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THE DESIGN OF A GAMMA IRRADIATION FACILITY FOR THE CONTROL OF INSECT INFESTATION IN FLOUR, MEAL, OR GRAIN

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DAMAGE TO CEREAL PRODUCTS BY INSECTS

Insect infestation results in a tremendous annual loss of stored flour, grain, and cereal products. The granary weevil, Sitophilus granarius (L), is probably the most damaging insect to grain, and the flour beetle, Tribolium confusum, the most damaging to flour and prepared cereal products.

The bean weevil, Acanthoscelides obtectus; the rice weevil, Sitophilus oryzae; and the lesser grain borer, Rhyzopertha dominica, as well as many other insects listed in Table 1[1], also contribute to the loss (estimated at $300,000,000 annually in the U.S.A.[2] of flour, grains, and cereal products as a result of insect infestation.

The confused flour beetle is the insect most frequently found in flour after it leaves the mill. Figure 1 shows the appearance of the beetle on an enlarged scale. The adult beetle normally has a length of about 1/7 of an inch.[1] Usually both the insects and the eggs can be screened out of the flour but the eggs are more difficult to remove. Under favorable conditions these eggs may develop into adult beetles in 30 days. The female beetle may live for a year or more during which period 400 to 500 eggs may be produced. However, the short period required from egg to adult may result in the production of many generations of insects and complete infestation of stored flour.

Figure 2 is a photograph of eggs of the confused flour beetle, and some other flour and grain insects resting on a piece of 10XX silk bolting cloth: (a) broad-horned flour beetle, (b) cadelle, (c) Mediterranean flour moth, and (d) confused flour beetle. The average layman seldom sees these eggs because of their small size (some as small as 1/150 of an inch). The eggs are white in color and are coated with an adhesive substance which causes particles of flour to stick to them.

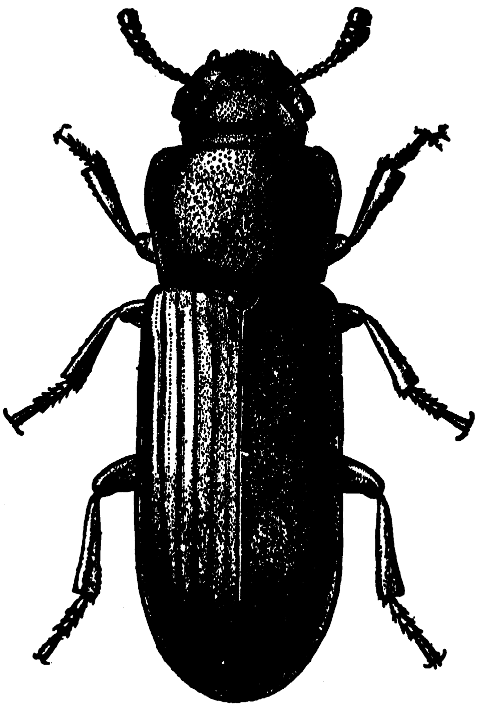

Fig. 1. The confused flour beetle, about one-seventh of an inch long.

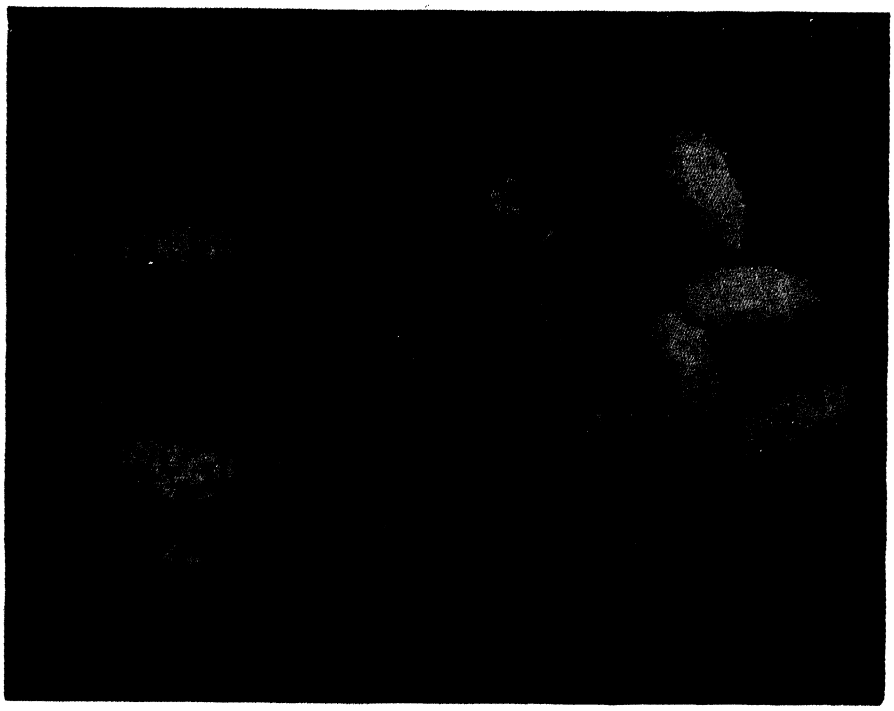

Fig. 2. Eggs of flour and grain insects shown resting on a piece of 10XX bolting cloth; a, Broad-horned flour beetle; b, cadelle; c, Mediterranean flour moth; d, confused flour beetle. Greatly enlarged.

EFFECT OF IONIZING RADIATION ON INSECTS

Ionizing radiation might be used to treat grains and cereal products such as flour to control insect infestation. Hassett and Jenkins[3] reported the effects of gamma radiation from cobalt-60 on eight species of insects including the flour beetle. Most of these tests were made with doses sufficient to destroy the adult insects. However, the general conclusions were made for six species, including the flour beetle, that a dose of 64,400 rep was lethal to adult insects and that doses of 16,000 to 32,000 rep inhibited reproduction.

