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# DESIGNS FOR POTATO IRRADIATION FACILITIES

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## 1. INTRODUCTION

Potatoes are the most important vegetable food in the domestic diet. A greater tonnage of potatoes is handled than of any other vegetable produce. The volume sold is quite constant throughout the year and from year to year. Annual production during the 10-year period 1941-50 averaged 415 million bushels with an average value of over $526,000,000.[1]

About 75 percent of potatoes planted are harvested in the fall and are known as late potatoes. The majority of these potatoes are grown in the northern states. The Snake River Valley of Idaho, the Red River Valley of Minnesota, Arvostook County of Maine, and Long Island, New York are well known for their production of potatoes. Dale County, Florida and Kern County, California, also produce large quantities of potatoes, particularly for use in the early summer months when mature northern-grown potatoes are not available.

Potatoes usually cannot be held in unrefrigerated storage later than early spring in even the northern states because of the seasonal temperature rise and the end of the dormant period for the potato tuber. This temperature rise following the period of dormancy results in rapid sprouting of the tubers. The use of refrigeration retards the sprouting and extends the storage period, but even with refrigeration it is difficult to hold untreated potatoes later than May.

In addition to sprouting and rotting there are other problems in storing potatoes, such as maintaining a low sugar content, a problem which is primarily important to potato processors. About 10 percent of the potatoes sold for food are processed into products such as potato chips, dehydrated potatoes, canned potatoes, etc. In 1951 over 23 million bushels of potatoes were processed into potato chips.

Potato processors demand potatoes of medium to large size with high starch content and low sugar content. The low sugar content is especially important to processors of potato chips. Sugar in the potato carmelizes when fried producing dark or burned spots on the chips which are not desirable. Also dehydrated potatoes having a high sugar content do not keep as well as dehydrated potatoes having a low sugar content.

If potatoes for processing are stored at too low a temperature, an accumulation of sugar in the potato results from the enzyme conversion of starch to sugar and from the low respiration rate at low temperatures. Potatoes stored at a higher temperature will have a sufficiently rapid respiration to oxidize the sugar so as to maintain a low sugar content. As the low storage temperatures (32 to 40°F) result in excessive accumulation of sugar and the higher temperatures (50°F and above) result in excessive spoilage from sprouting and rotting, some compromise temperature such as 45 to 50°F may be used. Another method is the storage of the potatoes at the low temperatures followed by the raising of the temperature about 20°F above storage temperature for a period of two weeks or more prior to processing. Both of these methods result in increased spoilage from sprouting and rotting. Potatoes that have been held dormant at low temperature for a number of months sprout rapidly after the temperature is raised.

A variety of chemicals has been found useful in treating potatoes to retard or prevent sprouting. Some of these chemicals are the esters of napthalene acetic acid and trichlorophenoxy-acetic acid; 3 chloroisoprophyl-N-phenyl carbonate; 2,3,5,6-tetrachloro benzene; and maleic hydrazide. However, the use of chemicals is associated with some disadvantages, such as:

(1) difficulty in obtaining a uniform application
(2) nonuniform response of treated tubers
(3) need of special equipment to treat potatoes on a large scale
(4) plugging of ventilation ducts with dust
(5) possible toxicity of some of the chemicals
(6) inability to control sugar content of tubers by chemical treatment
(7) cost of some chemicals and some methods of application
(8) undesirable appearance of dust on potatoes in dusting process.

One large processor of potatoes in the Michigan area tried a chemical dusting treatment but then discontinued it. Chemical treatment cannot be considered to be completely satisfactory.

## 2. EFFECT OF GAMMA IRRADIATION ON POTATOES

Gamma radiation has been shown by Sparrow and Christensen to prevent the sprouting of small Katahdin variety potatoes for 18 months.[2,3]

Tests in this laboratory with mature 1953 crop Minnesota-grown, Irish Cobbler and Idaho-grown, russet Burbank varieties of potatoes have also shown the ability of low doses of gamma radiation to prevent sprouting. Several 100-pound and smaller bags of storage potatoes of these varieties were irradiated, respectively, in January, 1954, and May, 1954, and were stored at 50°F until Spetember, 1954, at which time mature potatoes of the 1954 season had become available.

Figure 1 is a photograph taken in September, 1954, of Idaho-grown, russet Burbank variety potatoes of the 1953 crop. The irradiation of these potatoes was performed in May, 1954. Figures 2 and 3 show external and internal appearance of Minnesota-grown, Irish Cobbler variety potatoes of the 1953 crop stored for 6 months at 50°F subsequent to irradiation in January, 1954. Note that the sprouts on the control tubers have died and withered and that they have undergone severe decomposition in the interior. By September these control tubers were completely rotten, whereas the irradiated potatoes were still well preserved.

Over 2100 individual taste tests were made by a taste panel using irradiated potatoes and controls.[4] A statistical analysis of the results of these tests showed no preference for the controls over the irradiated potatoes. On the basis of these studies and some taste tests conducted at Brookhaven[3] there is no indication of a problem of off-flavor in potatoes as a result of irradiation in the dose range of 10,000 rep.

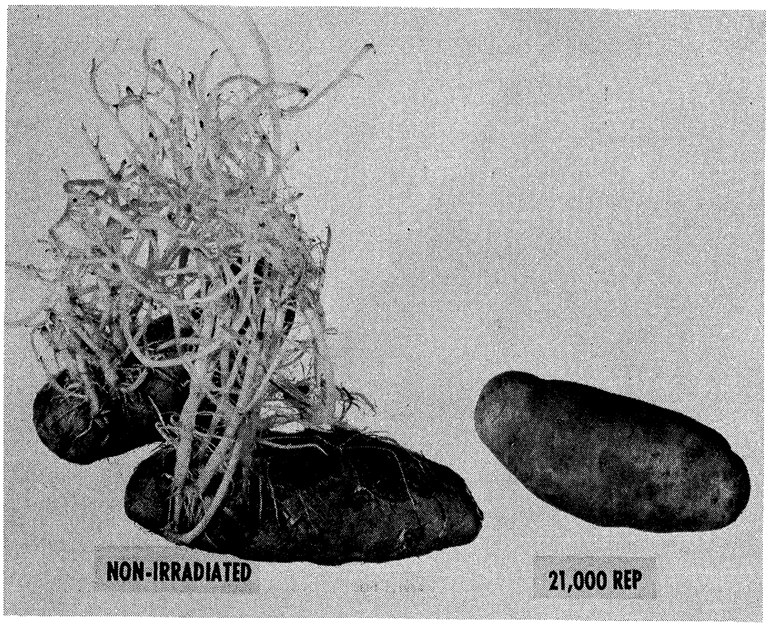


Fig. 1. Idaho-grown, Russet Burbank Variety Potatoes of the 1953 Crop, Irradiation Performed May, 1954. Stored at 50°F Until Photographing in September, 1954.

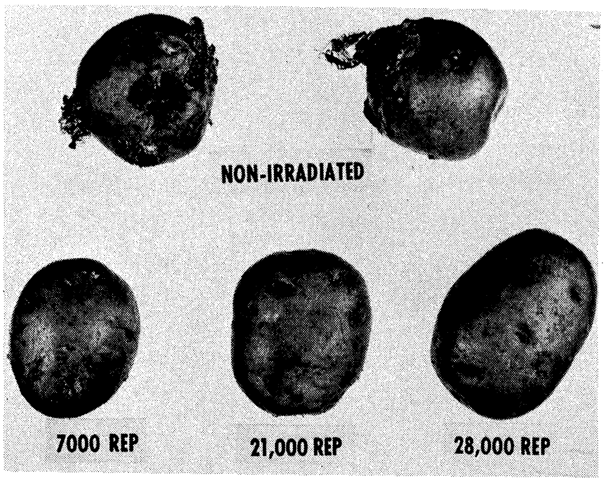


Fig. 2. Comparison of Exterior Appearance of Nonirradiated and Irradiated Minnesota-grown, Irish Cobbler Variety Potatoes Showing the Decay of Sprouts on the Controls.

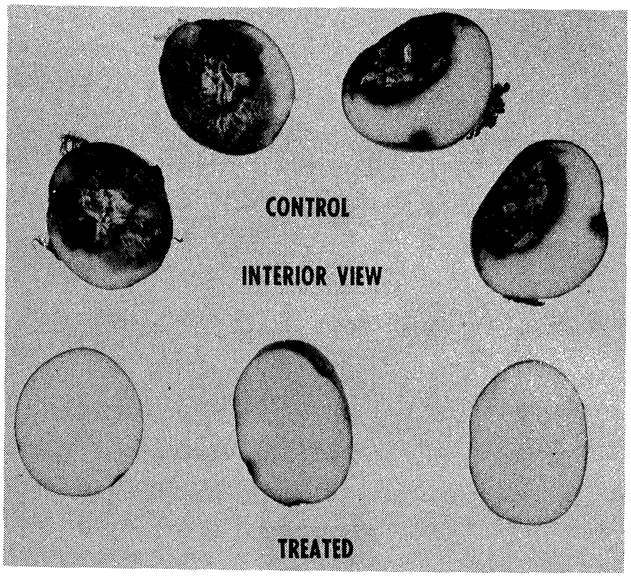


Fig. 3. Comparison of Interior Appearance of Nonirradiated and Irradiated Halved, Minnesota-grown, Irish Cobbler Variety of Potatoes, Showing Decay in Nonirradiated and Normal Appearance in Irradiated Specimens.

Tests by Sussman[5] on the respiration of irradiated potatoes have shown an increase up to sixfold in the respiration immediately following irradiation. This increase in respiration is observed without an increase in temperature. At present it is common practice to control the sugar content of potatoes stored at low temperature by increasing the respiration as a result of raising the temperature. However, this use of temperature to control respiration has the disadvantages of increasing the spoilage from sprouting and rotting and greatly limits the time available for processing. If irradiation were used to increase the respiration this might be accomplished without raising the temperature. Laboratory studies are needed to investigate this possibility. The use of irradiation to control the sugar content of stored potatoes should decrease the loss by spoilage, permit greater time for processing, and provide better control of the sugar content.

## 3. TYPES OF RADIATION SOURCES TO BE CONSIDERED

For purposes of comparison three different gamma sources have been selected; (1) refined cesium-137, (2) concentrated anhydrous mixed fission products, and (3) cooling reactor-fuel elements.

Since cooling reactor-fuel elements decay very rapidly the radiation facilities using this source of radiation will be designed to operate six months of the year during the late winter and spring. During the remainder of the year the plant will be shut down without a radiation source. Because of the slower decay of two-year-old fission products and cesium-137 the radiation facilities utilizing these materials as sources of radiation will be designed to operate 260 days out of the year.

In order to simplify calculations and comparisons, the radiation source will be assigned the same overall geometrical shape as the source in the radiation facility for the processing of prepackaged fresh meat described in Progress Report 6.[6] This source was a rectangular plaque 6 feet high, 12 feet long, and 0.40 inch thick. The plaque was divided into 12 vertical elements with different specific activities so as to provide a uniform radiation field. The cesium-137 and the mixed-fission-product sources being considered for the irradiation of potatoes will be designed to provide a rectangular source of the same width and length, except that rod sources arranged in a vertical plane will be substituted for the vertical rectangular plaque.

The radiation dose for treatment of potatoes to prevent sprouting has been found to be about 10,000 rep which is about 1/10 the dose required for pasteurization of prepackaged meat. The capacity of the meat plant was estimated to be about 14 tons per hour. This is probably the correct order to magnitude for a typical potato irradiation facility. Therefore, the total activity of the source can be decreased by a factor of 10 to about 150,000 curies of cesium-137 or mixed fission products.

The decrease in the total activity required permits the use of a discontinuous radiation source without requiring an excessive specific activity. Thus, the rectangular plaque 6' x 12' might be replaced by a number of rods 6 feet long and suitably spaced over a width of 12 feet, so as to provide a uniform radiation field. This arrangement has the advantage of using the same specific activity in each rod which simplifies the fabrication of rod sources and the addition or replacement of rods. These rod sources might consist initially of 20 rods of 2-inch stainless-steel pipe or tubing filled with either anhydrous cesium-137 or anhydrous mixed fission products and sealed at both ends. The cylindrical containers have the advantage of simplicity in shape and of mechanical strength.

