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THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Progress Report

DESIGN OF MTR FUEL-ELEMENT-SOURCE SHIPPING CASK FOR RAILWAY MOBILE IRRADIATION FACILITY

L. E. Brownell
J. Patterson
S. N. Purohit

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ABSTRACT

The gamma-radiation field from a battery of 10 MTR spent fuel elements has been calculated and a special shipping cask designed to contain the 10 elements. An internal water-cooled tank in the cask holds the 10 elements in the vertical position. Two external air-cooled, finned-tube heat exchangers control the water temperature. The sides of the cask open to convert the cask to a radiation source without changing the position of the elements. A unique feature of the design is a device for closing the sides of the cask by gravity in the event of accident or power failure. This provides a "fail-safe" safety feature.

OBJECTIVE

The purpose of this investigation was to design a shipping cask for 10 MTR elements to be used as a gamma-radiation source in a railway mobile irradiation facility.

I. INTRODUCTION

A 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 wide variety of commodities. It is predicted 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.

Some of the products best suited to irradiation are crops of a seasonal nature. Since harvest seasons occur at different times of the year in different parts of the country, the problem of providing a radiation source 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. After the entire crop of one locality has been treated, the unit can be moved elsewhere for treatment of another harvest crop, thus keeping the facility in more or less continuous use, and resulting in a lower operating cost per unit of product irradiated. Or, to illustrate another advantage inherent in a mobile unit, it can be taken to a seaport or border city and used for the irradiation of imported foods that might otherwise be restricted by quarantine. And, as a general device to demonstrate the advantages of irradiation treatment of foods to the public, a mobile unit would be very valuable.

Due to weight limitations, the only feasible method of land transportation of a large mobile irradiation source is by means of a rail-mounted vehicle. Even using a railroad car, it is desirable that the weight of the complete unit be low enough that the car may be safely moved onto the typical railroad siding existing in agricultural areas. In providing adequate shielding to attenuate the high-energy gammas radiated by spent fuel elements, the problem of weight limitations becomes extremely difficult. The shielding must be optimized, keeping the volume of the irradiation of the irradiation chamber to a minimum.

Since the allowable load when the car is stationary is several times the allowable load when in motion, it was first thought that the use of water for part of the shield could reduce the weight. Tanks could be filled before the unit was placed into operation and drained when the unit was moved. After considerable study, it was decided that the problems involved in the use of water might outweigh its advantages. An extremely large quantity of water is necessary to provide a significant savings in weight. Many hours would be required to fill the necessary water tanks, delaying the operation of the unit. The weight of the structure to support such tanks is also considerable.

To allow movement through various railroad tunnels throughout the country, the over-all car width should not exceed 8-1/2 ft and its height should be no more than 14 ft above the rails. For safety reasons the center of gravity cannot be more than 84 in. above the rail when the car is in motion.

A shipping cask containing a source of usable size is necessarily very heavy (25 tons in this case). It was decided that such a container could best be handled by picking it up with a crane and lowering it through a hole in the top of the car. Cranes of sufficient capacity are readily available along rail sidings in most areas of the country.

The radiation source used must be economical and readily available in sufficient quantities. At present the only type of source that fulfills these requirements is an arrangement of spent fuel elements. The most generally used fuel element is of the MTR type. Figure 1 shows this type of element with the end sections removed, as would be done before the element were used as a source. Besides the MTR, the following reactors are known to use this type of element:

LITR	The University of Michigan
BSF	Oak Ridge Research
CP-5	Battelle Memorial Institute
BORAX I and II	Brookhaven Medical Research Facility
Convair	Livermore
GRC	Watertown Arsenal
Pennsylvania State University	U. S. Naval Research Laboratory

Others are in the planning stage. If cesium sources become available in sufficient quantities at reasonable cost, their use will make possible a much higher-capacity unit requiring less shielding. The system was so designed that conversion to a cesium source is possible.

II. THE RADIATION SOURCE AND FIELD

A. THE RADIATION SOURCE

Fuel elements that are first removed from a reactor have a very high gamma activity, which decreases to a value of one half the original before two days of cooling. After three weeks of cooling, the original activity has decreased by a factor of 10. Figure 2 shows this decay as a plot of the average gamma dose rate vs. time after removal from the reactor.

In selecting a fuel element as a radiation source a compromise must be made between a high initial activity and slow decay rate. A young fuel element will decay so rapidly that it would be difficult to maintain a sufficiently uni-

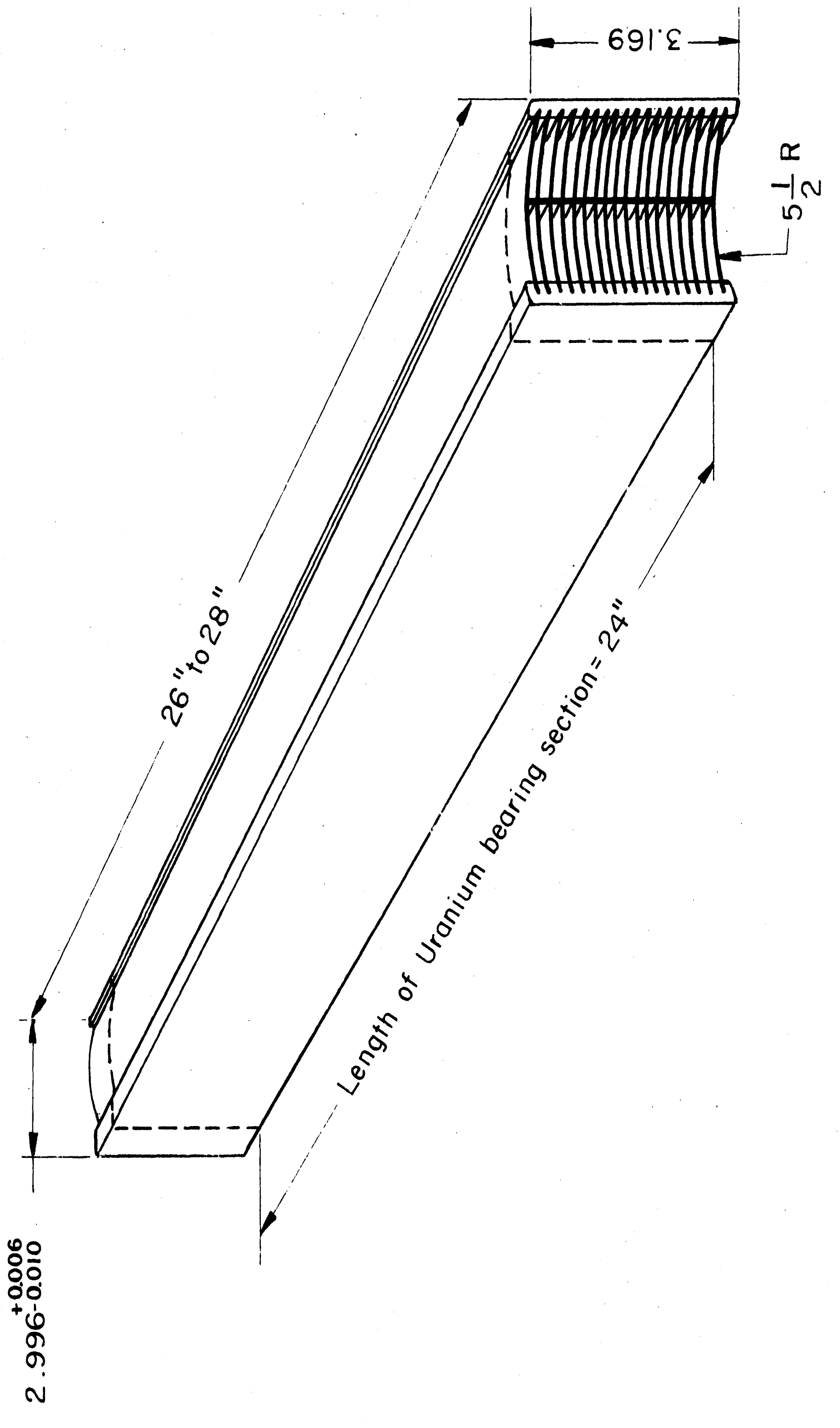


Fig. 1. The MTR-type fuel element with the end sections removed.

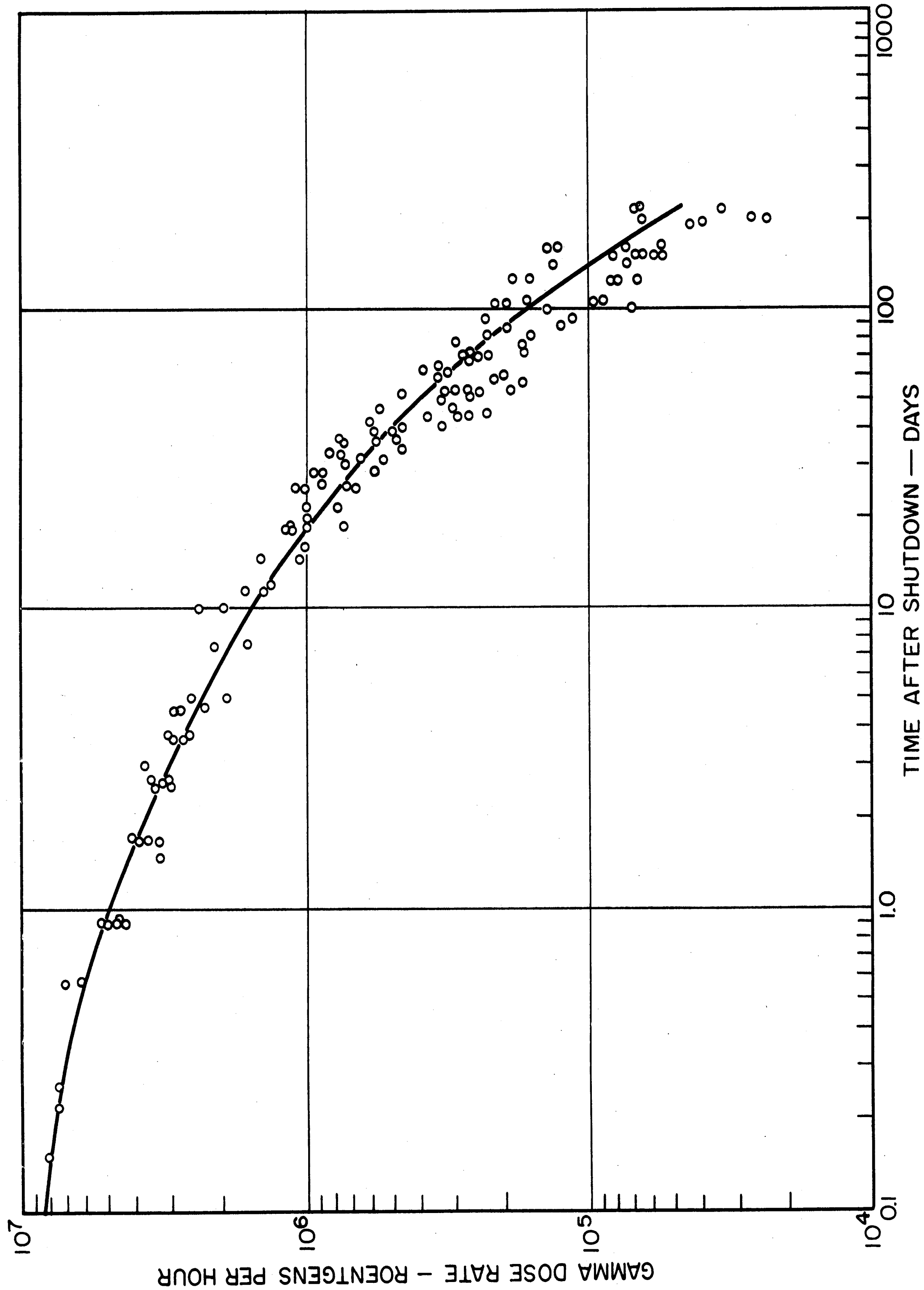


Fig. 2. Average gamma dose rate of MTR spent fuel elements vs. time after shutdown.

form radiation field, while old fuel elements result in low capacities. Thirty-day-old fuel elements were selected as a reasonable compromise, and radiation-field calculations were based on fuel elements of this age. To maintain a reasonable capacity, the fuel elements should be replaced with new ones every few months.

If cesium-137 or similar sources become available in sufficient quantities, it will certainly be desirable to switch to this type of source. Cs-137 has a half-life of 33 years and a 0.7-Mev gamma is emitted in the decay process. Thus there is the advantage of having a source that rarely or perhaps never has to be replaced during the life of radiation facility; the shield thickness required for 0.7-Mev gammas is also considerably lower than that required for higher-energy gammas associated with mixed fission products. A source strength many times larger could be used with the shield designed for spent fuel elements. The limiting factor for the capacity of such a radiation facility might be the highest speed at which the conveyor system could be run, rather than the largest practical shield weight.

B. ARRANGEMENT OF THE FUEL ELEMENTS

The fuel elements are arranged as shown in Fig. 3. The major reason for arranging the fuel elements in a vertical position is to facilitate the cooling of the elements and simplify handling problems. An almost equal efficiency as compared with a horizontal arrangement can also be obtained with a less complicated conveyor system.

The illustrated spacing of the 10 fuel elements is the result of a trial-and-error procedure aimed at obtaining the most uniform dose rates along lines parallel to the y axis.

C. MAPPING OF THE RADIATION FIELD

In calculating radiation intensities, the gamma spectrum of the source elements was broken down into 7 energy groups as shown in Table I. These energy groupings and source-strength values were taken from ADC-65.[1]

It was necessary to break the gamma spectrum down into multiple energy groups to obtain reliable values for radiation-field intensities. Using one average energy group as a basis for the calculations yields significantly different results for both the radiation field and shield thickness.

The fuel elements were assumed to be cylindrical sources 3 in. in diameter and 24 in. long, which approximates their actual dimensions. The undirected flux from a cylindrical source is described by Fig. 4 and the following group of equations taken from The Reactor Shielding Manual by Rockwell.[2]

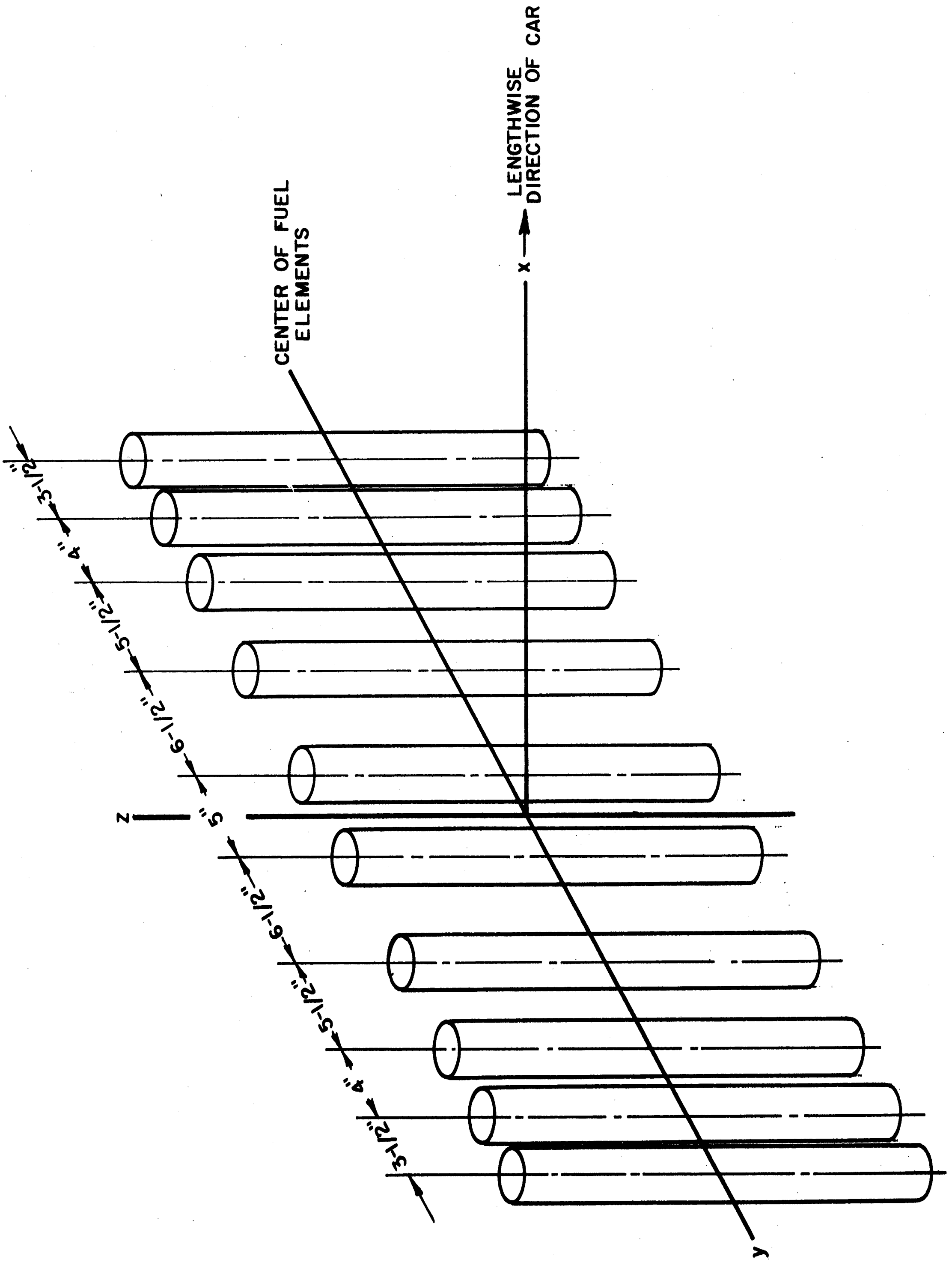


Fig. 3. Arrangement of fuel elements and coordinate system.

