 ft high and 5 ft long is selected. As a first approximation, the dosage rate 21 in. from a circular disk of equal area (3.08-ft radius) would be:

$$I = \pi\ (340{,}000)\ \ln\ [1 + (37/21)^2]$$

$$= 1{,}510{,}000\ \text{r/hr} \quad \text{at 21 in.}$$

2. Finite Rectangular Source

The objective was to determine the theoretical dose rate at a position P, 21 in. from the center of a plane rectangular 60- by 72-in. source (see Fig. 7).

Procedure: Consider the contribution of an infinitesmal rectangular element of the source, dx by dy, whose position in space is given by the coordinates (x, y, 0). The distance, r, of this element from the point P is given by

$$r = \sqrt{(x - 0)^2 + (y - 0)^2 + (0 - 21)^2}\ ,$$

$$= \sqrt{x^2 + y^2 + 441}\ .$$

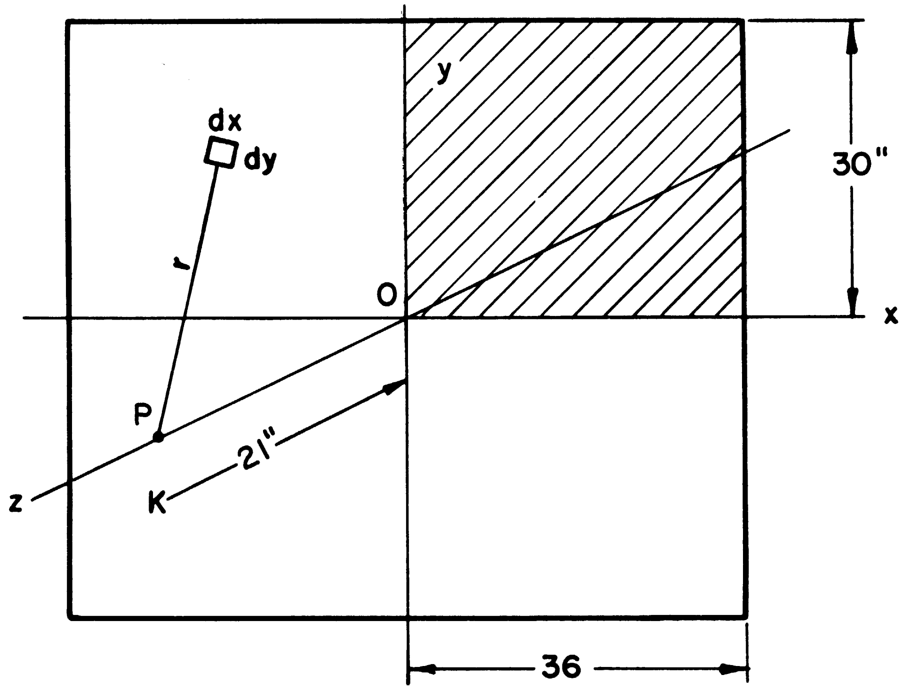

Fig. 7. Geometry of a Finite Rectangular Source.

By the inverse-square law, the contribution of this infinitesimal element is

$$\alpha\left(\frac{dy\ dx}{x^2 + y^2 + 441}\right),$$

where α is a coefficient determined by the characteristics of the source material.

Integrating this expression with respect to x from 0 to 36, and then with respect to y from 0 to 30, the contribution of the cross-hatched portion of the source shown in Fig. 7 is obtained; i.e.,

$$\alpha \int_0^{30}\int_0^{36} \frac{dy\ dx}{x^2 + y^2 + 441}.$$

Since the source is symmetric about the x and y axes, multiplication of the above expression by 4 yields the total dose rate I, at position P; i.e.,

$$I = 4\alpha \int_0^{30}\int_0^{36} \frac{dy\ dx}{x^2 + y^2 + 441} \qquad (4)$$

$$= 4\alpha H,$$

where, for convenience, the double integral is denoted by H.

Integration with respect to x yields

$$H = \int_0^{30} \frac{1}{\sqrt{y^2 + 441}} \tan^{-1} \frac{36}{\sqrt{y^2 + 441}} \, dy \quad . \qquad (5)$$

This integral cannot be integrated formally. Approximating H by means of Euler's quadrature formula,[6] using 31 equally spaced ordinates, yields the value

$$H = 1.097 \pm 0.001 \ .$$

Substituting this value and the proper value of α into Eq. 4 yields the dose rate:

$$\begin{aligned} I &= 4\alpha H \\ &= 4\ (340{,}000)\ (1.097 \pm 0.001)\ , \\ &= 1{,}491{,}920 \pm 1360 \text{ r/hr} \ . \end{aligned}$$