An important point of economics to be considered is that the use of a discontinuous source permits the simple addition of rods to replace activity lost by decay. Using this procedure the number of rods eventually will be increased until some of the rods must be removed and replaced. However, for the case of cesium-137 only 1/10 of the original number of rods needs to be added every 5 years to maintain the source activity (within 90 percent of the original activity) whereas 1/6 of the original number of rods would be needed if replacements were used. Thus, an original source consisting of 20 rods filled with cesium-137 could be kept at strength by adding 2 rods every 5 years for the next 30 years. Thereafter, the activity could be maintained by replacing an average of 3-2/3 of the older rods every 5 years. However, if replacement of rods had been used for the first 30 years rather than addition, the number of replacement rods required in the 30-year period would be increased by about 67 percent at a corresponding increase in expense. The same point of economics holds for rods filled with mixed fission products except that replacement would begin much earlier.

Cooling reactor-fuel elements should not be considered as suitable gamma sources for general use or for plants designed to operate continuously throughout the year. Reactor-fuel elements would be too expensive to use if the high inventory cost of fissionable material were charged against the fuel element when used as a source of radiation. However, for reasons relating to the processing techniques it is the practice in present processing plants to store these elements under water for several weeks before they are processed. During this period the intense radiation is dissipated in the water used to shield the cooling elements; except when used in some research experiments this radiation is presently being wasted. It is proposed that some of these elements be used as sources of radiation for a limited number of radiation facilities designed to process potatoes.

The potato irradiation facility using cooling reactor-fuel elements will be designed to operate only six months of the year commencing operations about December 15, and ceasing operations about June 15. During the other six months the facility will be without a radiation source. A different design for the radiation facility using the fuel rods would be required since they would have a much higher activity than would the mixed fission products or the processed cesium-137; also the fuel elements have a different geometry.

A single reactor-fuel element would not provide a sufficiently uniform radiation field; therefore, two reactor-fuel elements will be considered. Proper spacing of the fuel elements from each other and from the axis of the conveyor handling the potatoes and limiting the width and length of the conveyor buckets makes it possible to give the potatoes a quite uniform dose of radiation with only two fuel elements.

## 4. DESIGN OF IRRADIATION CHAMBER USING CESIUM-137

The radiation chamber using cesium-137 as a source of gamma radiation will have the same basic design as the radiation facility designed to pasteurize prepackaged meat described in Progress Report 6.[6] However, certain changes will be required in order to adapt the previous design to the handling of potatoes. In this design the conveyor trays will be proportioned so that either bulk potatoes or 100-pound bags of potatoes can be handled. The tray width will be increased from 8 inches to 12 inches and the tray height will be increased to 24 inches. This will require an increase in the conveyor pitch from 4-1/2 to 6 inches. Because of the increase in width of the conveyor trays the spacing between each pass will be increased from 15 to 24 inches.

The increase in width of conveyor trays and the increase in spacing between conveyor passes increase the distance of the absorber from the source. The radiation field is decreased by the inverse square relationship and because of the use of a much weaker source. Therefore, only two passes of the conveyor will be used on either side of the radiation source rather than four passes as used in the previous design reported in Progress Report 6.

Figure 4 shows a section of the elevation view of the modified radiation chamber designed to irradiate potatoes using either cesium-137 or mixed fission products as a source of radiation. One hundred-pound bags of potatoes or bulk potatoes will be brought by belt conveyor A from the potato warehouse. The bags of potatoes or the bulk potatoes move down slide B into tray 1 of the irradiation conveyor while this conveyor is in the stationary phase of its intermittent operation. As the irradiation conveyor moves, the potatoes are carried down into the radiation chamber through opening C and past concrete shield D. Two vertical passes, E and F, are made on the right side of the row of source rods G, and two passes, H and I, are made on the left side of the source. This arrangement permits irradiation of the potatoes from both sides so as to produce a more uniform radiation dose.

Well L is filled with water as in previous designs and is used to hold the source when the radiation must be shut off to permit entry to the radiation chamber for maintenance, routine inspection, or addition of source rods. If the radiation chamber is located above grade as shown in Fig. 4, a concrete wall, N, which is 3'0" thick, would be used for shielding. If the radiation chamber is placed below grade, the wall thickness may be reduced to that required for structural strength alone, as the

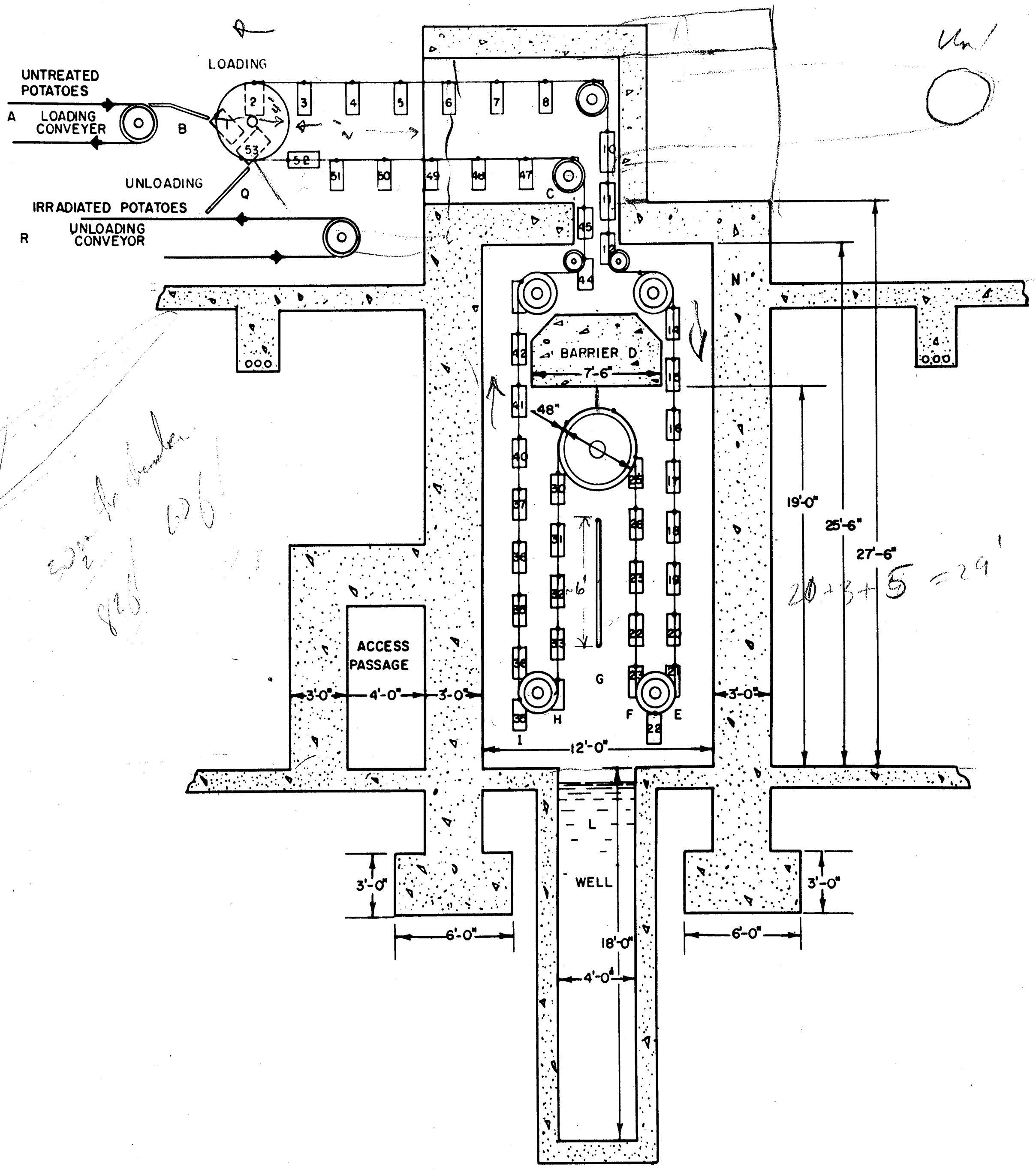


Fig. 4. Elevation View of Potato Irradiation Chambers Using Cesium-137 or Mixed Fission Products.

earth will act as a radiation shield. A labyrinthine entrance to the radiation chamber is provided at the lower left as shown in Fig. 4.

A plan view of the radiation chamber is presented in Fig. 5. This view shows the simple labyrinth used as an access passage for routine inspection and maintenance. The conveyor in the radiation chamber may be driven by

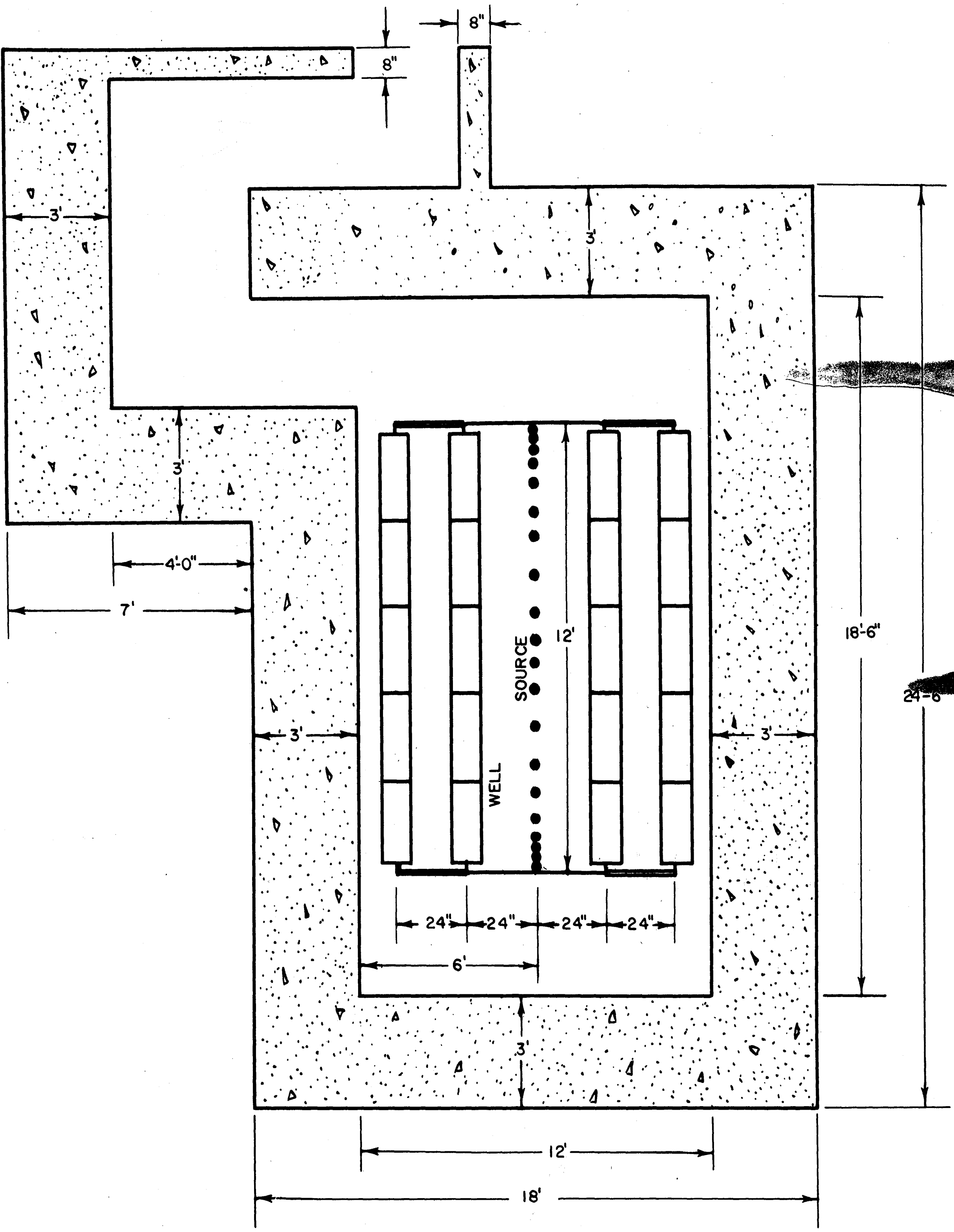
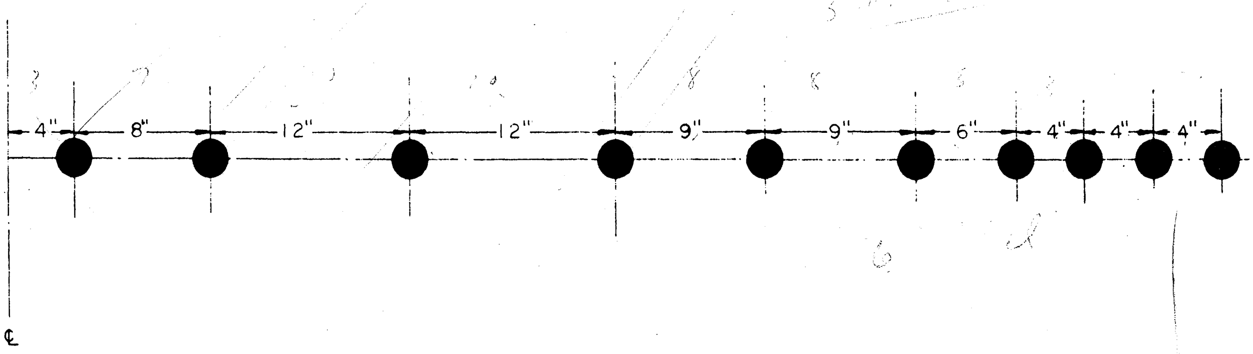