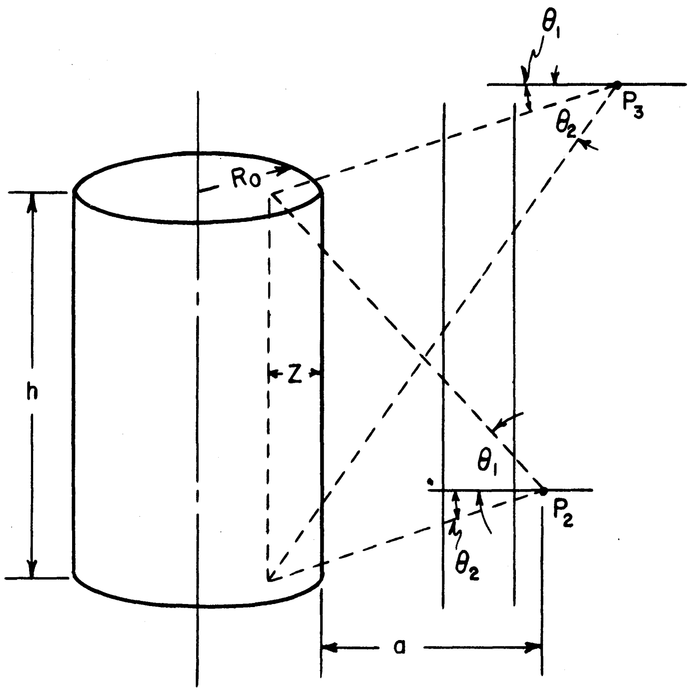


Fig. 4. Geometry for cylindrical source.

At P_2

$$\phi = \frac{BS_VR_0^2}{4(a+z)}\left[F(\theta_1,b_2) + F(\theta_2,b_2)\right] \qquad \theta_1 \neq \theta_2 \qquad (1)$$

At P_2

$$\phi = \frac{BS_VR_0^2}{2(a+z)} F(\theta,b_2) \qquad \theta_1 = \theta_2 = \theta \qquad \text{if } h = \infty,\ \theta = \pi/2 \qquad (2)$$

At P_3

$$\phi = \frac{BS_VR_0^2}{4(a+z)}\left[F(\theta_2,b_2) - F(\theta_1,b_2)\right] \qquad (3)$$

ϕ	Scalar flux ($cm^{-2}sec^{-1}$)
S_V	Source strength of volume source ($cm^{-3}sec^{-1}$)
μ_s	Macroscopic cross section of source material (cm^{-1})
$\mu_1, \mu_2, \ldots \mu_n$	Macroscopic cross sections of shields 1, 2, ... n (cm^{-1})
t_i	Thickness of *ith* shield (cm)
b_1	$\sum_1^n \mu_i t_i$
b_2	$b_1 + \mu_s Z$
Z	Effective self-attenuation distance (cm)
R_0	Radius of cylinder (cm)
B	Symbolic build-up factor
$F(\theta,b)$	$\int_0^\theta e^{-b \sec \theta'} d\theta'$

TABLE I

GAMMA-RADIATION ENERGY SPECTRUM
FOR MTR FUEL ELEMENTS

Group	Average Energy $\bar{E}$, Mev	S*	% Contribution to Total Activity
I	2.50	0.000260	0.8
II	1.75	0.005990	19.1
III	1.25	0.000026	0.1
IV	0.90	0.002720	8.7
V	0.70	0.007900	25.2
VI	0.50	0.005980	19.0
VII	0.35	0.008500	27.1

Irradiation Time = 17 days   Cooling Time = 30 days

*S = source strength in photons/sec based on one fission per second.

The average density of a fuel assembly plus water is approximately 1.65 g/cc. Thus the absorption coefficients for carbon (ρ = 1.67 g/cc) could be used in calculating the μs Z values. Buildup (B) is allowed for in the b_2 term as $b_2/1.2$. The absorption of radiation by the water between the elements and aluminum source container plus the absorption of the container was considered to be equal to the absorption of 1-1/2 in. of water. Table II lists the appropriate values of the above terms for the various energy groups.

TABLE II

SHIELDING CONSTANTS FOR VARIOUS ENERGY GROUPS

Value	Energy Group						
	I ($\bar{E}$=2.5 Mev)	II	III	IV	V	VI	VII
*μs	.067	.083	.097	.112	.125	.146	.169
*Z	2.69	2.69	2.68	2.59	2.56	2.47	2.43
$\mu_1 t_1$(1-1/2" H_2O)	.166	.202	.240	.284	.320	.369	.426
μ_2(air ft^{-1})	.00145	.00175	.00208	.00249	.00279	.00323	.00372

*Values obtained from Ref. 3.

The absorption of the gammas in air was taken into consideration in the calculations, although it did not make a significant difference in the results except at large distances from the source. The function $F(\theta,b_2)$ is plotted in Ref. 2. In the range of b_2 values that are of interest in radiation-field calculations, these plots of functions are extremely difficult to read accurately. To obtain the desired accuracy, the differential of the function was expanded using Maclaurin's series and integrated termwise. As a matter of general interest the resulting values of $F(\theta,b_2)$ are plotted in Fig. 5.

The value of Sv is obtained as follows:

$$Sv = \gamma S \tag{4}$$

γ = a reactor history factor,

$\frac{\text{No. of fissions occurring in element}}{\text{Element volume}}$

= 2.8×10^{13} fissions/cm^3 in our case for a 30-day-old element

S = Source strength given in Table I (photons/fission-sec)

The γ value was obtained from measurements obtained for actual spent MTR fuel elements.[3] The final dose rate is given by:

$$I = 6.95 \times 10^{-5} \, \phi \, \bar{E} \left(\frac{u-\sigma_s}{\rho}\right) \tag{5}$$

$(u-\sigma_s)/\rho$ = ratio of macroscopic cross section for energy absorption to density of tissue (cm^2/g). Given in Ref. 2.

I = dose rate (r/hr)

Figures 6 through 12 give dose rates resulting from <u>one</u> fuel element as a function of distance from the fuel-element face and distance above the center for each of the 7 energy groups. Figure 13 gives the total dose rate of all the groups, i.e., the total of Figs. 6 through 12. It can be observed that on certain planes above the element the dose rates tend to drop off as we get closer to the source. It should be pointed out that this is due to self-absorption in the source.

The contribution of each of the 10 fuel elements was obtained at numerous points throughout the irradiation chamber and a map of the radiation field was drawn. Maps of the irradiation for 4 horizontal planes (z = 0, 1, 2, and 4)

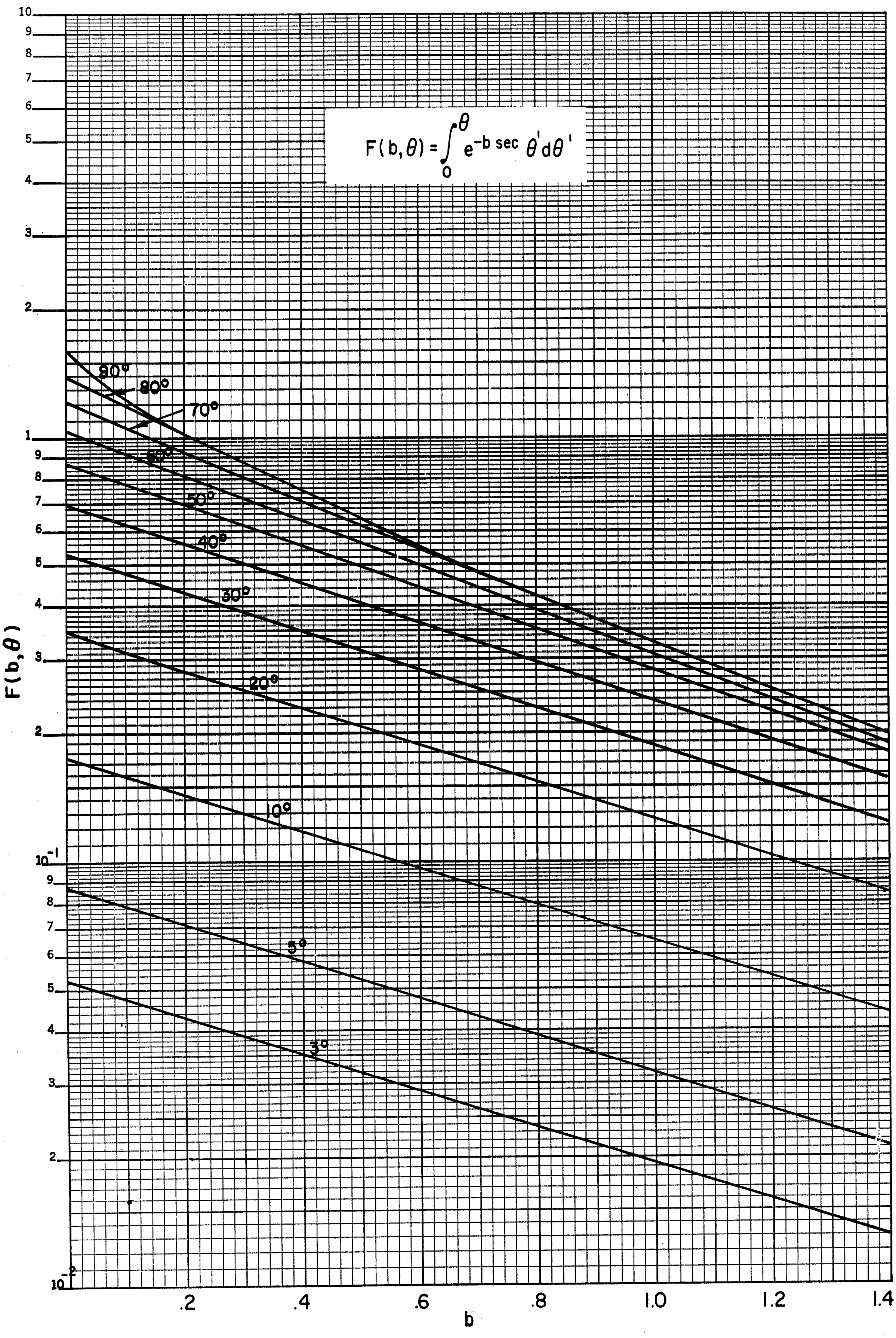


Fig. 5. The function F(θ,b) vs. b.

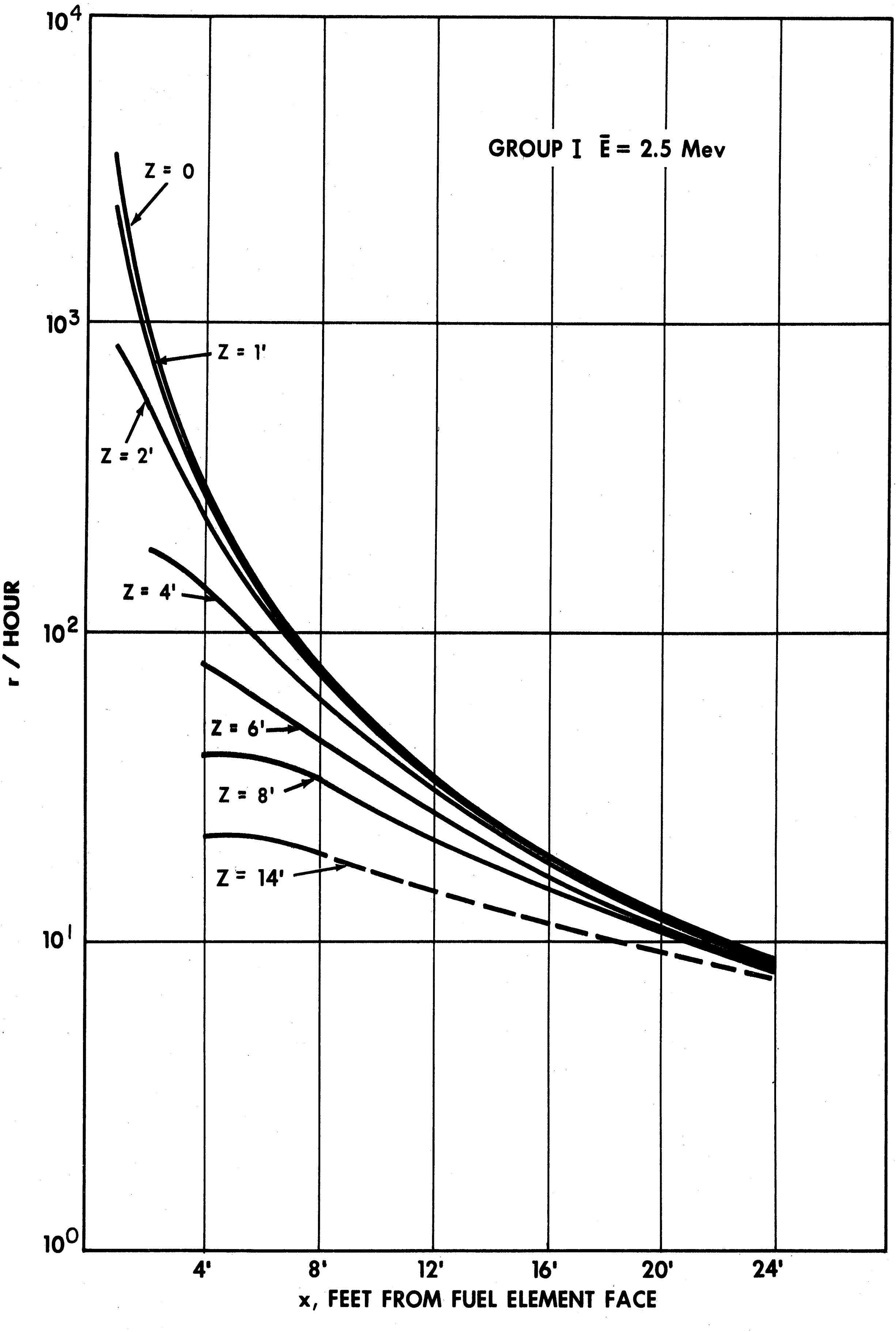


Fig. 6. Gamma intensity ($\bar{E}$ = 2.5 Mev) from a 30-day-old MTR fuel element vs. distance from element face.

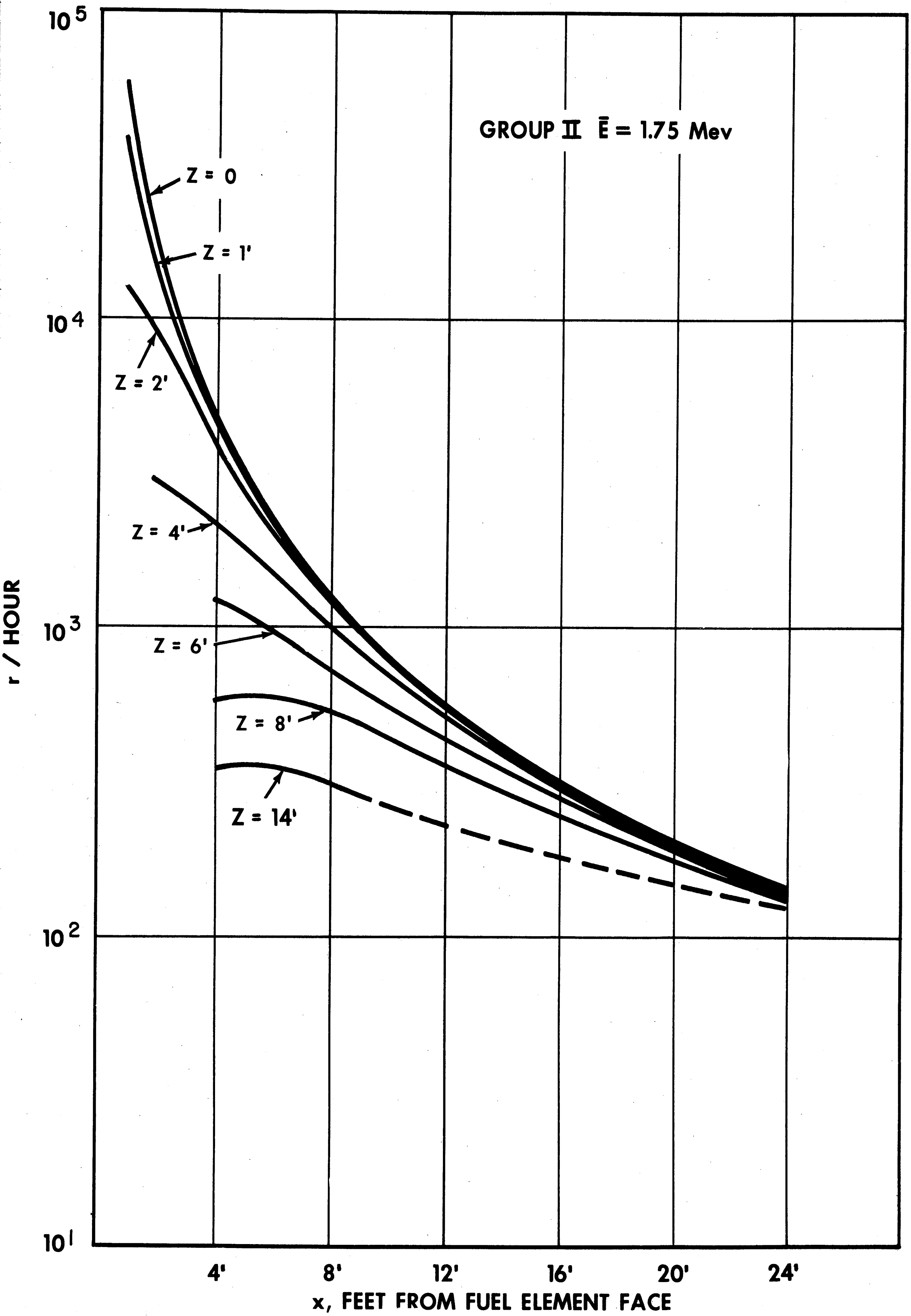


Fig. 7. Gamma intensity ($\bar{E}$ = 1.75 Mev) from a 30-day-old MTR fuel element vs. distance from element face.