In a graphical check solution of the integral:

$$I = 4\alpha \int_0^{30} \frac{1}{\sqrt{y^2 + 441}} \tan^{-1} \frac{36}{\sqrt{y^2 + 441}} \, dy \ , \qquad (6)$$

the values of the integrand (Y) as a function of y are plotted in Fig. 8, where

$$y = \frac{1}{\sqrt{y^2 + 441}} \tan^{-1} \frac{36}{\sqrt{y^2 + 441}} \quad .$$

GRAPHICAL INTEGRATION

y	Y	Δy	Area (YΔy)
0	0.0496	0-6	0.292
5	0.0477	6-12	0.264
10	0.0430	12-18	0.222
15	0.0368	18-24	0.179
20	0.0308	24-30	0.142
25	0.0256		1.099
30	0.0212		

The area beneath the curve from 0 to 30 is thus found to be 1.099 area units. Thus

$$\begin{aligned} I &= 4\ (340{,}000)\ 1.099 \\ &= 1{,}495{,}000 \text{ rep/hr.} \end{aligned}$$

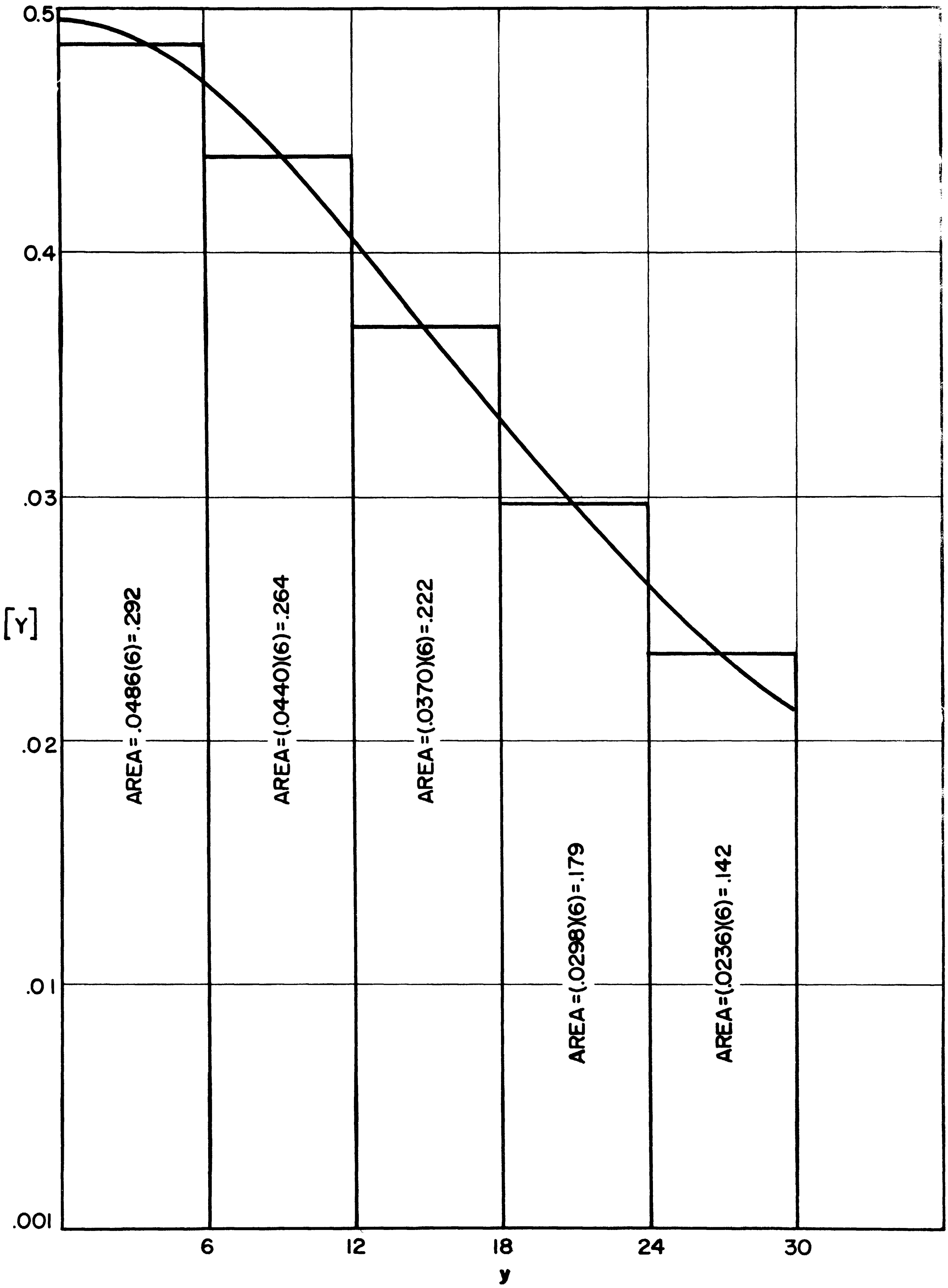

Fig. 8. Graphical integration of Eq 6.

