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DESIGN OF A RAILWAY MOBILE GAMMA
SOURCE FOR INDUSTRIAL IRRADIATIONS

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PREFACE

This preliminary design of a railway mobile irradiation unit is based on a report by Messrs. G. Gyorey, D. Harnsberger, and R. Treviño submitted as a solution to a student problem in Course 193 in Nuclear Engineering at The University of Michigan.

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ABSTRACT

A design has been developed for a railway mobile gamma-irradiation facility. The estimated capacity with 10 MTR fuel elements cooled for 40 days is 10 tons/hr with a 10,000-rep dose. This more than meets the army commitment of "a facility ready to process 1000 tons per month by 1958." This production results from more efficient absorption of gamma photons and use of a simple flexible conveying system. Cost has been minimized by using hot-rolled mild-steel mill plate 2 inches thick for shielding. Shielding thickness is varied from 4 inches to 16 inches by varying the number of plates with the radiation field. The steel shield is used to carry the carload, eliminating the structural undercarriage in the car. Double trucks are attached directly to the steel shield which acts as the car frame. The total car weight is estimated to be 173 tons. Fuel elements are kept in two water-cooled lead pigs weighing about 4 tons each and located on either side of the car. Fuel elements are kept submerged in a shallow 6-inch water trough during use but all irradiation is performed in air. A gear box on the conveyor drive permits variation of conveyor speed to allow delivery of dosages from a few thousand rep to several million rep. Capacity can be increased by using more 40-day-old MTR fuel elements or up to about 100-tons/hr maximum by using fuel elements or cesium sources with greater activity. Plans exist to build this unit and place it into operation within the next two years.

OBJECTIVE

To present a design of a mobile gamma-irradiation facility feasible at present both from the basis of economics and availability of gamma sources. It is proposed that this preliminary design be completed in detail and that such a facility be constructed and operated as a demonstration unit for industry by 1958.

I. INTRODUCTION

A. THE PROCESS OF IRRADIATION

A great number of studies recently completed or now in progress at various laboratories clearly indicate that gamma irradiation can increase the utility or economize the production of a great variety of commodities. It is safe to predict that as nuclear reactors in the United States increase in number, the process of gamma irradiation will become an integral part of the industry of the United States. On the basis of research performed to date it would appear that the impact of this new process of gamma irradiation may be greatest on the food industry.

In order to present the advantages that can be derived from the irradiation of foods, a short review is presented here of the results of research performed in this field at the Fission Products Laboratory of the Engineering Research Institute at The University of Michigan. The process in which food is subjected to such doses of gamma radiation which do not completely sterilize, that is, do not destroy all the microorganisms found in the food, is referred to as radiopasteurization.^{1,2} A high radiopasteurization dose of about one million roentgen equivalents physical (1 megarep) given to seafood, meats, and vegetables extends their storage life at room temperature several fold, and their unfrozen, refrigerated storage life to long periods of time.^{3,4} Medium radiopasteurization in the neighborhood of 100,000 rep still reduces the population of microorganisms in foods by over 90% and extends refrigerator shelf-life appreciably.^{5,6,7} A process that is very promising, and which might be the first approved by the Food and Drug Administration, is a subradiopasteurization dose of about 10,000 to 20,000 rep. A dose of this magnitude will not destroy a sufficient fraction of microorganisms found in fresh foods to affect appreciably the storage life. However, such a dose will inhibit sprouting in potatoes and onions.^{8,9,10,11} It will sterilize insects infesting grain and cereal products,^{12,13,14} and will sterilize eggs and larvae of the Mexican fruit fly in fruit from infested areas of the United States (such as certain areas of Texas), thereby preventing spread of the infestation.* Also, such a dose

*Shown by present studies at the Fission Products Laboratory.

will, through reproductive sterilization, break the cycle of trichinosis in pork and similarly control tapeworm in beef, pork, and fish, and a number of other diseases caused by parasites.^{14,15,16,17,18} At present, several types of food, such as certain tropical fruits, are banned as U.S. imports because of possible insect infestation. This ban could be lifted for foods given subradiopasteurizing doses which would render them free of contamination.

A design is presented for a gamma-irradiation unit which is capable of handling the irradiation of a wide variety of products at any desired dosage, and which is particularly well suited to subradiopasteurization of foods.

B. ADVANTAGE OF A MOBILE GAMMA-IRRADIATION UNIT

The types of products best suited to subradiopasteurization are very often those that are produced in crops of a seasonal nature. In addition to this, the harvest seasons occur at different times of the year in different parts of the country; therefore, the problem is geographic as well as seasonal. A mobile facility is thus an ideal means of providing for irradiation treatment of crops at the location where they are to be stored immediately after harvest. In this manner the entire crop of one locality can be treated and the mobile unit then moved to some other part of the country for treatment of another harvest crop, thus keeping it in more or less continuous use, resulting in a lower operating cost per unit of product irradiated.

At times when harvests are slack, a mobile unit is again advantageous in that it can be taken to a seaport or border city and used for the irradiation of imported foods that would otherwise be restricted by quarantine.

A mobile unit would also be of a very great public-service value as a general device for demonstration of the advantages of irradiation treatment of foods.

C. PRELIMINARY DESIGN CONSIDERATIONS FOR A MOBILE UNIT

A brief review of cost considerations indicates that high-capacity facilities will, in general, give lower unit costs for subradiopasteurization methods because shielding and source costs do not increase in proportion to capacity requirement. As high capacity and low unit cost are considered to be of prime importance in a prototype unit, highway transportation is not considered desirable due to weight limitations. River transportation is not considered desirable due to geographical limitations. As rail-mounted vehicles have reasonably high allowable weights, and rail lines extend to

nearly all parts of the country where storage and processing facilities are located, a railroad car is considered to be the best means of transporting a mobile irradiation unit.

Deciding on a rail-mounted unit imposes three interdependent limitations that will determine the ultimate capacity; namely, (1) maximum weight allowance (limits the maximum amount of shielding that can be carried and, consequently, the maximum source strength), (2) outside dimensions of the car (determines volume inside of shielding usable for irradiation), and (3) conveyor speed (must be slow enough to allow easy loading and unloading). Thus the design must include a combination of shielding configuration, source strength, and conveyor size which is consistent with weight, size, and conveyor speed limitations.

The radiation field and conveyor arrangement should be such that a uniform field will exist at right angles to the direction of conveyor travel, in order that all material passing through the conveyor system will receive a very nearly equal dose of radiation. This will also require that the conveyor pass on both sides of the source, so that all layers of absorber will be irradiated as uniformly as possible.

II. THE RADIATION SOURCE AND FIELD

A. THE RADIATION SOURCE

On the basis of the preliminary considerations described in the previous section, the source selected for this irradiation unit consists of ten separate source elements. Each of these elements is of uniform cross-section and of two-foot equivalent length enclosed in a suitable metallic jacket. The fuel element proposed to be used is the MTR fuel element as shown in Fig. 1. This figure is from a report by Francis and Marsden.¹⁹

A detailed description including fabrication methods for the MTR fuel element was given by J. E. Cunningham and E. J. Boyle at the Geneva Conference.²⁰ This information was summarized in the "Catalog of Nuclear Reactors" by AECL²¹ and this summary is quoted as follows:

"Because of the large number of reactors employing this type of fuel element, a description of its general features is given here. For details of the variations encountered, see the particular reactor (MTR, LITR, BSF, CP-5, BORAX I and II, Convair, and GCR were known to be thus equipped in August, 1955. Others in this class but not yet operating at that time were: Pennsylvania State University, Michigan Memorial-Phoenix, Oak Ridge Research, Battelle Memorial Institute, Brookhaven Medical Research Facility, Livermore,

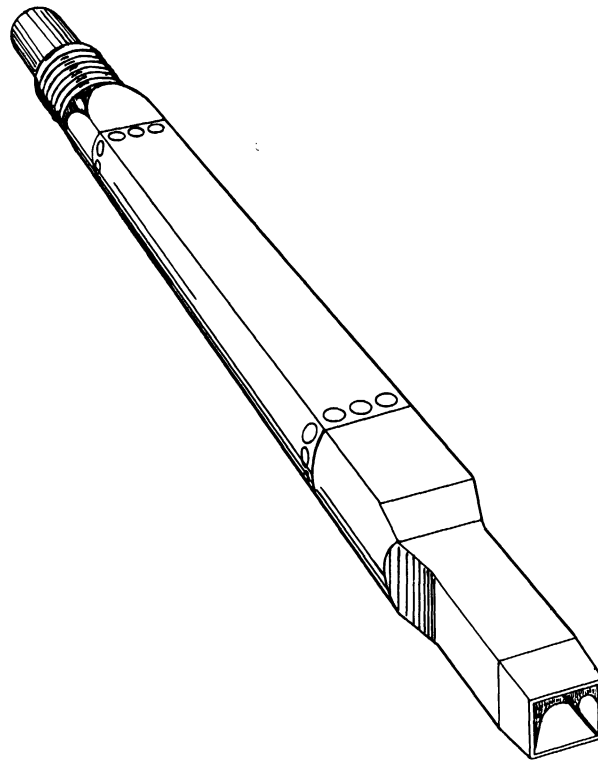


Fig. 1. MTR fuel assembly.

Watertown Arsenal, U.S. Naval Research Laboratory, and others in the planning stage.

"Each fuel element is assembled from a number of long thin plates (usually 18 or 19) measuring 24 in. in length, 3 in. in width, and about 0.06 in. in thickness. An end-on view of the plate shows that its transverse section is curved on a 5.5-in. radius to give it the shape of a shallow trough with a width slightly less than 3 in.

"An appropriate number of these plates are brazed into parallel grooves in thick aluminum side-plates, giving each element the configuration of a venetian blind with approximately 0.1-in. spacing between adjacent slats (plates). Cooling water flows longitudinally through the element in these spaces, and in some versions, a "comb" is inserted down the centre of the element parallel to the side plates to give extra rigidity.

"The assembled element is therefore 3 in. wide x 3.17 in. deep x about 3 to 4 ft long. The extra length is due to end fittings which plug into the reactor lattice grid and which provide a means for handling.

"Individual plates consist of a uranium-aluminum core, clad in wrought 72-S aluminum by hot-rolling to achieve a good metallurgical bond. The

active core is about 2.5 in. wide and 0.02 in. thick, and the total thickness of the "sandwich" is 0.05 to 0.06 in. (The two outermost plates of each element are sometimes given thicker cladding to yield a total thickness of 0.065 in.) Cores containing highly-enriched U^{235} (greater than 90%) are prepared by alloying 10 to 20 weight % of uranium with high-purity aluminum. Cores containing 20%-enriched uranium require a total uranium content of 50 to 60% and are prepared using powder-metallurgy techniques with UO_2 ; these cores are slightly thicker than 0.02 in. Total U^{235} per element may be from 140 to 200 gm; i.e. 8 to 14 gm per plate.

"It is said that MTR-type fuel elements containing five plates are available from Oak Ridge for \$120 each."

When the fuel elements are first removed from the reactor they have a very high gamma activity. However, they decay at a rapid rate when first removed, losing about half their initial activity before two days of cooling. After three weeks of cooling, their activity has decreased by a factor of approximately 10. Figure 2 shows this decay as a plot of the average gamma dose rate vs time after shutdown. This figure also is taken from the report by Francis and Marsden.¹⁹

In selecting a fuel element as a radiation source some compromise must be made between radiation intensity and the average half-life. If a very young fuel element is selected, it will have a high activity but will decay so rapidly as to make it difficult to maintain a sufficiently uniform radiation field for any appreciable length of time.

Another problem exists in the heat removal from the spent fuel elements both during shipping and during use as radiation sources. The heat from spent MTR fuel elements is shown in Fig. 3 (also from report by Francis and Marsden¹⁹).

As a compromise, fuel elements having an average age of 40 days after reactor shutdown were selected. Referring to Fig. 2, it is estimated that such fuel elements would have an average activity of 4.9×10^5 r/hr measured through water at a distance of three inches.

It is hoped that the procedure of using identical fuel elements in various configurations and numbers to make up the different radiation sources required by different irradiation processes will become widespread, so that the wide variety of radiation-source needs of industry will be satisfied by just a few types of efficiently mass-produced spent fuel elements or radioisotope sources having the same dimensions.

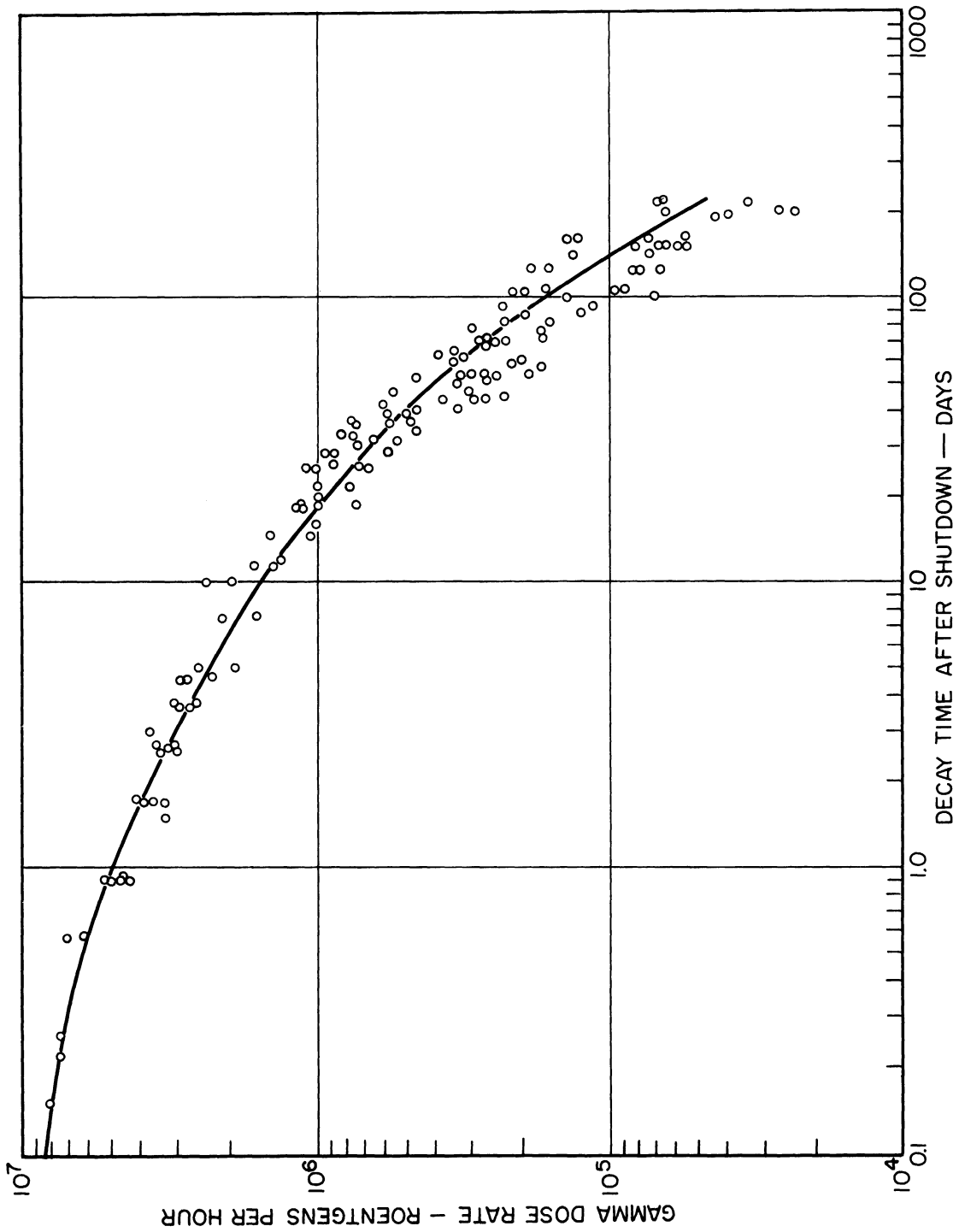


Fig. 2. Average gamma dose rate of MTR spent fuel elements vs time after shutdown.