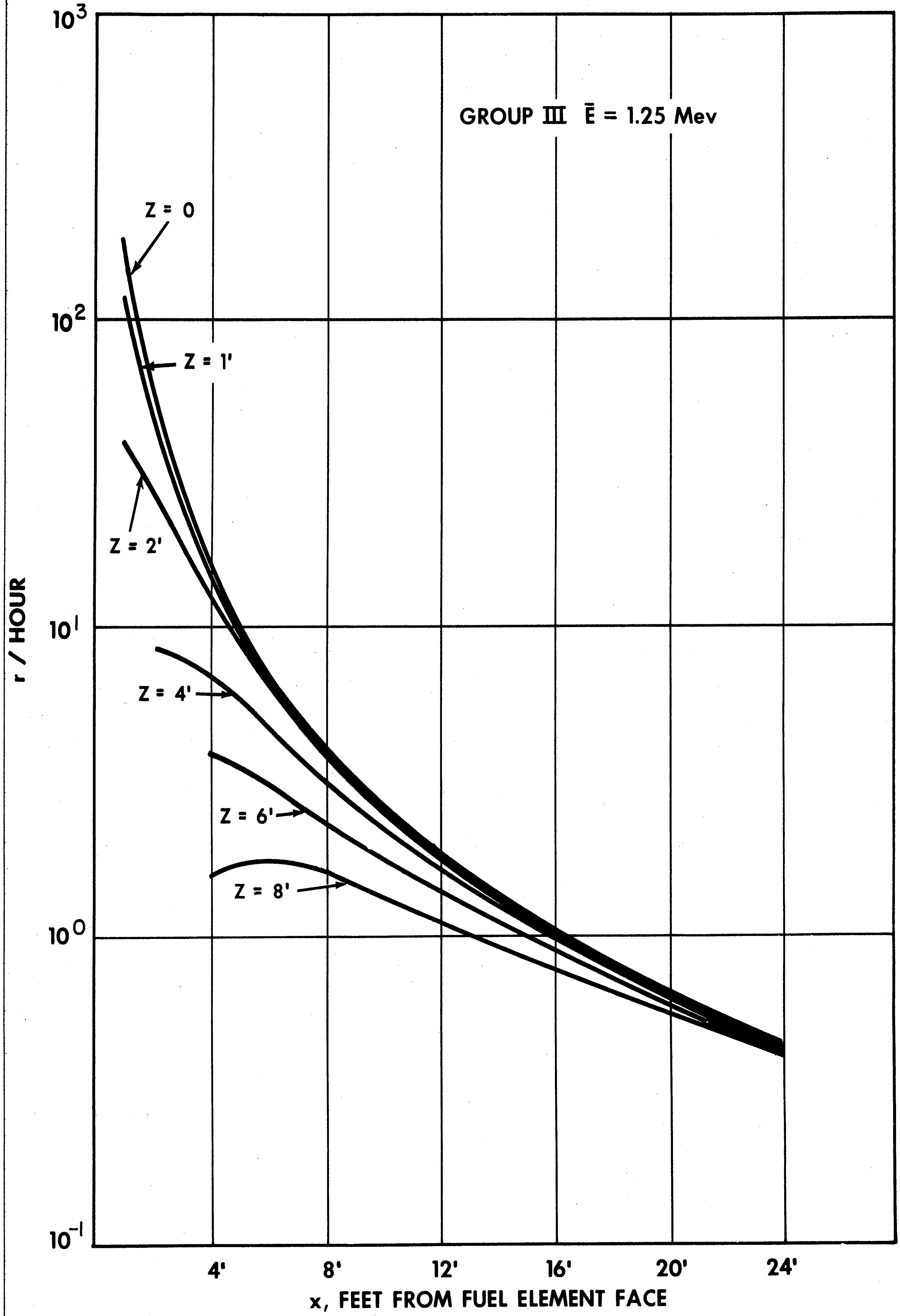


Fig. 8. Gamma intensity ($\bar{E}$ = 1.25 Mev) from a 30-day-old MTR fuel element vs. distance from element face.

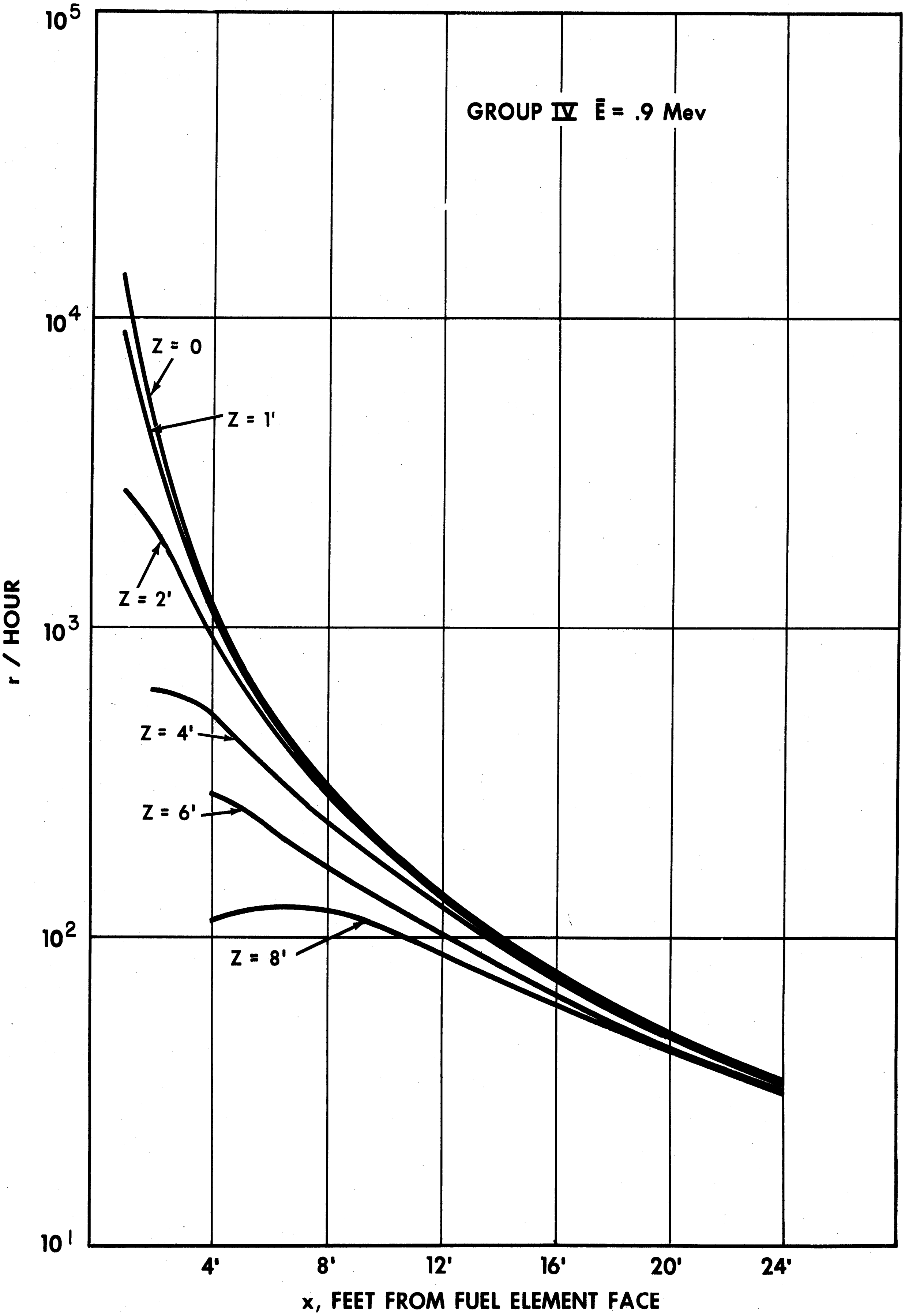


Fig. 9. Gamma intensity ($\bar{E}$ = 0.9 Mev) from a 30-day-old MTR fuel element vs. distance from element face.

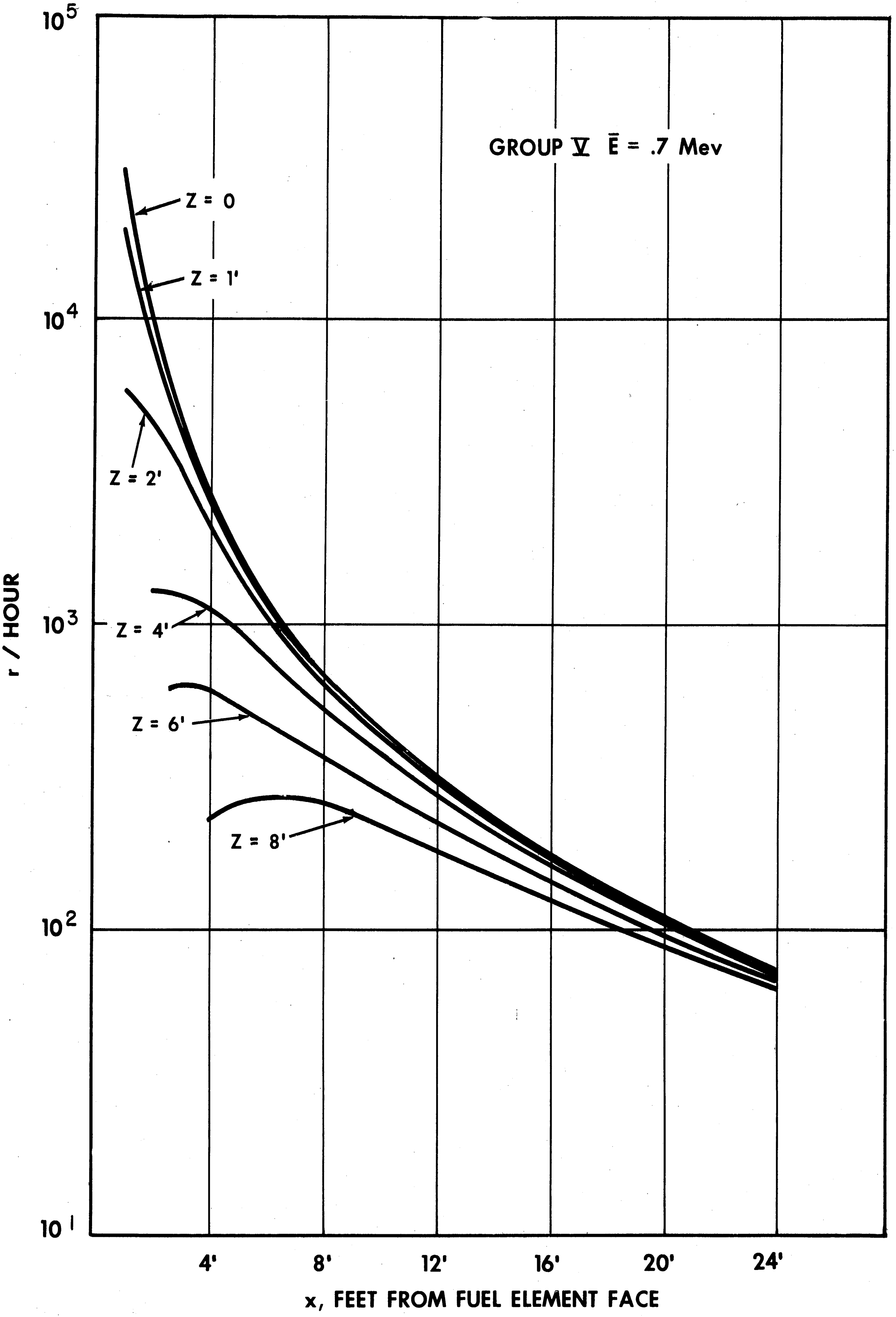


Fig. 10. Gamma intensity ($\bar{E}$ = 0.7 Mev) from a 30-day-old MTR fuel element vs. distance from element face.

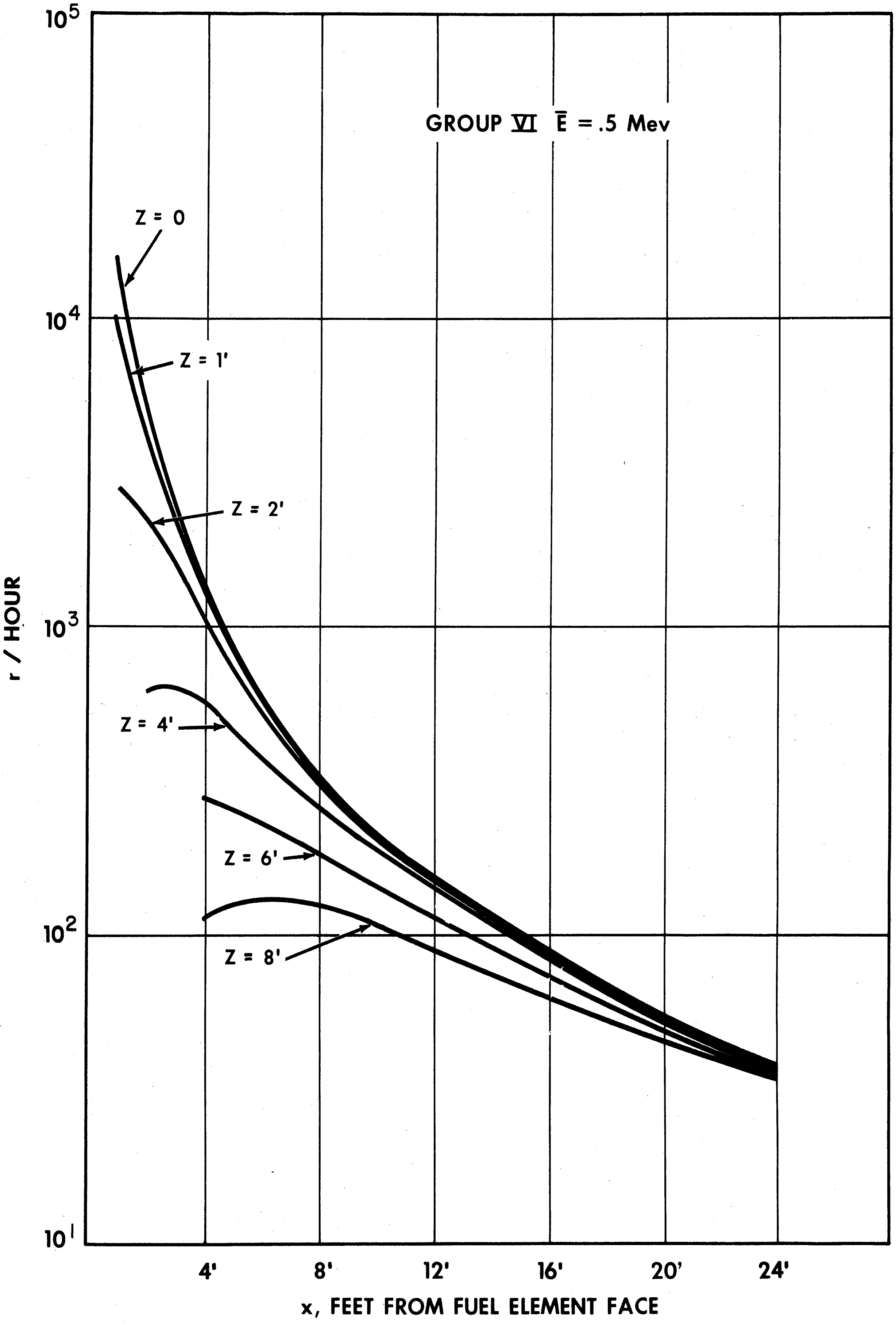


Fig. 11. Gamma intensity ($\bar{E}$ = 0.5 Mev) from a 30-day-old MTR fuel element vs. distance from element face.