TABLE 1

SOME INSECT PESTS THAT INFEST FLOUR, GRAIN, AND CEREAL PRODUCTS

- Grain weevils
  - Granary weevil
  - Rice or black weevil
  - Broad-nosed grain weevil
  - Coffee bean weevil
- Grain borers
  - Lesser grain borer
  - Larger grain borer
- Grain moths
  - Angoumois grain moth
  - European grain moth
  - Pink cornworm
  - Rice moth
- Flour moths
  - Indian-meal moth
  - Mediterranean flour moth
  - Meal moth
- Grain and flour beetles
  - Cadelle
  - Saw-toothed grain beetle
  - Square-necked grain beetle
  - Foreign grain beetle
  - Mexican grain beetle
  - Siamese grain beetle
- Grain and flour beetles (continued)
  - Flat grain beetle
  - Rusty grain beetle
  - Confused flour beetle
  - Red flour beetle
  - Black flour beetle
  - Long-headed flour beetle
  - Broad-horned flour beetle
  - Slender-horned flour beetle
  - Small-eyed flour beetle
  - Depressed flour beetle
  - Larger black flour beetle
- Eggs of flour and grain insects
- Mealworms
  - Yellow mealworm
  - Dark mealworm
  - Lesser mealworm
  - Black fungus beetle
  - Red-horned grain beetle
- Dermestid beetles
  - Black carpet beetle
  - Larger cabinet beetle
  - Varied carpet beetle

TABLE 1, Continued

- Spider beetles
    - Hairy spider beetle
    - White-marked spider beetle
    - Brown spider beetle
    - Other spider beetles
- Miscellaneous beetles
    - Two-banded fungus beetle
    - Hairy fungus beetle
    - Corn sap beetle
- Miscellaneous beetles, continued
    - Cigarette beetle
    - Drug-store beetle
    - Catorama beetle
- Others
    - Booklice, or psocids
    - Silverfish
    - Cockroaches
    - Flour or grain mites

An extensive series of tests was reported by Baker, Taboada, and Wiant[4,5] in "The Lethal Effect of Electrons on Insects Which Infest Wheat, Flour, and Beans." As a result of these studies the following conclusions, among others, were stated:

1. "An electron dose of 10,000 rep will sterilize flour beetle and granary weevil eggs, and this same dose will prevent the adults from reproducing.

2. "A dose of 5.0×10^5 rep was lethal to 100 percent of adult flour beetles immediately after treatment. A dose of 2.5×10^5 rep was lethal to 92 percent of adult flour beetles one week after treatment."

Goldblith[6] made the observation that a given ionizing radiation dosage produces similar biological effects whether from electrons or from gamma radiation. Based on this and the data on the effects of radiation on insects, it is concluded that a gamma radiation dose of 10,000 rep might be sufficient for control of insect infestation of screened flour. However, to provide some margin of assurance of egg and insect sterility a design dose of 25,000 rep is recommended.

THE EFFECT OF GAMMA RADIATION ON THE BAKING QUALITY OF SOME WHEAT FLOURS

The effect of gamma radiation on the baking quality of some wheat flours was investigated to explore the feasibility of gamma irradiation of stored wheat and wheat flour for the control of insect infestation.[7] Bread, cake, and all-purpose flours were each given a range of doses of gamma radiation and bread, biscuits, and cakes were prepared from the irradiated flours. Taste-panel tests were made using the incomplete block ranking procedure.

Bread loaves made with 20,000-rep bread flour were equal to those made with the nonirradiated flour in all respects except in total volume, in which the 20,000-rep loaves were slightly smaller. Bread flour given a dose higher than 50,000 rep was considered to be undesirably altered by gamma radiation. Cakes made with irradiated bread flour were progressively of poorer quality with increasing doses of gamma radiation.

When making biscuits with irradiated flour receiving 20,000 to 150,000 rep, it was necessary to add more fluid to obtain a workable dough. This dryness of irradiated flour was also noticed when mixing cakes. Biscuits made with irradiated flour had a satisfactory appearance but the eating qualities and flavor of those given higher radiation dosages were not equal to those of the controls.

In summarizing these tests it may be stated that cake flour, all-purpose flour, and bread flour were considered to be unchanged when given a dose of 25,000 rep gamma radiation. Cakes made with these different flours were similar to the controls in all respects.

TYPE OF GAMMA RADIATION FACILITY

Several types of radiation facilities have been considered by the personnel of this laboratory for the irradiation of other materials such as hog carcasses,[8,9] bulk potatoes,[7,10] and prepackaged fresh meat.[11,12] In these previous designs the initial investment for the irradiation facility was a major item in the consideration of economic feasibility. In the design presented here, an attempt was made to minimize capital investment by use of a number of economies such as locating the radiation facility in the corner of the basement floor of an existing building as shown in Figs. 3, 4, 5, and 6. Existing walls and exterior earth are used for part of the shielding as a further economy. A large part of the concrete used for shielding inside the building consists of commercial 4- x 8- x 16-inch concrete building slabs stacked without mortar. Such construction has been successfully used for shielding in the ceiling of the "cave" in the Fission Products Laboratory.[8,13] These slabs can be laid very rapidly and are held in place by steel angles. Vertical joints are staggered, but staggering is not necessary on horizontal joints because the weight of the slabs results in a joint sufficiently tight for good shielding. These blocks have a high salvage value if and when the facility is modified or dismantled.