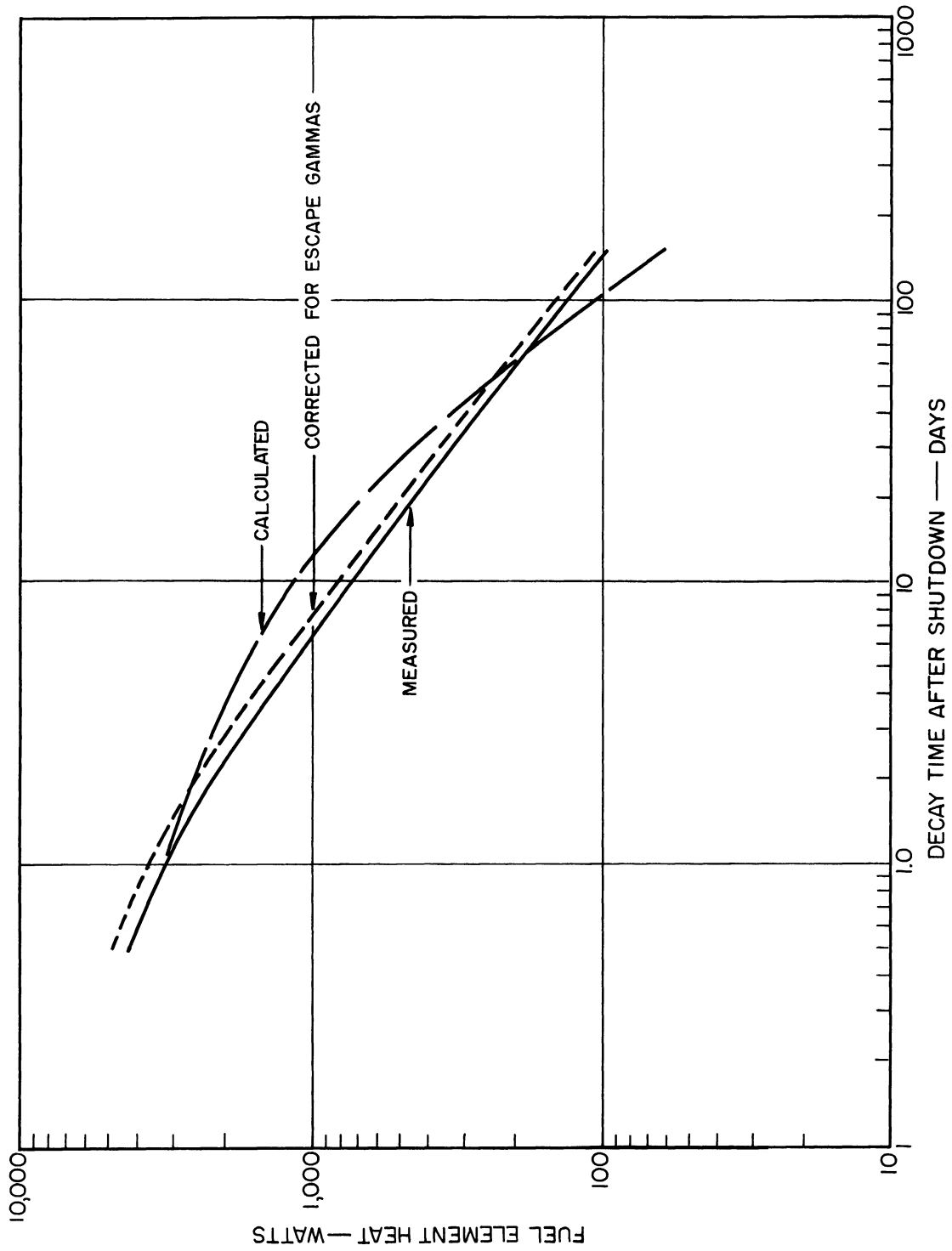


Fig. 3. Heat production from spent MTR fuel elements.

B. THE MAPPING OF THE RADIATION FIELD

For purposes of reference a coordinate system as shown in Fig. 4 was established. In order to facilitate the calculation, the variation of the field strength with distance from the midpoint of one element was calculated, using the following relationship:

$$I = k \int_{z-z_1}^{z-z_2} \frac{dz}{x^2 + (y-y_1)^2 + z^2}$$

or

$$I = \frac{k}{\sqrt{x^2 + (y-y_1)^2}} \tan^{-1} \left[\frac{z}{\sqrt{x^2 + (y-y_1)^2}} \right]_{(z-z_1)}^{(z-z_2)} \quad (1)$$

where (x,y,z) are the coordinates of the field point, dose rate I is to be determined, and $(0,y_1,z_1)$ and $(0,y_1,z_2)$ are the coordinates of the end points of the source element. The curve between dose rate vs distance from the source element is shown in Fig. 5. This curve was normalized to 4.9×10^5 r/hr at a distance of three inches through water, so as to correspond with the experimental dose rate for MTR fuel element cooled for 40 days as reported by Francis and Marsden.¹⁹ The value of k using the above normalization dose rate is equal to 4.6×10^4 .

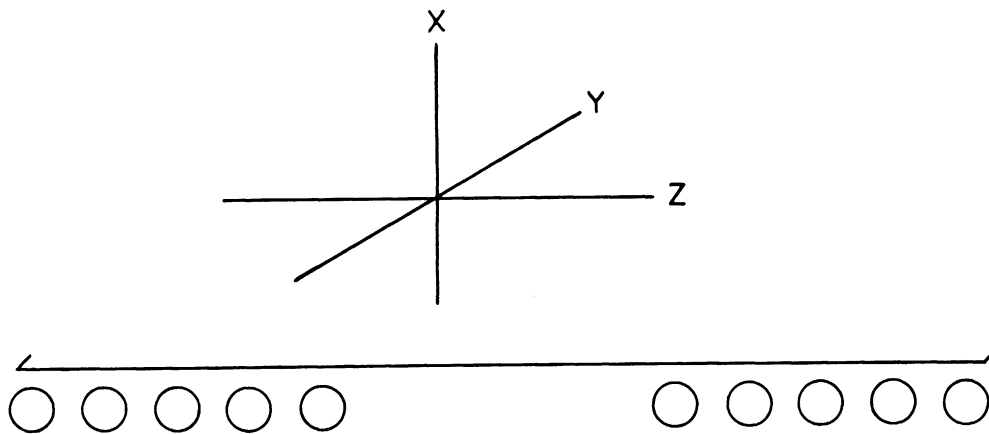


Fig. 4. The coordinate system.

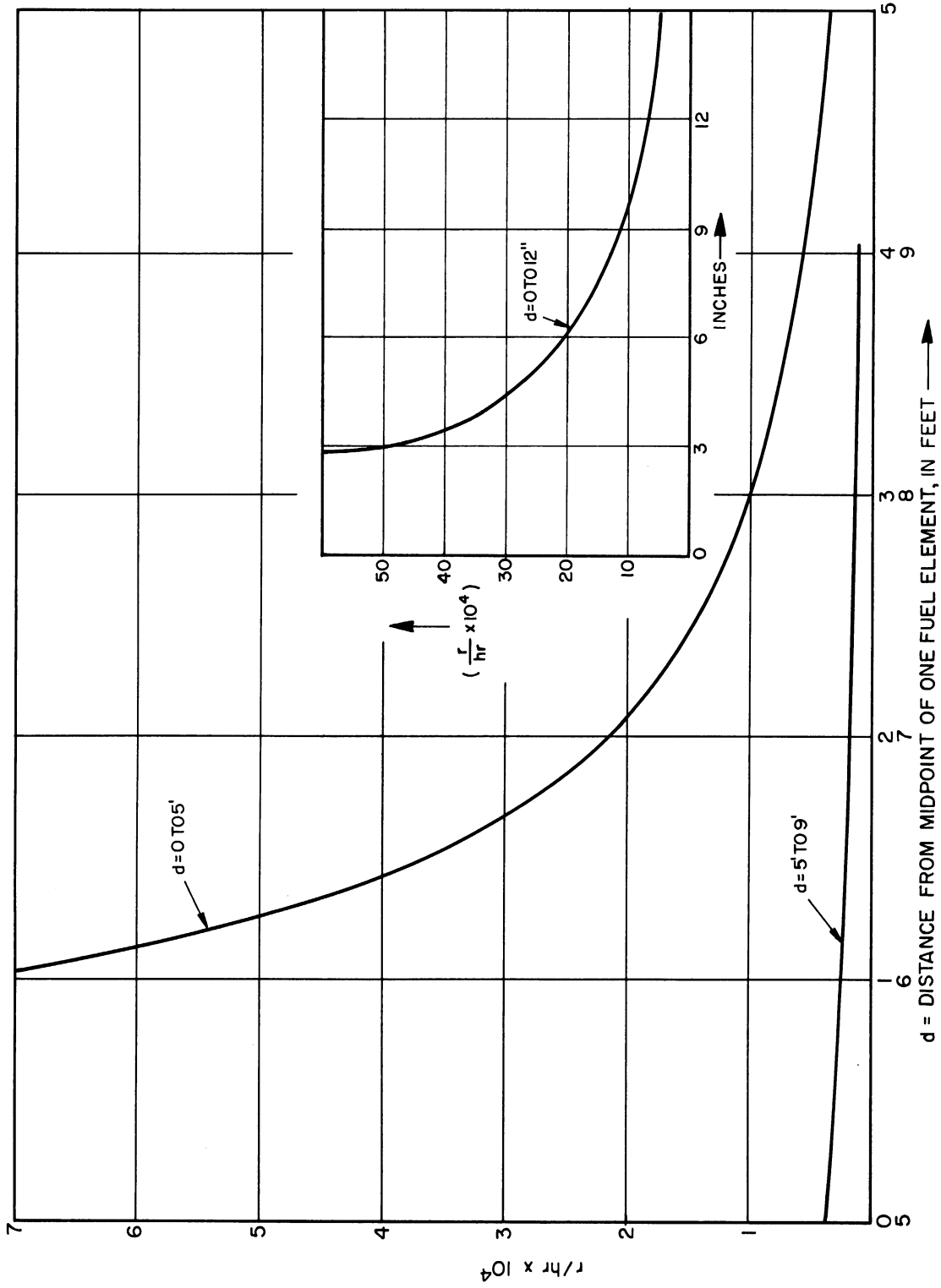


Fig. 5. Variation of field strength with distance from midpoint of uniform 2-foot-rod source, normalized to 10^4 r/hr at 3 feet.

The field strength at any point was calculated by summing the contributions due to ten elements, neglecting self-absorption. Elements had been arranged in a group of five separated by an optimum distance. This optimum spacing had been obtained by trial-and-error method so as to produce a fairly uniform dose along the y-axis. Final spacing is shown in Fig. 6. Although it might be possible to replace the group of five elements by a single element with a still higher activity, this is not considered desirable as the source elements can be used much more economically by replacing them in pairs, one in each group, when needed. In the case of replacement, a pair of elements with stronger activity can be installed to make up for the depleted activity of other elements.

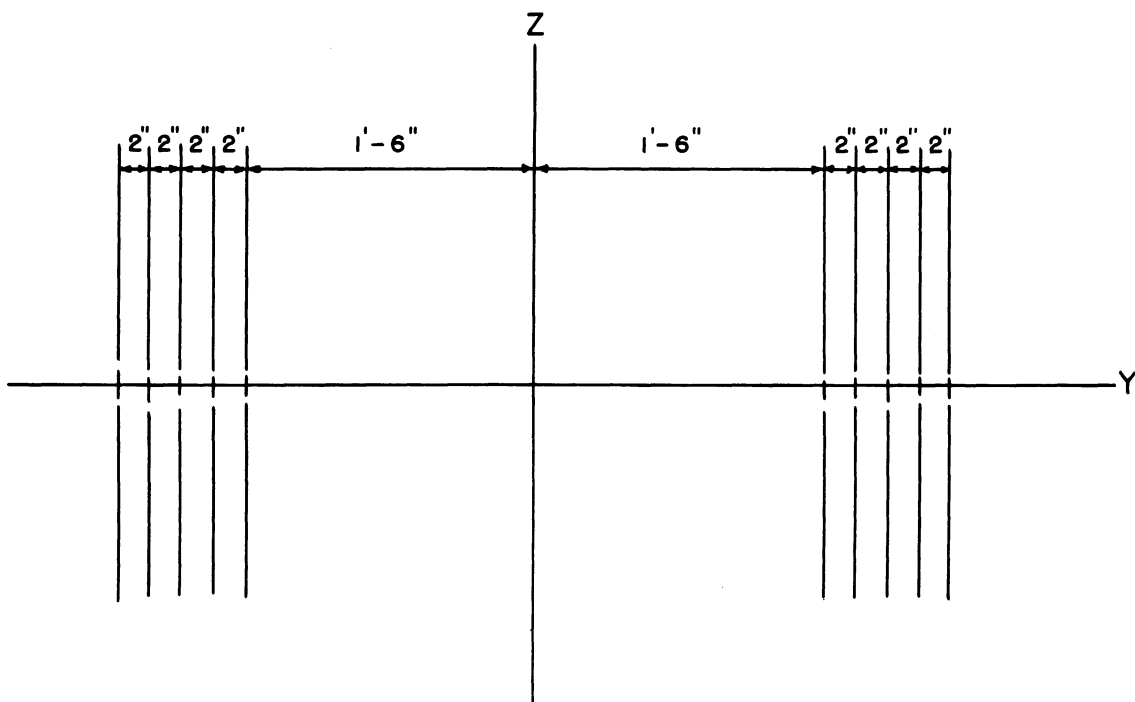


Fig. 6. The spacing of the source elements.