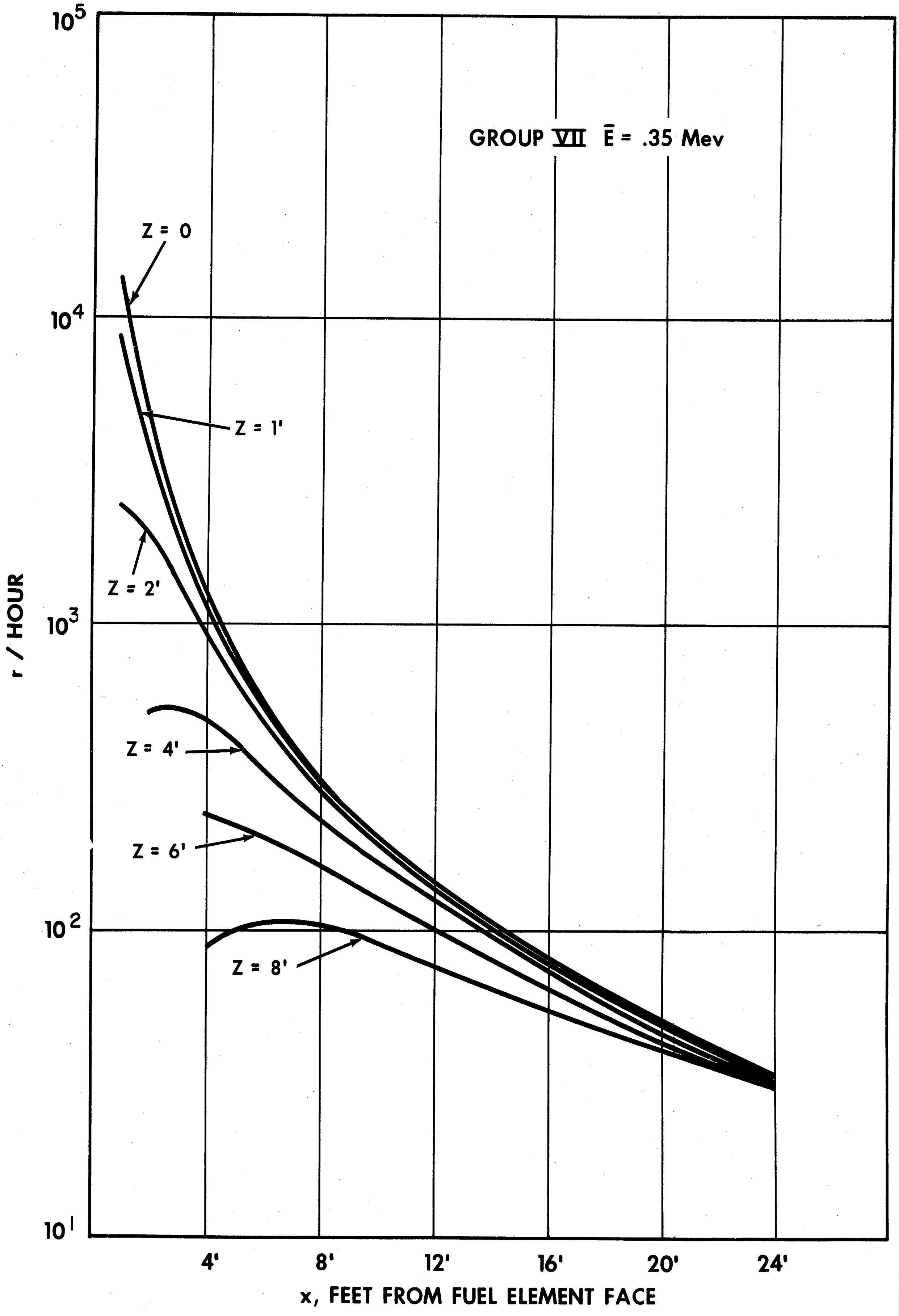


Fig. 12. Gamma intensity ($\bar{E}$ = 0.35 Mev) from a 30-day-old MTR fuel element vs. distance from element face.

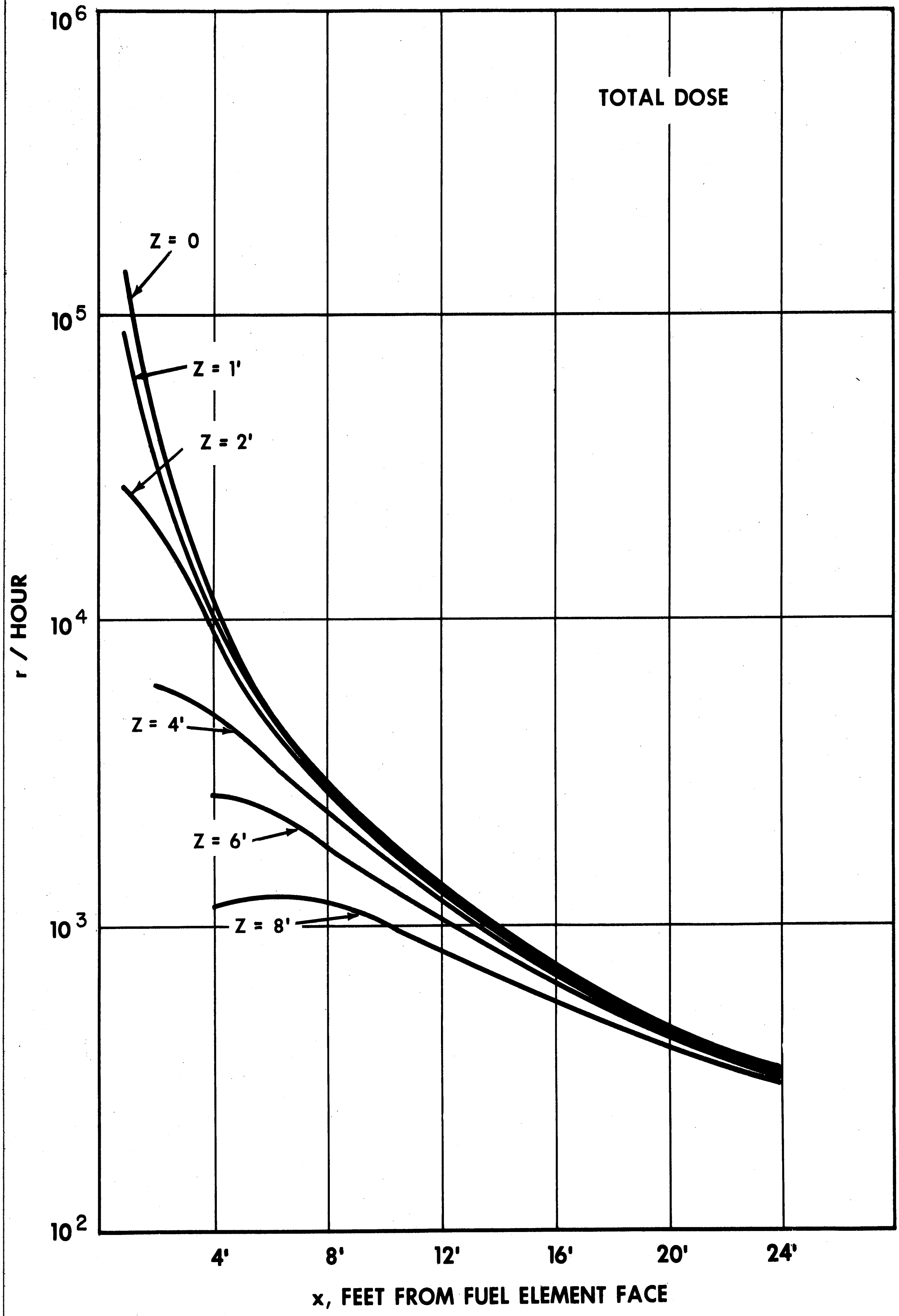


Fig. 13. Total intensity from a 30-day-old MTR fuel element vs. distance from element face.

are given in Figs. 14 through 17. Isodose curves for vertical planes (y = 0, 1, and 2) are given in Figs. 18 through 20.

III. THE SHIPPING CASK

A. GENERAL DESCRIPTION

The 10 source elements are arranged vertically in a rectangular shipping cask weighing approximately 25 tons. A scale model of the cask has been fabricated to demonstrate and test the operation of the cask-closing mechanism. Photographs of this model are shown in Figs. 21, 22, and 23.

Loading and unloading of the cask may be accomplished under water by removing the top plug with a crane and transferring the fuel elements with a long-handled tool. As an alternate method, this operation might be accomplished in a hot cave using a mechanical manipulator. Facilities necessary to accomplish this transfer operation are available at most reactors using MTR-type fuel elements.

In the design of the cask and source system, two general approaches may be taken: a mechanism may be designed to remove the source from the container and to position it in the irradiation chamber; or the source can be left within the cask and a means provided to remove the sides of the cask. The latter approach was decided upon to minimize the handling of the fuel elements.

The cask sides are pivoted on bearings at the bottom. Opening of the sides is accomplished by raising the cask with a hydraulic lift and allowing the doors to swing out against cams. (See Figs. 21-23 and also drawings E-101 and E-201 for details.) The sides are closed by merely lowering the cask.

The pivot point of each door is purposely placed to the inside of the center of gravity so that a force is available to aid the opening of the door as soon as the cask is slightly raised. The cams are designed to provide a uniform acceleration of the door movement at the beginning of the closing operation and a small deceleration towards the end of this operation. The speed at which the sides are closed can easily be controlled by regulating the rate at which the oil leaves the hydraulic lift cylinder. The vertical travel of the lift mechanism to open the sides completely is 18 in.

The advantages of this type of system can be summarized as follows:

1. The possibility of jamming the mechanical system resulting in a situation where the source cannot be safely closed up in the shipping cask is extremely small.

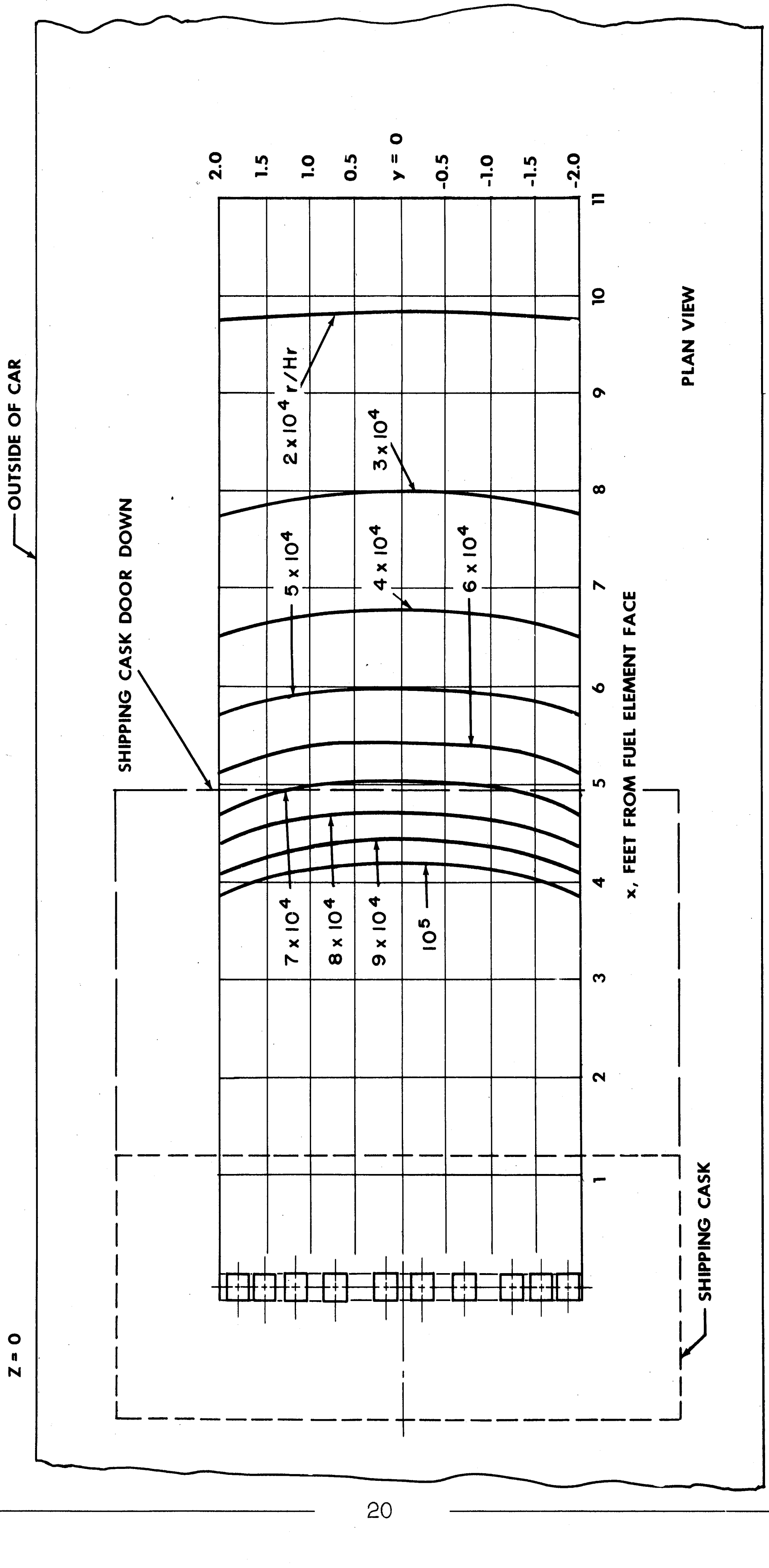


Fig. 14. Isodose curves on the horizontal plane, z = 0 ft.

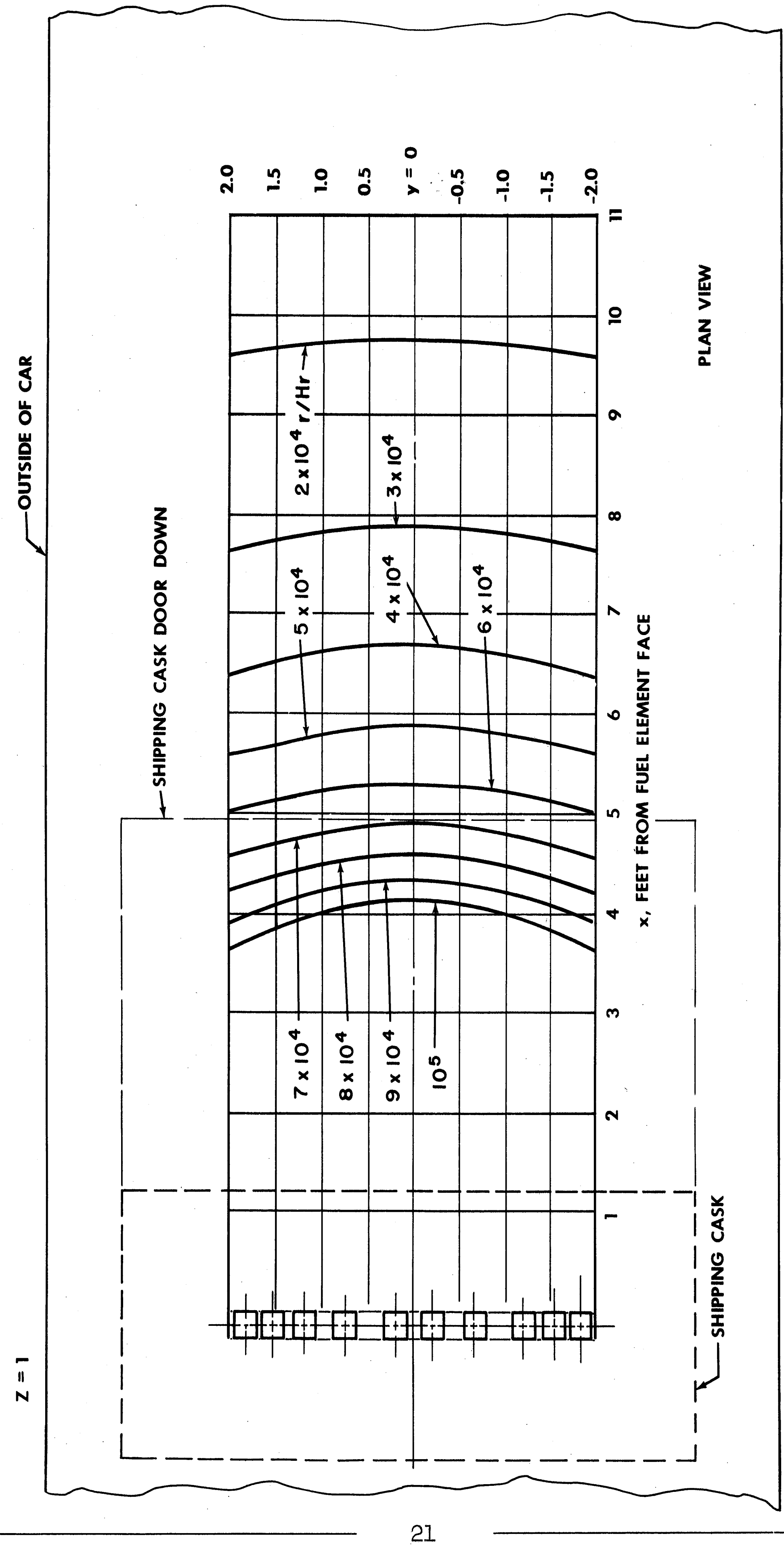


Fig. 15. Isodose curves on the horizontal plane, z = 1 ft.