Fig. 5. Plan View of Irradiated Chamber Using Cesium-137 or Mixed Fission Products.

sprockets on stub shafts. Some of the sprockets may be "idlers", with one or more sprockets to be used as a "driver". Figure 6 also shows the spacing between centers of the 2-inch source pipes filled with fission products. Variation in spacing with smaller pitch near the ends is used to produce a more uniform radiation field on either side of the source.



20 Rod Source Distribution, Symmetrical about ℄

Fig. 6. Plan View Showing Spacing of One Half of Source Rods for Potato Irradiation Facility Using Either Cesium-137 or Mixed Fission Products.

## 5. CAPACITY CALCULATIONS FOR A MIXED FISSION PRODUCT OR CESIUM-137 SOURCE

The capacity of the radiation chamber shown in Figs. 4 and 5 will depend on the activity of the source and the dose required. The total gamma activity of the source has been set at 150,000 curies so as to provide a capacity considered typical. Fixing this activity fixes the magnitude of the radiation field. A specific gamma activity of 230 curies per pound is sufficient to provide 150,000 curies in the 20-source rods.

The radiation flux in a plane perpendicular to the face of the source at its center line was calculated for the lines 24 inches from the source and 48 inches from the source. The values determined are shown in Fig. 7. This figure shows that the radiation flux along the horizontal axis parallel to the source can be made approximately uniform by varying the activity of the source along the horizontal axis; this dimension may be eliminated from the calculations of the radiation field permitting the plotting of the radiation field in two dimensions.

As the centerline of the conveyor passes are spaced at 24 and 48 inches from the source, the dose rates in air were calculated at these distances as a function of the vertical distance above the center line of the source.

These data were cross plotted to give the isodose curves shown in Fig. 8. The dose rates shown are for radiation in air and must be corrected for absorption in the potatoes. This correction was made using 8 inches as the half-value thickness for absorption in bulk potatoes for gamma radiation of 0.7 mev energy with an absorber efficiency of 80 percent. The isodose curves corrected for absorption are shown in Fig. 9.

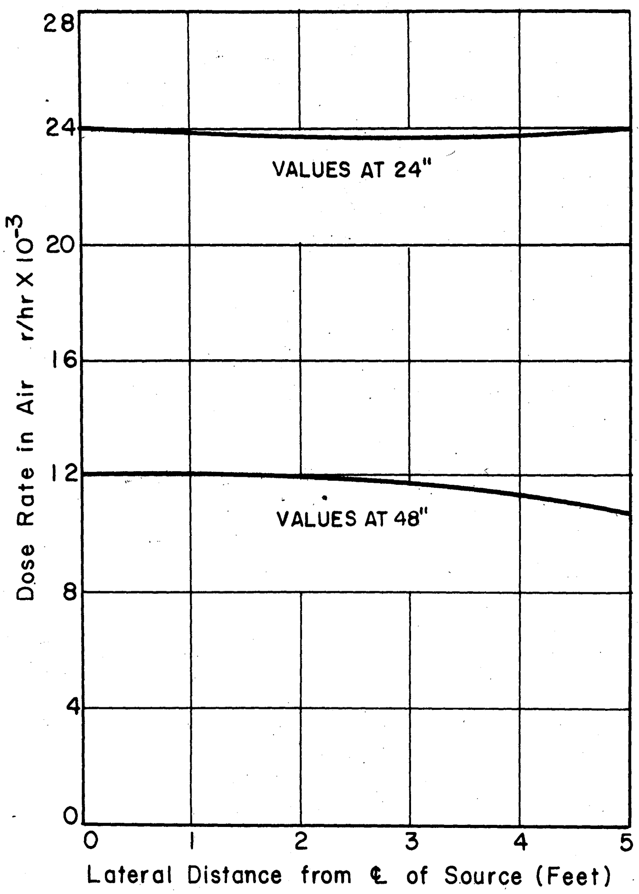


Fig. 7. Radiation Flux Versus Lateral Distance for Source Consisting of Selectively Spaced Rods.

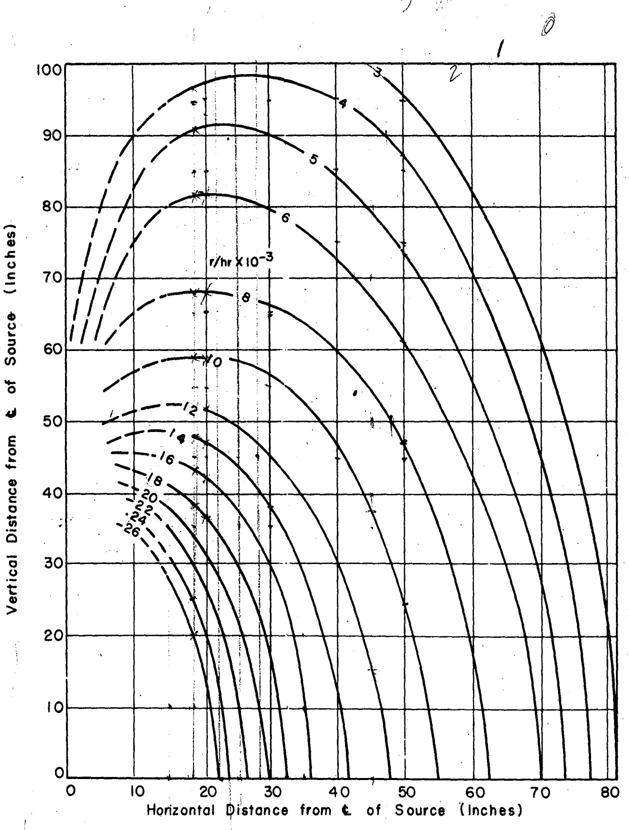


Fig. 8. Isodose Curves in Vertical Plane Perpendicular to Source at Center Line for One Quadrant of Radiation Chamber Using Cesium-137 or Mixed-Fission-Products Sources.

Figure 10 shows a plot of the radiation flux in rep/hour at the center position of the potatoes being conveyed after corrections are made for absorption. The radiation flux is plotted as a function of the length of path traveled through the first half of the radiation chamber. The plot of radiation flux for the second half of travel through the radiation chamber is a mirror image of this curve and is not shown. To determine the time required to absorb a given dose, the curve must be integrated graphically. Twice this integral

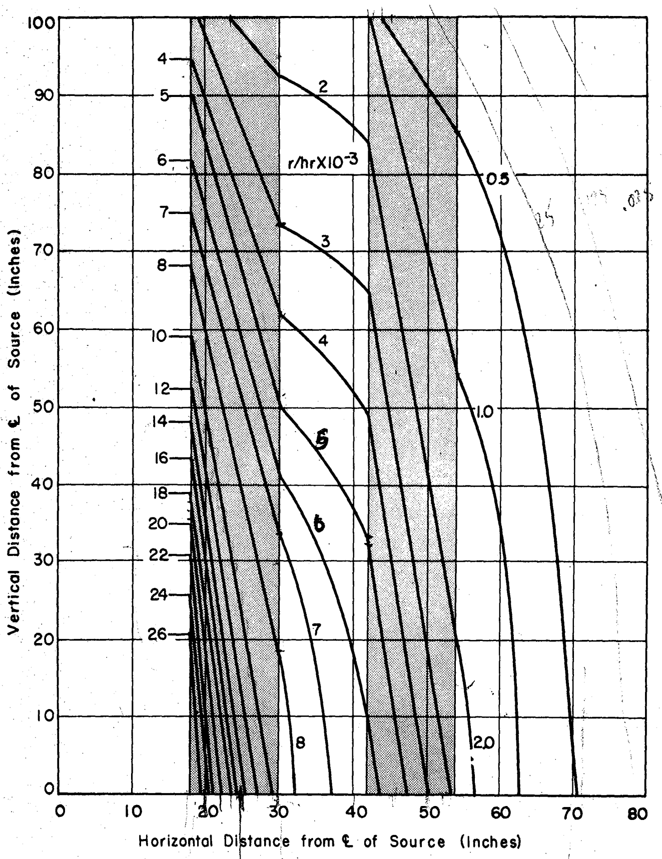


Fig. 9. Isodose Curves from Fig. 8 Corrected for Absorption.

gives the accumulated dose for the potatoes in the center of the conveyor tray as a function of the tray speed through the chamber. The accumulated dose may be expressed as

$$\text{accumulated dose in center} = \frac{\text{rep ft/hr}}{\text{x ft/hr}}$$

where

x = tray speed in feet per hour.

From the plot of dose rate versus length of path traveled, Fig. 10, the accumulated dose at a tray speed of 1 foot per hour was determined to be $3.82 (10)^5$ rep

Dividing the specified dose by the accumulated dose as a function of tray speed yields a value which has the reciprocal units of tray speed.