In order to obtain the isodose curves and dose distribution throughout the conveyor at different points, the following curves were prepared:

- Dose rate vs x for different values of z for the case $y=0$ (Fig. 7).
- Dose rate vs x for different values of z for the case $y=1$ foot (Fig. 8).
- Dose rate vs x for different values of z for the case $y=2$ feet (Fig. 9).

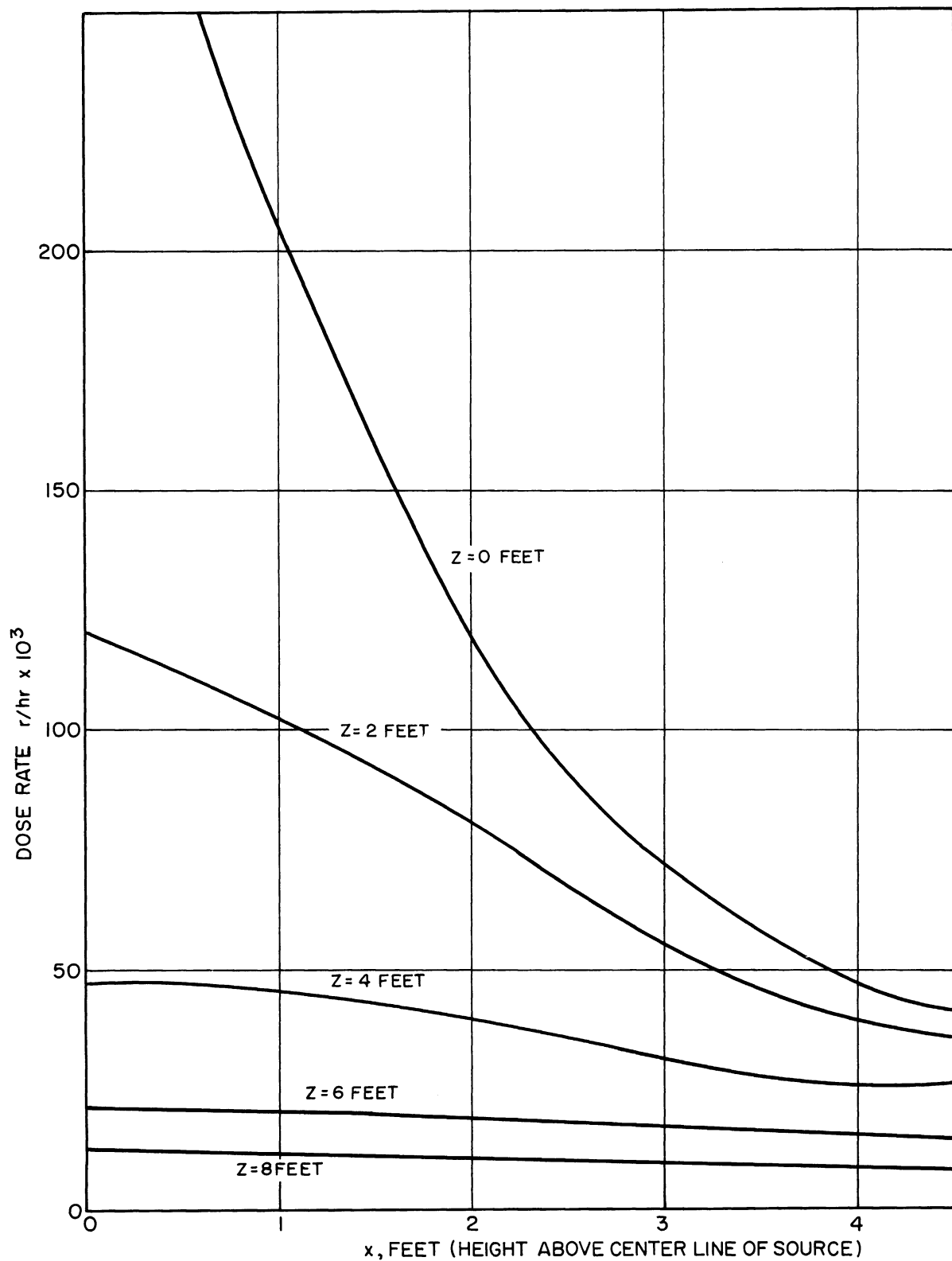


Fig. 7. Dose rate vs x for different values of z for the case $y=0$.

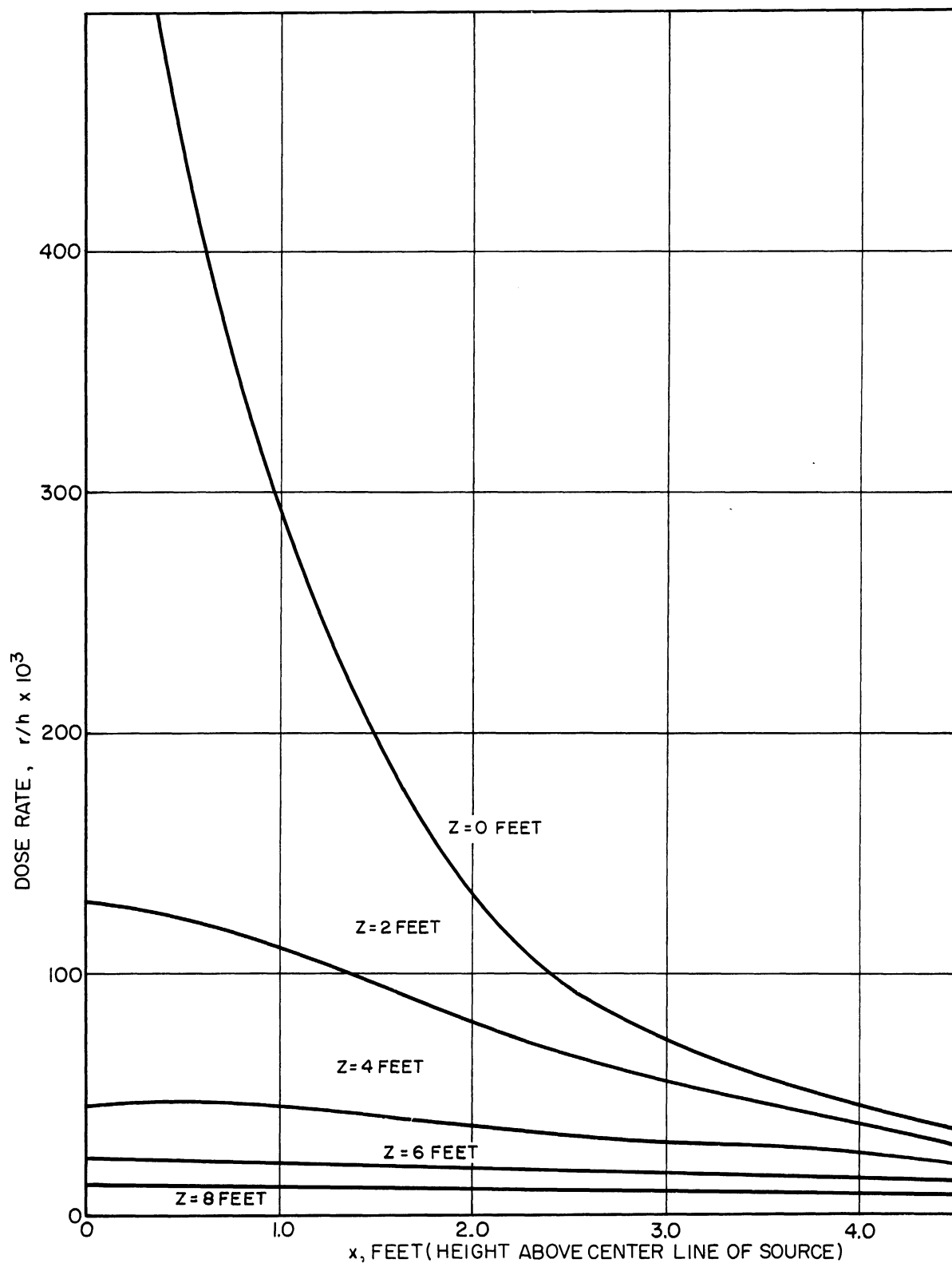


Fig. 8. Dose rate vs x for different values of z for the case $y=1$ foot.

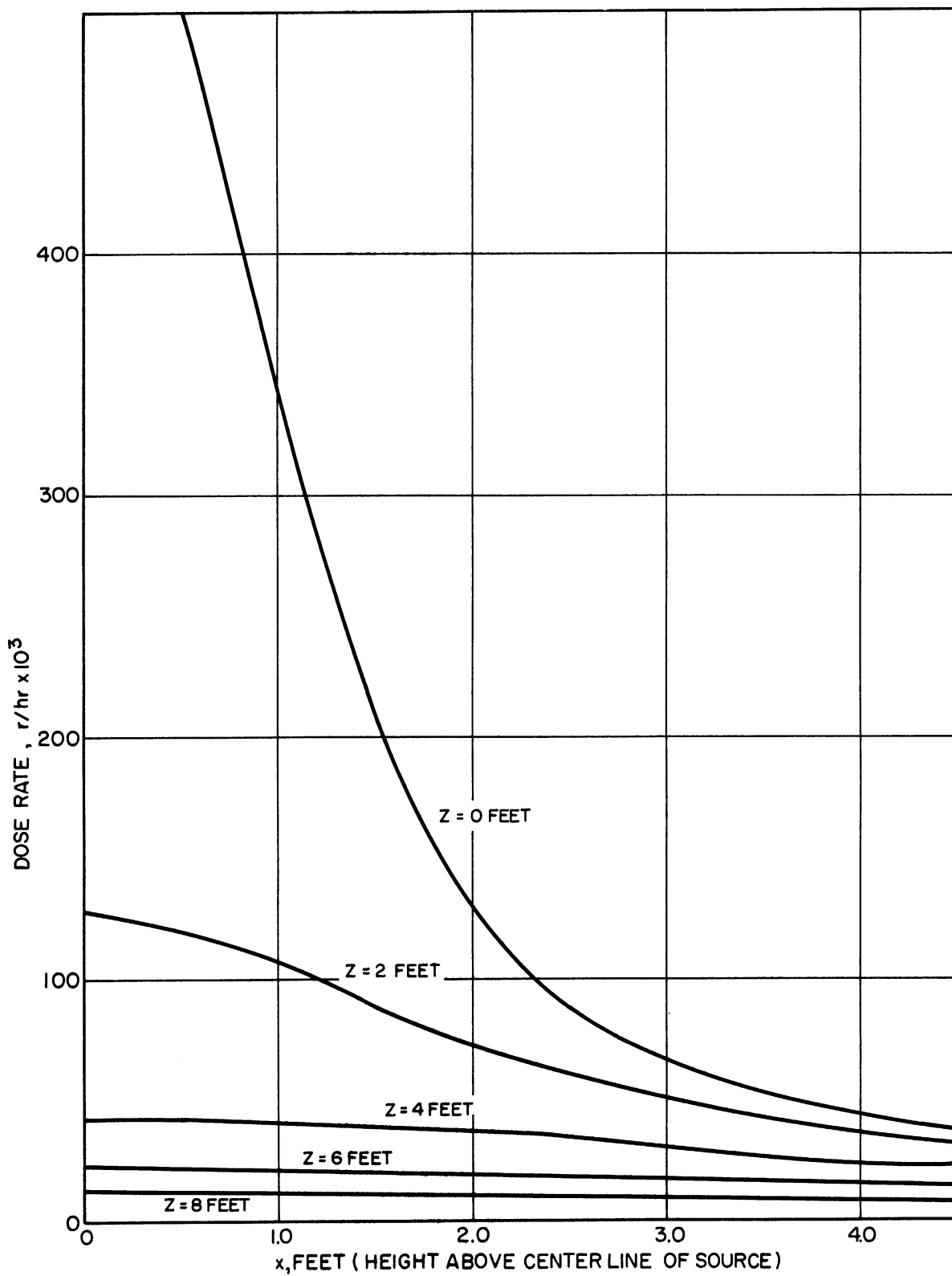


Fig. 9. Dose rate vs x for different values of z for the case $y=2$ feet.

These curves were utilized to obtain the isodose curves in (x-y) vertical plane for different values of z and the dose-rate distribution throughout the conveyor as shown in Figs. 10, 11, and 12. Dose distribution and isodose curves obtained in Figs. 10, 11, and 12 indicate the nonuniformity of dose. Inside the two conveyor paths shown by the two rectangles points of maximum and minimum dose distribution exist. For small distances from the fuel elements the isodose curves exhibit a dip in dose rate. The dip becomes sharper as the source elements are approached. For the case of the isodose curves with the dip, the minimum value occurs at $y=0$, and the maximum value is at $y=1.5$ feet. Away from the source, the isodose curves indicate a fairly uniform dose distribution along the y-axis.

C. ABSORPTION CORRECTION

The dose-rate distributions shown in Figs. 10, 11, and 12 were corrected for absorption by material inside the conveyor. It was assumed that the conveyor trays are filled with 10 inches of material and that this thickness attenuates the gamma rays by 50%. This is an average of experimental values obtained for the bulk potatoes and similar foods¹⁰. The absorption coefficient using this half-value thickness can be termed as broad-beam coefficient; it includes the correction due to build-up factor arising from the multiple scattering inside the material.

$$\mu = \frac{0.693}{T_{1/2}}$$

$$\mu = \frac{0.693 \times 6 \text{ feet}^{-1}}{5}$$

$\mu = 0.832 \text{ feet}^{-1}$

Dose-rate distributions corrected for absorption are shown in Figs. 13, 14, and 15.