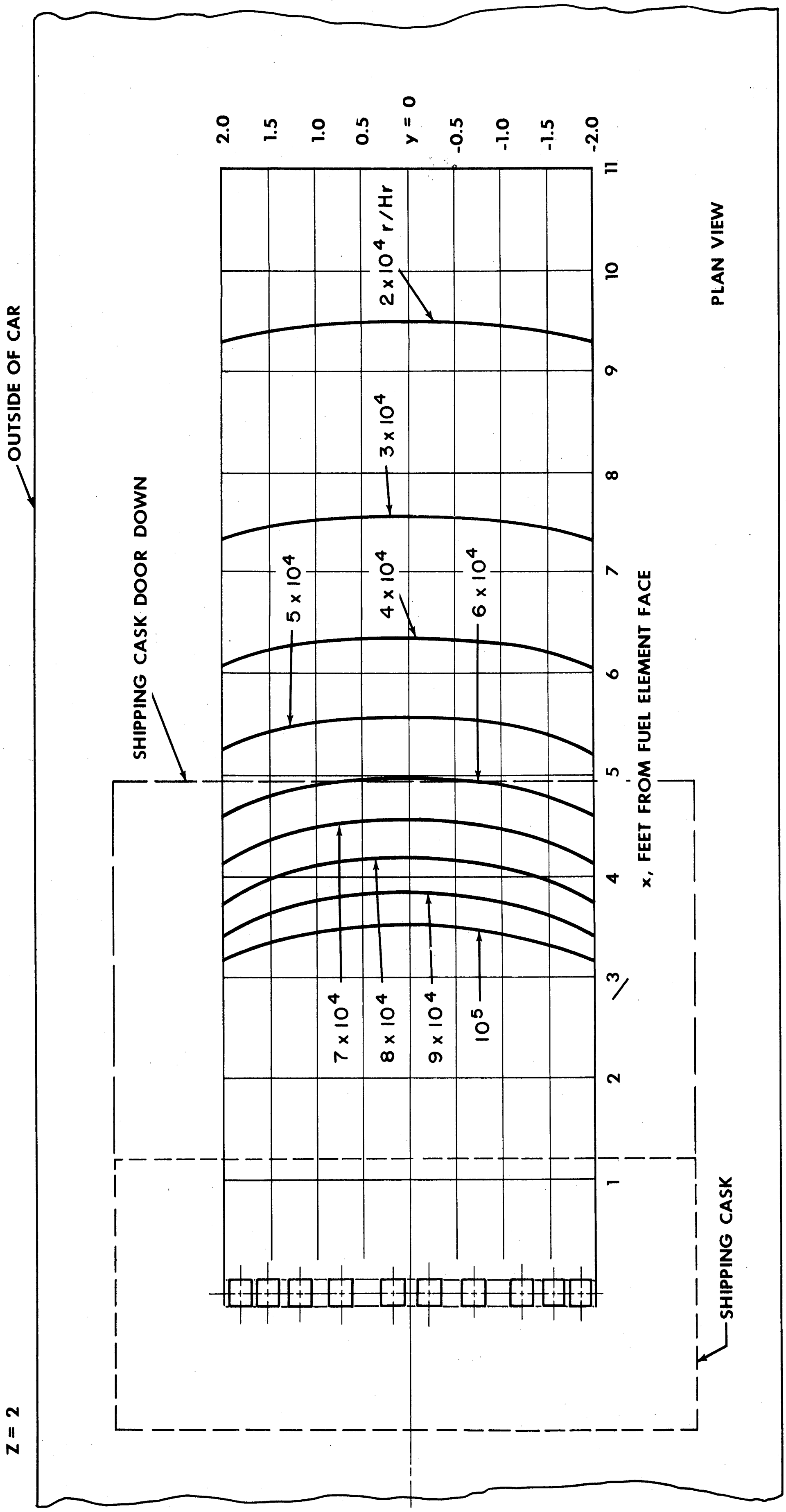


Fig. 16. Isodose curves on the horizontal plane, z = 2 ft.

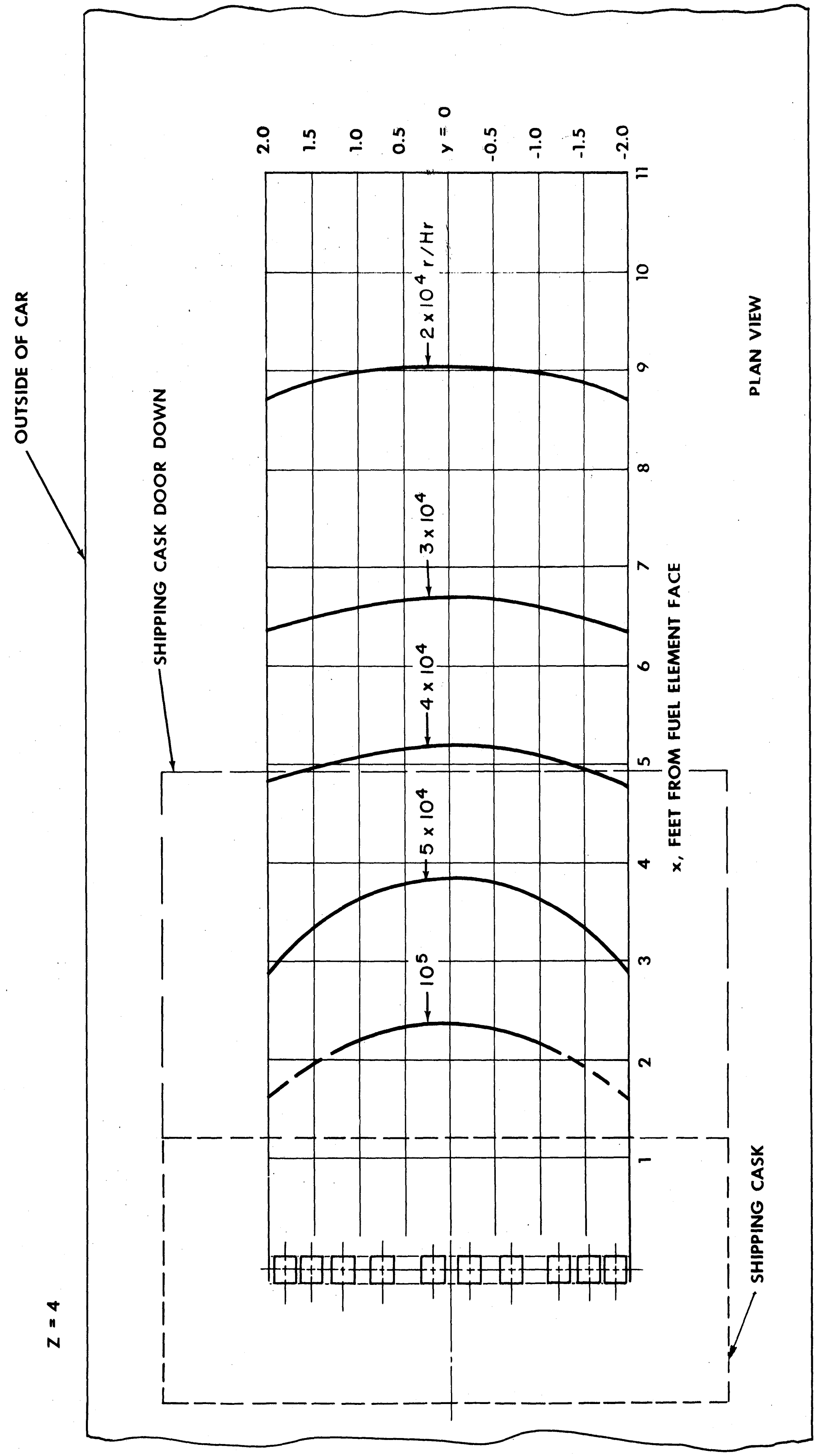


Fig. 17. Isodose curves on the horizontal plane, z = 4 ft.

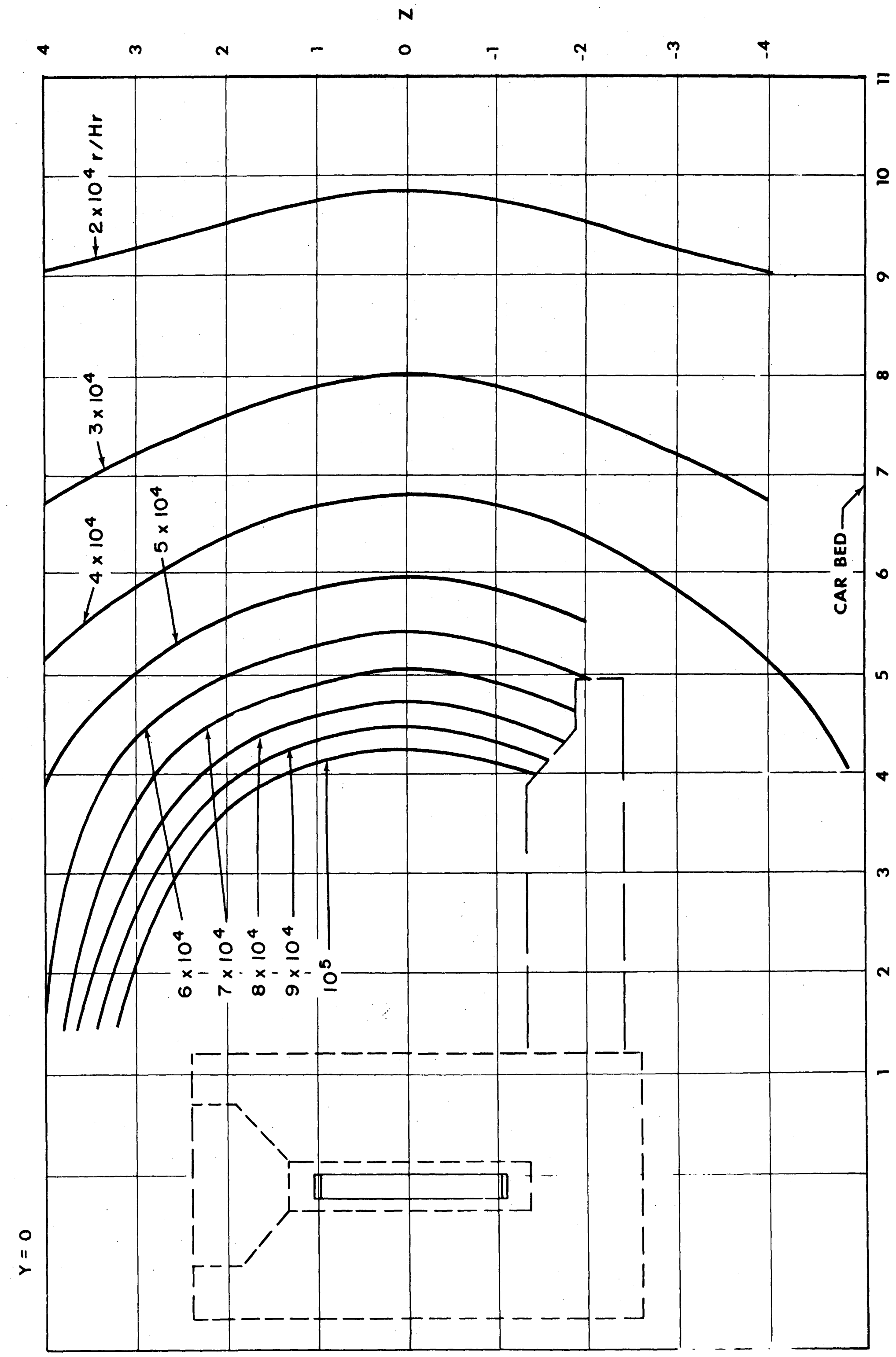


Fig. 18. Isodose curves on the vertical plane, y = 0 ft.

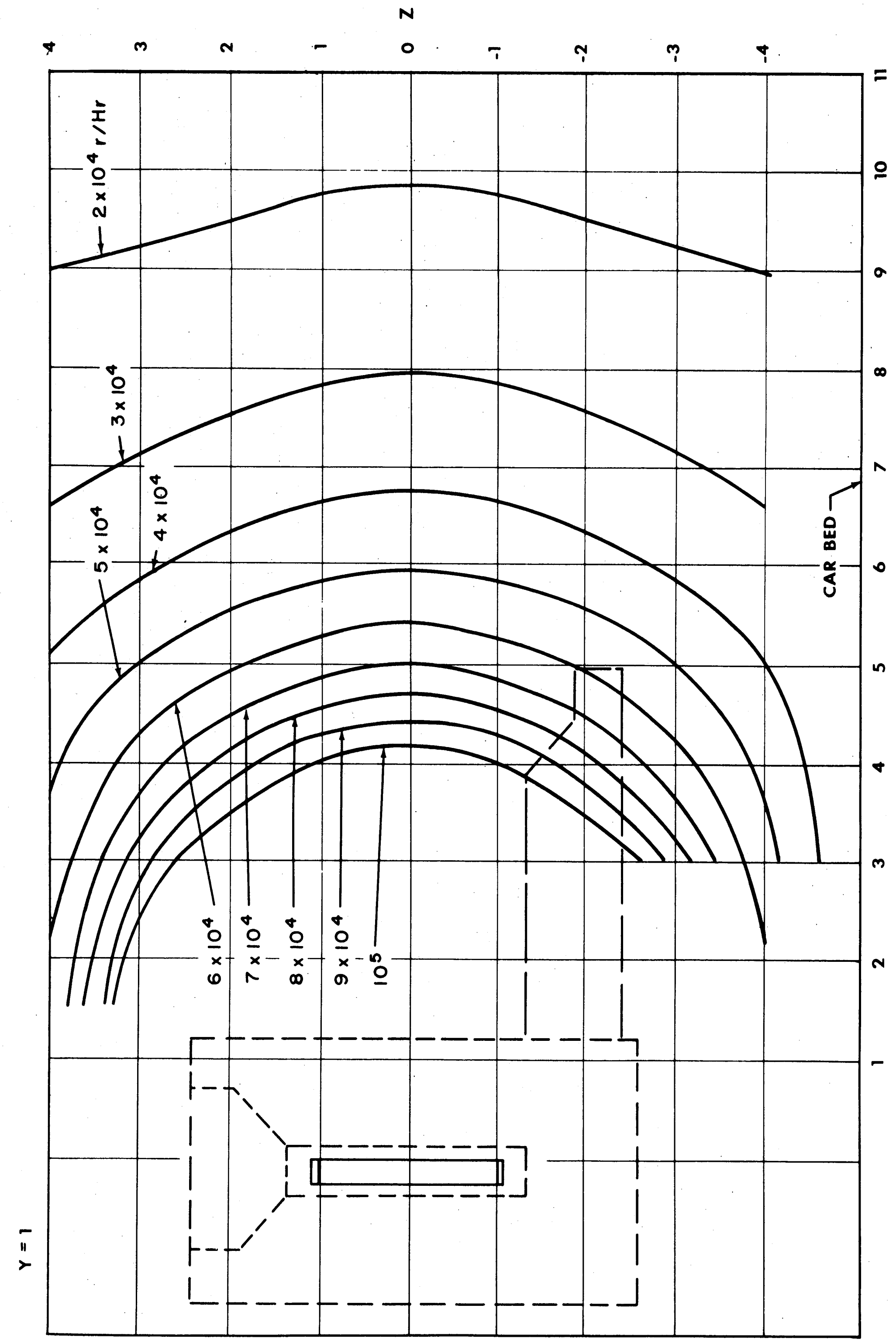


Fig. 19. Isodose curves on the vertical plane, y = 1 ft.