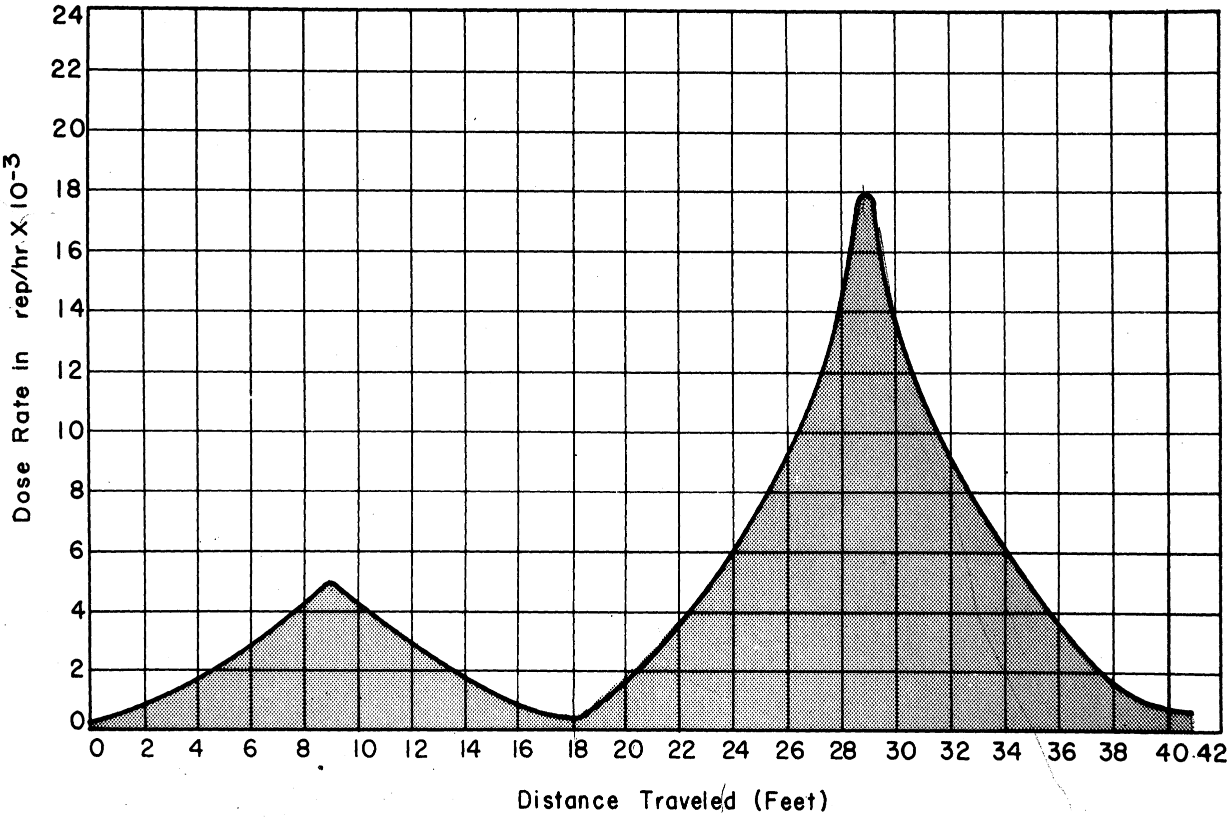


Fig. 10. Dosage Rate Received at Center (12-Inch Wide Conveyor Tray Filled with Potatoes) As a Function of Distance along Path in Radiation Chamber.

Multiplying this value times the length of path traveled in feet gives the time required per cycle for the potatoes to obtain a specified dose.

covered conveyed

$$\text{Radiation time per cycle (for } 1 \times 10^4 \text{ rep dose)} = \frac{10^4 \text{ rep}}{3.82(10)^5 \text{ rep ft/hr}} (82) \text{ ft} = (2.14) \frac{\text{hr}}{\text{cycle}}$$

There are 30 trays within the chamber each containing 2' x 1' x 12' = 24 cu ft of potatoes per tray; or 24 cu ft x 0.804 bu per cu ft = 19.3 bu of potatoes per tray. The capacity in bushels of potatoes per cycle would then be

$$\text{Capacity/Cycle} = (30) \frac{\text{trays in chamber}}{\text{cycle}} \times \frac{19.3 \text{ bu}}{\text{tray}}$$

$$= (579) \text{ bu/cycle.}$$

The capacity in bushels per hour may be obtained by dividing by the exposure time required per cycle.

$$\text{Capacity/Hour} = (579)\ \frac{\text{bu}}{\text{cycle}}\ \frac{1}{(2.14)\ \text{hr/cycle}} = (270)\ \text{bu/hr}\ .$$

[illegible] ~ 2,000 bu/h. [illegible]

## 6. TYPICAL SHIELDING CALCULATION

Using the latest broad beam shielding data (National Bureau of Standards Handbook 54) dosage rates at points outside the radiation chamber were calculated from Fig. 11.

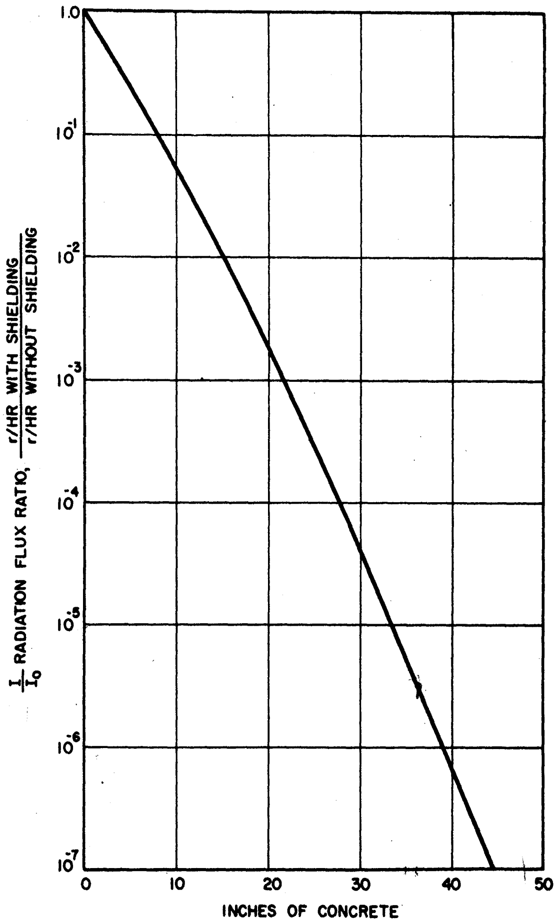


Fig. 11. Broad-Beam Attenuation in Concrete for Cesium-137 Gamma Radiation.

The dosage rate at a point S (see Fig. 4) on the center line of the source just outside the shielding wall (9 feet from the source) is calculated to be 350 r per hour with no shielding. This value is obtained by extrapolation of the data in Fig. 8. Figure 11 shows that 3 feet of concrete will reduce this dosage rate by a factor of $3 \times 10^{-6}$ to a level of approximately 1 mr/hr which is considered to be sufficiently below tolerance. Calculations for water shielding have been described in previous designs of plant irradiation facilities.[6]

## 7. COST ESTIMATES BASED ON THE USE OF CESIUM-137

### (a) Total Investment

The radiation chamber for treating potatoes using either cesium-137 or mixed fission products as a source of radiation is very similar to the radiation facility designed to pasteurize prepackaged meat.[6] An itemized cost estimate indicated that this latter radiation facility exclusive of the radiation source would cost $82,500. The facility to treat potatoes will have two passes on either side of the source rather than four, will have fewer trays, and will have slightly smaller overall dimensions. It is estimated that the radiation facility would cost 80 percent of the facility to pasteurize meats or $66,000.

Using the 0.6 scaling factor[7] for estimating the installed cost of the source of radiation and using the figure $6,000 for a 1,000-curie cesium-137 source, the installed cost of 150 kilocuries of cesium-137 is estimated to be

$$x = \$6{,}000 \left(\frac{150{,}000}{1000}\right)^{0.6}$$

$$x = \$120{,}000 .$$

50

The cost of a steel-reinforced lead container for shipping 150 kilocuries is estimated to be $5,000. Thus, the total investment becomes

| | |
|---|---|
| Cost of radiation chamber and accessories | $ 66,000 |
| Cost of shipping container | 5,000 |
| Cost of 150,000 curie cesium-137 source installed | 120,000 |
| Total installed cost | $191,000 . |

67,500

### (b) Operation Costs

If the radiation facility were operated as a part of a large potato warehouse or a potato processing plant, the annual operating costs might be estimated in a manner similar to the case of the pork-irradiation unit (Nucleonics, September, 1954) and as shown in Table A.

### TABLE A

### ESTIMATED ANNUAL OPERATION COSTS FOR POTATO IRRADIATION FACILITY USING CESIUM-137

#### Wages, Salaries

| | | |
|---|---|---|
| Two full time operators with limited health-physics training | $10,000 | |
| Supervisor and clerical labor (10% of operational labor) | 1,000 | |
| Salaries and wages not associated with operation of radiation chamber (50% for direct labor and supervising costs) | 5,500 | |
| | $16,500 | A Could |

#### Other Operation Costs

1 000 1

| | | |
|---|---|---|
| Maintaining source activity ($30,000 every 5 yr) | 1 000<br>~~6,000~~ | |
| Utilities | 1,000 | |
| Repairs and maintenance on chamber and conveyor (5% of chamber and conveyor cost) | ~~3,300~~ | 4000 |
| Miscellaneous ~~contingeneies~~ cost | 10,000<br>1,000 | |
| | $11,300 | 7000 |

Replacement of source - miscellaneous costs

10,000

45
45
495

#### Overhead

27800
1300

| | | |
|---|---|---|
| Payroll overhead (15% of cost of labor and supervision) | 2,480 | |
| General plant overhead (50% of cost of labor and operations) | 13,900 | |
| General Administration overhead (10% of cost of labor and operations) | 2,780 | |
| | $19,160 | |

3300
9000
1230

#### Taxes, Interest, Insurance

| | | |
|---|---|---|
| Property tax (2% cost of radiation chamber) | 1,320 | 1600 |
| Income tax (2-1/2% of total investment) | 4,780 | 2250 |
| Interest (5% of total investment) | 9,550 | 4500 |
| Insurance (1% of total investment) | 1,910 | 900 |
| | $17,560 | 9250 |

50

19 259 25

TABLE A (Cont.)

Depreciation, Obsolesence

| | | |
|---|---|---|
| | 80 | 6400 |
| Radiation chamber | = (66,000 x 0.08) | $ 5,280 |
| Radiation source: | (initial cost-salvage value) x 8% | 1000 |
| | = (120,000 - 60,000 x 0.08) = | 4,800 |
| | | $10,080 7400 |
| | 9 | |
| | 1000 | |
| | | $74,600 |

A cesium-137 source will lose 10 percent of its activity in 5 years; the cost of restoring this activity is calculated to be $30,000 once every 5 years. Straight-line amortization would make 20 percent chargeable each year or $6,000 per year. Overhead on the payroll, general plant operation, and general administration is estimated according to recommended methods for chemical plants.[8]

The radiation chamber is considered taxable as property, but the radiation source is a piece of equipment and not subject to property tax. Income tax should be calculated on the basis of profits, but since the value of irradiated potatoes has not yet been determined, 2-1/2 percent of the total investment is used as an estimate of income tax considered chargeable to the irradiation facilities.

In estimating depreciation and obsolescence, the radiation chamber and radiation source are considered to have a 10-year useful life. The total investment is amortized in a 10-year period by use of a sinking fund. The interest on cash paid into the sinking fund reduces the percentage of the initial investment chargeable each year from 10 percent to about 8 percent. This depreciation would provide for complete replacement of the chamber after 10 years. The source is assumed to have only 50 percent salvage value at the end of the 10-year amortization period even though it will be at full strength through activity replacement.

## (c) Unit Costs

Based on a minimum dose of 10,000 rep and an operation schedule of 2 shifts (16 hrs/day) and 260 operating days per year, the annual capacity is calculated to be

$$270 \text{ bu/hr } (16 \text{ hrs/day})(260 \text{ days/yr}) = 1.12(10)^6 \text{ bu/yr} .$$

Cost per bushel to be added to potatoes for a dose of 10,000 rep using a cesium-137 source will be

$$\frac{\$\ 74{,}600}{1.12(10)^6} = \$0.066/\text{bu} .$$

Using a bulk density of 42 lbs/cu ft the cost per ton will be

$$\frac{\$0.066(2000)}{0.804(42)} = \$3.91/\text{ton} .$$

## 8. COST ESTIMATES BASED ON THE USE OF MIXED FISSION PRODUCTS AS A RADIATION SOURCE

### (a) Some Factors Affecting the Cost of Mixed Fission Products

If processed concentrated fission products are used as a source of radiation, their cost might be determined in large part by the cost of concentrating and packaging. However, such information is not available because large quantities of the mixed fission products have not yet been concentrated and a cost estimate for the processing, to be reliable, would require a rather thorough design of the process being considered. As there are many different types of fission-product wastes and also as many different types of processes might be used in preparing these materials for industrial use, a direct approach to this cost estimate will be avoided. Another approach to the estimate of the value of mixed fission products might be made on the basis of the comparative value of such radioactive materials and cesium-137. Calculations described in Progress Report 6 indicate that 2-year-old fission products have gamma activity essentially from cesium-barium-137 and from cerium-praseodymium-144. The cerium-144 present in 2-year-old mixed fission products has 7-1/2 times the activity of cesium-137 but has a half life of only 290 days as compared to 33 years for the cesium.