III. SHIELDING

A. FOR HIGH-FLUX SOURCE ELEMENTS ($I = 10^4$ r/hr at 3'0")

The first consideration in the design of the shielding was an appropriate choice between steel and lead. In this case steel can be shown to be more economical for the shielding of the irradiation chamber whereas

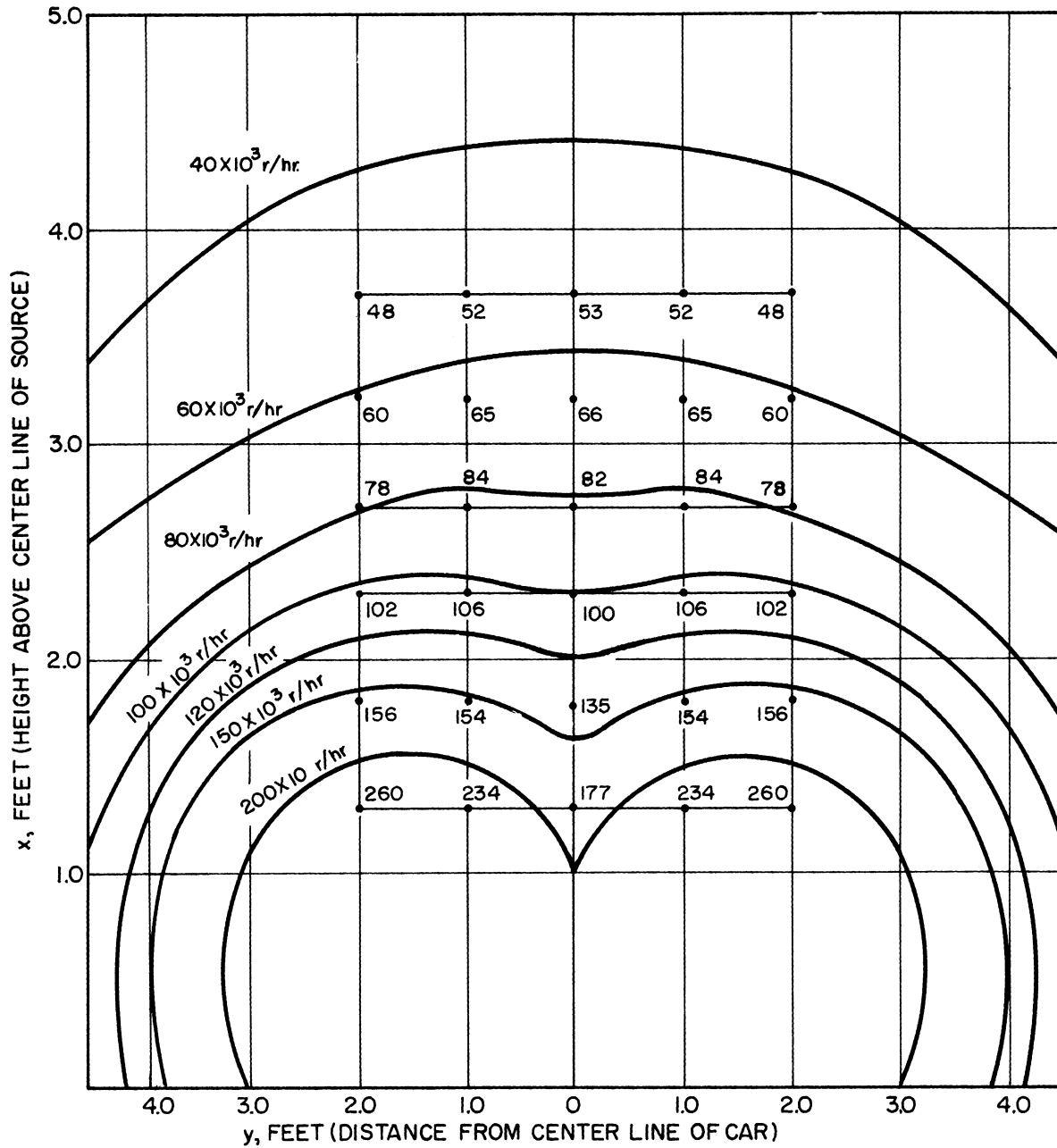


Fig. 10. Isodose curves and dose distribution for z=0 feet.

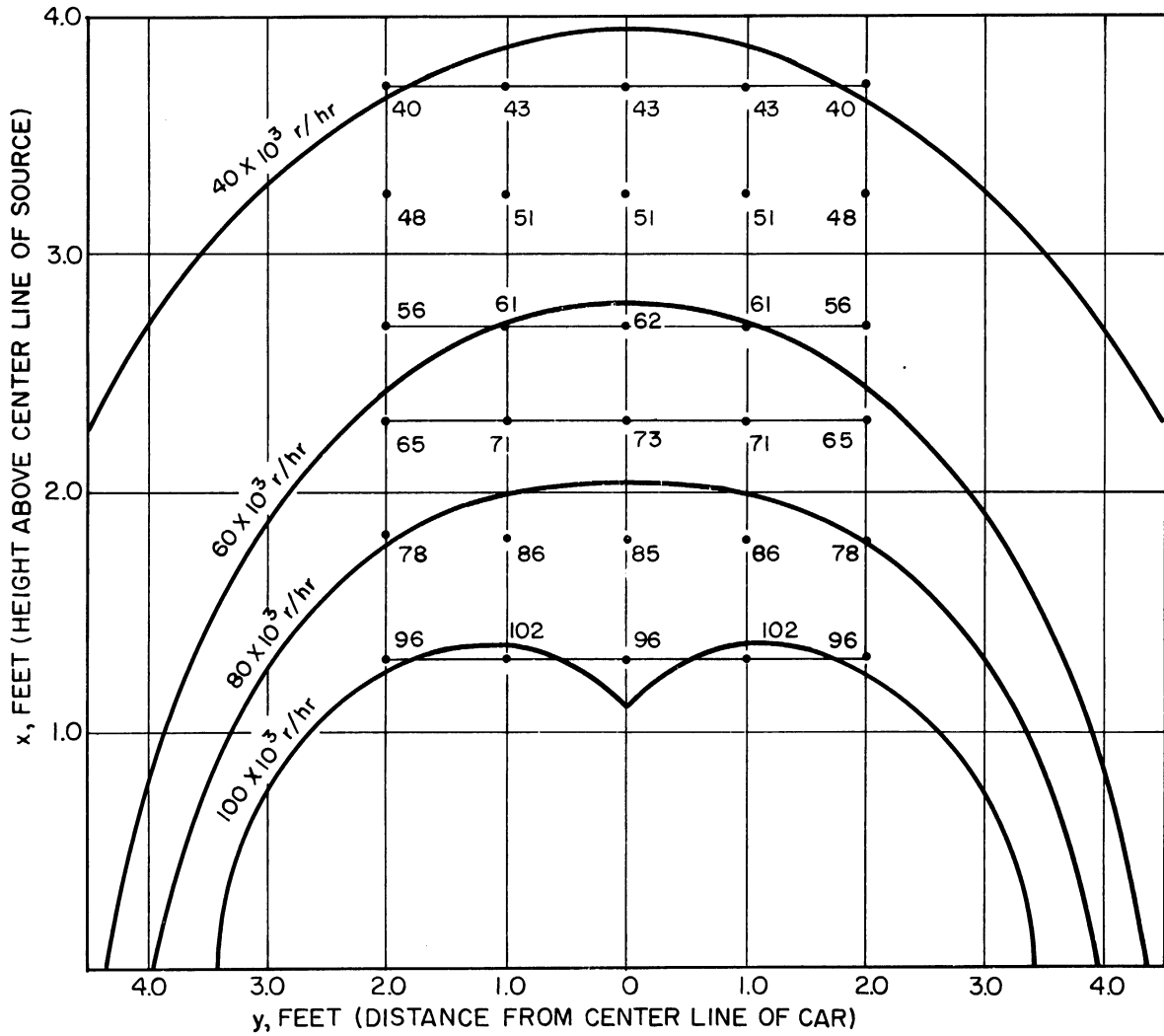


Fig. 11. Isodose curves and dose distribution for $z=2$ feet.

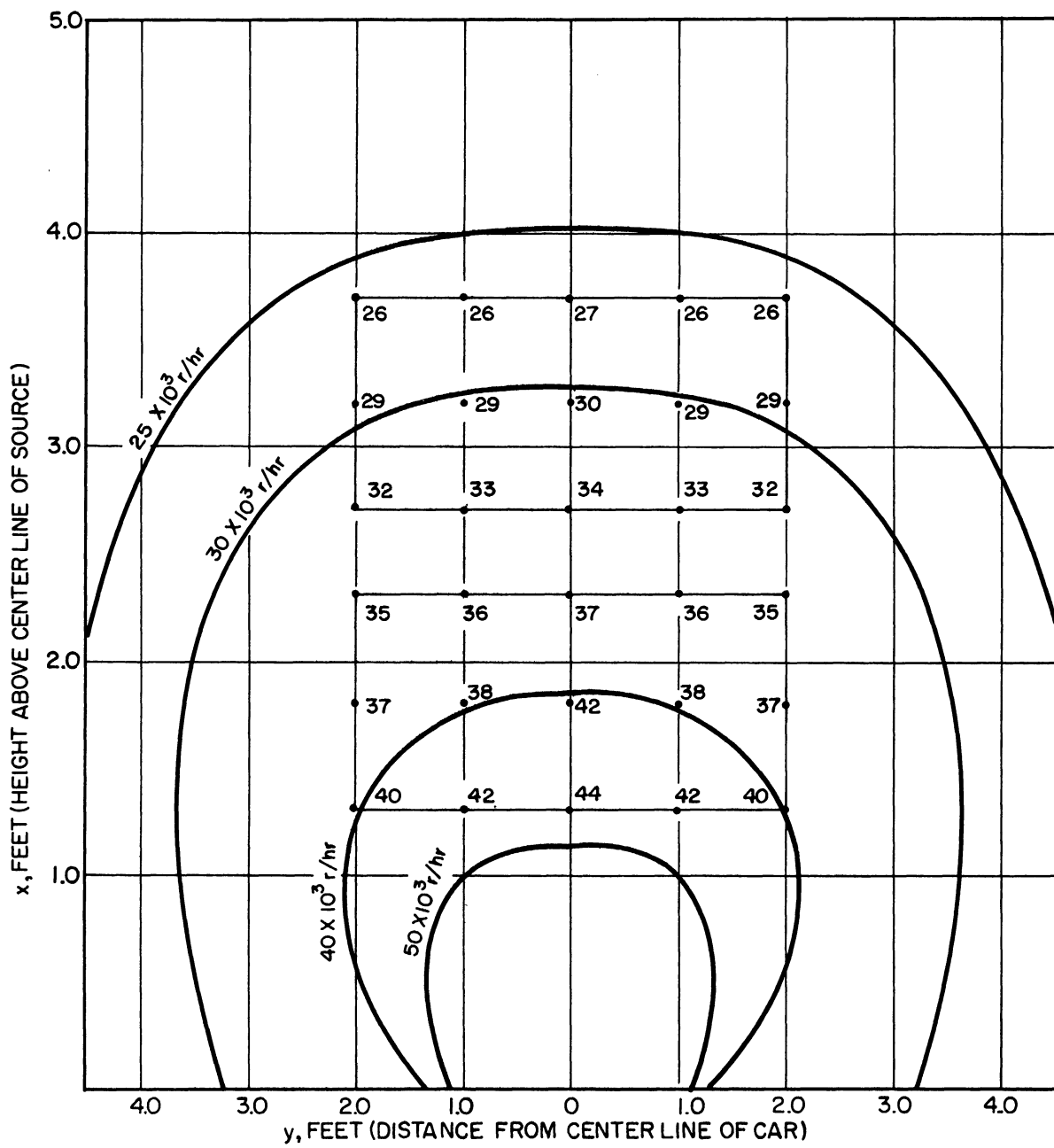


Fig. 12. Isodose curves and dose distribution for $z=4$ feet.

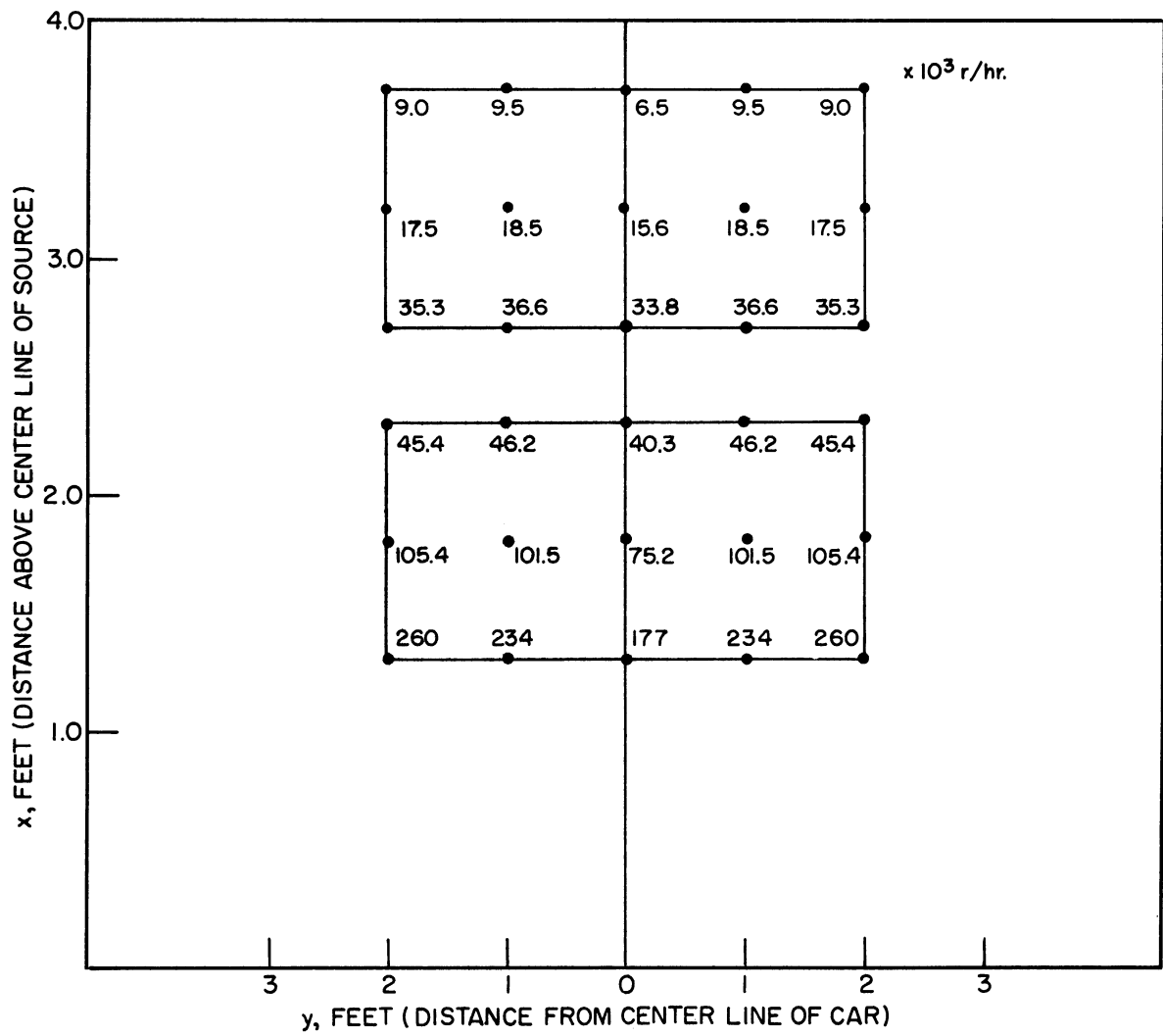


Fig. 13. Dose distributions corrected for absorption and for $z=0$.