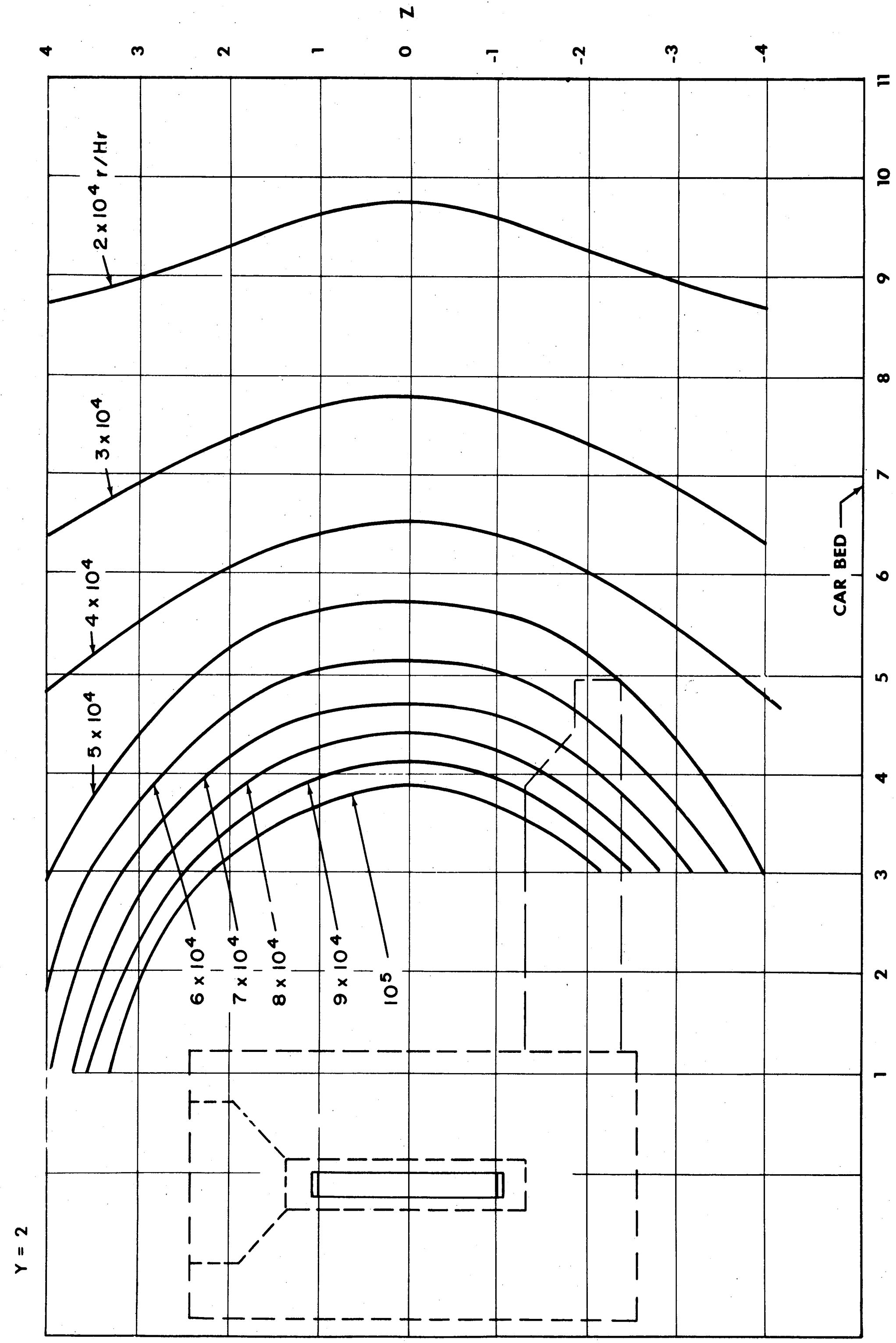


Fig. 20. Isodose curves on the vertical plane, y = 2 ft.

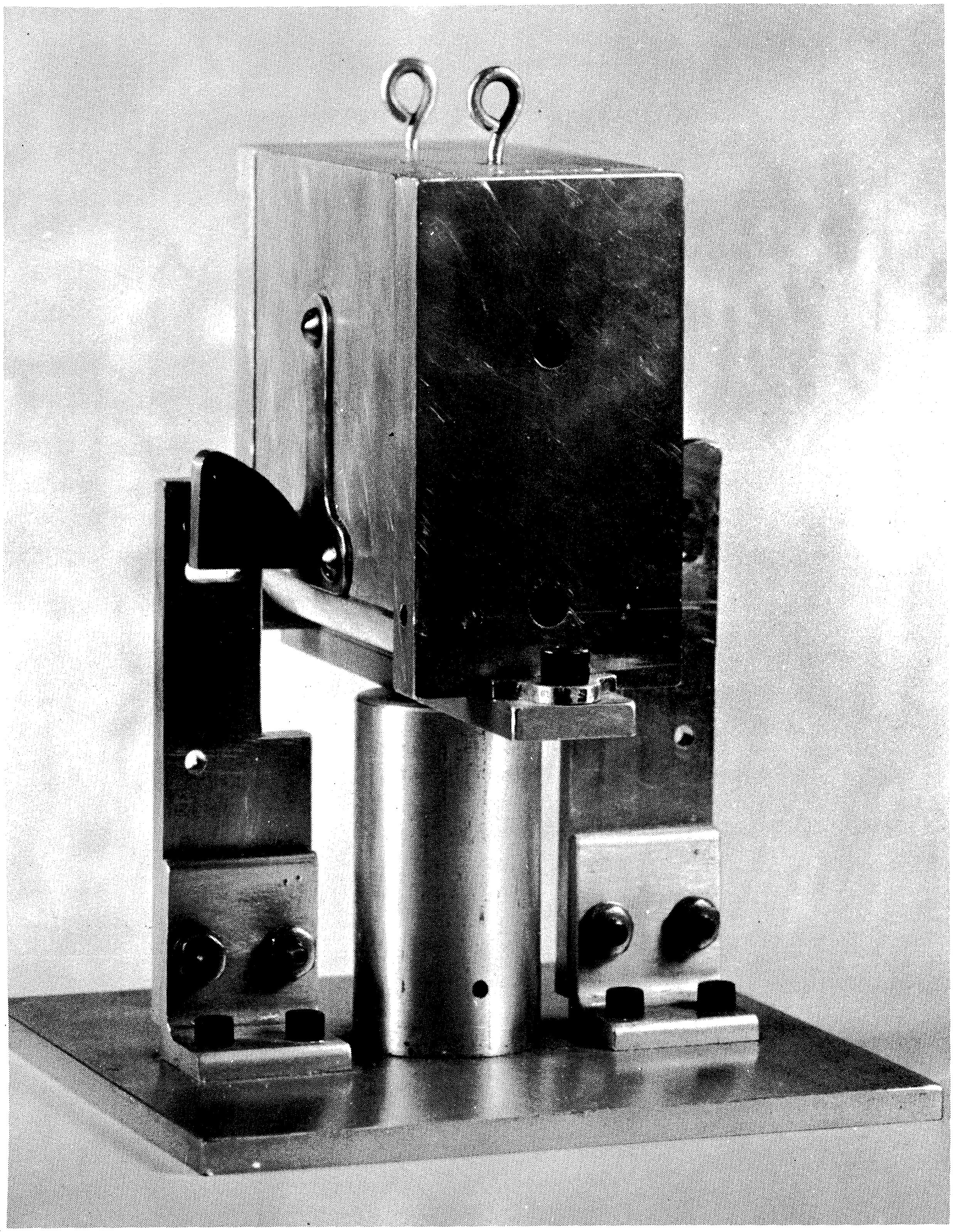


Fig. 21. The model shipping container closed.

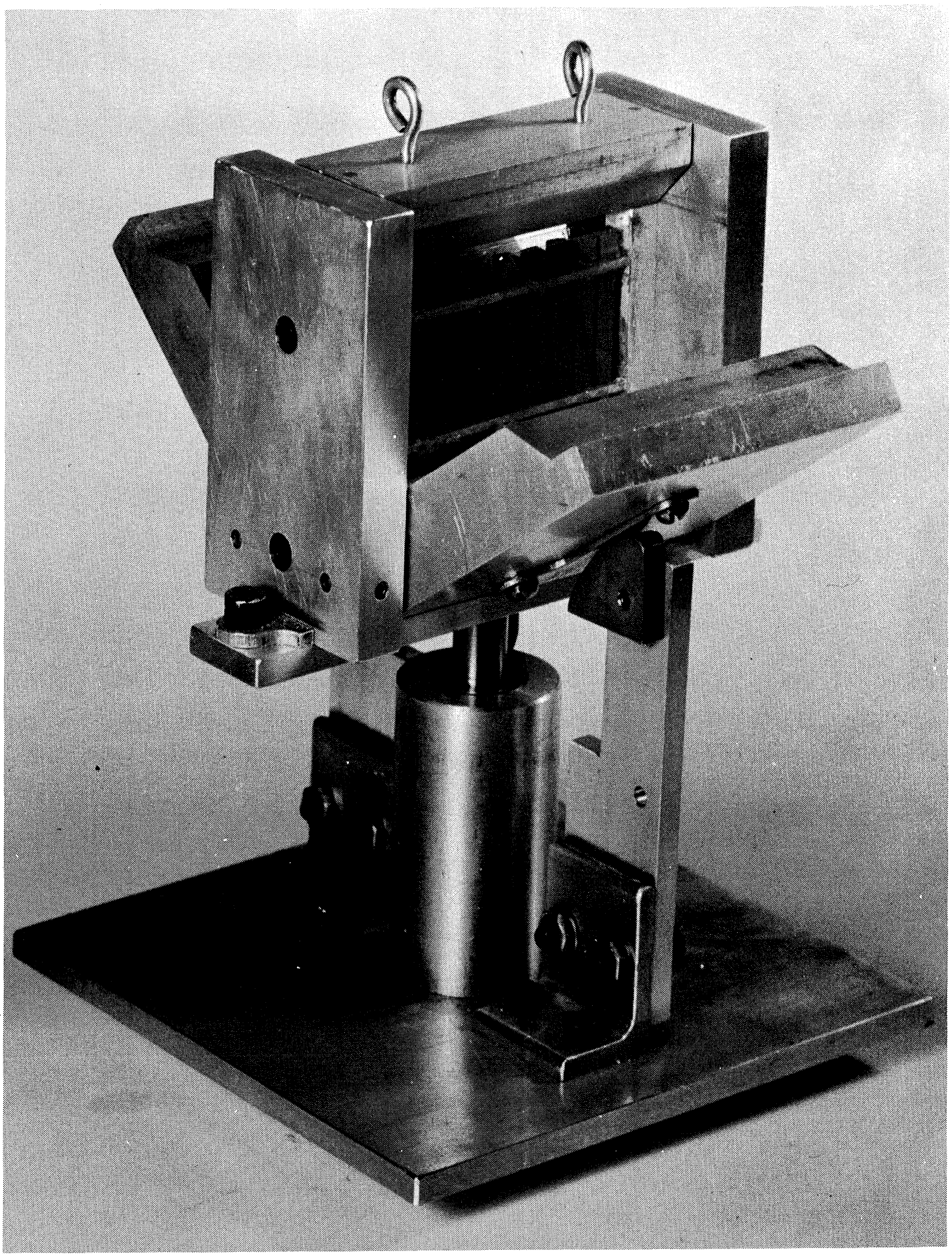


Fig. 22. The model shipping container partly closed.

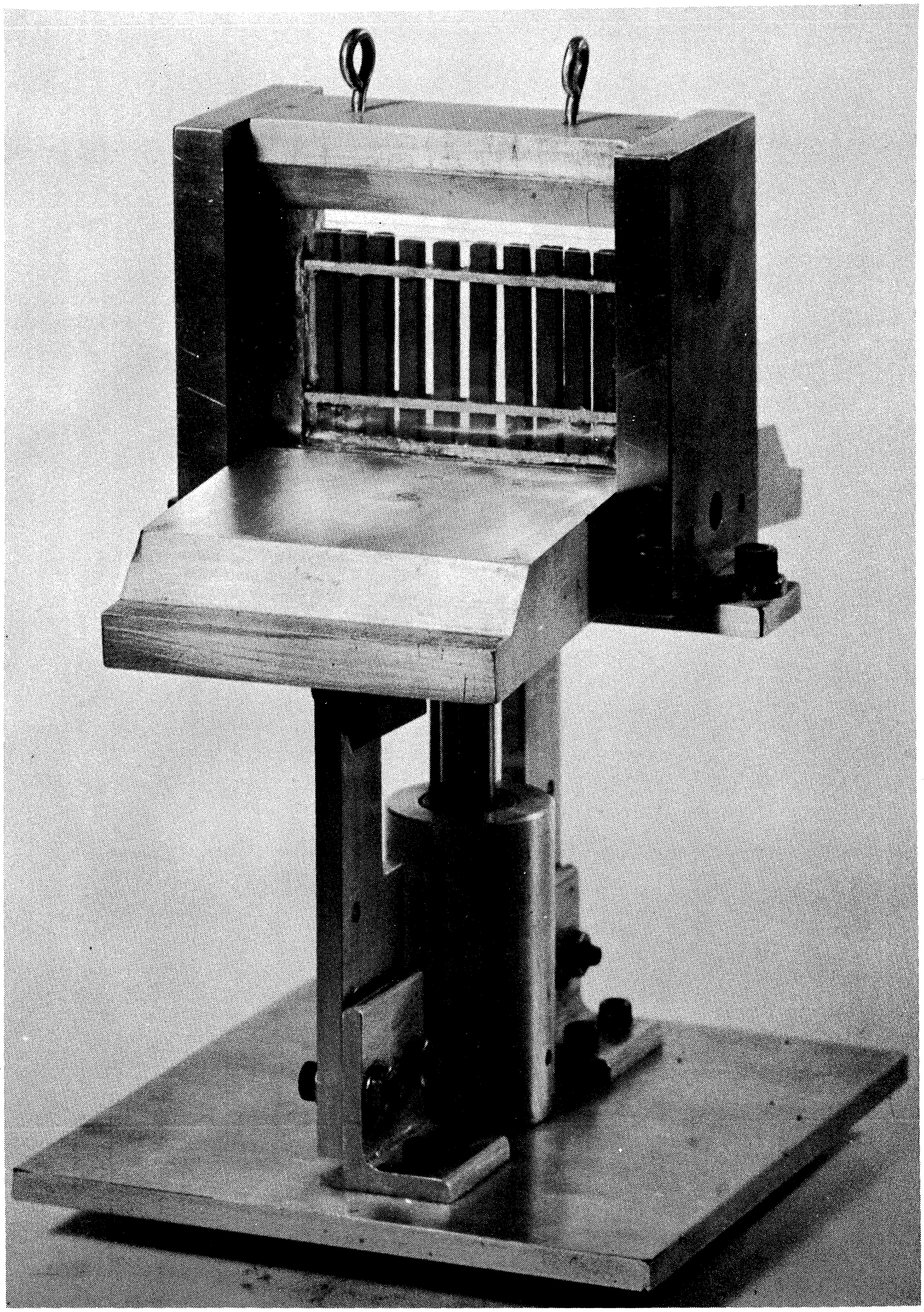
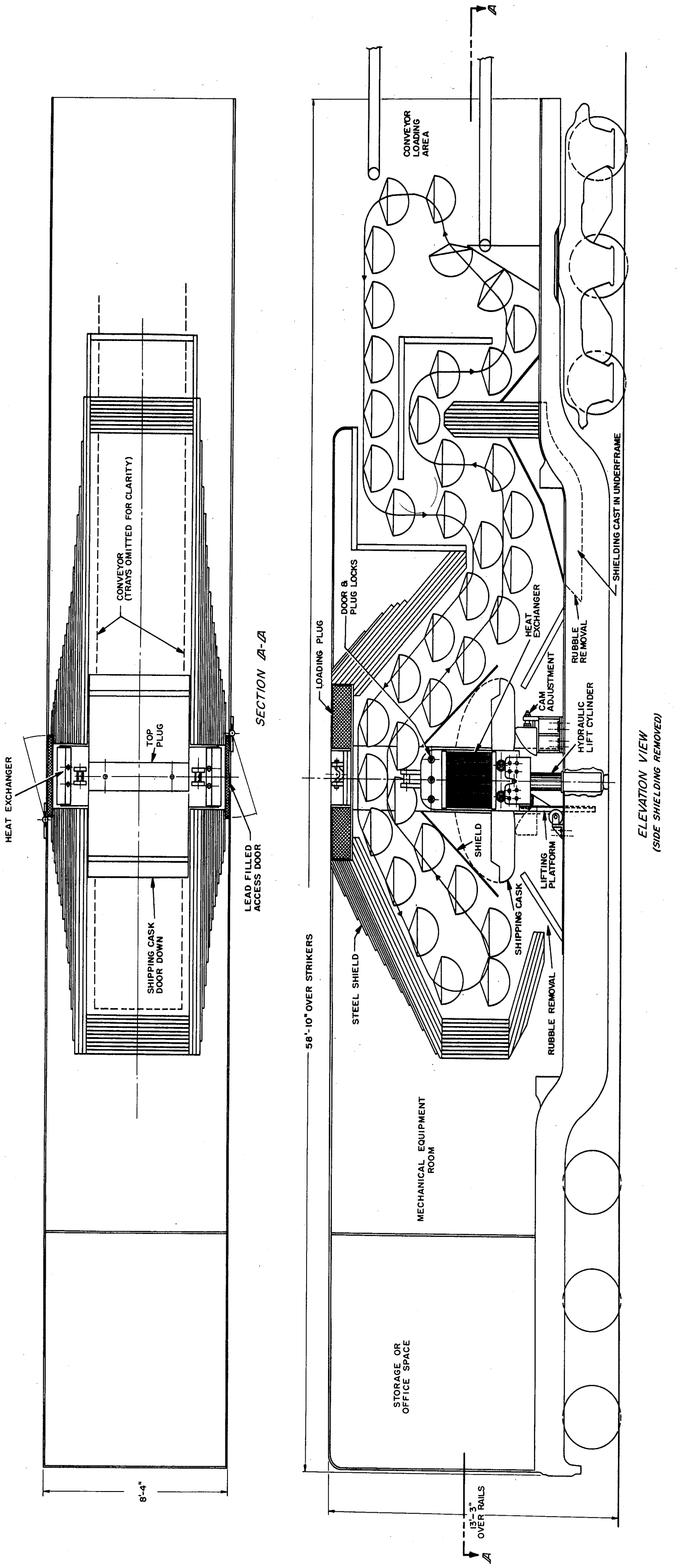
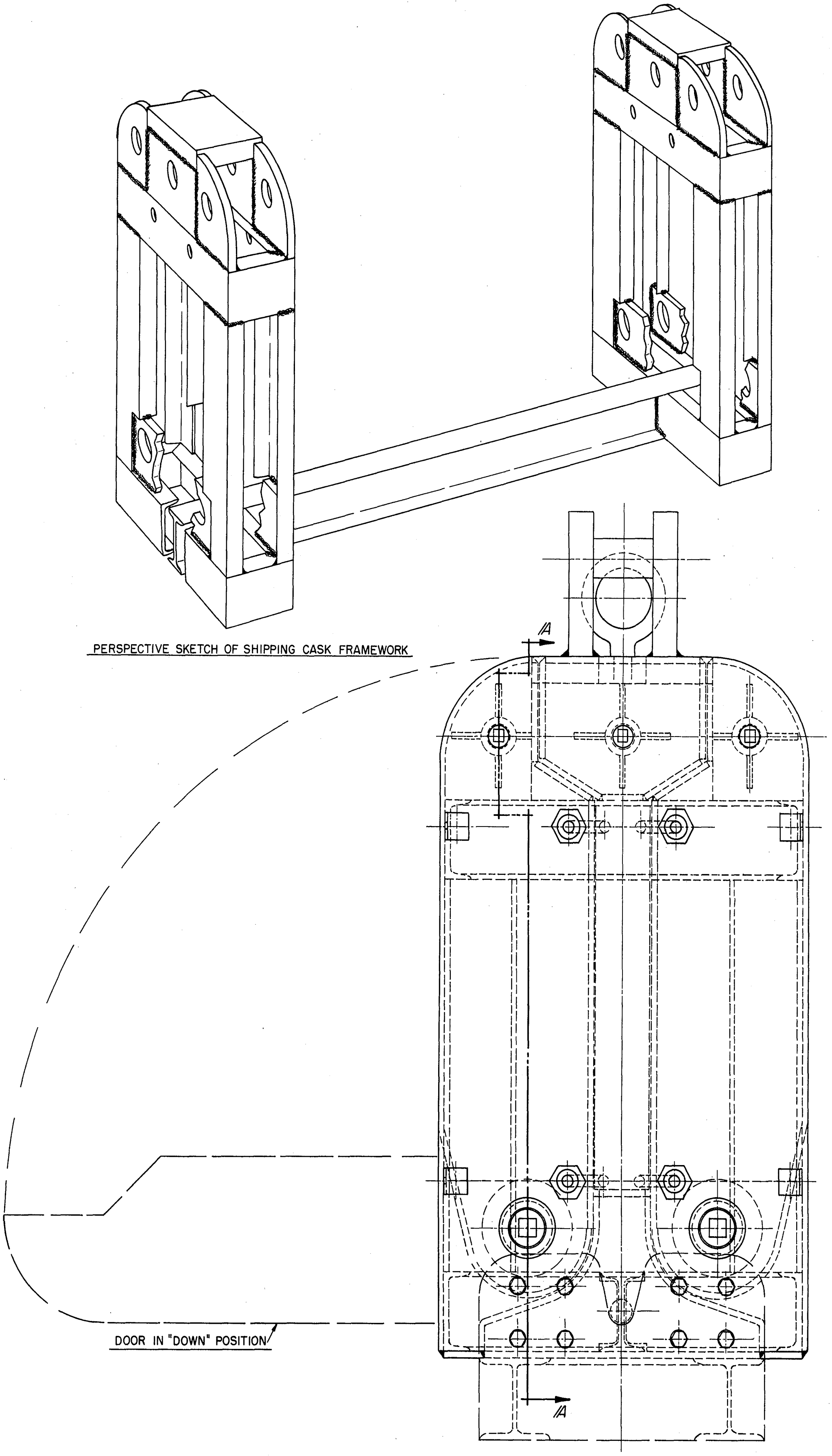