The relative value of gamma sources having different half lives might be expressed in terms of some function of the ratio of the half lives. The nature of this function will be discussed briefly with regard to (1) total dose delivered, (2) replacement costs, (3) total curie requirement, and (4) relative cost proportional to half lives.

(1) Total Dose Delivered. To estimate the relative values of two isotopes of approximately equal energy but different half lives, reference may be made to the total dose delivered.

The dosage rate, as a function of time, is

$$I = I_o e^{-\lambda t} ,$$

where

$I_o$ = the dosage rate at time zero, rep/hr

$\lambda = \frac{.693}{T}$ = the decay constant of the isotope in question,

$T$ = half life

and $t$ = elapsed time.

The total dose in rep delivered in any time (t) then is

$$\text{rep} = \int_o^t I \, dt = I_o \int_o^t e^{-\lambda t} \, dt$$

$$= \frac{I_o}{\lambda} [1 - e^{-\lambda t}] \quad .$$

When the elapsed time (t) is large compared to the half life (T) the term in the brackets $[1 - e^{-\lambda t}]$ approaches unity and the dose delivered becomes proportional to the initial dose rate $I_o$ and to the half life, T. When comparing isotopes of different half lives at a given time, t, the value of the long-lived isotope may be short of this "saturation value" while the short-lived isotope has reached its saturation value. Thus, the relative values would not be directly proportional to the half life, and the shorter-lived isotope would be given a relatively higher value. In practice, however, this apparent advantage in radiation value for the shorter-lived isotope would tend to be cancelled by the increased costs required for replacement. Therefore, it is probably a reasonable estimate that radiation value can be considered to be approximately proportional to half life based on total dose delivered.

(2) Replacement Costs. To analyze further the relative values of isotopes having different half lives, replacement costs will be considered. To maintain a radiation facility at design capacity, a replacement of a part of the radiation source will be required wherever the radiation level falls below a predetermined minimum level.

On permitting, for example, a 10 percent drop in radiation intensity

$$\frac{I}{I_o} = 0.9 = e^{-\frac{.693t}{T}}$$

$$.693\,\frac{t}{T} = 0.115$$

$$\frac{t}{T} = \frac{0.115}{0.693} = \text{a constant.}$$

As $(\frac{t}{T})$ is constant dependent on the time, the time that will elapse between replacements is proportional to half life. Thus, on the basis of replacement cost alone it is valid to assume a radiation value directly proportional to half life.

(3) Total Curie Requirement. Other things being equal, the number of curies required at each replacement will be the same, independent of half life. Thus, the total number of curies required to maintain operation at a given rate for a considerable period of time would be inversely proportional to half life. Once again, a reasonable estimate of the relative values of two isotopes of different half lives would appear to be in proportion to their half lives.

(4) Relative Cost Proportional to Half Lives. On the basis of these limited considerations the relative value of gamma sources having different values of half life can be expressed in terms of the linear ratios of the half life values, or in other words cerium-144 might be considered to have 290/(365 x 33) or about 2.4 percent of the dollar value of cesium-137 as a gamma source over a long-term basis.

## (b) Cost Estimate for Mixed Fission Products

(1) Total Investment. The 150,000-curie gamma source used for the potato radiation facility if composed of 2-year-old mixed fission products would contain approximately 18,000 curies of cesium-137 and 132,000 curies of cerium-144 plus about 130,000 curies of promethium-147, ruthenium-106, and strontium-90, none of which have any gamma activity and are pure beta emitters. The daughter product of the ruthenium-106 and rhodium-106 contributes slightly to the gamma radiation from the mixture.

If the 132,000 curies of cerium-144 are considered to have a dollar value of 2.4 percent of cerium-144, they would have a value equivalent to 3,200 curies of cesium-137. Thus, the dollar value of the 150,000-curie gamma source of 2-year-old mixed fission products might be calculated as having a value equivalent to 18,000 + 3,200 or 21,200 curies of cesium-137. Using the 0.6 scaling factor and the figure for installed cost of $6,000 for a 1,000-curie cesium-137 source the estimate is made that the value of 21,200-curie source would be

$$\text{Source Cost} = x = \$6{,}000 \left(\frac{21{,}200}{1{,}000}\right)^{0.6}$$

$$x = \$38{,}200.$$

$$\text{Total Investment} = \$38{,}200 + 5{,}000 + 66{,}000 = \$109{,}200.$$

Also

$$\frac{\$38{,}200}{21{,}200 \text{ curies}} = \$1.80/\text{equivalent curies cesium-137}$$

$$\frac{\$38{,}200}{150{,}000 \text{ curies}} = \$0.25/\text{total curies of gamma activity.}$$

Using the same figure of $5,000 for shipping container and $66,000 for radiation chamber, the total installed cost is $109,200.

(2) Operation Costs. As a result of a more rapid decay of the mixed-fission-product source it will be necessary to replace 1/6 of the source every 4 months. This will amount to an operating expense estimated to be about $25,000 per year for replacement of mixed fission products plus installation charges. Using the same method of estimating annual operation cost as given in Table A, but substituting the different figures for cost of source installed, total installed cost, and cost of replacement, Table B was obtained.

TABLE B

ESTIMATED ANNUAL OPERATION COSTS FOR POTATO IRRADIATION FACILITY USING MIXED FISSION PRODUCTS

| | |
|---|---:|
| 1. Wages, salaries | $16,500 |
| 2. Other operation costs | 30,000 |
| 3. Overhead | 30,380 |
| 4. Taxes, interest, and insurance | 10,570 |
| 5. Depreciation, obsolescence | 6,410 |
| | $94,160 |

In Table B the estimated costs for wages and salaries (1) remain the same for the mixed-fission-product facility as for the cesium-137 facility. The estimated costs for taxes, interest, and insurance (4) and depreciation and obsolescence (5) will be somewhat lower for the mixed-fission-product facility than for the cesium-137 facility because of the lower investment in the source. However, the other estimated operation costs (2) have increased about threefold because of the added costs for replacement for the shorter half-lived, mixed-fission-product source. This results in a higher estimated annual operation cost using mixed fission products ($94,160 per year) then using cesium-137 ($74,700).

(3) Unit Costs. Based again on a minimum dose of 10,000 rep and an operation schedule of 2 shifts (16 hours per day) and 260 operating days per year, the annual irradiation capacity is calculated to be $1.12 \times (10)^6$ bushels per year. Based on an annual operation cost of $82,440 per year the following costs are estimated. 94160

Cost per bushel to be added to potatoes for a dose of 10,000 rep using a 2-year-old mixed-fission-product source will be

$$\frac{\$94,160}{1.12(10)^6} = \$0.084/\text{bu}.$$

Using a bulk density of 42 lb/cu ft the cost per ton will be

$$\frac{\$0.084(2000)}{0.804(42)} = \$4.98/\text{ton}.$$

Thus, although a very low value was placed on the cerium-144 the cost of replacement is sufficient to indicate that the use of mixed fission products would be more expensive than cesium-137.

## 9. DESIGN OF IRRADIATION FACILITY USING COOLING REACTOR-FUEL ELEMENTS

Cooling reactor-fuel elements have a very high gamma activity but decay at a very rapid rate. It is proposed that reactor-fuel elements be used for a period of 2 months and then should be replaced. During each 2-month period, weekly adjustments can be made in the speed of the conveyor moving potatoes through the irradiation room to compensate for decay. If the radiation facility were operated for 6 months starting with freshly installed fuel elements about December 15 and operated until June 15, one replacement of fuel elements would be required about February 15 and the second replacement about April 15.

### (a) Design of Radiation Chamber

Figures 12, 13, 14, and 15 show the plan, elevation, end and perspective views, respectively, for a potato irradiation chamber using two cooling reactor-fuel elements as a source of radiation. This radiation facility would be operated only about 6 months of the year and shut down for 6 months. This design probably would be preferred by potato growers or a potato-grower cooperative association, as the needs of potato growers for irradiation treatment of their stored potatoes would be seasonal. Therefore, an irradiation facility designed for seasonal operation would be preferred to a facility designed for operation the year around or for a major portion of the year.

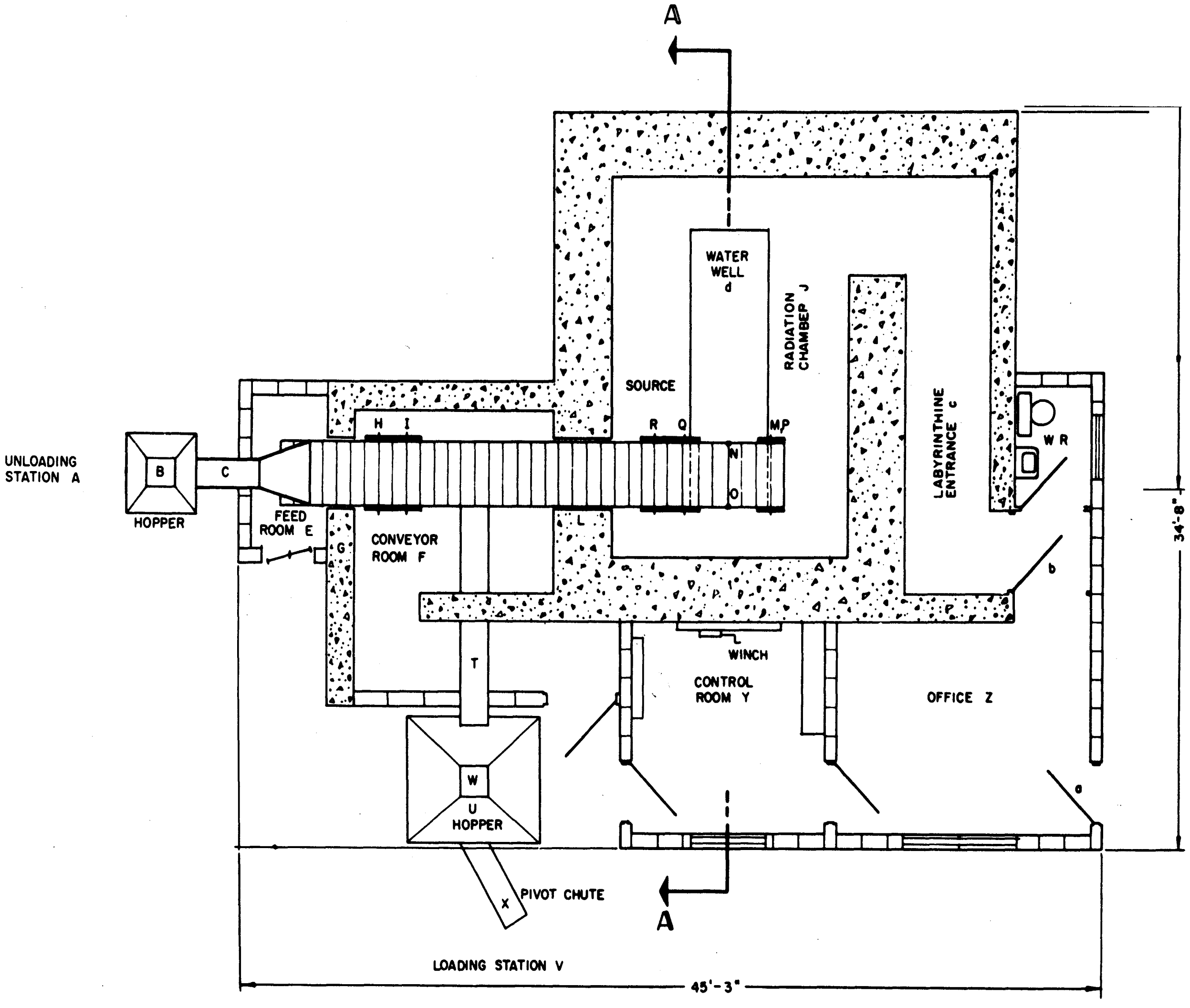


Fig. 12. Plan View of Potato Irradiation Facility Using Cooling Reactor-Fuel Elements.