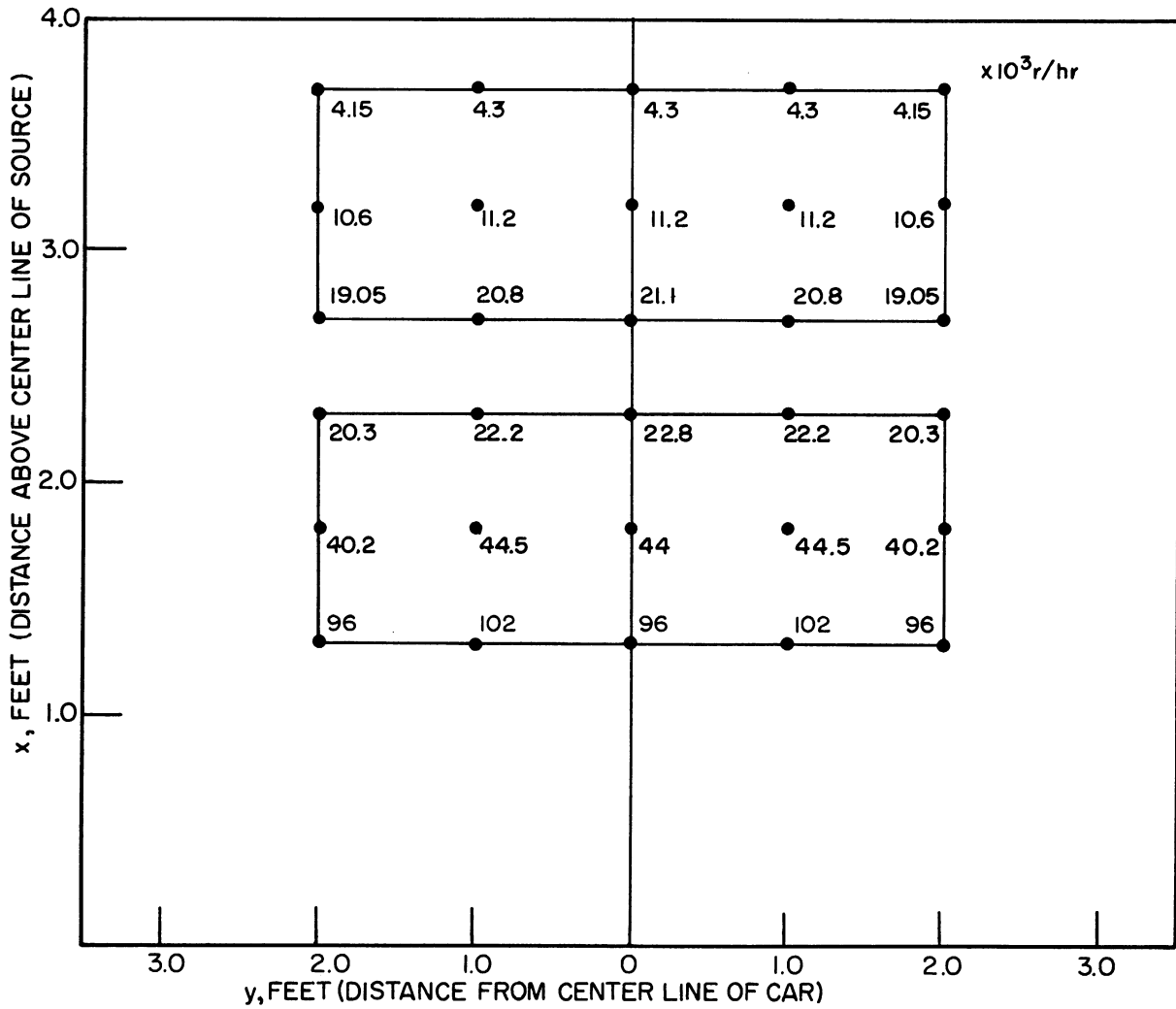


Fig. 14. Dose distributions corrected for absorption and for $z=2$ feet.

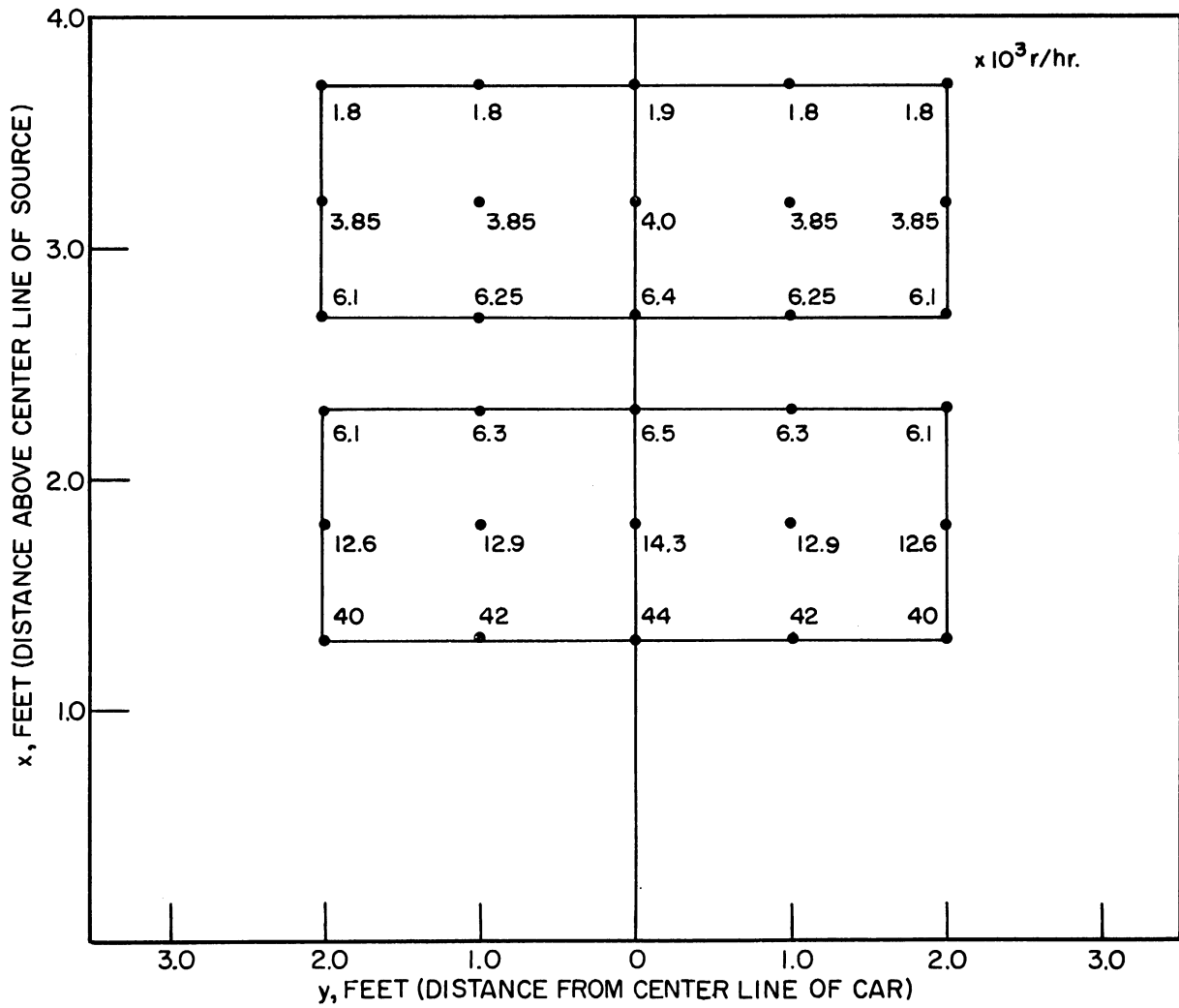


Fig. 15. Dose distributions corrected for absorption and for $z=4$ feet.

lead was chosen for the source shipping containers in order to minimize their size. The chamber thus is constructed of layers of two-inch hot-rolled run-of-the-mill plate steel which, in addition to being readily available and easy to fabricate, can have a high salvage value at the termination of the life of the facility.

In the shielding calculations consideration is given to the secondary effects of gamma radiation. Compton scattering is considered to be the major attenuating process. The intensity of gamma radiation is given by the following relationship:

$$I = I_0 B e^{-\mu_0 x},$$

where B is the dose build-up factor, μ_0 is the total linear absorption coefficient for 0.7-mev gamma rays, and x is thickness of the shielding that is necessary to reduce the ratio of I/I_0 to an acceptable value. Plots of I/I_0 for steel and lead are shown in Figs. 16 and 17 for 0.7-mev gamma rays. These plots include the build-up factor correction. For steel μ_0 was taken as 0.55 cm^{-1} and for lead 1.2 cm^{-1} .

In the design of the shield, use is made of the fact that near the corners of the irradiation chamber the gamma rays enter the walls at an angle much less than 90 degrees and pass through more than the perpendicular thickness of the shield.

If a source emitting high-energy rays of more than 0.7 mev is selected, the total activity of the radiation source should be less for the shield design given, since it was designed for 0.7 mev.

When the unit is in operation, the maximum dose rate immediately at the outside surface of the chamber is calculated to be 15 mr/hr, and the dose rate at a distance of 15 feet from the car is less than 1 mr/hr for the shield design shown. Extra-heavy shielding is provided to reduce the radiation level at the loading area to an estimated value of 1 mr/hr for the safety of the personnel. The maximum dose rate outside the car when the unit is in transit and the same elements are retracted into their lead containers is 1 mr/hr.

The outside dimensions of the shielded chambers are 25' x 9' x 10' high, and the weight of the shield, for the design using high-flux source elements, is 160 tons. The detailed drawing and dimensions of the shield are shown on Fig. 18.

Note on Shielding Dimensions

The shielding dimensions shown in Fig. 18 are for 10 rod sources having 10 times the activity of 10 MTR fuel elements 40 days old. A thickness of two inches should be subtracted from all the dimensions for steel

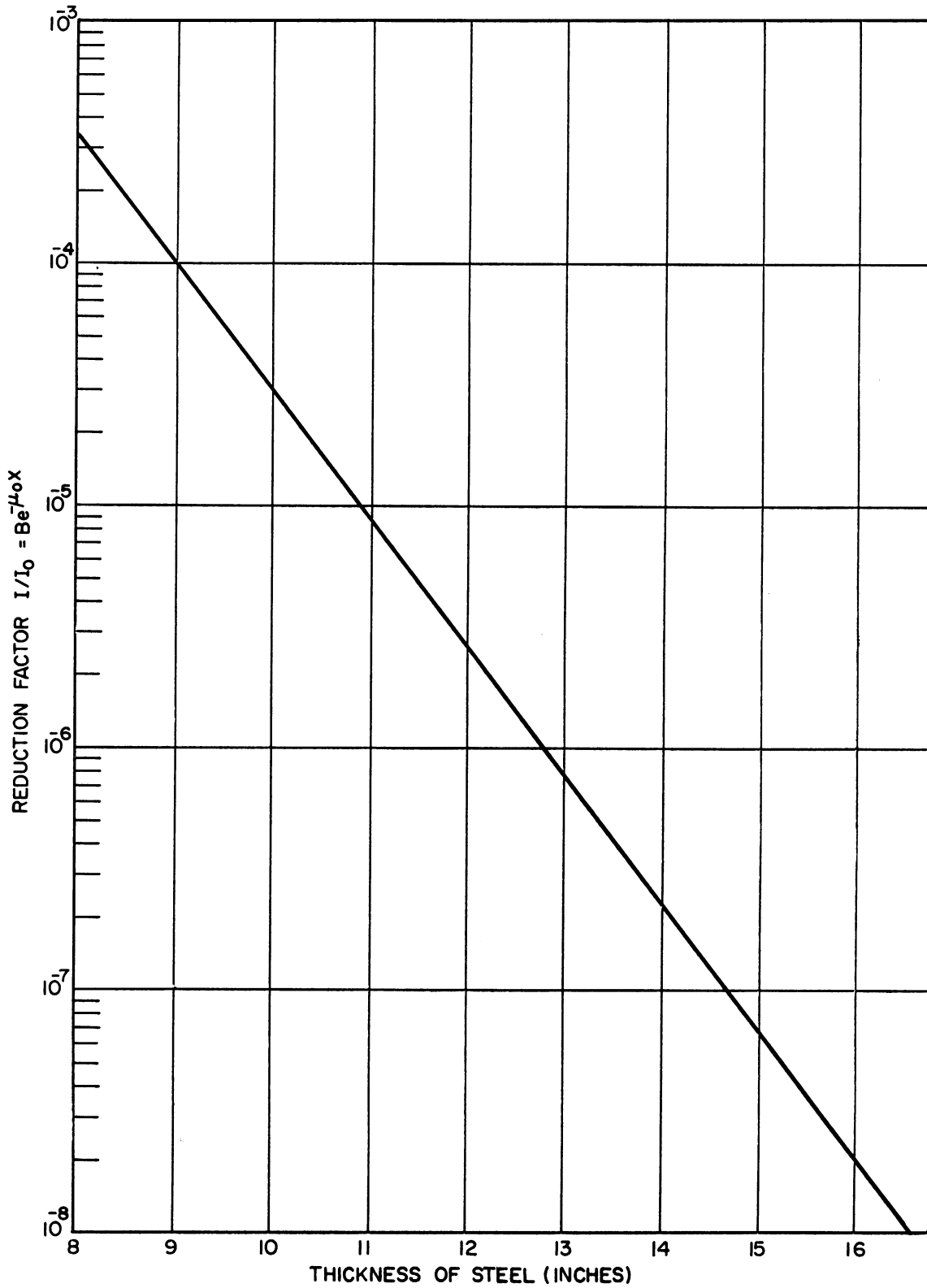


Fig. 16. Thickness reduction factor for steel shielding (including build-up) of .7-mev gamma radiation.