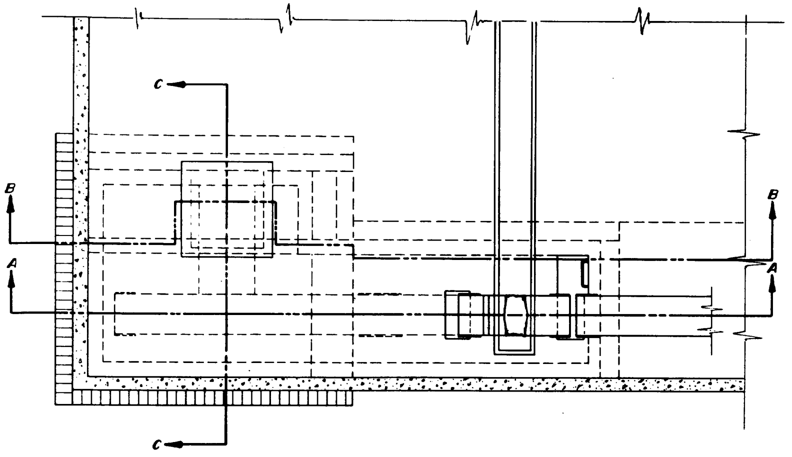

Fig. 3. The plan

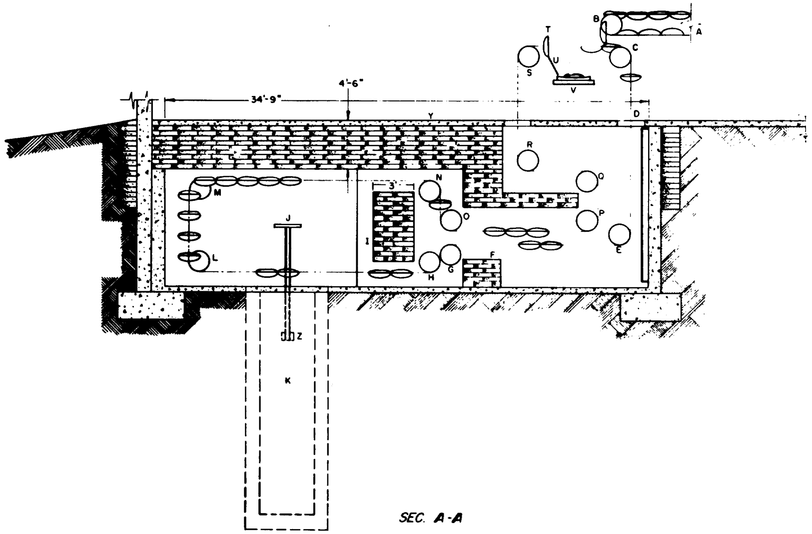

Fig. 4. Elevation

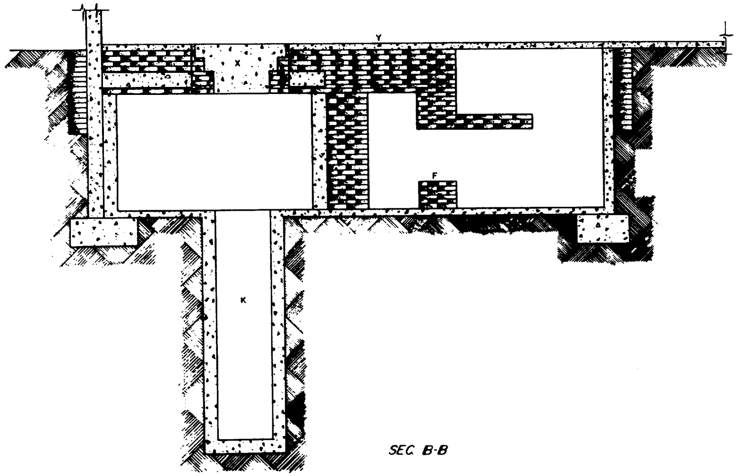

Fig. 5. Elevation

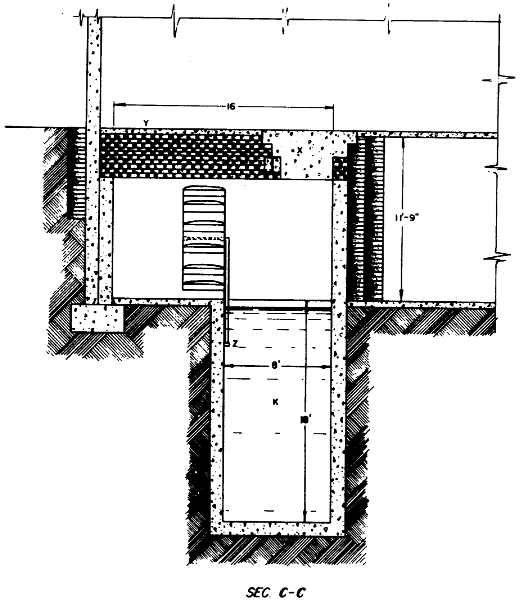

Fig. 6. End view

FLOUR IRRADIATION FACILITY

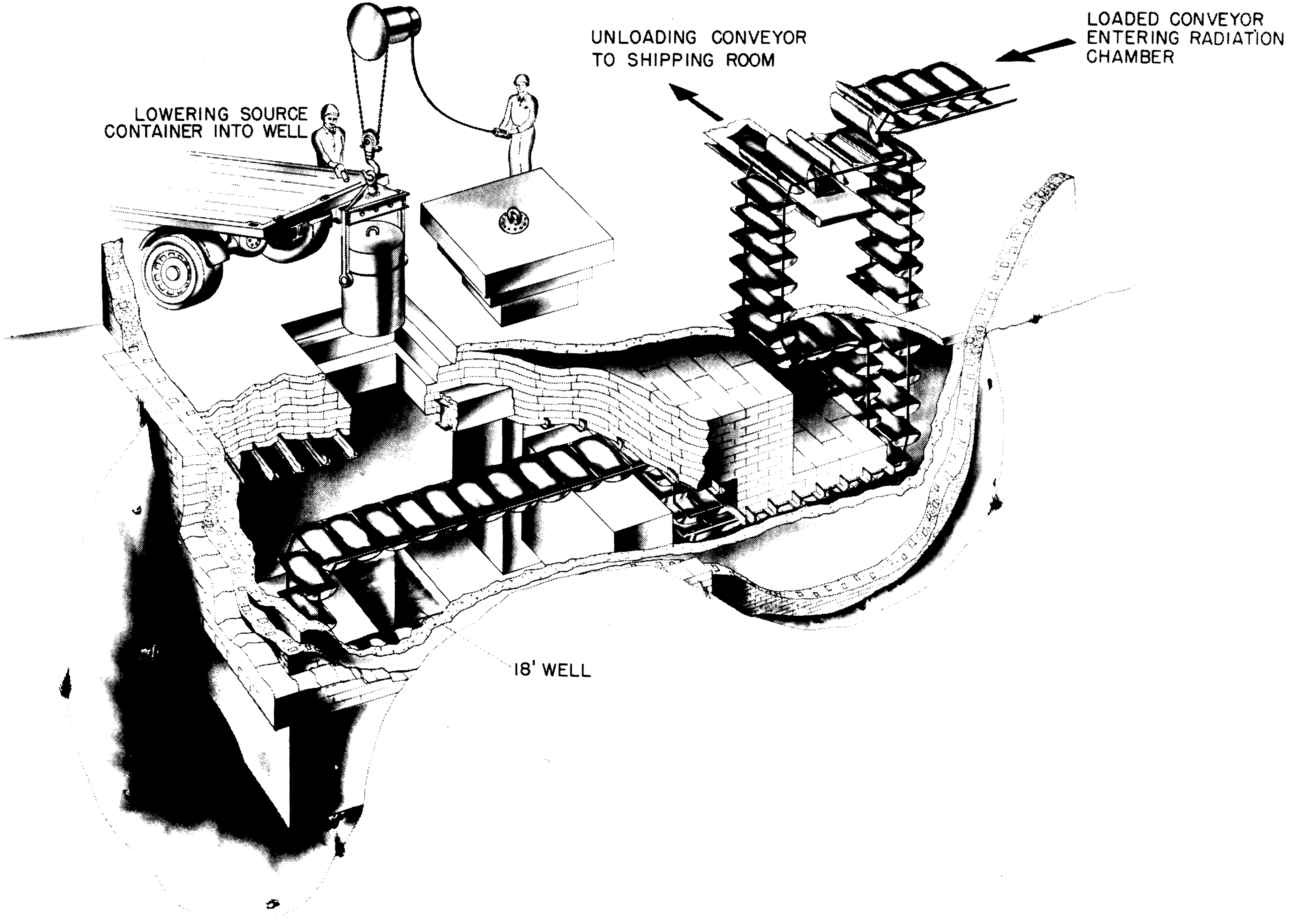

Fig. 7. Perspective view of flour irradiation facility.

A labyrinthine entrance has been used very successfully for the experimental "cave" in the Fission Products Laboratory and has been specified in preliminary designs for the irradiation of pork,[8,9] potatoes,[9,10] and packaged meats.[11,12] However, in the present design further economy is obtained by the use of a concrete stepped plug in the roof. This opening is used as the point of ingress and egress both for personnel and for the shipping container used for the fuel elements. This facility represents the simplest and cheapest design that has yet been conceived by the authors for the commercial gamma irradiation of a food item on a continuous basis.

USE OF COOLING REACTOR-FUEL ELEMENTS AS A SOURCE OF RADIATION

A current practice employed in chemical processing plants for the treatment of spent reactor-fuel elements is the storage of the fuel elements under water for several weeks before processing. During this time the intense radiation of the fuel elements is dissipated in the water used as a shield and usually is wasted except when used in experimental investigations. The costs of this storage period could be partially defrayed by using the cooling reactor-fuel elements as sources of radiation in commercial irradiation facilities.

Cooling reactor-fuel elements have a very high gamma activity but decay rapidly. To maintain the production of such a facility at an economic level of operation the reactor-fuel elements would be replaced approximately every two months. During the two-month operational period adjustments would be made in the speed of the conveyor to compensate for the radioactive decay.

Two reactor-fuel elements were chosen as the radiation source, since a single reactor-fuel element would not provide a sufficiently uniform radiation field. It is possible to provide a uniform dose to bags of flour, meal, or grain by proper spacing of the fuel elements from each other and the axis of the conveyor, and by limiting the length and width of the conveyor buckets.

DESIGN OF CHAMBER