A similar solution at the edge of the plaque and 1 ft past the edge of the plaque yields dosage rates of 1,010,000 rep/hr and 696,000 rep/hr respectively. The average dosage rate over the traverse of the plaque plus an additional 1 ft on either end is approximately 1,140,000 rep/hr or 19,000 rep/min. Similar calculations for the case in which the hogs are spaced 17 in. and 25 in. from the plaque give radiation fluxes of 23,500 and 15,700 rep/min respectively.

E. CAPACITY CALCULATIONS

1. Absorption Correction

The hogs to be irradiated will traverse 14 ft of radiation field having an average flux of 19,000 rep/min. This flux must be corrected for absorption in determining the dosage rate. Tests reported previously,[1] describing irradiation of pork using cooling reactor fuel slugs, indicated that the thickness of pork required to reduce the field of 0.7-mev gamma radiation to one-half value is approximately 8 in. as shown in Fig. 9.

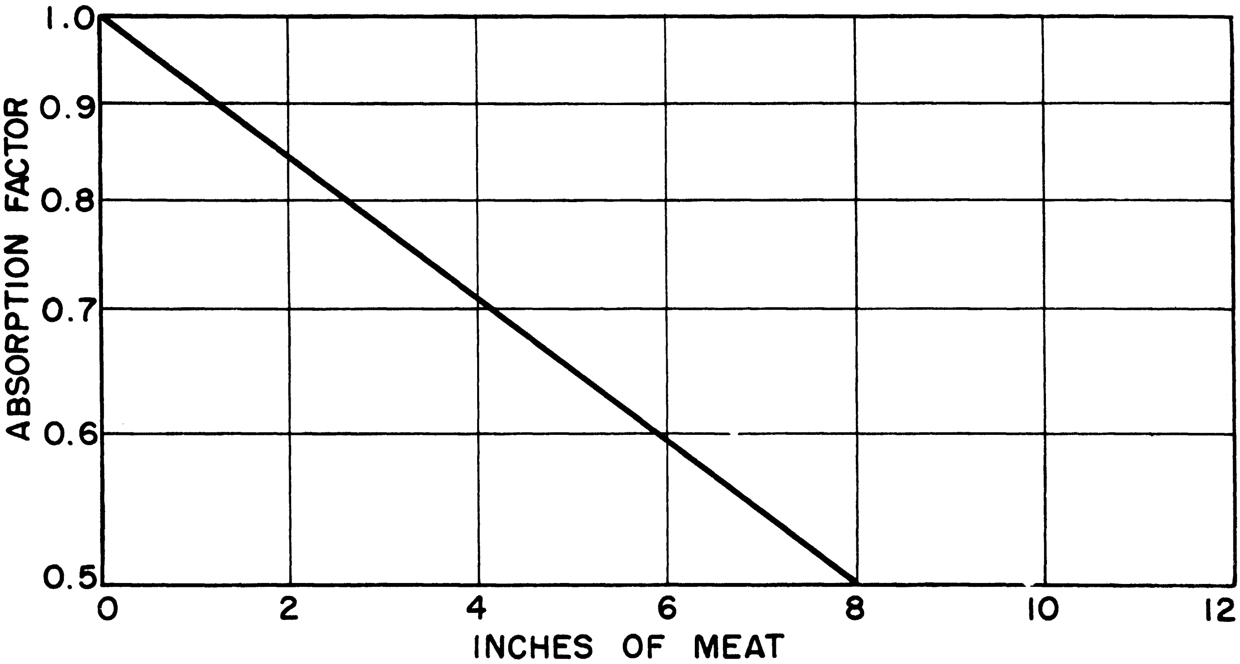

Fig. 9. Absorption of Gamma Radiation in Pork.

Reading from Fig. 9 for 4 in. of pork absorption, the radiation field will be reduced by 0.71. Therefore the center of the hog at 21 in. from the plaque will receive an average dose of

$$\text{Average Center Flux} = I = 19{,}000\ (0.71) = 13{,}500 \text{ rep/min.}$$

The surface of a hog 8 in. thick will be exposed to one traverse at 25 in. with 8 in. of absorption and one traverse at 17 in. with no absorption. For 17 in.,

$$I = 23{,}500 \text{ rep/min;}$$

for 25 in.,

$$I = 15{,}700\ (.5) = 7{,}850 \text{ rep/min.}$$

$$\text{Average surface flux} = \frac{23{,}500 + 7{,}850}{2} = 15{,}675 \text{ rep/min.}$$