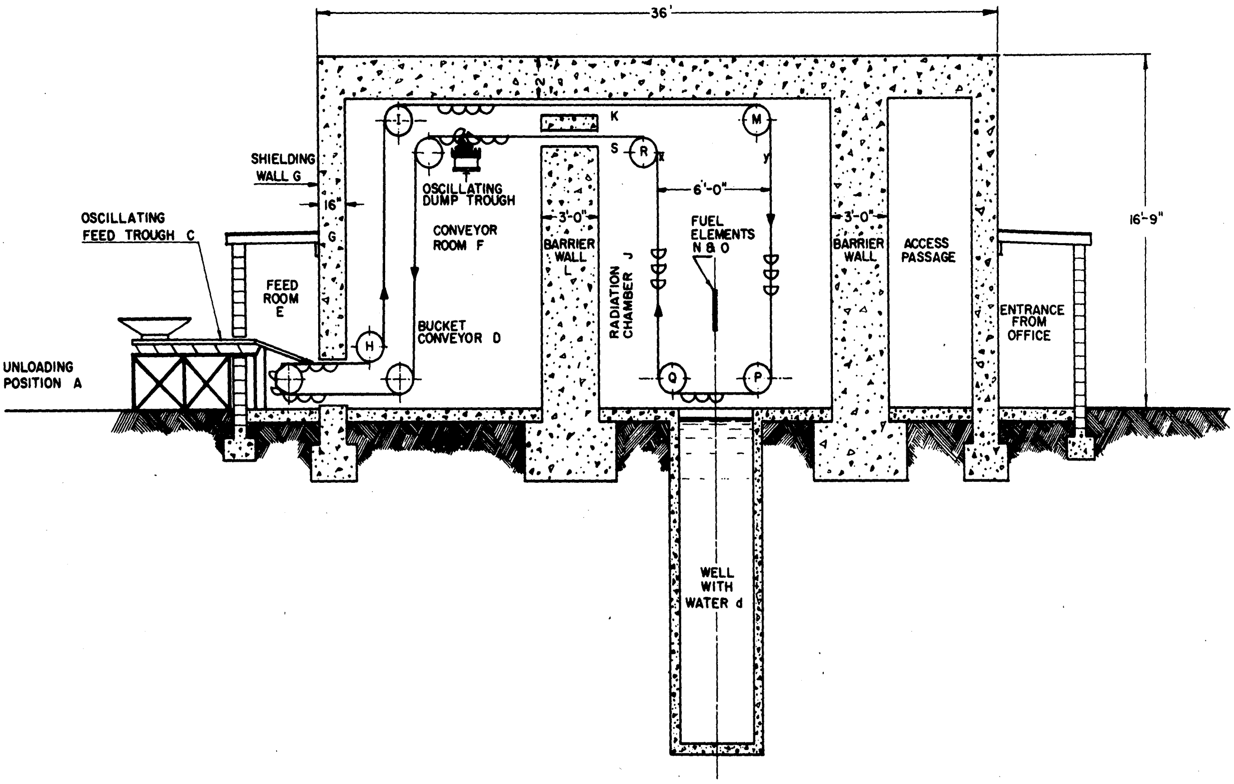


Fig. 13. Elevation View of Potato Irradiation Facility Using Cooling Reactor-Fuel Elements.

Referring to Figs. 12 and 13, potatoes would be brought from storage in either sacks or barrels by the truckload. Trucks would unload potatoes at station A into hopper B. Hopper B would be lined with a cushioning material such as sponge rubber to prevent bruising in this operation. As the load of potatoes is being emptied into hopper B, oscillating conveyor C is put in operation. Potatoes are fed at a maximum rate of 14 tons per hour by oscillating feed trough C in feed room E onto bucket conveyor D. The potatoes then move into the conveyor room F through an opening in the 16-inch shielding wall G. The bucket conveyor becomes a bucket elevator as the chain makes a 90° turn around the sprockets H and then another 90° turn around sprockets I. The potatoes enter the radiation chamber J through slot K in 3'0" barrier wall L. The slots are small so as to minimize the radiation entering the conveyor room from the radiation chamber. The potatoes then pass around sprockets M and down past fuel elements N and O. The conveyor then turns a 90° angle around sprockets P and passes underneath the fuel elements. Another 90° bend brings the conveyor with potatoes around sprockets Q and up past the other side of the radiation source. Irradiating both sides of the buckets in this manner provides a more uniform dosage to the potato. Making another 90° bend around sprockets R the conveyor buckets pass out of the irradiation chamber

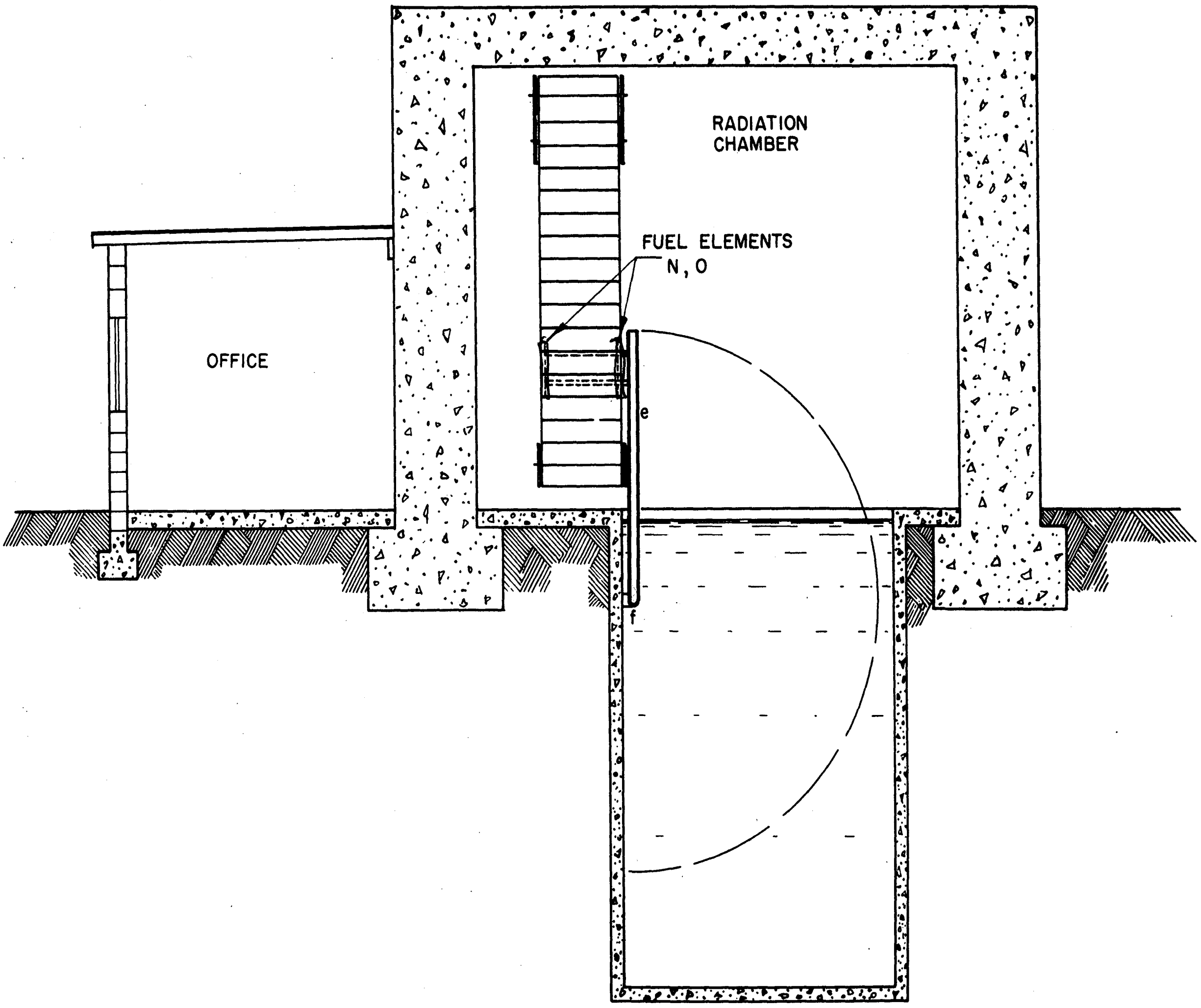


Fig. 14. End View of Potato Irradiation Facility Using Cooling Reactor-Fuel Elements.

through exit slot S. The buckets are tripped by a cam onto the oscillating dump through T and are passed from the conveyor room into hopper U on the loading platform.

During this operation the truck which had unloaded at unloading station A moves down to loading station V and the irradiated potatoes which accumulate in hopper U are reloaded into the truck by opening gate W and use of pivot chute X.

The control room Y shown in the plan view contains a panel board and switches for operating the motors for the conveyors and the solenoids for the hopper gates. Also the winch used to raise and lower the cooling fuel elements is located in the control room. An office Z is shown for use in maintaining records of irradiation services, correspondence, etc.

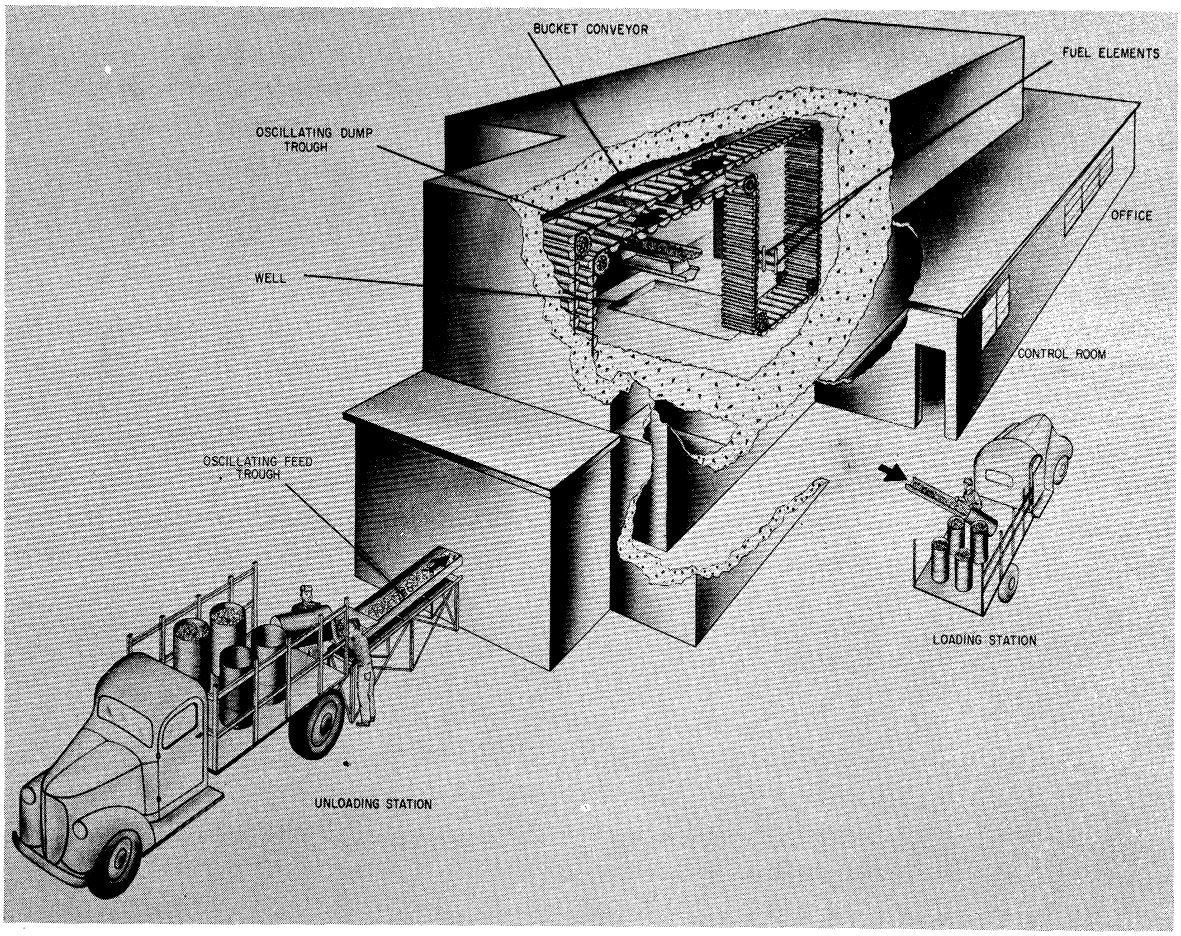


Fig. 15. Perspective Cut-Away View of Potato Irradiation Facility Using Cooling Reactor-Fuel Elements.