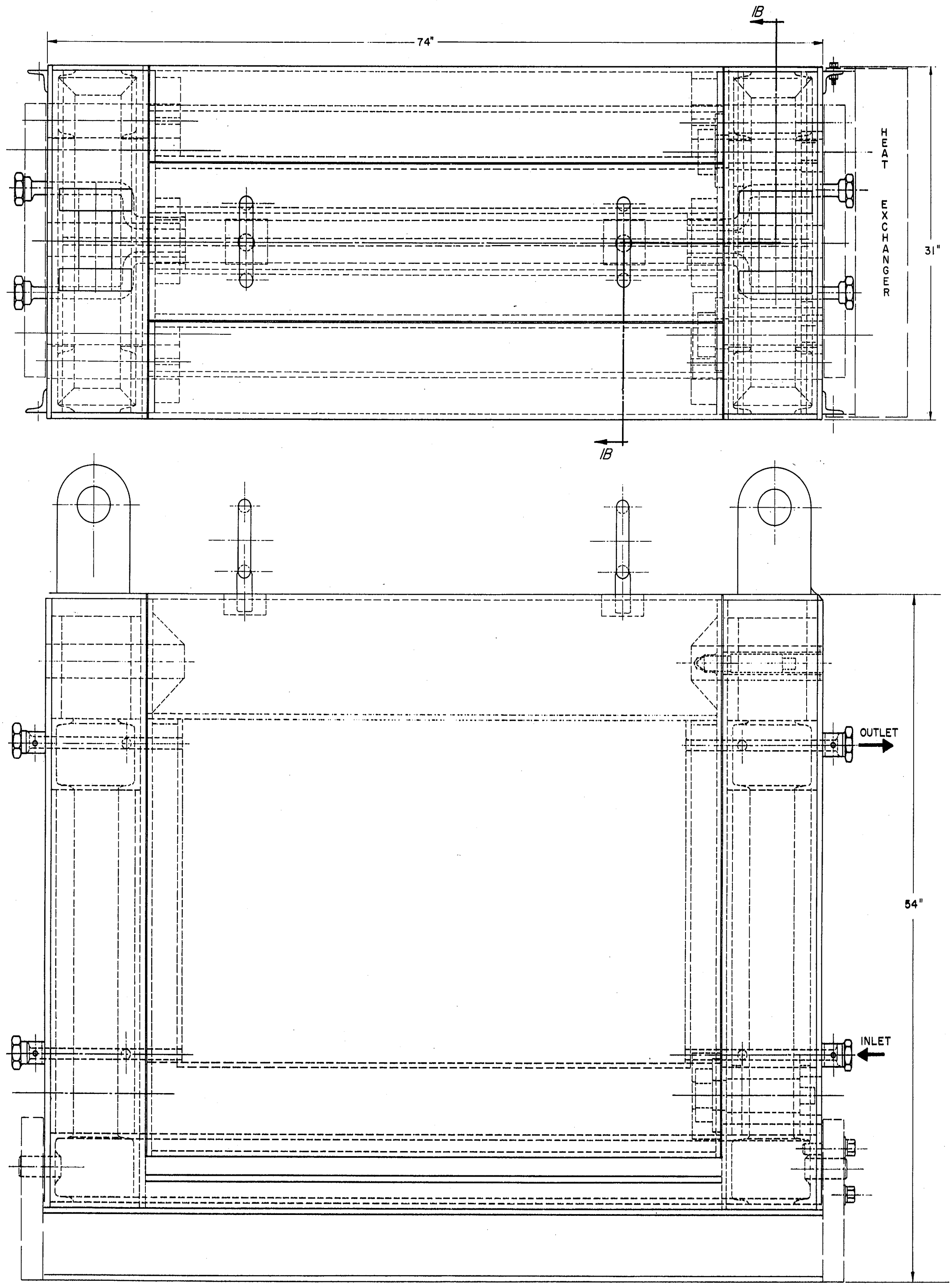
Fig. 23. The model shipping container open.



Drawing E-101. General layout of mobile gamma-irradiation facility.



Drawing E-201. Assembly view of shipping cask



Drawing E-201. (Concluded)

2. Any foreseeable mechanical failure cannot prevent the closing of the sides.

3. A major part of the shielding required for the car botton is provided by the doors when the cask is open.

4. No external power source is required to close the door.

5. When the car is being moved, the cask will always be closed and thus be at its lowest possible position in the car. The resulting dynamic center of gravity of the car (maximum limit 8 ft 4 in. above the rails) is much lower than would be possible with the cask in a fixed position.

6. In the event of an emergency, the cask can be quickly closed by simply opening a valve. This valve could be operated electrically, being tied into an interlock system. These interlocks resulting in the closing of the cask might be activated when:

a. radiation measuring devices reach a set limit;
b. either door providing access to the irradiation chamber is opened;
c. the conveyor stops, preventing overdoses of material in the irradiation chamber;
d. one of the manual switches placed at strategic positions about the car is pushed.

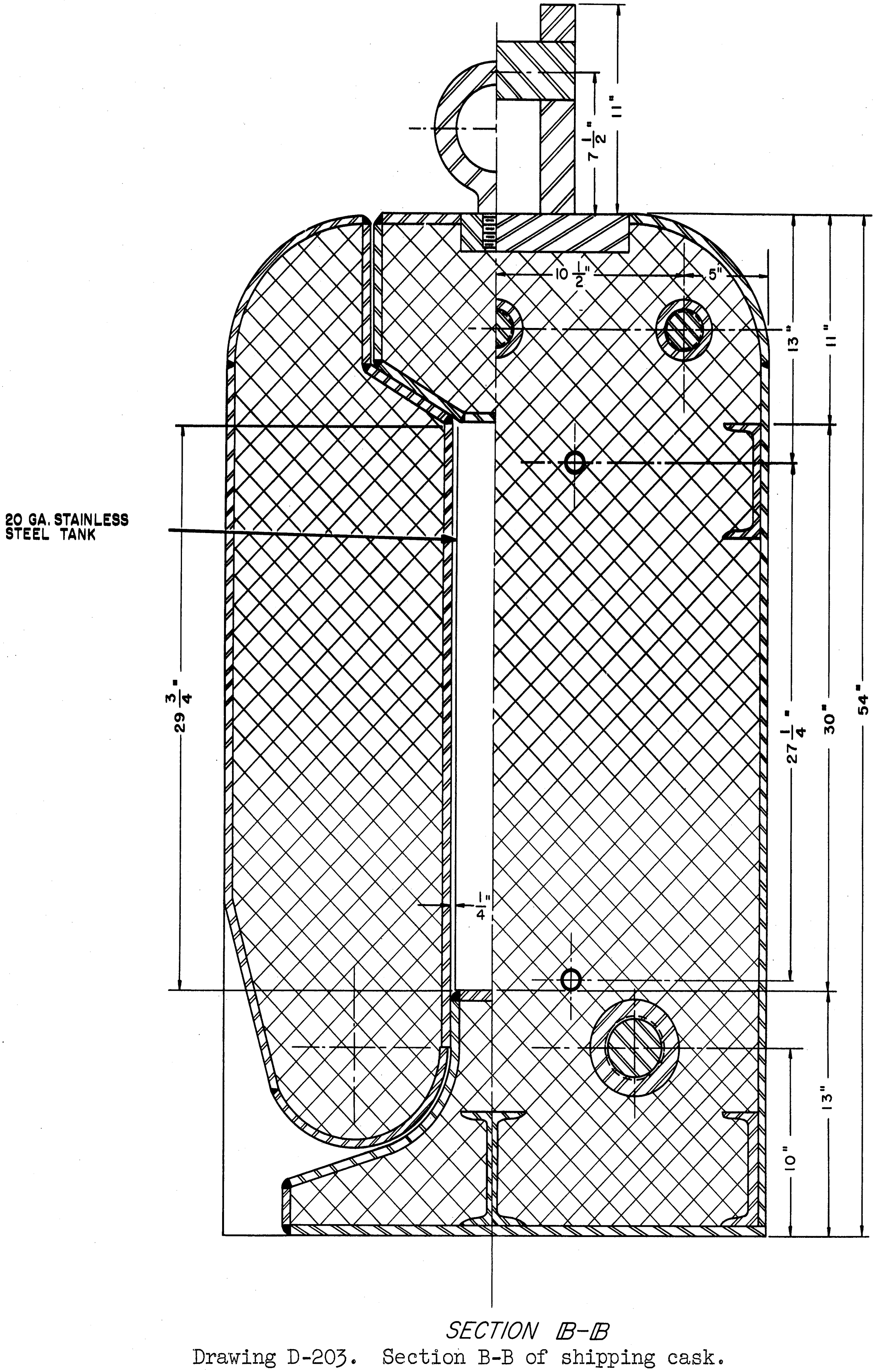
B. MECHANICAL DETAILS OF THE CASK ASSEMBLY

The lead-filled cask is designed to take loads and rough handling far in excess of that normally expected. The heart of the cask structure is a skeleton constructed of 6-in. channels, a 6-in.-wide flange beam and steel plates (see drawing E-201). The sides are pivoted on self-aligning spherical bearings. Heavy brackets are provided to which a lifting hook can be attached so that the cask may be handled with a crane. Two eyes are attached to the top plug to facilitate the fuel-element loading and unloading operation. These eyes are removable to provide clearance for the conveyor trays during the operation of the unit (see drawings E-201 and D-203).

Pins are welded to the cask structure near the bottom to aid in the positioning of the cask on the lifting platform. Positive attachment to the lifting platform is provided by sixteen 1-in. cap screws.

The lifting platform consists essentially of two 6-in.-wide flange beams. The following specifications are proposed for the double-acting hydraulic cylinder which raises the lifting platform:

Bore - 8-7/16 in.
Stroke - 19 in.
Capacity at 1000 psi: push - 55,860 lb; pull - 50,952 lb



SECTION B-B

Drawing D-203. Section B-B of shipping cask.

Under normal operating conditions, the downward power stroke will not be utilized and the associated oil supply will be valved off. Oil pressure to power the downward movement of the lifting platform will be used only as a last resort in an effort to close the cask in the case of jamming. Jamming could conceivably be caused by poor adjustment of the cams or the presence of a foreign object between either the cam surface and a door or between a door and the main cask structure. A shield is provided around the whole cask assembly to prevent material from falling from the conveyor trays into the mechanism.

Horizontal adjustment of the two closing cams on each side of the cask is provided by a screw mechanism which may be locked into position. Once the adjusting screw is locked into position there can be no horizontal movement of the cams in the direction towards the cask. The horizontal movement of each set of cams in the direction away from the cask is restrained by a heavy compression spring (see drawing E-301). In the event that oil pressure must be used to close the cask because of a jam, the two springs are designed with sufficient compression to prevent failure of any major part. Under normal operating conditions, if the cams are adjusted properly, there should be little or no compressive action by the springs.

Locking mechanisms are provided both to lock the top plug in position and to lock the doors in a closed position when the unit is not operating (see drawing D-202). These mechanisms are designed so that they can be operated only with a special tool. Access to the locking mechanism, the cask-cooling system, and the irradiation chamber may be provided through a steel-clad, lead-filled door.