For a spacing of 4 ft between hogs and a plant capacity of 2000 hogs/day:

$$\text{Conveyor Speed} = \frac{2000 \text{ hogs/day } (4 \text{ ft/hog})}{20 \text{ hrs/day } (60 \text{ min/hr})} = 6.67 \text{ ft/min.}$$

$$\text{Irradiation time} = \frac{14 \text{ ft}}{6.67 \text{ ft/min}} = 2.1 \text{ min.}$$

$$\text{Center Dose} = 2.1 \text{ min } (13{,}500 \text{ rep/min}) = 28{,}400 \text{ rep.}$$

$$\text{Surface Dose} = 2.1 \text{ min } (15{,}600 \text{ rep/min}) = 32{,}800 \text{ rep.}$$

2. Thermal Considerations

For a 0.4-in.-thick plaque of specific activity 10,000 curies/lb,

$$\sigma = \rho t S \,, \qquad (7)$$

where

σ = curies/ft^2,

ρ = typical density = 4.0 gm/cc or 250 lbs/ft^3,

t = plaque thickness = 0.4 in., and

S = specific activity.

$$\sigma = 250 \text{ lbs/ft}^3 \left(\frac{0.4}{12} \text{ ft}\right) (10{,}000 \text{ curies/lb}) = 83{,}200 \text{ curies/ft}^2.$$

To compute the energy absorbed per square foot of plaque:

$$\text{particles/sec-ft}^2 = 83{,}200\ (3.7 \times 10^{10})$$

$$= 3.08 \times 10^{15} \text{ particles/sec-ft}^2.$$

Ignoring the small energy absorption due to gamma photons, the average energy per disintegration will be derived from the absorption of beta particles and may be calculated as follows:

$$\frac{\text{Average Energy}}{\text{Disintegration}} = 0.4\ [0.05\ (1.2) - 0.95\ (0.51)]$$

$$= 0.218\ \text{mev/disintegration.}$$

(The beta particles emitted by decay of cesium-137 have a maximum energy of 1.2 mev 5 percent of the time and 0.51 mev 95 percent of the time. In this region, average energy is approximately equal to 0.4 of the maximum energy.)[5]

$$\frac{\text{Energy Absorbed}}{\text{ft}^2} =$$

$$\left(0.218\ \frac{\text{mev}}{\text{dis}}\right)\left(3.08 \times 10^{15}\ \frac{\text{dis}}{\text{ft}^2}\right)\left(1.6 \times 10^{6}\ \frac{\text{erg}}{\text{mev}}\right)\left(10^{-7}\ \frac{\text{joules}}{\text{erg}}\right)\left(360\ \frac{\text{sec}}{\text{hr}}\right)\left(\frac{1}{1054.8}\ \frac{\text{Btu}}{\text{joule}}\right)$$

$$= 3.66 \times 10^{2}\ \text{Btu/ft}^2 \ .$$

If all this energy is transferred by convection to the air

$$Q = hA\Delta T \ ; \qquad (8)$$

assuming

$h = 4.0$ Btu/hr-ft^2-°F, and

ΔT = temperature difference between air and plaque surface,

then

$$\Delta T = Q/hA$$

$$= (3.66 \times 10^2)\ (1/4) = 92.5°\text{F},$$

At a mean room temperature of 60°F the temperature of the surface of the plaque becomes

$$t_s = 60°\text{F} + 92.5°\text{F} = 132.5°\text{F} \ .$$

F. DESIGN OF RADIATION CHAMBER

Using a single plaque 6 ft long by 5 ft by 0.4 in., 2000 hogs can be irradiated each day by bringing the hogs on a conveyor past both sides of the plaque. The flux at 21 in. is calculated to be approximately 13,500 rep/min. Therefore, the necessary time for the pork to accumulate 30,000 rep will be 2.22 minutes in the radiation chamber. Using a radioactive plaque 6 ft by 5 ft, the pork should be conveyed at a speed of 6.67 ft/min. The amount of radioactivity required is calculated to be 1.5 megacuries. This amount of cesium activity would require 3 ft 4 in. of concrete shielding if placed above grade, as shown below.

1. Shielding Calculations for Concrete

At 8 ft from the plaque the dosage rate (without shielding) would be:

$$I = (340{,}000) \ln \left[1 + \left(\frac{37 \text{ in.}}{96 \text{ in.}} \right)^2 \right]$$

$$= 50{,}000 \text{ r/hr.}$$

The tenth-thickness of concrete for gamma radiation of 0.7 mev is 4.5 inches.[8] Nine tenth-thicknesses (40.5 in.) reduce this to 0.05 mr/hr, which is considered safe. To check this value: solve $I = I_0 e^{-\mu x}$, where $\mu = 0.2 \text{ cm}^{-1}$:[9]

$$0.05 = I = 50{,}000 \, e^{-\mu x} = 50{,}000 \, e^{-0.2(40)2.54}$$

$$0.05 = 50{,}000{,}000 \, e^{-\mu x}$$

$$10^{-9} = e^{-\mu x} .$$

Substituting for μ and taking the logarithms,

$$9(2.303) = (0.2 \text{ cm}^{-1}) \, (x \text{ cm})$$

$$x = 103.6 \text{ cm}, \quad \text{or } 41 \text{ in.}$$

2. Shielding Calculation for Water

The tenth-thickness of water for this radiation is 11 in.[8] In this case seven tenth-thicknesses (6 ft 5 in.) would reduce the dosage rate at 8 ft to 5 mr/hr, probably an acceptable level inside the cave. To be conservative, however, the design allows 6 ft 6 in. of water above the vertical source, whereas the calculated dose is on a normal to the plane.