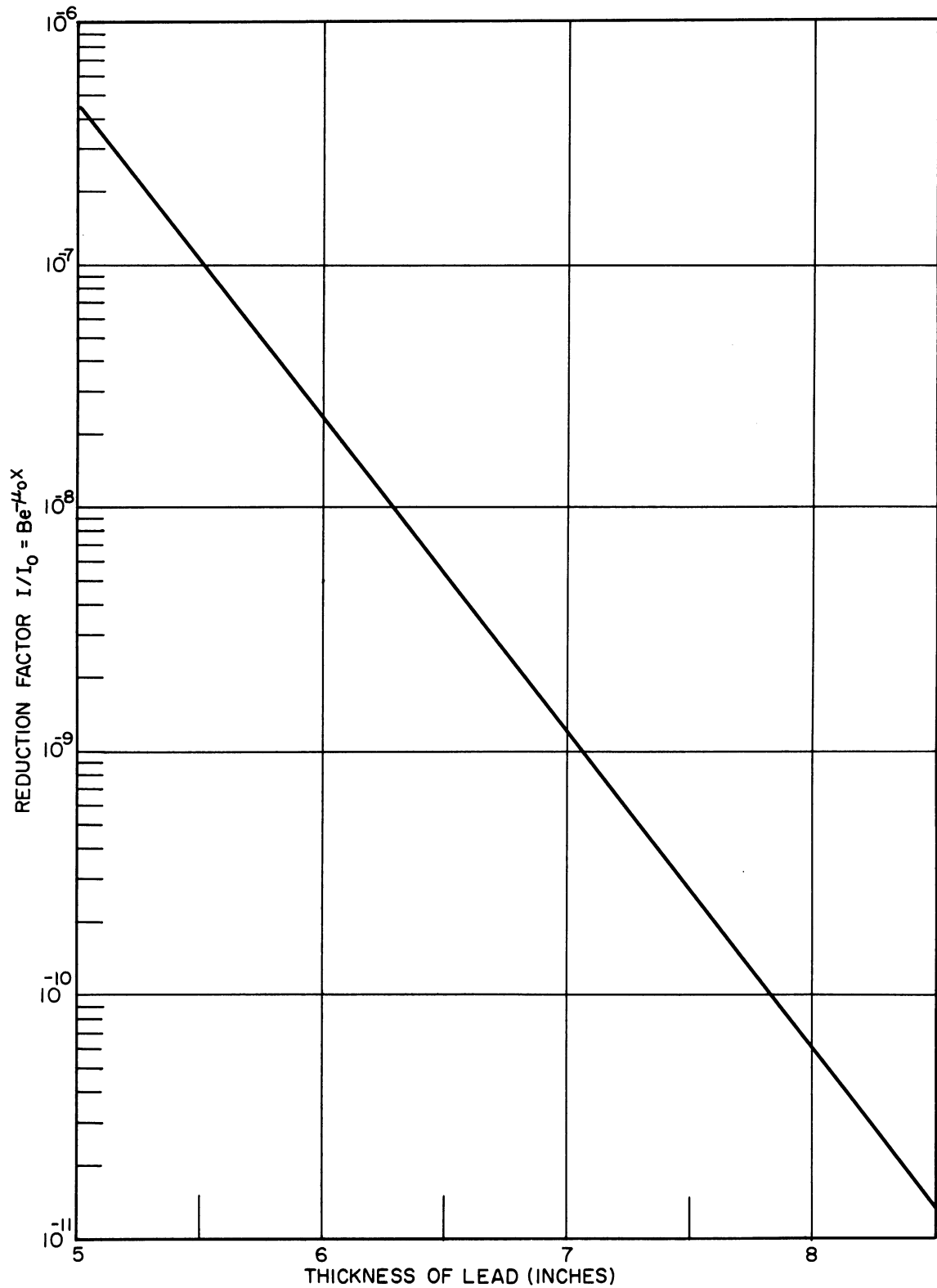


Fig. 17. Thickness reduction factor for lead shielding (including build-up) of .7-mev gamma radiation.

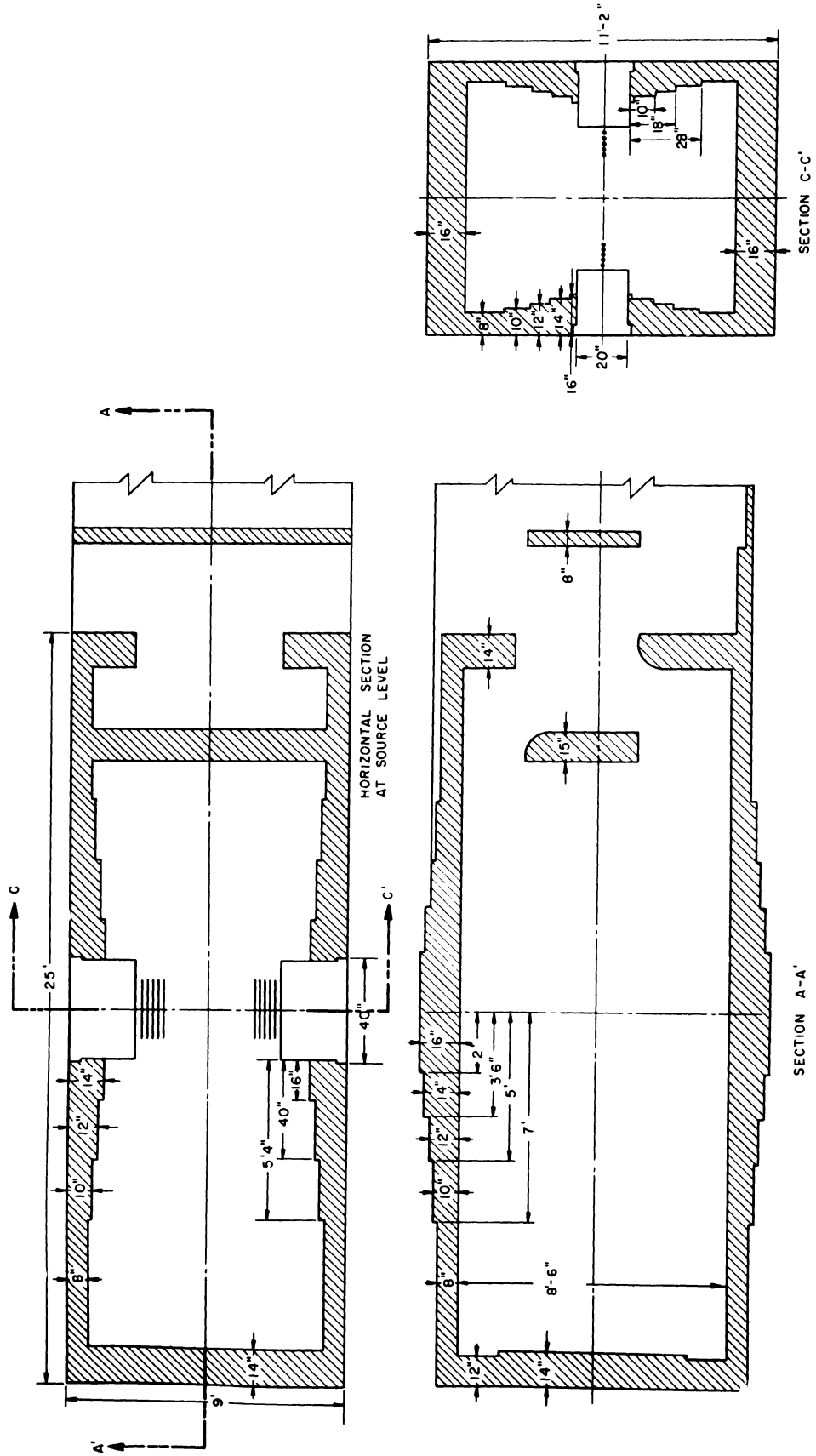


Fig. 18. Shielding for railway irradiation facility (see preceding note).

shields and a thickness of one inch from the lead shields. With these corrections the following shield weights were calculated for the case of 40-day-old MTR fuel elements.

Weight of steel shield	155 tons
Weight of two lead casks	8 tons
Weight of car trucks and accessories	<u>10 tons</u>
Total	173 tons

IV. MECHANICAL DESIGN OF THE FACILITY

A. THE RAILROAD CAR

The weight and dimensional limitations involved are of primary interest in the design of a mobile facility. Investigation of standard heavy-duty railway flat cars indicates that a type such as the New York Central—Delaware and Hudson 250-ton car having a cast-steel underframe is the largest in general use.²² The "light" (unloaded) weight of this car is 50 tons. It is mounted on four four-wheel trucks to keep rail loading within tolerance.

As a fabricated plate-steel shield for this facility is designed to act also as the main structural member, the weight of the cast-steel underframe is saved, resulting in a maximum allowable weight limit of approximately 275 tons. The total weight of the facility as designed for use with the 40-day-old source elements is 173 tons, giving a loading factor of only 63%, thus margin is provided for increased shielding if more intense radiation fields inside or lower radiation fields outside are desired for the irradiation chamber.

The exterior dimensions of the railroad car were chosen to be identical with those of a standard 50-foot box car: length 50' 6", body height 10' 6" (15' maximum over rail), width 9' 0". The taper of the shielding is directed inward on the sides to provide a smooth exterior surface and to allow access space for conveyor maintenance in the interior. The shield taper is directed outward on the top and bottom to provide straight paths for the conveyor rails and to gain a slight chamber-height advantage by being able to "belly" the lower surface down between the two sets of trucks. The center of gravity of the radiation chamber is located midway between the truck center lines to equalize wheel loadings. A cutaway perspective view of the proposed unit is shown in Fig. 19 and elevation, plan, and end sectional views are shown in Fig. 20.