Figures 3, 4, 5, 6, and 7 show the plan, two elevations, end view, and perspective view, respectively for a flour irradiation facility which might be located in the existing basement of a large flour mill. The radiation facility would become an integral part of the overall manufacturing operation and would be so situated that the flour, after bagging, could be easily conveyed to the entrance of the chamber and introduced into a bucket conveyor which would transport it through the radiation facility. After leaving the radiation facility, the bags of flour would be carried by a belt conveyor to a shipping or storage area.

Referring to Figs. 3, 4, 5, and 6, the flour would be brought from the previous packaging operation by conveyor A around sprocket B and transfer loaded at C to the chamber bucket conveyor. The conveyor functions then as an elevator as it lowers the buckets through an opening in the floor D to the access passageway of the chamber. After a 90-degree bend around sprocket E, the conveyor progresses to the first barrier wall F. The conveyor makes two 90-degree bends around sprockets G and H and then travels into the chamber past the second barrier wall I. The conveyor then makes a first pass through the chamber under the radiation source J. The conveyor becomes an elevator again as it makes a 90-degree bend around sprocket L. After traveling around sprocket M, the conveyor travels again past the radiation source J and barrier wall I. The bucket conveyor makes two 90-degree bends around sprockets N and O, and subsequently travels around sprockets P, Q, R, and S. The buckets are dumped at T and the sacks of flour or grain slide down ramp U to belt conveyor V which removes them to a shipping or storage area.

The reactor-fuel elements used as the radiation source would be shipped in a lead cylindrical container, 3'6" in diameter, which would be moved by a dolly to a position over the radiation chamber. Access to the chamber would be obtained by removal of concrete plug X from the roof Y by an overhead crane. The source holder would then be lowered into the radiation chamber and on down into well K where the fresh fuel elements would be removed under water. The older fuel elements would be loaded into the shipping container which would then be removed and the fresh fuel elements would be inserted into the source holder shown in the end view. The source holder is attached to a stainless-steel channel which pivots about bushing Z located under the surface of the water. The entire transfer operation could be completed in less than 1/2 day and would be performed under the supervision of an experienced health physicist who might accompany the shipment.