A plan view of the radiation chamber is shown in Fig. 10. With the radiation chamber in this location the dimensions on the outside of the shielding are 28 ft 10 in. by 20 ft 6 in. Figure 11 shows a cutaway isometric view of the design shown in Fig. 10.

Alternative designs are feasible in which the radiation chamber is placed one story below grade or one story above grade. There are some advantages and disadvantages for each location. Placing the radiation chamber below grade would reduce the amount of concrete shielding required. However, this advantage is partially

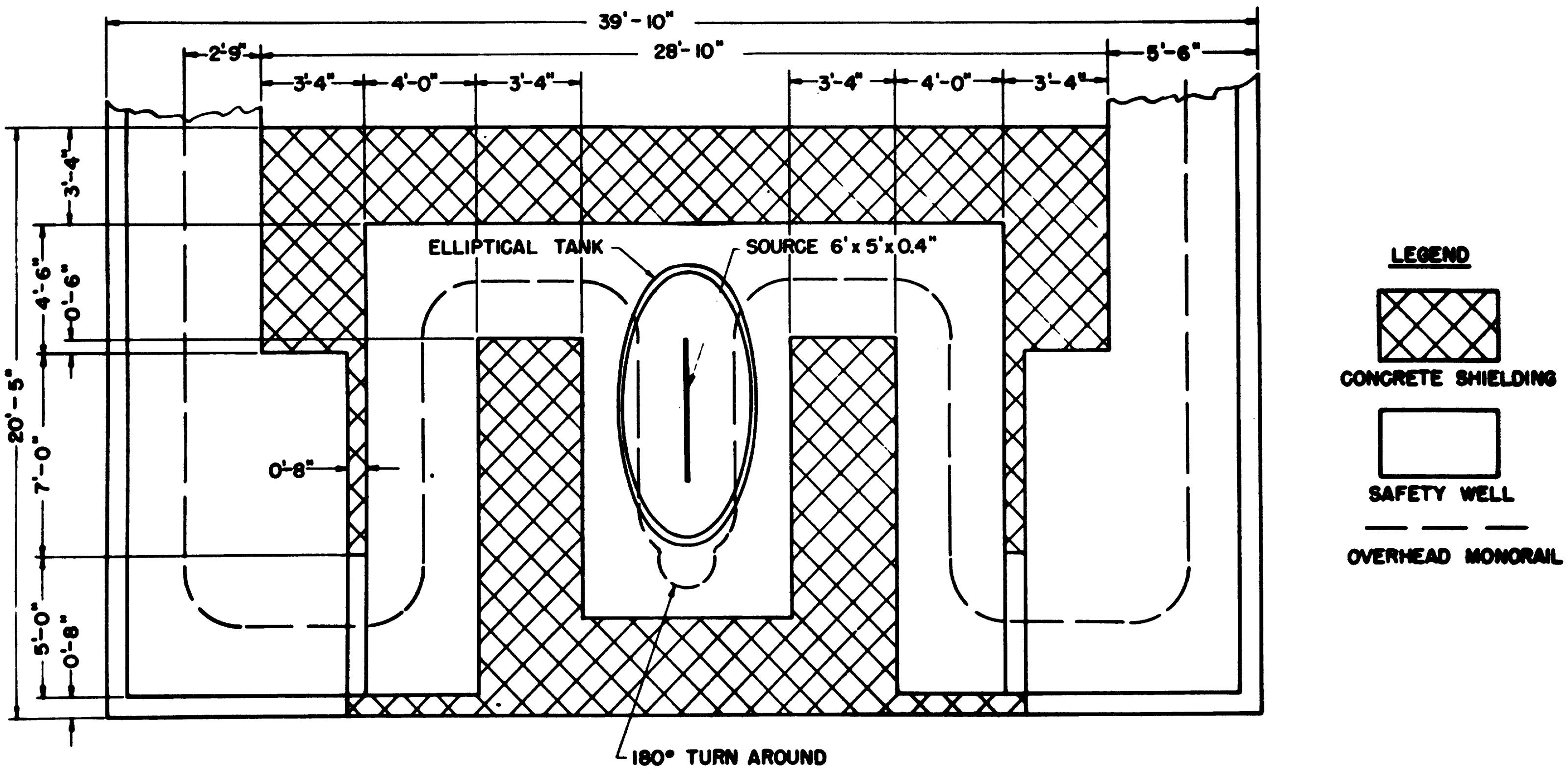

Fig. 10. Plan view of radiation chamber.