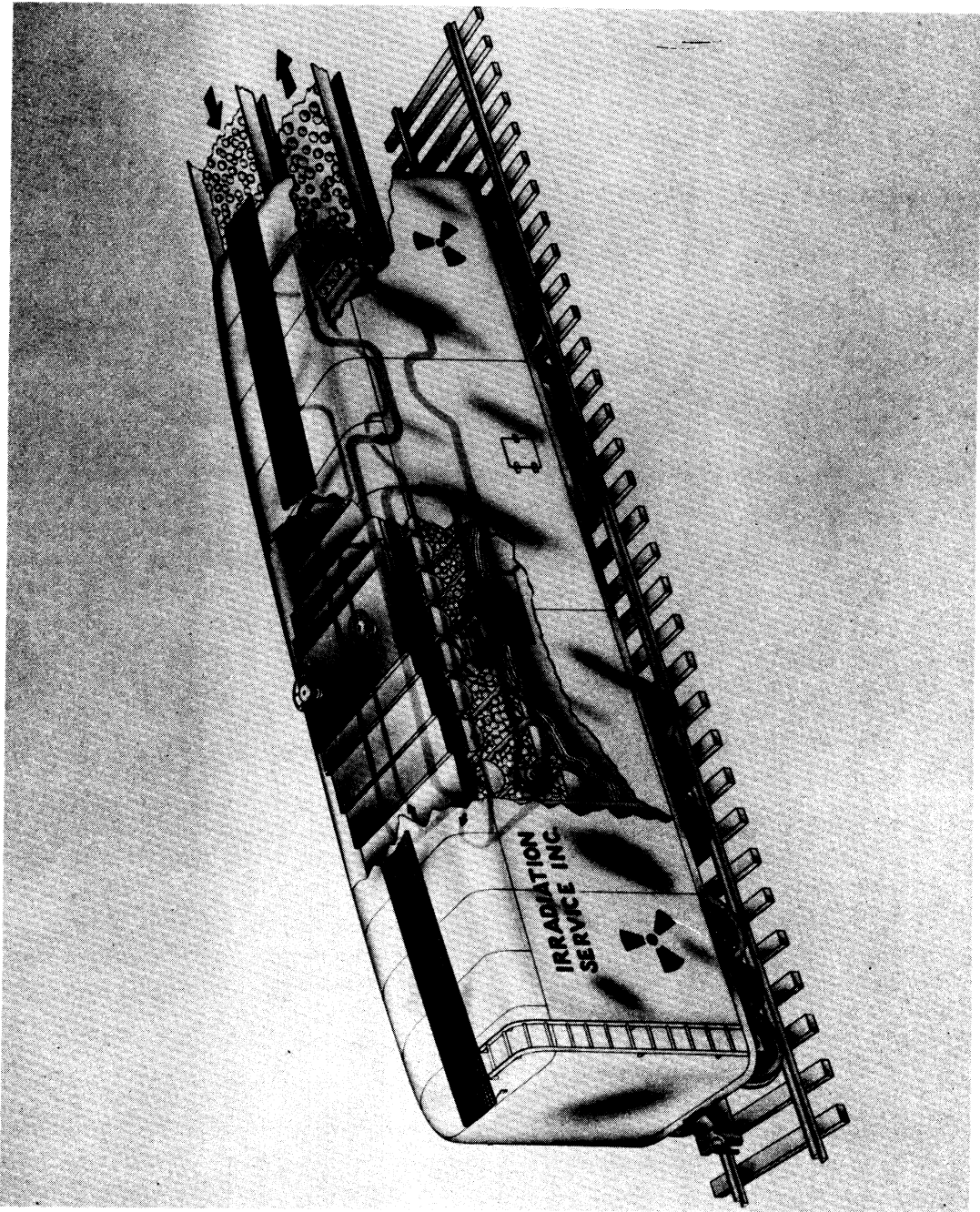
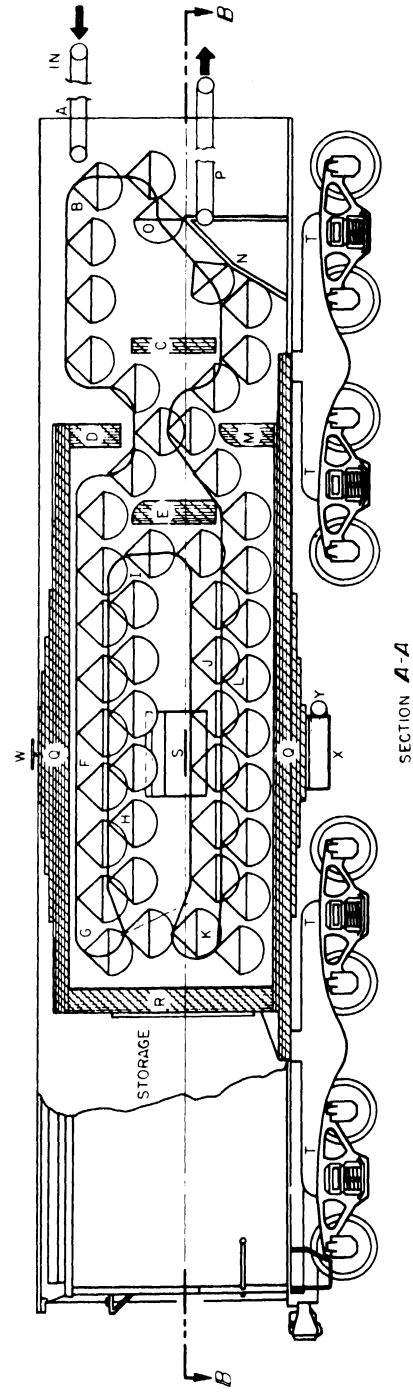
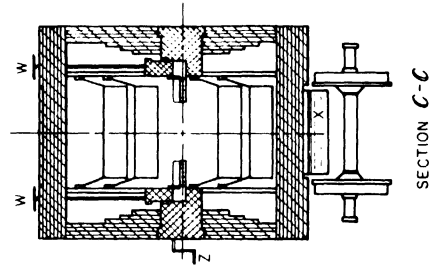
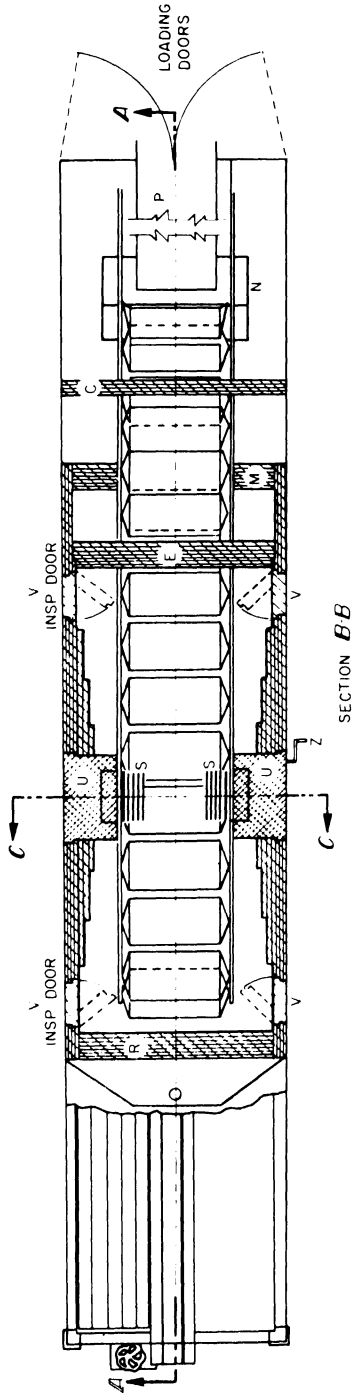


Fig. 19. Cutaway view of railway mobile gamma-irradiation facility shown irradiating citrus fruit.



SECTION A-A
SECTION C-C
Fig. 20. Plan, elevation, and end sectional views of railway mobile irradiation facility.

B. THE CONVEYOR

The preliminary considerations in the design of a tray conveyor for an irradiation facility are: (1) a tray size suitable for the type of product to be irradiated, (2) minimum tray spacing for maximum use of radiation field, (3) minimum handling required for loading and unloading especially for a high-capacity facility where the cost of such labor would be appreciable. As a general-purpose facility is considered, a tray size of 4' x 2' x 1' high is chosen as it will conveniently handle the following products:

1. loose items, such as grain, vegetables, and fruits,
2. bags of material, such as potatoes, onions, fruits,
3. bulk items, such as slabs of meat, and
4. boxed or canned items, such as packaged meat or other food products.

The trays are made of sheet 24S aluminum alloy and are supported by arms having a pivot point 18 inches above the center of gravity of the loaded tray, thus providing stability in transit and ease of unloading after transit by means of simple dump runners (see Fig. 20). Each tray is carried by roller-bearing wheels running in "U" beam tracks, adjacent trays being connected by link rods supported by additional idler wheels. Drive is by means of a variable-speed electric motor through a gear train or belts to the link rods. Power for the drive can be supplied by a d-c generator driven by a gasoline motor. This packaged unit would be located at the front of the car outside the shield.

Using a minimum turning radius of the conveyor track of 12 inches, the tray spacing can be reduced to 4 inches, thereby making maximum use of the available radiation field. Placing two supplementary belt-type conveyors at the loading end of the car (either built in or extended into the car from the adjacent plant or storage building) allows completely automatic loading and unloading of the materials being handled, provided the feeds are synchronized. The slope of the dump runners is matched to the track slope so that the trays are tilted and then returned to the horizontal position in a smooth path, with no free oscillations to disturb the loading operation. A free traveling belt is provided on the runner surfaces to eliminate rubbing friction on the trays. The loading operation is such that an empty tray is always immediately below the one being loaded, thereby minimizing spillage of loose materials such as grain.

C. THE SOURCE CONTAINERS

In order to effect a maximum saving of weight, the source containers

are placed at points in the side walls of the car where maximum shielding thickness would ordinarily be required (see Figs. 19 and 20). This location also gives the minimum possible distance required for withdrawal of the sources from their respective containers. As explained in the section on radiation-field calculations, two close groupings of five rods each give the most efficient field pattern in this case, therefore two separate source containers are desirable for handling purposes. As the containers are compact and weigh about three tons each, they can be placed in position readily by suitable fork-lift trucks or an overhead crane. The containers are held in the wall by lugs bolted to the steel shield wall. The exterior surfaces of the containers are "stepped" to match corresponding steps in the shielding wall and prevent leakage of radiation while the facility is in operation. After the containers are placed in the side walls of the chamber, a lifting screw is attached to each door which is operated by a hand wheel on top of the car to provide for opening and closing the container doors. Details of the shipping containers are shown in Fig. 21. Ample space is provided inside the car for access to the source containers and for general maintenance of the conveyor system. While outside of the containers, the sources are supported in lightweight external "U" section tracks in a trough which also acts as the support for the tank of water used for cooling fuel elements. The lower edges of the container doors are notched to allow for the internal rails for support of the source assembly.

If reactor fuel elements are used as the source elements, the elements may be cooled by circulating cool water through the lead source containers during shipping and through the trough in the radiation chamber during radiation processing. Since changing of source elements may be required, if spent reactor fuel elements are used, it would be desirable to provide two extra source containers for shipment and reloading while the other set is in use. Thus, maximum use of the facility could be made at all times.

D. DESCRIPTION OF OPERATION

To operate the facility the sources of radiation must first be installed. If spent MTR fuel elements are used, the shipping containers are first sent to the reactor site and five elements are loaded under water into each shipping container. The shipping containers are water-cooled and are supplied with a reserve tank of make-up water to replace that lost by evaporation during shipment to the mobile facility.

Referring to Fig. 20, the shipping containers "U" are loaded into shield Q. Water pump "Y" pumps cooled water from sump "X" to cool the fuel elements. Handwheel "W" and crank "Z" are then connected to provide the mechanism to raise the source doors and to move the source elements out of the shipping container, respectively.

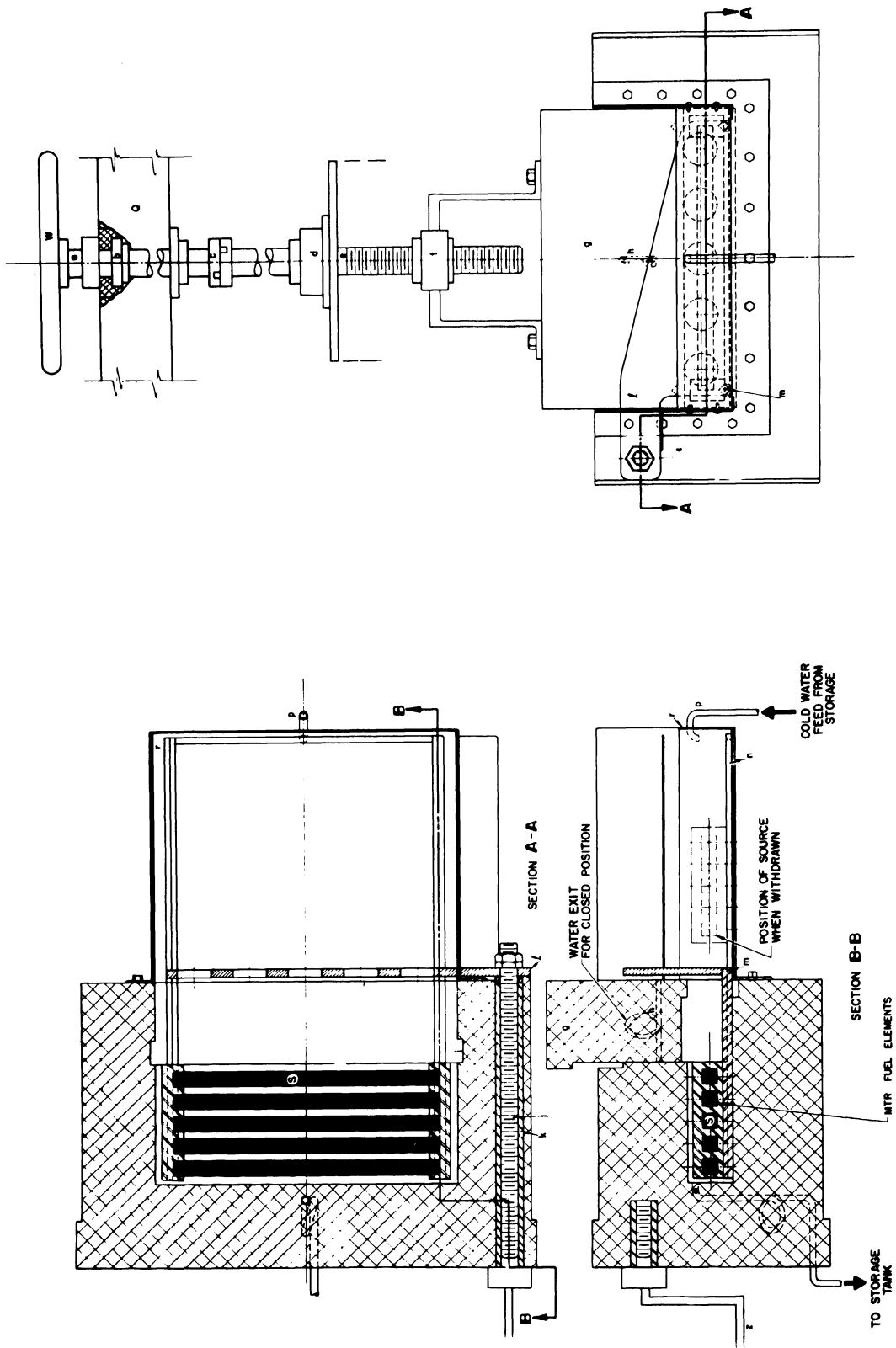


Fig. 21. Details of water-cooled lead shipping container for five spent fuel elements.

Details of this operation can be described by referring to Fig. 21. Handwheel "W" is located on the roof of the car. In transit this wheel will be kept locked with the source enclosed in the shipping container. Handwheel "W" turns shaft "a" which rides in bearing "b" sitting in shield "Q." The motion is transferred by coupling "c" to screw "e" which lifts lead door "g" by means of nut "f." The load of the lead door is carried by bearing "d."

Prior to raising lead door "g," a trough "r" is bolted to each shipping container with a gasket joint to be water tight. Pipe "p" is attached and brings cold water from a sump to cool the fuel elements. Water flows through the shipping container by loop "h" when the door is closed and directly through the door opening when the door is raised to overflow "o" and then returns to storage where it is cooled.

After the water circulating system is operating and the source doors have been raised by handwheel "W," crank "Z" is attached to the side of the car to withdraw the sources from the shipping containers. Crank "Z" turns screw "j" inside tubular nut "k" which moves bar "l" toward the center of the car. Bar "l" is attached to two square rods "m" which serve as tracks for the assembly of five fuel elements. These tracks ride in groove "n." On shutting down the facility in preparation for travel to another location, the reverse procedure is used; the sources are drawn back into the shipping container and the shipping-container doors are lowered and locked.

Details of the conveyor operation can be described by referring to Fig. 20. When the car is on location and cooling water is pumped from sump "X" by pump "Y," the source doors are raised by handwheels "W" and sources "S" withdrawn from lead containers "V" by means of crank "U," making the facility operative. Material to be irradiated is brought in via conveyor "A" from an adjacent warehouse, processing plant, or grain elevator and is fed into buckets at point "B." The conveyor in the car carries the material from point "B" past and over shield "C," under shield "D" over shield "E" into radiation zone "F." After traveling the length of the upper pass "F," a turn is made about sprocket "G" and a lower pass "H" is made directly over sources "S." A turn is made around sprocket "I" and two identical passes "J" and "L" are made below the source passing around sprocket "K." Thus the material is first irradiated from the underside of the buckets in two passes and then from the top side of the buckets in two identical passes to equalize the dosage on top and bottom of the conveyor buckets. The material leaves the radiation zone, passing under shield "E," over shield "M" and under shield "C," traveling up incline "N" where a guide cam tilts the bucket and empties it at point "O." Conveyor "P" returns the irradiated material to the warehouse, processing plant, or grain elevator.