Cooling reactor-fuel elements would be shipped in a lead cylindrical container 3'6" in diameter which will be moved by a dolly through the office door a, the cave door b, and into the radiation chamber J by means of labyrinthine entrance C. The shipping container will be lowered into the water well d and the cooling reactor-fuel rods will be removed under water. The shipping container can then be removed from the well and the two fuel elements can be attached to the fuel-element holder shown in the end view. The fuel-element holder is attached to a stainless steel channel e which pivots about bushing t located 3 feet under water.

An interlock between the door to the irradiation cave and the winch operating the lift to the source prevent entrance to the radiation cave when the source is raised; a suitable monitor indicates the position of the source and radiation level in the cave. The barrier wall at the labyrinthine entrance and the three 90° bends in passing from the radiation cave to the cave door reduce the radiation field at the cave door to levels that can be safely tolerated from the standpoint of health physics. The hard gamma radiation passing through slots K and S will result in radiation levels above tolerance for routine operations in the conveyor room. Therefore, the conveyor room is considered to be a low-level radiation cave with 16 inches of concrete used in the outside wall for purposes of shielding. Again the use of a labyrinthine entrance reduces the radiation field at the outside entrance of the conveyor room to a safe level.

The water for the well and for the wash room will either be piped underground to the radiation facility or supplied by a well and a water pump located in the control room. A tool crib is also shown in the control room to provide for a small number of tools such as wrenches and grease-guns, which may be required in the maintenance and servicing of the conveyors and controls.

### (b) Uniformity of Radiation Dose

The high gamma activity of the cooling fuel elements permits the use of a small number of fuel elements as the gamma source. The use of a single element would not be very satisfactory because of the space attenuation of the gamma field and the resulting difficulty in delivering a uniform radiation dose to potatoes conveyed through the radiation field. Proper spacing of two fuel elements results in the addition of the radiation field of one element to the radiation field of the other, which for a limited distance will give a zone of uniform radiation in one direction. If the conveyor moves perpendicular to this line of uniform-radiation field the potatoes distributed across the conveyor will receive a uniform radiation dose.

The gamma flux from cooling fuel elements varies with time and with the original activity. Based on calculations for fuel elements cooled 1 to 5 months it is estimated that a typical cooling element used for 2 months might have a radiation flux of 1 x $10^5$ r/hr at a radius of 3 feet from the midpoint of the element. Using this estimated flux Fig. 16 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 vertical pass. Approximate uniformity of the radiation field at 27" from the axis of the source in the lateral direction is shown by the nearly flat curve. This insures uniform dose to the potatoes independent of their lateral position. Isodose curves were plotted for the plane perpendicular to this direction. Figure 17 shows such isodose curves plotted for this plane which is parallel to the axis of the fuel element and equal distant from both elements.

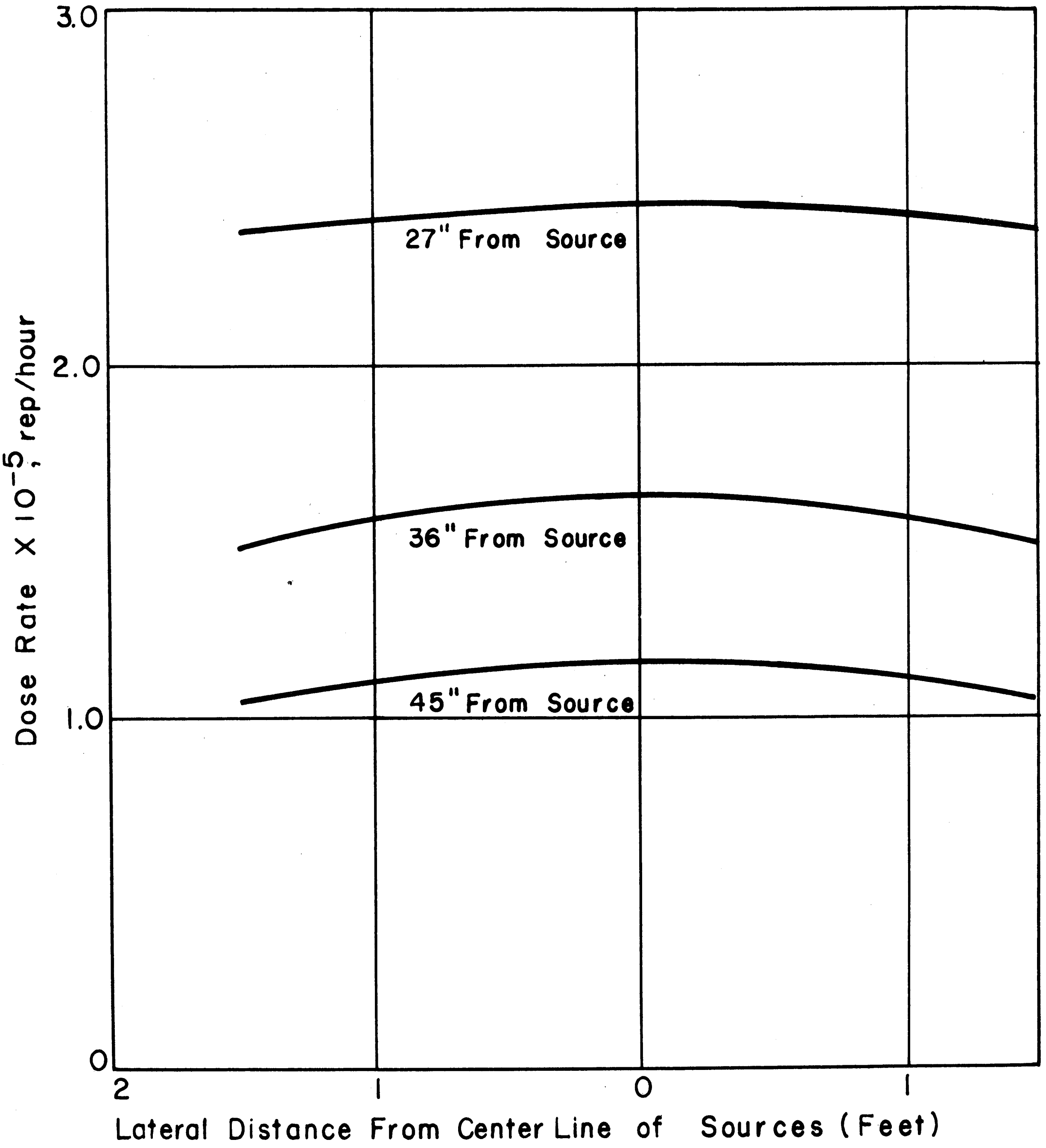


Fig. 16. Radiation Field in a Plane Perpendicular to the Center Lines of Two Parallel Fuel Elements Spaced 3'0" Apart.

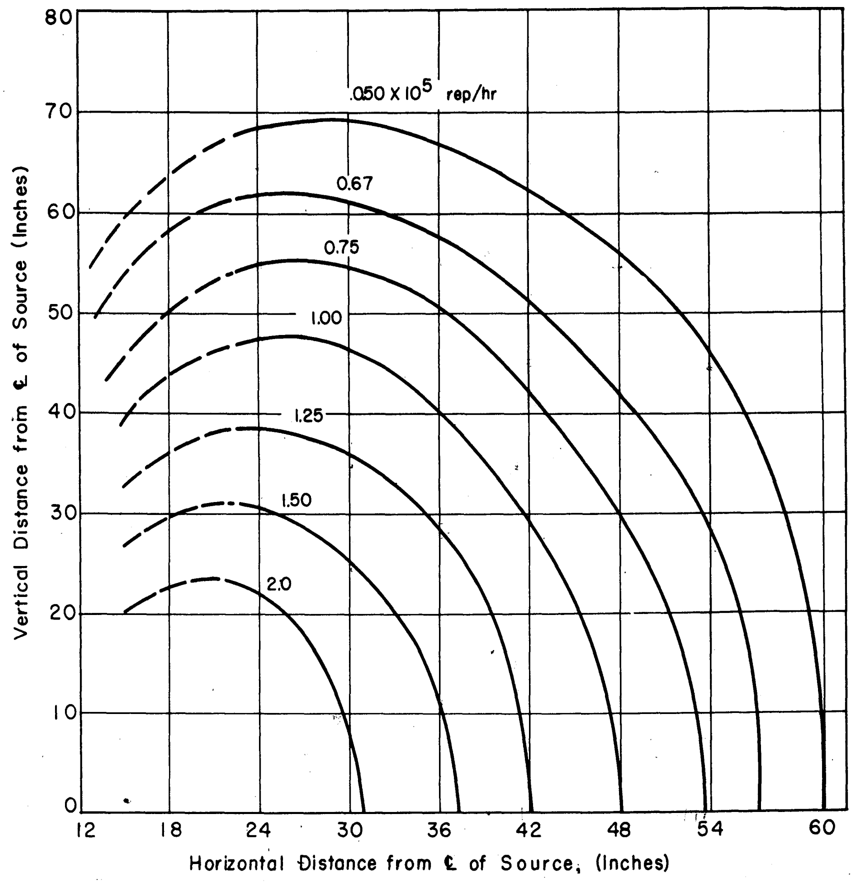


Fig. 17. Isodose Curves (r/hr in Air) in a Vertical Plane Equidistant from Two Parallel Vertical Fuel Elements Spaced 3'0" Apart.

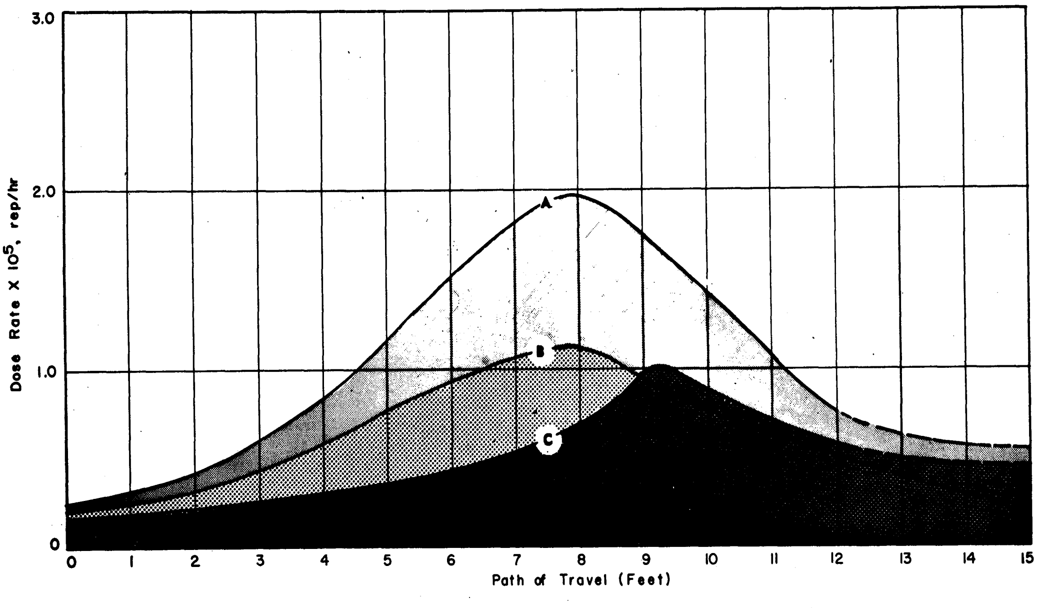


Fig. 18. Dose Rate Received by Potatoes in Three Positions (A-Nearest to Source, B-Center, C-Farthest from Source) as a Function of Distance along Path in Radiation Chamber.