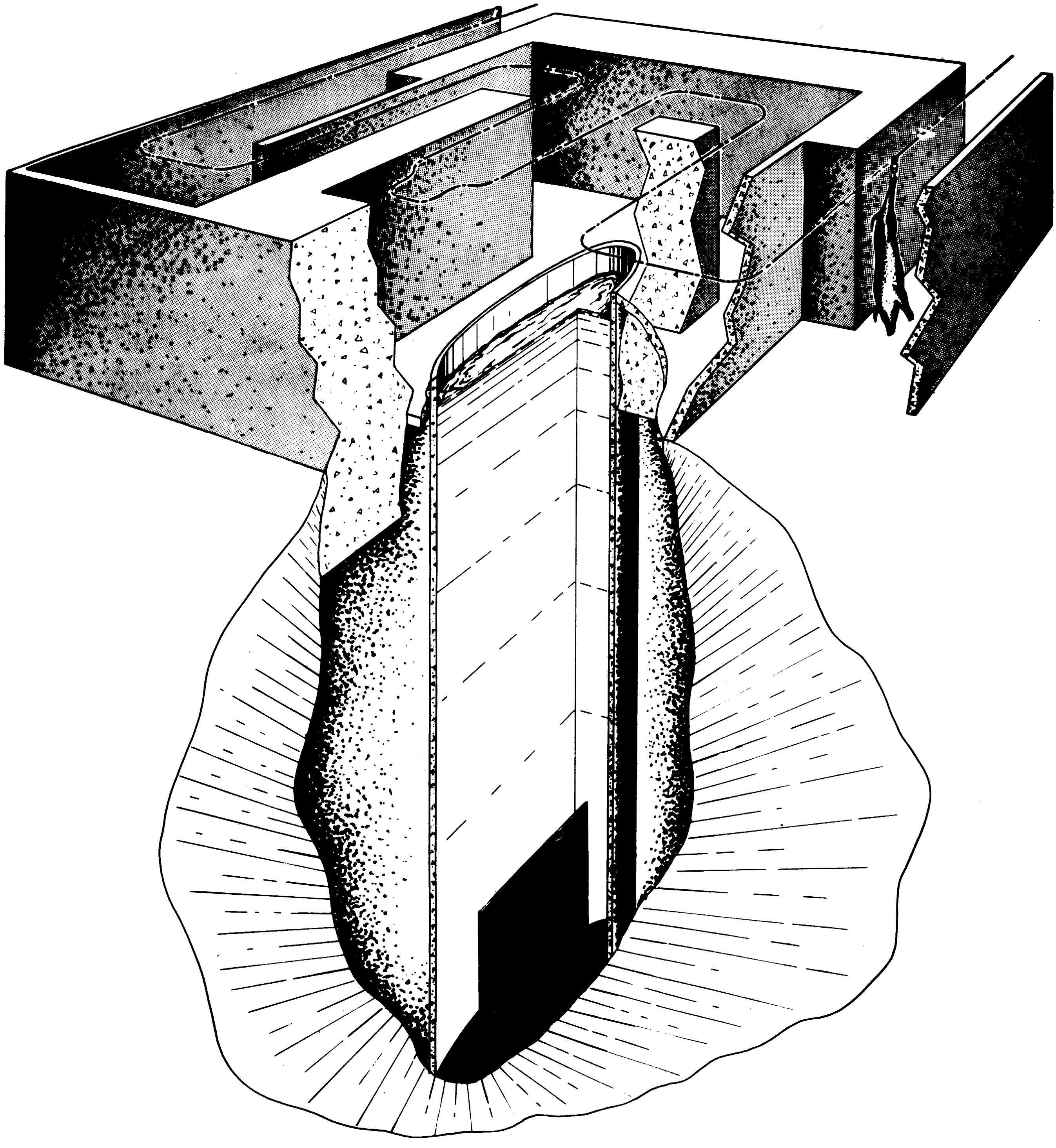

Fig. 11. Perspective view of radiation chamber.

offset by the additional cost of excavation and the requirement of steel reinforcing for retaining walls, waterproofing or installation of water sump pumps, etc. Placing the radiation chamber on either the first floor above grade or the first floor below grade has the disadvantage of performing the irradiation below the floor at which the pork is being handled and therefore requiring the use of a conveyor traveling up an incline or an elevator.

The design proposed is shown in Fig. 12, in which the radiation well and chamber are both placed above grade, with the radiation chamber at the level of the second floor so as to make it possible to irradiate the pork on the second floor.