Access to the chamber for maintenance is made possible by lowering the source into the well. The water for the well would be obtained from the plant's normal water supply. However, additional precautions would have to be taken with the well water to prevent corrosion of the jacketing material for the cooling fuel elements. This necessitates circulating the water through a demineralizing system.

RADIATION DOSE

The activity of the fuel elements is such that a sufficient dose may be acquired by using only two fuel elements as a radiation source. The use of only one fuel element is not preferred because of the difficulties experienced in delivering a uniform dose to the flour. Proper spacing of the two fuel elements results in a zone of nearly uniform radiation in one direction. If the conveyer moves in a path perpendicular to the direction of uniform radiation, each section of the flour bags which are aligned across the conveyor will receive approximately the same dose.

The gamma flux from cooling fuel elements varies with time and with the original activity. Based on calculations for fuel elements, it is estimated that a typical cooling element might have an average radiation flux of 1×10^6 r per hour at a radius of 3 feet from the midpoint of the element. (Note: This flux is 10 times that used in a previous design[8,9] as a result of a revised estimate.) Using this estimated flux, Fig. 7 was prepared. This figure shows the radiation field along a plane perpendicular to the center line of two fuel elements spaced 3'0" from the center line of the horizontal pass. Approximate uniformity of the radiation field at 27 inches from the axis of the source in the lateral direction is shown by the nearly flat curves in Fig. 8. This insures uniform dose to the flour independent of lateral position. Isodose curves were plotted for the plane perpendicular to this direction. Figure 9 shows such isodose curves plotted for this plane which is parallel to the axis of the fuel element and equidistant from both elements.

Absorption measurements performed in the radiation "cave" at the Fission Products Laboratory on wheat flour and bulk potatoes are plotted in Fig. 10. The dose rate in a selected position was measured with increasing thicknesses of flour between the source and a Victoreen rate meter. These data indicate that the half-value thickness for flour is approximately 10 inches for cobalt-60 gamma radiation. Correcting this value for the average energy assumed for the fuel-element source reduces the half-value thickness to approximately 8 inches. The flour closest to the source in one pass of the conveyor receives a higher radiation dose than the flour farther away. This is compensated for by the lower dose received in the second pass since the top of the flour sack would be more distant from the source. The sum of these two doses will be slightly greater than the dose received at the center of the bucket, but with the conveyor at an optimum location with respect to the source this difference will be small.

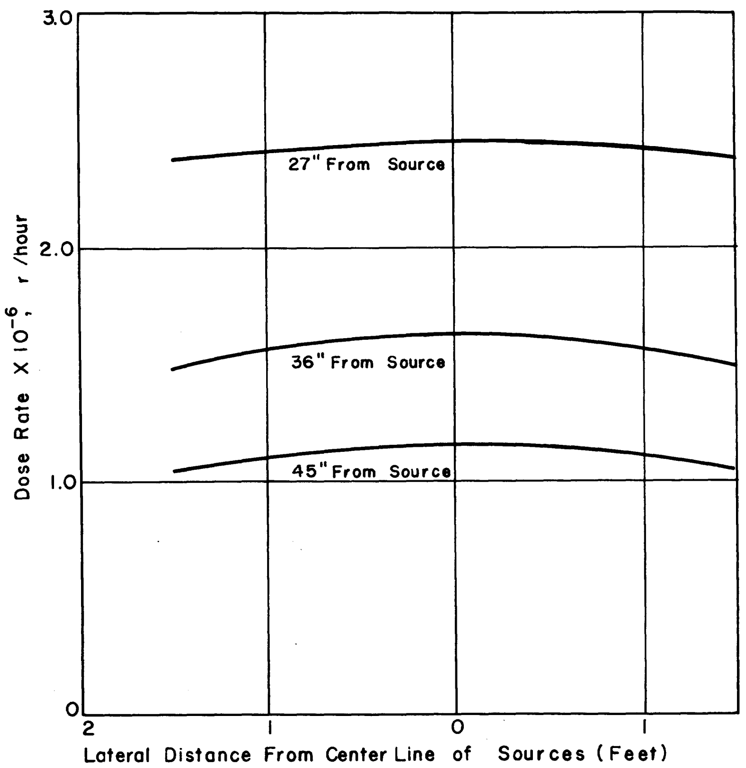

Fig. 8. Radiation field in a plane perpendicular to the center lines of two parallel fuel elements spaced 3 feet apart.

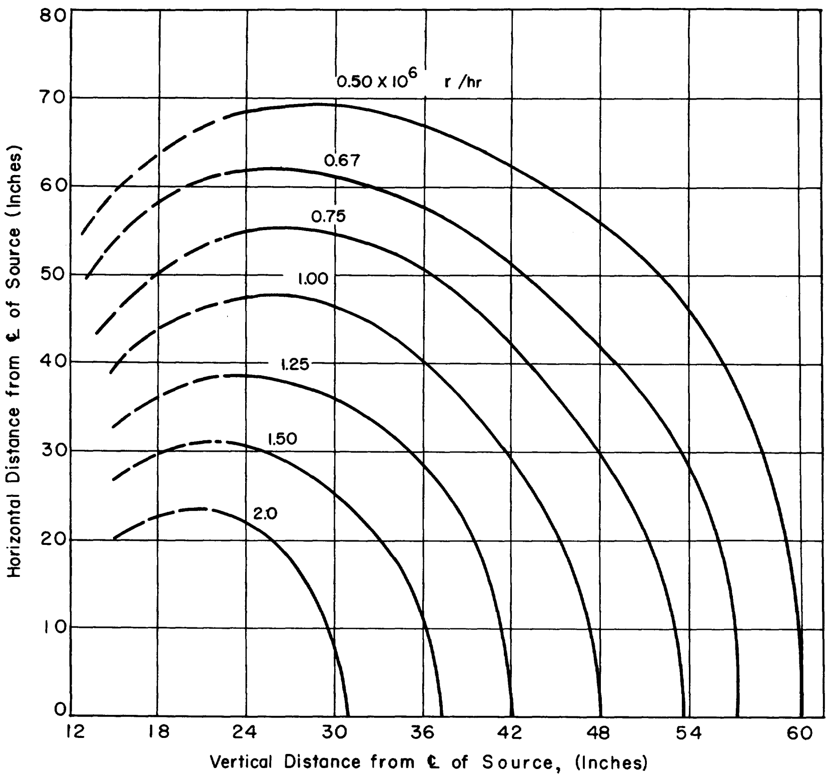

Fig. 9. Isodose curves (r/hr) in a vertical plane equidistant from two parallel vertical fuel elements spaced 3 feet apart.