V. CAPACITY OF THE IRRADIATION UNIT

In order to calculate the capacity of the irradiation unit, the dose received by the material being irradiated as it passes through the conveyor system must be determined. Total dose received is obtained by the numerical integration of the integral dose curve, which is obtained by plotting the distance traveled against the dose rate.

It is desirable to know maximum integral dose so as to limit over-dosage and possible off-flavors in irradiated foods and minimum integral dose so as to assure the completion of the purpose of irradiation such as the destruction of insects. Therefore, maximum and minimum integral dose curves were prepared as shown in Figs. 22 and 23 and the areas under the curve have been determined by the numerical integration.

(a) Minimum Integral Dose.—The minimum integral dose curve was drawn by plotting the dose received by a point on $y=0$ on the central line of the tray. Since the conveyor makes two passes, outer and inner, on each side of the source, the integral dose determined for a travel of 40 feet (half the total distance) is multiplied by a factor of two.

$$\text{Minimum integral dose} = 1.07 \times 10^6 \frac{\text{rep-ft}}{\text{hr}}$$

(b) Maximum Integral Dose.—The maximum integral dose curve was drawn by plotting the dose received by a point on $y=2$ feet and situated at $x=2.7$ feet (outer pass) and $x=1.3$ feet (inner pass) while passing on one side of the source and at $x=2.3$ feet (inner pass) and $x=3.2$ feet (outer pass) while passing on the other side of the source against the distance traveled. Total distance traveled is 80 feet.

$$\text{Maximum integral dose} = 1.8 \times 10^6 \frac{\text{rep-ft}}{\text{hr}}$$

(c) Capacity Calculation.—For calculating capacity, the average integral dose should be used (checking the minimum dosage so as to assure no underirradiation).

$$\text{Average integral dose} = 1.435 \times 10^6 \frac{\text{rep-ft}}{\text{hr}}$$

$$\begin{aligned} \text{Conveyor speed for 20,000-rep dose} &= \frac{1.435 \times 10^6 \text{ rep-ft}}{2.0 \times 10^4 \text{ rep hr}} \\ &= 71.8 \text{ ft/hr} \end{aligned}$$

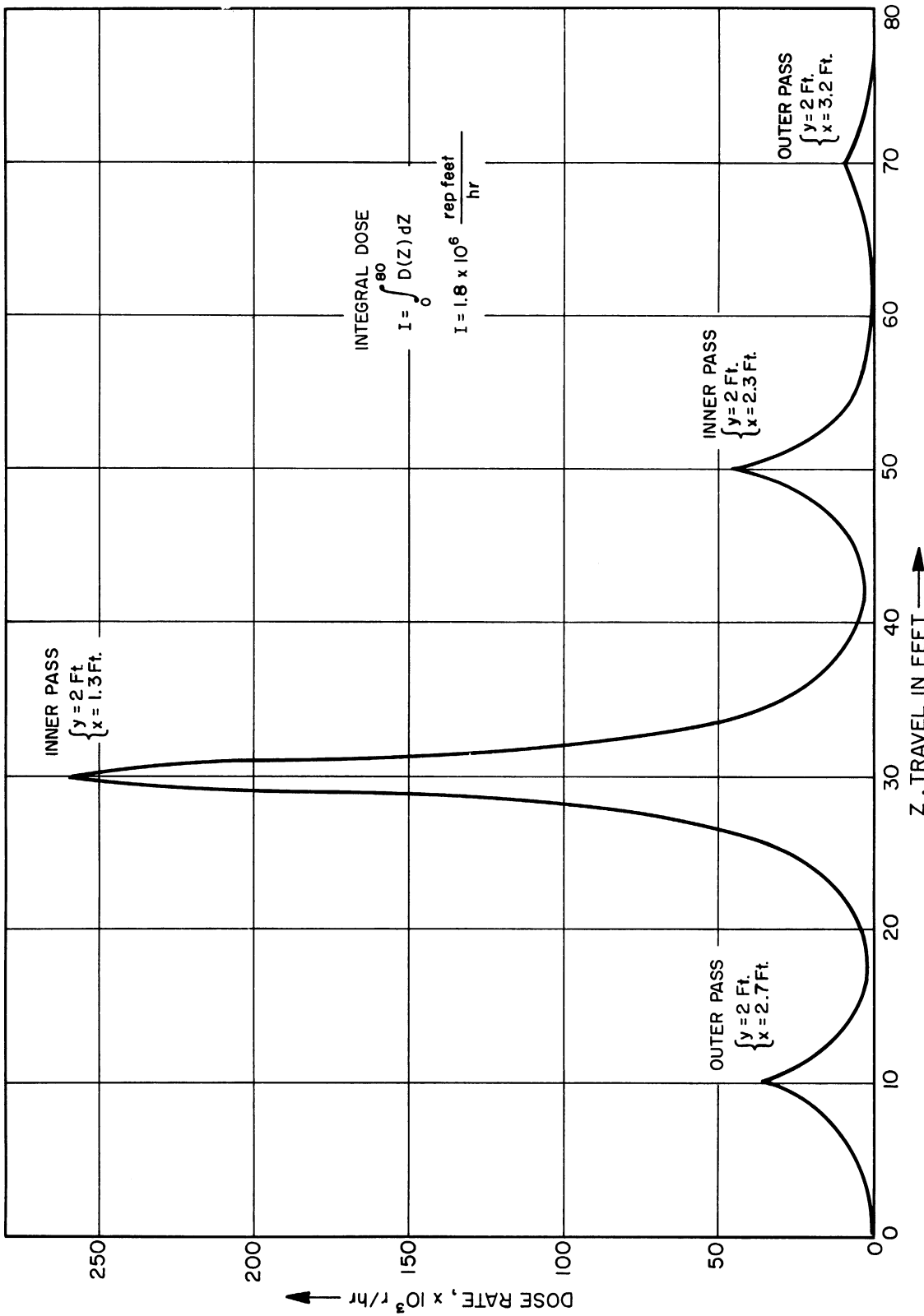


Fig. 22. Maximum integral dose corrected for absorption.

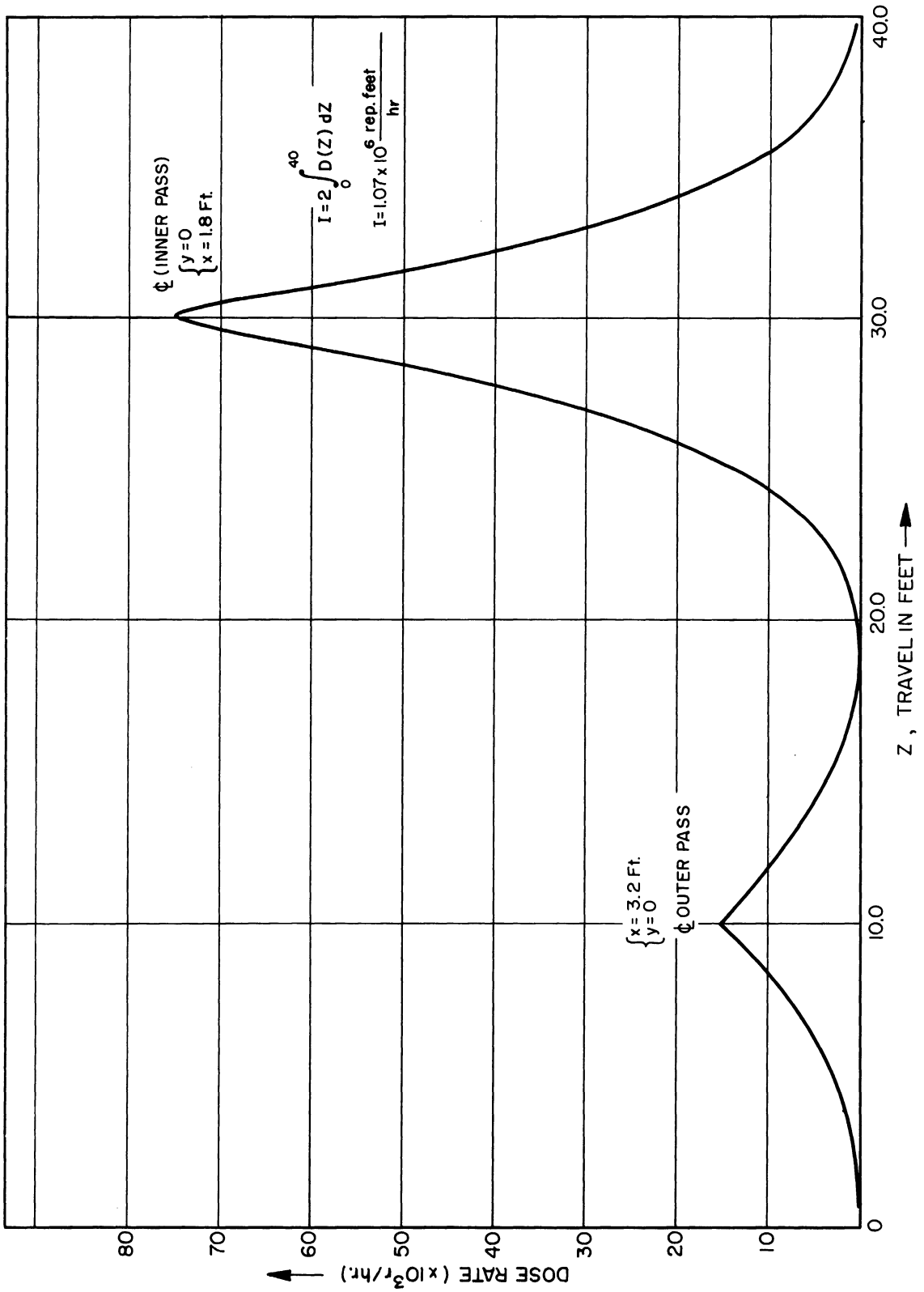


Fig. 23. Minimum integral dose corrected for absorption.

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Volume of material on 1 ft of conveyor = 3 cu ft

Capacity in bushels per hr = $\frac{2.41 \text{ bu}}{\text{ft}} \times 71.8 \frac{\text{ft}}{\text{hr}}$

= 175 bu/hr

Weight of material on 1 ft of conveyor = 150 lb

Capacity in tons per hr = $\frac{150 \times 71.8 \text{ tons}}{2000 \text{ hr}} = 5.4 \frac{\text{tons}}{\text{hr}}$

Capacity for 20,000-rep dose
= 5.4 tons/hr

For operation of 16 hours per day for an average of 5 days per week, that is, 4160 hours per year, the yearly output of the unit is

$175 \frac{\text{bu}}{\text{hr}} \times 4160 \frac{\text{hr}}{\text{yr}} = 730,000 \text{ bu/yr}$

Table I gives the capacity of the unit for different irradiation doses using MTR fuel elements cooled for different periods of time.

TABLE I
CAPACITY IN TONS PER HOUR

No.	Cooling Period	R/Hr x 10 ⁵	Capacity Tons/Hr for Different Doses			
			10,000 Rep	20,000 Rep	50,000 Rep	100,000 Rep
1	20 days	10.0	22.02	11.01	4.4	2.2
2	40 days	4.9	10.8	5.4	2.16	1.08
3	60 days	3.0	6.62	3.31	1.32	0.66
4	70 days	2.5	5.5	2.75	1.1	0.55
5	80 days	2.1	4.63	2.32	0.93	0.46

VI. COST ESTIMATES

An attempt is made to be as realistic as possible concerning the probable construction and operating costs of this facility; however, the cost of rental or purchase of a source of the size required is an elusive figure and a considerable part of the total estimated operating cost must be recognized to be contingent on this rather uncertain estimate.

The following assumptions are made in the cost estimates:

1. Source rental, or depreciation if purchased: \$250 per month per element.
2. Desired capital recovery period of three years at 8% interest.
3. Salvage value of the steel and lead shielding will be estimated at 50% of the original cost of materials.
4. Operating time will be 16 hours per day, an average of 5 days per week, that is, 4160 hours per year.

TABLE II

ORIGINAL COST OF THE FACILITY

The original cost of the facility is estimated as follows:

1. Steel shielding, 160 tons at \$120 (material only)	\$19,200
2. Lead containers and miscellaneous shielding, 8 tons at \$400 (material only)	3,200
3. Railway cars (trucks and outer frame only)	10,000
4. Conveyor system, including 46 trays	8,000
5. Motors, instruments	6,000
6. Source mechanism and cooling system	10,000
7. Engineering	5,000
8. Construction	<u>32,000</u>
Total	\$93,400

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The annual operating cost, including capital recovery, of the facility is estimated as follows:

TABLE III

ANNUAL OPERATING COST

1. Source rental: \$250 x 12 x 10	\$ 30,000
2. Operating personnel	20,000
3. Maintenance and plant overhead (10% of investment, excluding source)	10,000
4. Taxes and insurance (10% of investment)	10,000
5. Replacement of source elements (every 2 months at reactor site)	10,000
6. Capital recovery and interest (10,000-14,500) x .3880 + 14,500 x .08	34,300
Total	<u>\$114,300</u>

The cost of irradiation per ton is calculated using 4160 operating hrs (260 days at 16 hrs/day) and a dose of 20,000 rep:

$$5.4 \frac{\text{tons}}{\text{hr}} \times 4,160 \frac{\text{hr}}{\text{year}} = 22,500 \frac{\text{tons}}{\text{year}}$$

$$\text{Cost per ton} = \frac{114,300 \text{ dollars}}{22,500 \text{ tons}}$$

$$= \$5.10 \text{ per ton.}$$

It is quite probable that doses other than 20,000 rep will be desired as discussed in the introduction, or that fewer or more hours of operation per year will be possible. Table 4 summarizes the cost per ton of the product under a few operating conditions.

TABLE IV
SUMMARY OF UNIT RADIATION COSTS

Dose (Rep)	Capacity (Tons/Hr)	Cost (Dollars/Ton) for 4160 Hr/Yr
10,000	10.8	2.55
20,000	5.4	5.1
50,000	2.16	10.2
100,000	1.08	20.4
200,000	0.54	40.8

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