G. ESTIMATION OF COST OF RADIATION CHAMBER

Although a radiation chamber is essentially a room with thick walls of concrete, the cost of the concrete is not a large part of the total cost. It is estimated that the concrete for shielding would cost in the range of $30 to $50 per cubic yard for poured concrete, including the cost of forms. The cost would be slightly higher if the structure is formed of solid concrete blocks, with mortar joints, because of the additional cost for masons' time.

It is estimated that a suitable radiation chamber of the type shown in Figs. 10 and 11 might be constructed for a total cost of $46,200, not including the cost of the radiation source itself or shipping and installation charges. Cost estimates are given in Table V.

To date there is not sufficient information to make a reliable estimate of the cost of packaged fission products. However, an estimate may be made of the magnitude of the cost of the fission products, using the 0.6-power scaling factor frequently used in estimating the costs of chemical plants.[7] Kilocurie gamma sources of cesium-137 processed from fission products can be supplied by the Radioisotopes Division of the Atomic Energy Commission, Oak Ridge, Tennessee, for $5000. The experience of the Fission Products Laboratory with a 1000-curie cobalt-60 source indicates that shipping (700 miles) and installation costs (not including the cost of the shipping container) would total about $1000. Therefore it is assumed that $6000 is a reasonable installed cost for 1000 curies of cesium-137. Using the 0.6-power factor for scaling up to a 1.5-megacurie source, the installed cost is estimated to be:

$$x = \$6,000 \left(\frac{1,500,000}{1,000} \right)^{0.6}$$

$$= \$483,000 .$$

Another approach to estimation of costs may be made on the basis of prices for cesium-137 therapy sources, which are now $100 for the first curie and $25 per curie for additional activity. Using the same scaling-factor approach

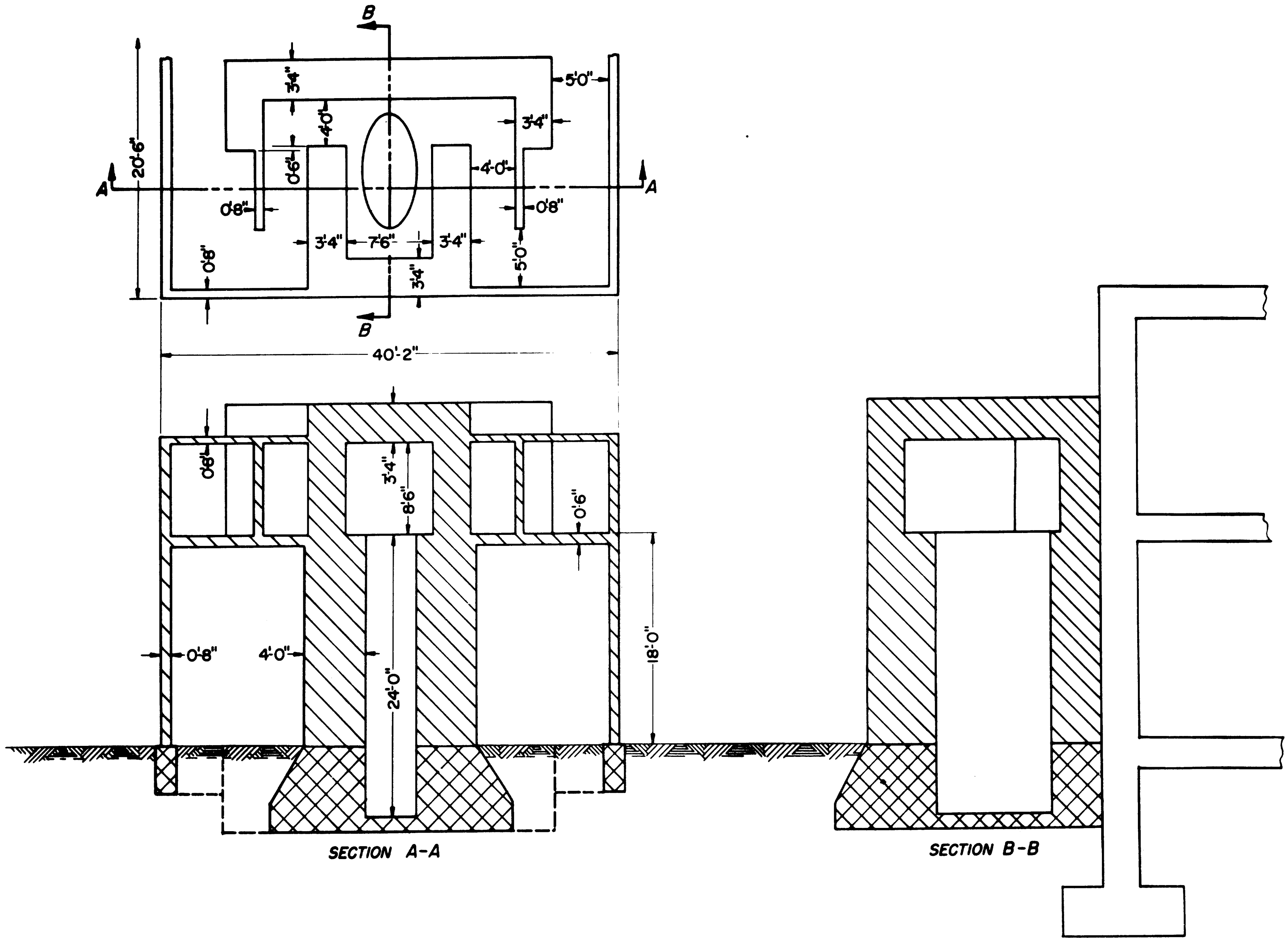

Fig. 12. Radiation chamber two floors above grade.