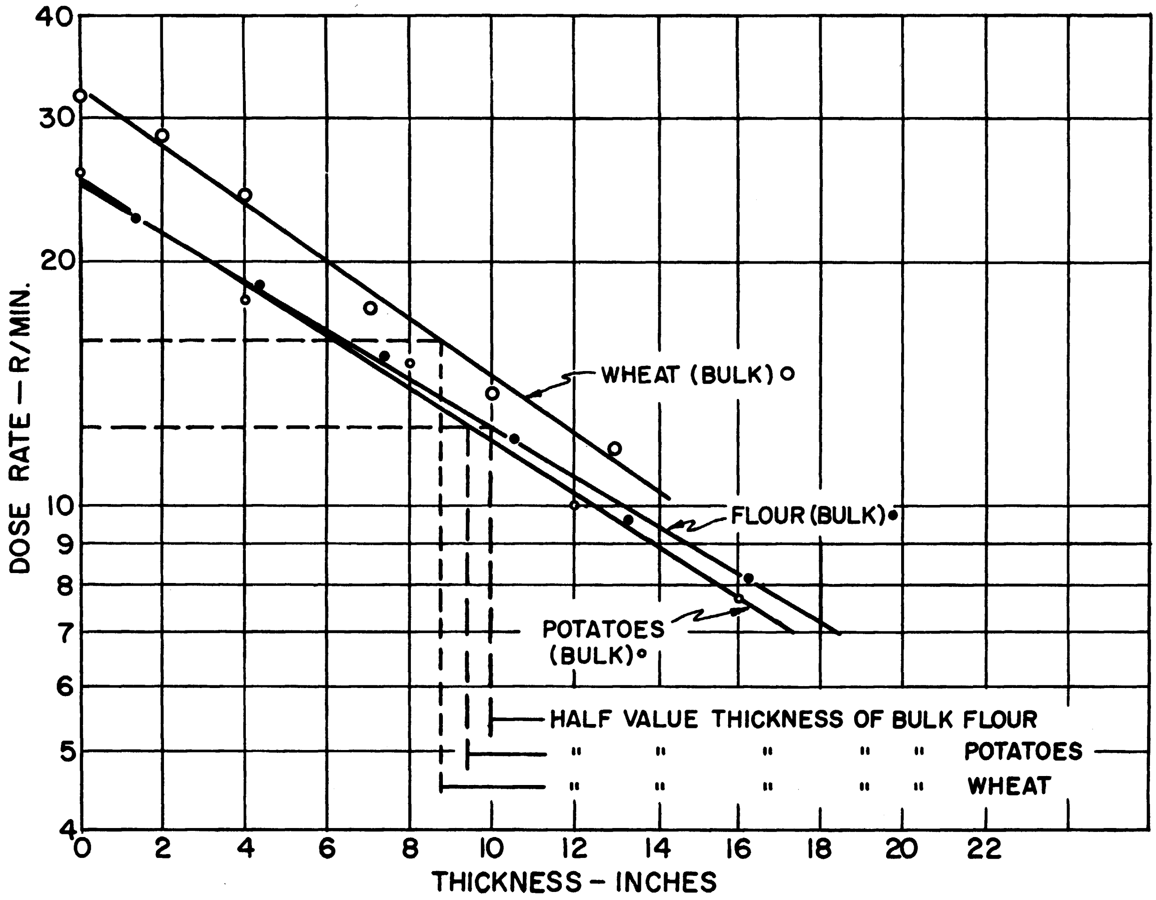

Fig. 10. Absorption measurements performed in the radiation "cave" at the Fission Products Laboratory.

TYPICAL SHIELDING CALCULATION

The point of nearest approach to the source for employees of the flour plant is at A, directly above the source (see Fig. 4). A point at the floor level is 8 feet from the source and is shielded by 3'10" of concrete. By extrapolation from the data of Fig. 9, the dosage rate at this point is found to be approximately 200,000 r/hr.

The dosage rate at point A with shielding is

$$R = BR_o e^{-\mu_o x}$$

where

R = dosage rate at point A in mr/hr with 4'2" of concrete shielding
R_o = dosage rate at point A in mr/hr with no shielding
B = dose buildup factor in concrete
μ_o = main-beam absorption coefficient of the radiation in concrete
x = thickness of concrete.

B and μ_o are evaluated from the data of Goldstein[14] and Kineman,[15] assuming an effective energy of 0.7 mev for the radiation from the fuel rods.

B = 115 for 46 inches of concrete and 0.7 mev
μ_o = 0.117 cm^{-1} for concrete at 0.7 mev.

Then

$$\begin{aligned} R &= 130\ (200 \times 10^6)\ e^{-.177(2.54)50} \\ &= 4.42 \text{ mr/hr.} \end{aligned}$$

This is considered to be an acceptable figure for the dosage rate at point A, since only plant operating personnel will have access to this area. The total body dosage accumulated by an individual working in this general area would be at a much lower rate than at point A because of the additional distance from the source at other points. There is a rapid decrease in expected dosage rate in all lateral directions from point A, due both to distance and to increased effective shield thickness.

The point of nearest approach to the source for persons outside the plant is at B, obliquely above the source, in the direction farthest from the conveyor entrance. A point at the ground level is 16 feet from the source and is shielded by 4'9" of concrete. B and R_o evaluated as for point A are then: $B = 160$; $R_o = 50 \times 10^6$ mr/hr.

Then

$$R = 160\ (5 \times 10^6)\ e^{-.117(2.54)57}$$

$$\cong 0.1 \text{ mr/hr}$$

which is considered to be an acceptable radiation level.