The minimum radiation dose will be received by the potatoes located in the center of the conveyor bucket. Potatoes located on the edge of the bucket facing the fuel elements will receive a higher radiation dose than the potatoes in the center of the bucket as they pass down along the inner traverse because of the shorter distance between these potatoes and the source. However, this will be compensated for, to a large extent, by the lesser dose these same potatoes receive as they travel upwards in a position more distant from the radiation source. The sum of the doses in these two positions will be greater than the dose in the center of the bucket, but this difference will not be great if the bucket is placed a sufficient distance from the source and if the bucket is not excessively wide.

(c) Capacity Calculations

Figure 18 is a plot of the dose rate as a function of distance traveled in the irradiation chamber for 3 potato positions. Position C depicts the dose received by a potato in the furthest position; B, the central position; and A, the nearest position of the bucket to the source. For any given conveyor speed this plot then becomes a plot of dose rate versus time, and the integrated area under the curve becomes the accumulated dose as the potatoes travel through the radiation cave. For equal exposure from either side a potato located at position B would receive the minimum dose equal to twice the area under curve B. The maximum dose for a potato at the edge and exposed from either side is equal to the sum of the areas under curves A plus C.

The area under the curve of Fig. 17 for position B was graphically determined to be $18.0 \times 10^5$ rep ft/hr. Dividing the value of this integral into the dose requirement of 10,000 rep and multiplying by the feet of travel yield the time required for the potatoes to accumulate the specified minimum dose. This time was calculated to be 10 minutes. It is expected that it will be necessary to change the setting of the conveyor speed regulator each week in proportion to the change in radiation flux as a result of decay. A variable speed drive has been specified having a 3 to 1 speed variation to facilitate changing the conveyor speed as required.

The conveyor bucket of conveyor elevator D will have a semicircular shape with a radius of 9 inches and a bucket length between chains of 3'0". The chain will have a pitch of 18 inches. Each bucket will carry an estimated 2.65 cu ft of potatoes in bulk, and using a conveyor speed of 3 ft per minute, a total of 2.65 cu ft buckets x 120 buckets/hr = 318 cu ft/hr, will pass through the irradiation chamber. This capacity is equal to 318 x 0.804 bu/cu ft x 8 hr/shift = 2050 bu/8 hr shift. Since potato growers probably would truck potatoes chiefly during the daylight hours, 2 daily shifts of 8 hours each probably would be desirable and the plant would operate on only a 5 or 6-day week. Thus, the maximum capacity using 2 shifts per day and a 6-day week over 26 weeks would be 2050 x 2 x 6 x 26 = $6.40(10)^5$ bu potatoes/year.

## 10. COST ESTIMATES BASED ON THE USE OF REACTOR-FUEL ELEMENTS 26 WEEKS PER YEAR

### (a) Total Investment

Table C itemizes the cost estimated for the construction of the irradiation facility, not including the radiation source. Since the source is rented the cost of the irradiation facility will be the total investment.

### (b) Operation Costs

Since this installation will be used only 6 months out of the year, it is estimated that the facility should be depreciated over a period no shorter than 10 years. If this radiation facility is operated by a group of potato growers on a cooperative basis, it is believed that 3 employees working 40 hours per week for 26 weeks of the year could operate the installation. One of the employees would be capable of handling routine maintenance, operation, and control; he should have sufficient health-physics training to follow approved health-physics procedures in routine operation and should know what to do in case of any unexpected emergency. The second employee would have the same training and duties and would act as relief for the first employee. The third employee would be expected to answer the telephone and handle the clerical work, such as records, correspondence, etc. Supervision and continuity of operation from year to year could be supplied on a part time basis by an administrator from a potato-growers association or cooperative group.

Table D shows an estimate for the annual costs of operation for a potato irradiation facility operated on the basis described.

### (c) Unit Costs

Based on an expected average operating capacity for a period of 26 weeks of the year this plant might be expected to irradiate $6.40 \times 10^5$ bushels of potatoes per season. With an annual estimated operating cost of $40,940 the cost for irradiation of potatoes is calculated.

## TABLE C

## ESTIMATED COST OF POTATO IRRADIATION FACILITY USING COOLING FUEL ELEMENTS

| | |
|---|---|
| Excavation and shoring for footing and well | $ 800 |
| Concrete for 4' x 10' x 16' well (20 yd at $20/yd) | 400 |
| Reinforcing for well (1000 lb at $0.10/lb) | 100 |
| Asphalt lining for well | 150 |
| Forms for well (1000 bd ft at $100/M) | 100 |
| Labor for forming and pouring well | 600 |
| Concrete for walls and footings (225 yd at $20/yd) | 4,500 |
| Forms for wall (4500 bd ft at $100/M) | 450 |
| Labor for forming and pouring wall | 2,500 |
| Concrete for floor (30 yd at $20/yd) | 600 |
| Reinforcing for floor (500 lb at $0.10/lb) | 50 |
| Labor for pouring floor | 250 |
| Concrete for roof (50 yd at $20/yd) | 1,000 |
| Forms for roof | 800 |
| Reinforcing for roof (4000 lb at $0.10/lb) | 400 |
| Labor for forming and pouring roof | 800 |
| Lift mechanism for source | 1,500 |
| Ion-exchange system for well water | 3,000 |
| Monitoring equipment | 4,000 |
| Unloading hopper | 400 |
| Loading hopper | 800 |
| Oscillating feed trough | 1,000 |
| Oscillating dump trough | 1,000 |
| Bucket conveyor L | 6,000 |
| Bucket conveyor drive (3 P variable speed) | 1,000 |
| Washroom fixtures | 200 |
| Office furniture | 400 |
| Maintenance tools and supplies | 200 |
| Heating and ventilating | 1,200 |
| Access doors (with safety interlock) | 1,400 |
| Road grading | 600 |
| Wiring | 400 |
| Water lines and labor for pipe fitting | 800 |
| Backgrading | 200 |
| Painting | 600 |
| Subtotal for labor and materials | 38,200 |
| Miscellaneous contingencies (10% of subtotal) | 3,820 |
| Engineering costs (7% labor and materials) | 2,670 |
| Contractors fee (10% of costs) | 4,470 |
| Total | $49,160 |

see note 1

## TABLE D

## ESTIMATED ANNUAL OPERATION COSTS FOR POTATO IRRADIATION FACILITY USING COOLING REACTOR-FUEL ELEMENTS AND OPERATING SIX MONTHS PER YEAR

$5000

| | | |
|---|---|---|
| **Wages and Salaries** | | |
| Two operators with limited health-physics training (Full time for 6 months per year--$10,000 year) | $5,000 | |
| Supervision and clerical labor (10% of operational labor at full salary) | 1,000 | |
| Salaries and wages not associated with operation of radiation chamber (50% of direct labor and supervising costs) | 3,000 | |
| | | $ 9,000 |
| **Other Operation Costs** | | |
| Shipping costs for fuel elements 3 x 200 (every 2 months) | 600* | |
| Handling costs for fuel elements during transfer and installation 3 at $1,000 | 3,000 | |
| Rental of two fuel elements (nominal charge assumed) ($500/mo)(6 months) | 3,000 | |
| Repairs and maintenance on chamber and conveyor (5% of chamber and conveyor cost) | 2,460 | |
| Miscellaneous contingencies | 1,000 | |
| | | $10,060 |
| **Overhead** | | |
| Payroll overhead (15% of cost of labor and supervision) | 1,350 | |
| General plant overhead (50% of cost of labor and operations) | 9,530 | |
| General administration overhead (10% of cost of labor and operation) | 1,910 | |
| | | $12,790 |
| **Taxes, Interest, Insurance** | | |
| Property tax (2% cost of radiation chamber) | 980 | |
| Income tax (2-1/2% of total investment) | 1,230 | |
| Interest (5% of total investment) | 2,460 | |
| Insurance (1% of total investment) | 490 | |
| | | $ 5,160 |
| **Depreciation, Obsolesence** | | |
| Radiation chamber (49,160 x 0.08) | 3,930 | |
| | | $ 3,930 |
| | | $40,940 |

* For facility at Idaho Falls, Idaho.

Cost per bushel to be added to potatoes for a dose of 10,000 rep using 2 cooling reactor-fuel elements 26 weeks of the year will be

$$\frac{\$40,940}{6.40(10)^5} = \$\ .064/\text{bu.}$$

Using a bulk density of 42 lb/cu ft the cost per ton will be

$$\frac{\$.064(2000)}{0.804(42)} = \$3.78/\text{ton.}$$

## 11. COST ESTIMATES BASED ON THE USE OF REACTOR-FUEL ELEMENTS 260 DAYS PER YEAR

These unit costs based on the use of fuel elements for 156 days per year are slightly less than the case of using cesium-137 for 260 days per year. If, however, this facility were operated with fuel rods for 260 days per year the annual capacity will be increased to 1.06 $(10)^6$ bu/yr which is only slightly less than for the design using tray conveyors with 2 passes on either side of the source. The estimated annual operating cost is given in Table E.

TABLE E

ESTIMATED ANNUAL OPERATION COSTS FOR POTATO IRRADIATION FACILITY USING COOLING REACTOR-FUEL ELEMENTS AND OPERATING 260 DAYS PER YEAR

| | |
|---|---|
| 1. Wages, salaries | $16,500 |
| 2. Other operation costs | 16,880 |
| 3. Overhead | 22,550 |
| 4. Taxes, interest and insurance | 5,160 |
| 5. Depreciation, obsolesence | 3,930 |
| | $65,020 |

In Table E the estimated costs for wages and salaries (1) are the same as for the mixed-fission product and the cesium-137 facilities. The estimated costs for taxes, interest, and insurance (4) and depreciation and obsolescence (5) are lower for the fuel-element facility than for both the cesium-137 facility and the mixed-fission-product facility because of the lower total investment in the source. However, the other estimated operation costs (2) for the fuel-element facility are greater than for the cesium-137 facility because of the added costs for replacement for the fuel elements. The net result is a slightly lower estimated annual operating cost using fuel elements ($65,020/yr) than using cesium-137 ($74,700).

Based on a minimum dose of 10,000 rep, 260 operating days per year, an annual irradiation capacity of $1.06\ (10)^6$ bu/yr, and on an annual operation cost of $65,020/yr the following costs are estimated.

Cost per bushel to be added to potatoes for a dose of 10,000 rep using 2 cooling reactor-fuel elements 260 days/yr will be

$$\frac{\$65{,}020}{1.06(10)^6} = 0.061$$

Using a bulk density of 42 lb/cu ft the cost per ton will be

$$\frac{\$0.061(2000)}{0.804(42)} = \$3.62/\text{ton}.$$

## 12. DISCUSSION

Based on a radiation dose of 10,000 rep, an operation schedule of 260 days per year, and plant amortization over a 10-year period, the estimated minimum cost for irradiation of potatoes is $3.62 per ton when using two cooling reactor-fuel elements as a source of radiation. If cesium-137 were used as the source of radiation the estimated cost would be about 15 percent greater or $3.91 per ton. If two-year-old mixed fission products were used the estimated cost would be about 36 percent greater or $4.98 per ton. However, if greater than 10% variation in radiation flux were permitted this cost might be reduced to less than that based on cesium-137.

For an irradiation season of 26 weeks per year rather than 260 days per year the minimum estimated irradiation cost (using fuel elements) is increased 4 percent to $3.78 per ton.

These costs are slightly higher than costs for chemical treatment to prevent sprouting of potatoes. The approximate cost of applying a dust of the methylester of naphthalene acetic acid is $2.50 per ton of potatoes treated.[9] Maleic hydrazide can be applied as a spray to plants in the field at a cost of about $15 per acre.[9] For a moderate yield of 10 tons per acre this corresponds to a cost of $1.50 per ton. Irradiation of potatoes for the dose given would probably cost at least twice as much as chemical treatment. However, irradiation at this level would result in a very uniform treatment believed to be superior in uniformity to a chemical treatment. If cost is a controlling factor the dose might be reduced by as much as 50 percent, resulting in an irradiation treatment anticipated as being competitive with chemical treatment both with regard to cost and probable uniformity of product.

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