TABLE V

COST ESTIMATES FOR RADIATION CHAMBER FOR PORK

Excavation for footings and shoring	$ 600
Stainless-steel well (elliptical: 16 ga x 9 ft 0 in. x 4 ft 6 in. x 24 ft 0 in.)	2,500
Forms for concrete walls of radiation chamber (9,000 bd ft at $100.00/M)	900
Concrete for walls (320 yds at $20.00/yd)	6,400
Labor for forming and pouring walls	3,100
Forms and reinforcing for roof	150
Concrete for roof (50 yds at $20.00/yd)	1,000
Labor for forming and pouring roof	400
Concrete for floor (5 yds at $20.00/yd)	100
Reinforcing and labor for floor	100
Use of crane to raise concrete to second floor	600
Elevator mechanism	2,500
Ion exchange for well water	3,000
Monitoring equipment	4,000
Wiring	200
Water lines and labor for pipe fitting	800
Access doors (with safety interlock)	1,200
Ventilation system	2,000
Backgrading	200
Painting	250
Conveyor mechanism in radiation chamber	3,200
Conveyor mechanism to and from refrigerator room	3,200
Subtotal for labor and materials	$ 36,400
Miscellaneous contingencies (10% of subtotal)	3,600
Engineering costs (5% of labor and materials)	2,000
Contractor's fee (10% of costs)	4,200
Total	$ 46,200

for transition from small- to large-scale operations and using a base price of \$100 per curie, the cost of 1.5 megacuries would be \$507,600. On the same basis with a \$50 base cost per curie, the total cost would be \$253,800 and for the \$25 base cost, the total would be only \$126,900.

A third approach to price was made with the aid of experts* in the field of uranium processing. It is estimated that through the use of modern large-scale techniques cesium-137 can be separated in megacurie amounts for about \$0.30 per curie. The cost of a 1.5-megacurie source would then be \$450,000

Considering the range of values obtained from these varied approaches, it is felt that the value chosen, \$483,000, represents a reasonable estimate.

A shipping container for such sources might be supplied by the Atomic Energy Commission or an industrial handler of fission product sources. If not, a steel-reinforced lead container approximately 2 ft by 7 ft by 8 ft would cost \$25,000. This container would weigh about 50 tons and therefore could be shipped on a flat car. A much cheaper but more unwieldy container could be constructed of concrete.

The cost for a radiation chamber on the second floor, including the cost of a lead shipping container, is estimated to be:

Cost of radiation chamber	\$ 46,200
Shipping container	25,000
1.5-megacurie source, installed	483,000
	\$554,200

On a five-year basis, including 6% interest on the investment, the annual cost of such a plant would be

$$\frac{1.18}{5}(554{,}000) = \$130{,}500 \quad .$$

An estimate of \$30,000 per year is made for operation with two experienced health physicists and for maintenance, making the total annual cost:

$$\$130{,}500 + \$30{,}000 = \$160{,}500 \quad .$$

Based on the production figures for 1950, 68,504,000 head of hogs yielded 9.265 million pounds of pork; thus the average hog yields 135 pounds of pork, excluding lard. Basing the design on a rate of 2,000 hogs/day and operation 260 days/year, the plant production would be:

$$(2{,}000 \text{ hogs/day})(260 \text{ days/year})(135 \text{ lbs pork/hog}) = 70{,}200{,}000 \text{ lbs pork/year.}$$

*Private communication from Dr. Harold Ohlgren, formerly chief engineer of Chemical Processing Plant, Idaho Falls, Idaho.

The cost of operating the irradiation chamber to be added to the price of pork would thus be:

$$\frac{\$160,500/\text{year}}{70,200,000\ \text{lbs/year}} = \$0.0023/\text{lb} = 2.3\ \text{mills/lb}$$

or

$$(\$0.0023/\text{lb})(135\ \text{lbs/hog}) = \$0.31/\text{hog}\ .$$

Cesium-137 has a half-life of 33 years. Therefore, depreciation of the plant might readily be over a period of ten years rather than five years, which would approximately halve the computed costs. Even 2.3 mills/lb or $0.31/hog would be a small price to pay to aid in wiping out the problem of trichinosis.

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