CAPACITY CALCULATIONS

Figure 11 is a plot of the dose rate at the center of the loaded bucket as a function of the distance traveled in the radiation facility. For a specific conveyor speed, this plot may be considered as a plot of dose rate as a function of time. The area under the curve of Fig. 11 represents one half of the total dose acquired by the flour in the center position as it travels through the chamber and this area was determined by graphical integration to be 1.05×10^7 rep-ft/hr. The total value of the integral for the entire traverse is twice this amount or 2.1×10^7 rep-ft/hr. Dividing this value into the dose required and multiplying by the feet of travel yield the time required for the center of the flour package to receive the specified dose,

$$\frac{25{,}000 \text{ rep}}{2.1 \times 10^7 \text{ rep-ft/hr}} \times 34 = 0.0405 \text{ hour.}$$

The decay characteristics of the radiation source require a variable speed drive to be installed on the conveyor mechanism to permit changing the conveyor speed as the radiation flux decreases with time.

The conveyor buckets have a semicircular shape with a 9-inch radius and a bucket length between chains of 3'0". The chain will have an 18-inch pitch, and each bucket will hold a 100-pound bag of flour.

The conveyor speed is determined by dividing the length of travel by the cycle time:

$$\frac{34 \text{ ft}}{\text{cycle}} \times \frac{1 \text{ cycle}}{0.0405 \text{ hr}} \times \frac{\text{hr}}{60 \text{ min}} = \frac{14 \text{ ft}}{\text{min}}.$$

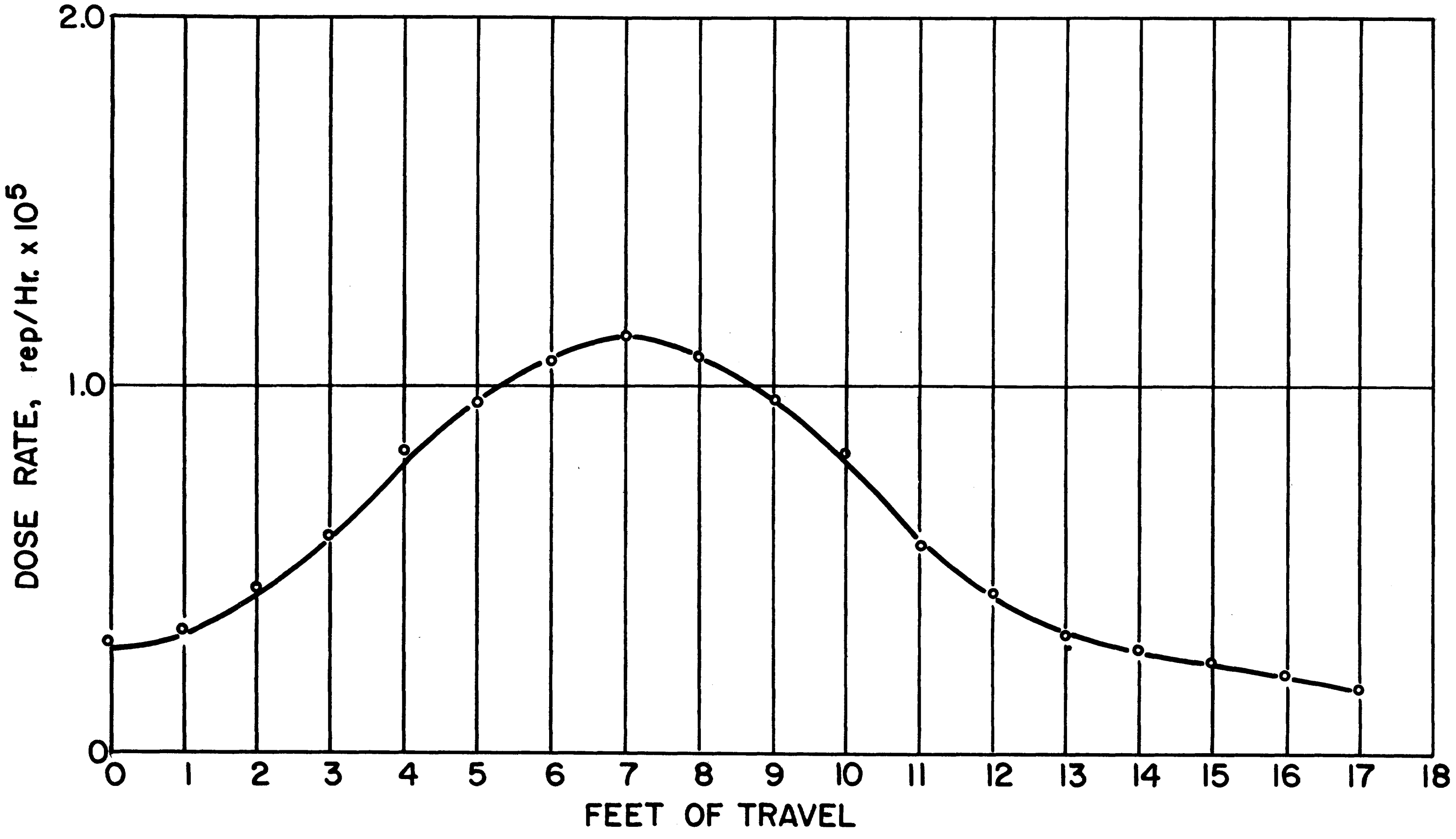

Fig. 11. Dose rate to which flour is exposed as a function of distance along path in radiation chamber for one half of chamber.