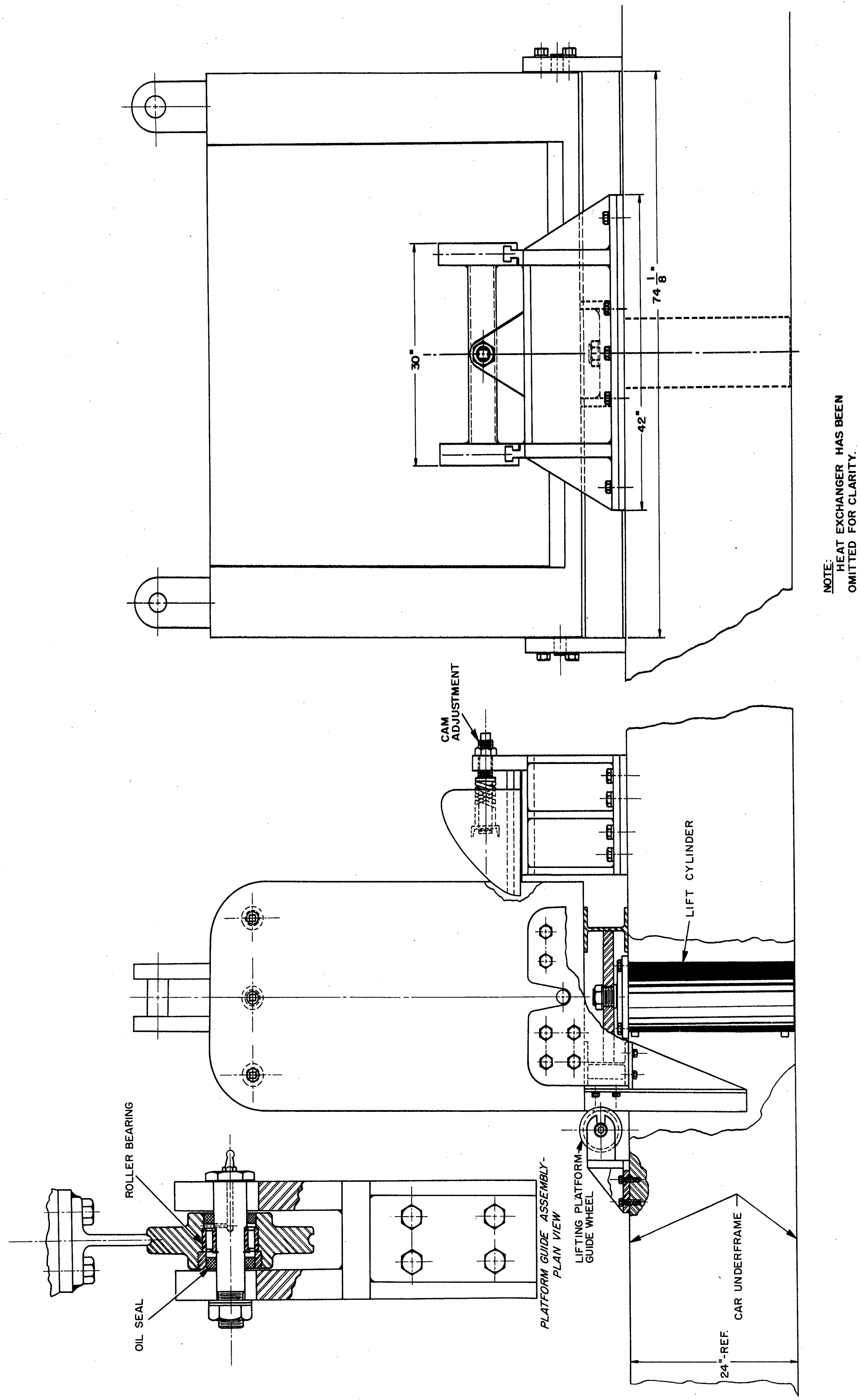
In addition to the locking mechanisms described above, a steel frame has been designed to be placed around the cask during shipment. Its use is proposed in an effort to reduce completely the possibility of the cask being opened by deliberate action or as a result of an accident.

The lifting platform is kept in alignment during operation by two T-shaped beams riding on guide wheels (see drawing E-301 for details).

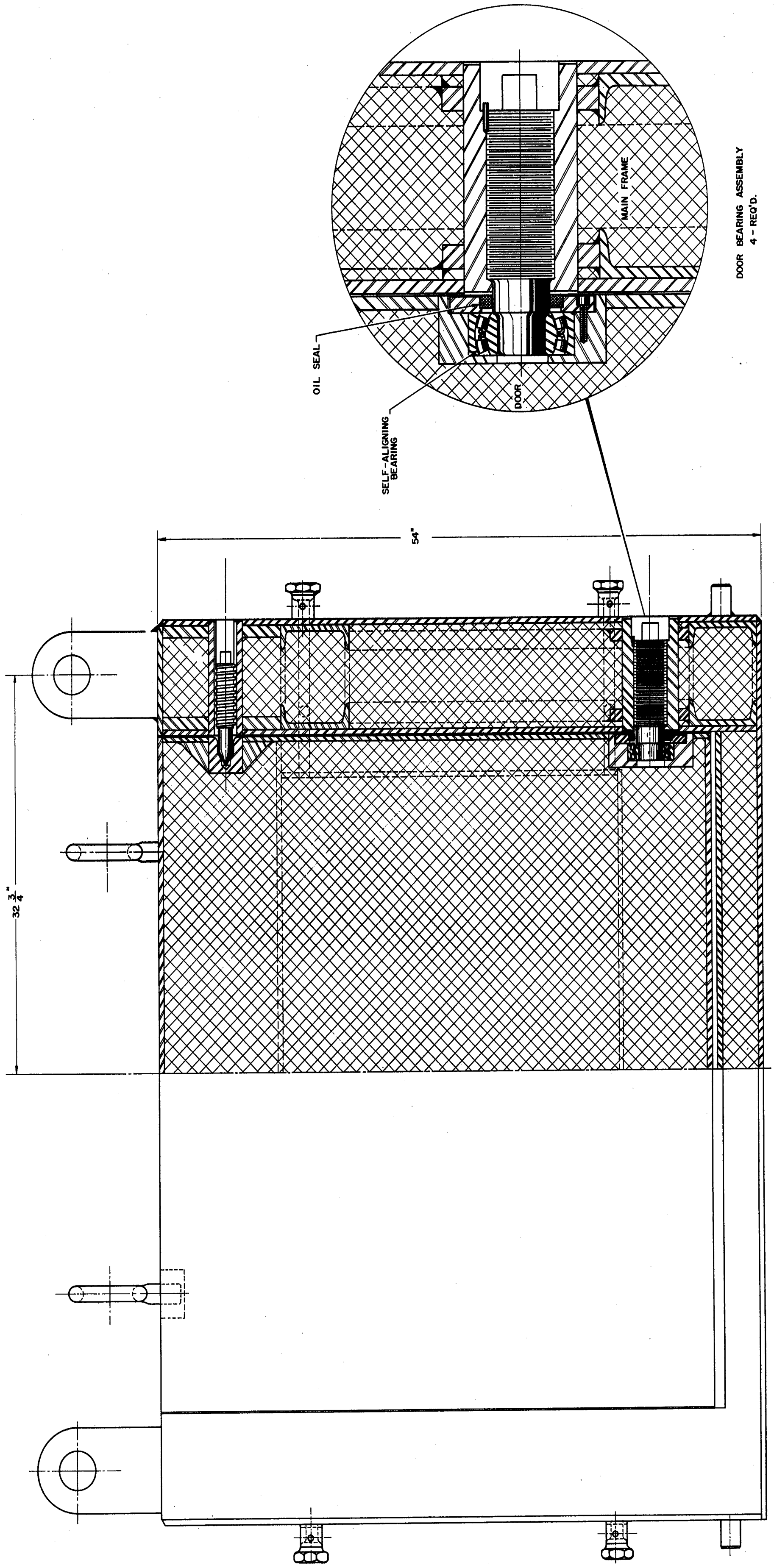
C. DESIGN OF THE COOLING SYSTEM FOR THE SHIPPING CONTAINER

In the design for the shipping container, it was necessary to take into consideration the heat produced by the absorption of beta and gamma radiation not only in the fuel elements themselves but also in the container. It was decided that the heat would be removed by circulating the water in the inner container through a heat-exchange system by which the heat is rejected into the atmosphere. The system is designed so that both the water and the cooling air will flow by natural convection, eliminating the problems inherent in power failure in the case of a forced convection system.

The heat-exchange system consists of two identical heat exchangers,



Drawing E-301. Lifting platform assembly.



Drawing D-202. Section A-A of shipping cask.

one mounted on each end of the shipping cask. The design heat load on each exchanger is 5,400 Btu/hr, this being the heating rate corresponding to 10 MTR fuel elements, all 30 days old (see Fig. 24). (As the fuel elements age, the heat load drops off approximately exponentially; thus the heat-transfer calculations presented here represent the most severe anticipated operating conditions of the system.) The temperature of the hot water entering the exchanger was taken to be 170°F, which is below the boiling point of water at any altitude where the shipping container would be used. The temperature of the ambient air was taken as 100°F, and the over-all heat-transfer coefficient was taken as 1.5.[4]

Based on these parameters, a "reasonable" geometry for the heat exchanger was established and then the temperature of the water leaving the exchanger was computed. This was found to be 103°F, indicating that the heat exchanger was grossly overdesigned. However, the geometry originally selected was retained, the overdesign serving as a factor of safety. If a storage source is to be substituted in the future, i.e., cesium-137, there need be no change in the heat-exchanger size.

The following considerations governed the design of the heat exchanger. Since the water was to flow in natural convection, the only driving head for the flow was provided by the density difference of the water flowing in and out of the exchanger, for the given height of the exchanger. Thus a great pressure loss due to flow in the exchanger could not be tolerated; this pointed to a parallel-flow system. It was realized that with both the water and coolant air flowing in natural convection, a large heat-transfer area was necessary. This was obtained through the use of externally finned tubing (see drawing C-204).

The design parameters for the exchanger are as follows:

1. There are 54 finned tubes in three rows, 18 tubes per row, spaced on 1-5/8-in. centers.

2. The tubes themselves are 9/16-in. OD, 21 BWG.

3. There are 16 fins/tube; each fin is 1/2 in. high and 0.032 in. thick (21 BWG).

4. The tubes are manifolded into headers consisting of boxes fabricated of steel. The header dimensions are 30 x 5 x 2-1/2 in.

More complete details of the heat-exchanger design may be found in drawing C-104.

Once a heat exchanger has been constructed, it may be desirable to test its operational capacity using electrical heating as a substitute for fuel elements.

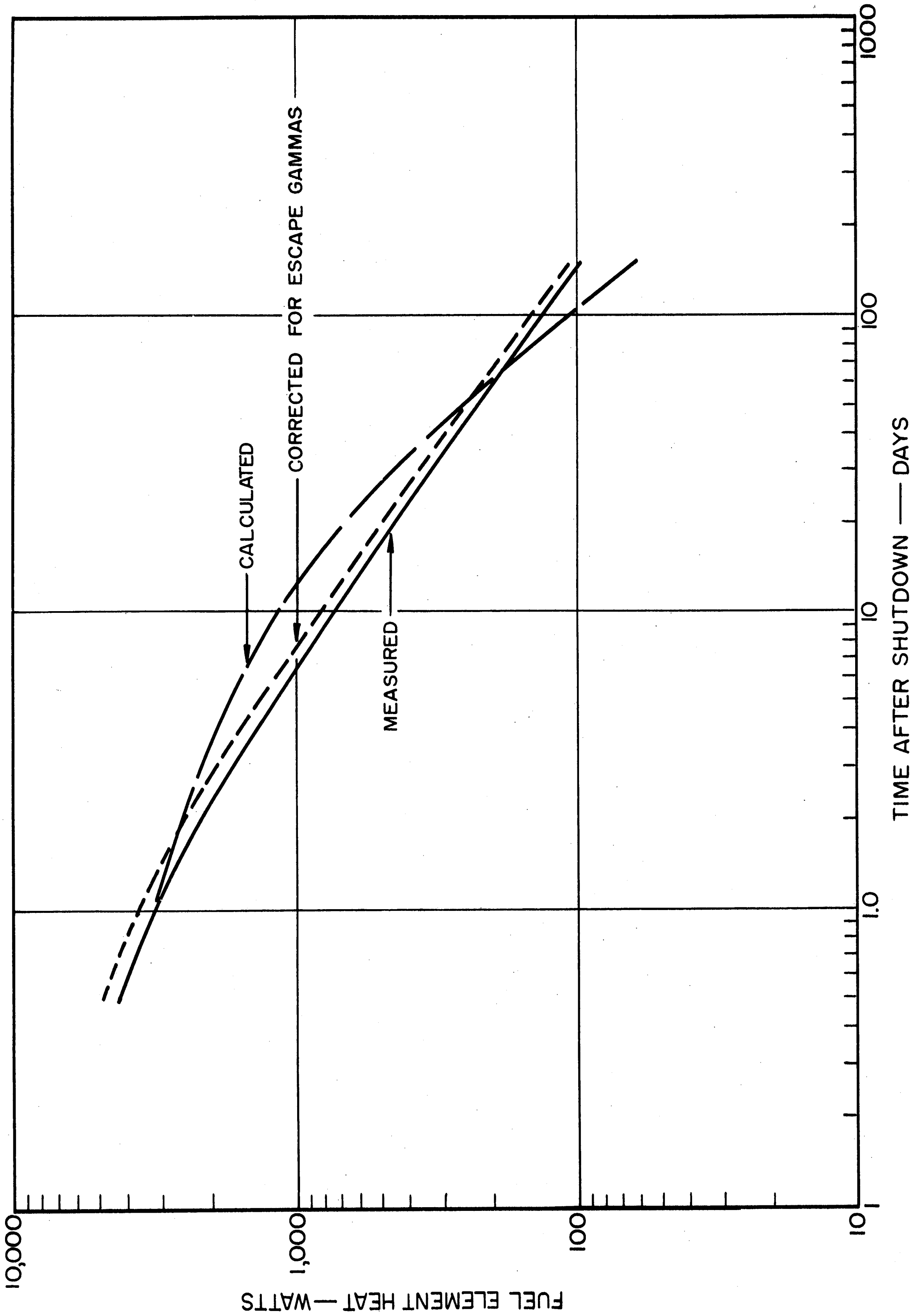
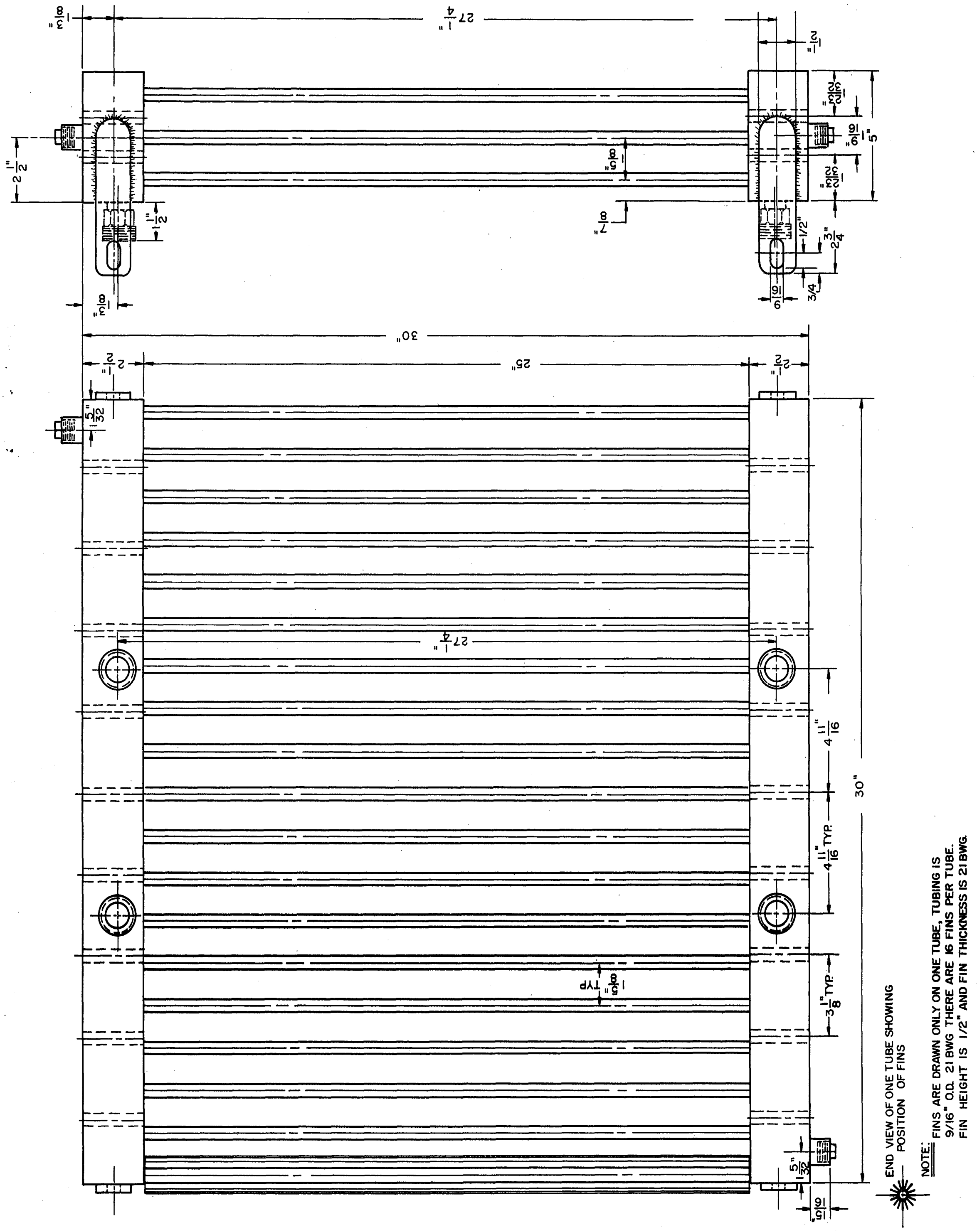


Fig. 24. Heat (generated) production from spent MTR fuel elements.



Drawing C-204. Preliminary layout of heat exchanger (two required).

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