The capacity of the chamber can be calculated by multiplying the number of buckets per cycle times the capacity per bucket and dividing by the cycle time:

$$\frac{22\ \text{buckets}}{\text{cycle}} \times \frac{100\ \text{lb of flour}}{\text{bucket}} \times \frac{1\ \text{cycle}}{0.0405\ \text{hr}} \times \frac{1\ \text{ton}}{2000\ \text{lb}} = \frac{27.2\ \text{tons}}{\text{hr}} .$$

Operating on an 8-hour day for a 5-day week the yearly capacity would be:

$$\frac{27.2\ \text{tons}}{\text{hr}} \times \frac{8\ \text{hr}}{\text{day}} \times \frac{260\ \text{days}}{\text{yr}} = 5.66\ (10)^4\ \frac{\text{tons}}{\text{yr}} .$$

COST ESTIMATES

Table II itemizes the cost estimated for the construction of the radiation facility, not including the cost of the conveyors bringing the flour bags to and from the radiation chamber nor the cost of the radiation source. It is assumed that the radiation source would be rented, which would make the cost of the irradiation facility and conveyor the total investment.

DISCUSSION

Using two cooling reactor-fuel elements to provide a radiation dose of 25,000 rep, and based on operation for 260 days per year and plant amortization over a 10-year period, the cost for the irradiation of flour is estimated to be \$0.0373 per 100-pound sack. Fuel elements were chosen as a radiation source in lieu of the mixed fission products or separated radioisotopes, because of the availability of such fuel elements. The plant was designed to operate for one 8-hour shift per day. If two or three shifts were used, the cost of irradiation could be decreased. Using three shifts per day, it was estimated that the cost for irradiation could be reduced to less than \$0.02 per 100-pound sack. Another method of reducing costs would be to increase the capacity by increasing the radiation flux. Thus, four, six, or eight fuel elements might be used rather than two. The limit to increasing the radiation flux would be determined primarily by the handling capacity of the flour mill.

TABLE II

ESTIMATED COST OF FLOUR IRRADIATION FACILITY USING COOLING FUEL ELEMENTS

Alterations to existing building including excavation and shoring for facing and well	$ 3,000	
Concrete for 4' x 8' x 18' well (20 yd at $20/yd)	400	
Reinforcing for well (1000 lb at $0.10/lb)	100	
Forms for well (1000 bd ft at $100/M)	100	
Labor for forming and pouring well	800	
Asphalt lining for well	150	
Concrete for walls and footings (54 yd at $20/yd)	1,080	
Forms for wall (2000 bd ft at $100/M)	200	
Labor for forming and pouring wall	2,100	
Concrete for floor (10 yd at $20/yd)	200	
Reinforcing for floor (500 lb at $0.10/lb)	50	
Labor for pouring floor	400	
Concrete blocks for shielding (4" x 8" x 16") (3500 at $0.20/block)	700	
Labor for placing loose blocks ($0.06/block)	210	
Support beams (5200 lb at $0.10/lb)	520	
Concrete for plug (4 yd at $20/yd)	80	
Forms for plug (100 sq ft at $100/M)	10	
Labor for forming and pouring concrete for plug	160	
Ten-ton trolley with 15" beam for lifting plug and shipping container	2,000	
Lift mechanism for source	1,500	
Ion exchange system for well water	3,000	
Monitoring equipment	2,500	
Bucket conveyor	6,000	
Bucket conveyor drive	1,500	
Maintenance tools and supplies	200	
Heating and ventilating	1,200	
Wiring	200	
Water lines and labor for pipe fitting	800	
Painting	600	
Subtotal for labor and materials		$29,760
Miscellaneous contingencies (10% of subtotal)		2,976
Engineering costs (7% of labor and materials)		2,100
Contractors fee (10% of costs)		3,484
Grand Total		$38,320

TABLE III

ESTIMATED ANNUAL OPERATIONAL COSTS

Wages and Salaries		
One operator with limited health-physics training	$ 5,000	
Supervision and clerical labor (10% of operational labor)	500	
Salaries and wages not associated with the operation of the radiation chamber (50% of direct labor and supervising costs)	2,750	
		$ 8,250
Other Operation Costs		
Shipping costs for fuel elements 6 x 200 (every 2 months)	1,200	
Handling costs for fuel elements during transfer and installation (6 at $500)	3,000	
Rental of two fuel elements (assumed $500/month)	6,000	
Repairs and maintenance on chamber and conveyor (5% of chamber and conveyor costs)	1,925	
Miscellaneous contingencies	1,000	
		13,125
Overhead		
Payroll overhead (15% of cost of labor and supervision)	1,250	
General plant overhead (50% of cost of labor and supervision)	10,700	
General administration overhead (10% of cost of labor and operation)	2,150	
		14,100
Taxes, Interest, Insurance		
Property tax (2% of cost of radiation chamber)	765	
Income tax (2-1/2% of total investment)	850	
Interest (5% of total investment)	1,700	
Insurance (1% of total investment)	385	
		3,700
Depreciation, Obsolescence		
Radiation chamber (38,320 x .08)		3,065
Grand Total		$42,240

Experiments[4,5] have shown that a dose of 10,000 rep will prevent reproduction of the confused flour beetle. However, the design was based on a dose of 25,000 rep to provide a factor of safety. Experience should make possible the reduction of this dosage possibly to 10,000 rep or less with a corresponding decrease in cost for irradiation.

The great advantage of gamma radiation over chemical fumigation is the effect of gamma radiation on the eggs. Chemical fumigation may be quite effective on larval or adult insects, but is not very effective on insect eggs. Thus, unless the fumigation is repeated to destroy insects hatched from eggs subsequent to the initial fumigation, freedom from insect infestation is not assured. Gamma radiation sterilizes eggs as well as adult insects.

Although the design was prepared primarily for the irradiation of flour in 100-pound bags, similar-size bags of meal, mash, and a variety of other cereal products might be irradiated in such a facility. The conveyor buckets shown could also handle bulk grains or bulk flour, although more simple conveyor systems would suffice for the handling of bulk products.

The design shown represents an attempt to minimize initial capital investment rather than to develop maximum efficiency in utilization of radiation. The use of a basement corner of an existing building, the use of existing walls and earth for part of the shielding, and the use of commercial concrete building slabs without mortar helped to lower the estimated cost of the facility. The estimated $38,320 for the radiation facility, including conveyor, crane, etc., is believed to be about a minimum for a commercial radiation facility of this design.

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